WHEN TRUST MATTERS

ENERGY TRANSITION NORTH AMERICA 2023

A regional forecast to 2050

FOREWORD

2023 marks the 125th anniversary of DNV's operations in the USA. We are celebrating this milestone with this deep-dive report on the energy transition in North America. This forecast showcases the advances being made by our customers towards a clean energy future along with the insights from our expert teams across North America who are working with those customers today to qualify, certify and advise on the energy infrastructure of tomorrow.

The passage of the Inflation Reduction Act and the refocused Canadian Federal Budget provide extra impetus for this forecast. As we explain more fully in the pages that follow, these policy packages are a major boost for clean energy in North America. They are accelerating the buildout of renewable energy and the growth of whole new demand sectors for that clean energy, from EVs through to electrolyzers producing green hydrogen.

Over the past year or so, any serious energy forecaster, including DNV, has had to revisit their views on North America, which is now moving closer to achieving its climate pledges. That is remarkable, considering how historically dependent North America has been on fossil fuels. In fact, over the next three decades North America will be responsible for fully half of the global reduction in crude oil use primarily through the electrification of road transport, and the indirect electrification via hydrogen of other major demand sectors like maritime, aviation and manufacturing.

By more than doubling electrification in the region and transitioning to an almost fully decarbonized electricity mix, vast amounts of energy waste will be eliminated in North America. Combined with the plunging costs of renewables and battery storage, the positive impacts of reduced energy intensity on economic activity are profound. This includes our finding that the average North American household will be spending only half as much on energy in 2050 compared with today.

That the green shift comes with such an upside for so many suggests that North America should set its sights on an even faster transition, including an urgent focus on electricity transmission and distribution infrastructure. DNV stands ready to work with our North American customers to achieve that.

Remi Eriksen

Group President and CEO

DNV

HIGHLIGHTS

- **The IRA has accelerated North America's energy transition**
  - The energy-industrial policy incentivizes wind, solar, storage, low-carbon hydrogen, carbon capture technologies as well as regional manufacturing, and supports historically fossil-fuel dependent and underserved communities
- **Grid and renewables are a USD 12trn opportunity with clean CAPEX overtaking fossil CAPEX by 2040**
- **Fossil fuel demand declines 60%, mainly in transport and power sectors, but export remains stable while domestic use is declining**
  - Falling oil use in North America accounts for almost half of the global oil demand reduction by 2050
- **Household energy expenditure halves by 2050 driven by higher energy efficiencies mainly associated with a cleaner, cheaper energy mix**
- **Electrification share doubles to 41% and is a substantial driver for the North American transition, driven by strong growth in transport, buildings, and manufacturing**
- **The energy transition is still not fast enough to reach net-zero**
  - 1.3 $GtCO_2$ annual emissions remain even in 2050

HIGHLIGHTS

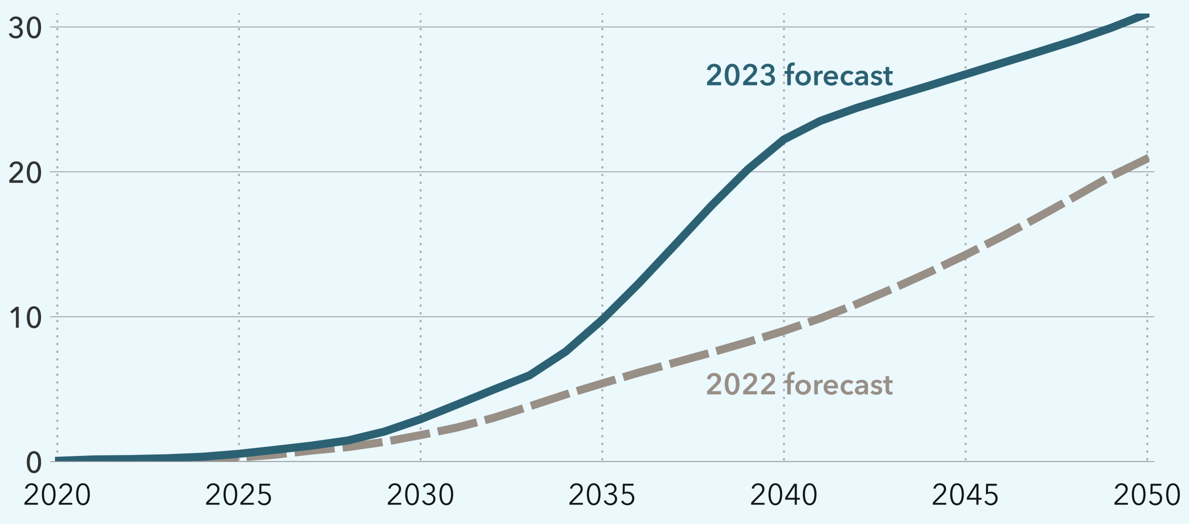
The IRA has accelerated North America's energy transition

The energy-industrial policy incentivizes wind, solar, storage, low-carbon hydrogen, carbon capture technologies as well as regional manufacturing, and historically fossil fuel dependent and underserved communities. This year's forecast for solar + storage as a percentage of the electricity mix jumps from 5% last year to 17%, while green hydrogen from dedicated renewables rises from 20% to 35%, overtaking blue hydrogen production by 2040.

HIGHLIGHT 1

Hydrogen production

Units: MtH_2/yr



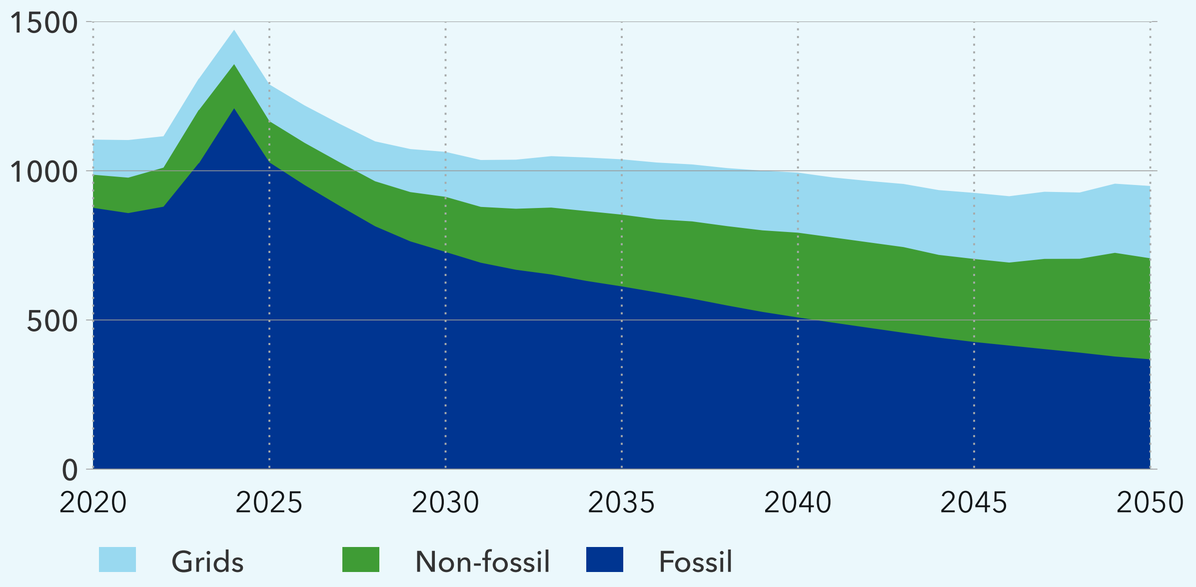
Grid and renewables are a USD 12trn opportunity

By 2050 a cumulative USD 12trn will be spent on clean energy in North America, comprising USD 7trn invested in clean energy sources, including nuclear and hydrogen, and a further USD 5trn on grids and operational expenditure. Non-fossil CAPEX overtakes fossil CAPEX by 2040, making energy and its transmission cheaper and cleaner. Cumulative solar investments of USD 2.3trn, and wind investments of USD 1.6trn will power the renewables market, along with storage solutions. The trend has been firmly set by the USD 240bn already committed in clean investments in the US, as part of the IRA.

HIGHLIGHT 2

Energy expenditures

Units: billion USD/yr



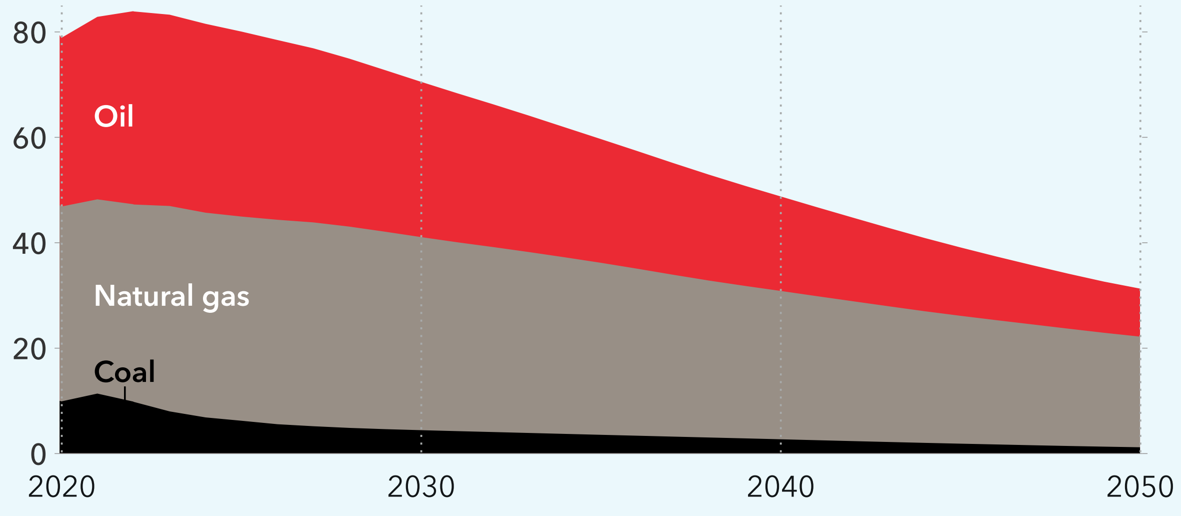
Fossil fuel demand declines 60%, mainly in the transport and power sectors, but exports remain fairly stable

Coal use declines by 80%, oil by 75% and natural gas by 40%. Reduction of oil in North America accounts for almost half of the global oil demand reduction by 2050. Coal demand peaked in 2000, oil demand peaked in 2021, gas demand is forecast to peak in 2024, while production reduces due to declining domestic demand through to 2050. Electrification of transport leads to a drastic cut in oil demand, while coal is phased down in power sector due to the rise of solar and wind.

HIGHLIGHT 3

Fossil fuel primary energy consumption

Units: EJ/yr



HIGHLIGHTS

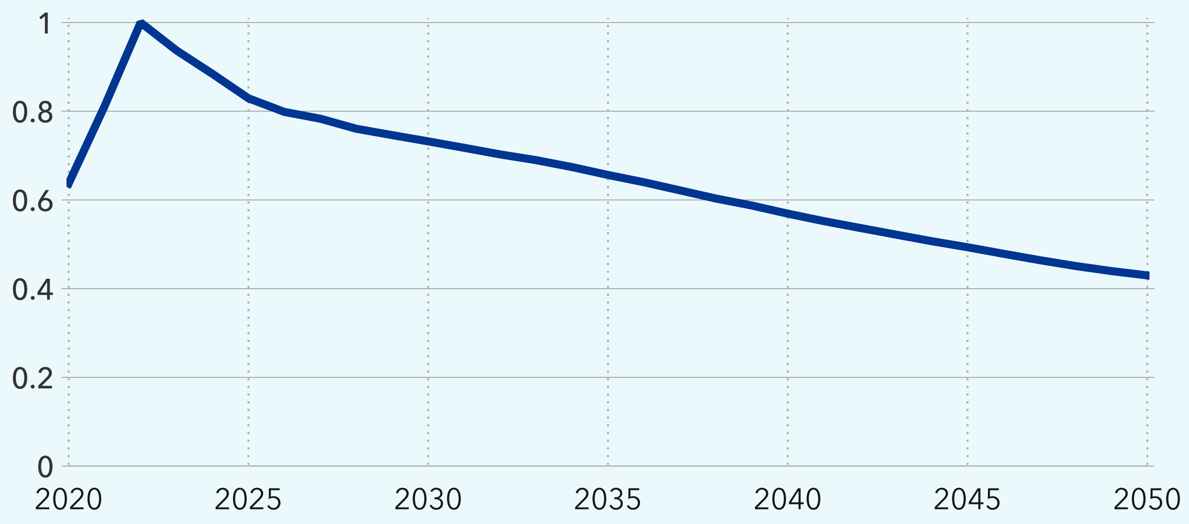
Household energy expenditure halves to 2050

Despite a short-term cost hike, on average, households will spend progressively less on energy, thanks to affordable electrification of demand sectors and improving energy efficiencies. By 2050, household energy expenditure will be half of what it is today, effectively transferring the benefits of the energy transition to the public.

HIGHLIGHT 4

Household energy expenditure

Units: Unitless, 2022 value =1



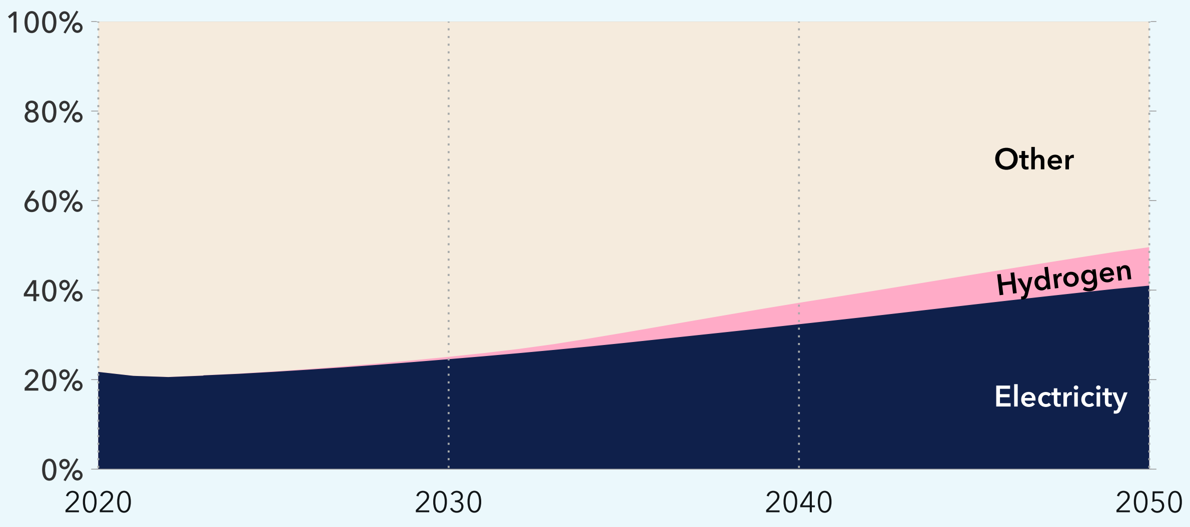
Electrification of final energy doubles and will be the main driver of the North American transition

The North American economy will be powering forward in the next 30 years, growing by over 30%, requiring ever-greater amounts of energy services. Solar grows 15-fold, and wind 8-fold, spurring clean electrification of all demand sectors. Hydrogen and its derivatives also provide indirect electrification.

HIGHLIGHT 5

Share of electricity and hydrogen in final energy demand

Units: Percentages



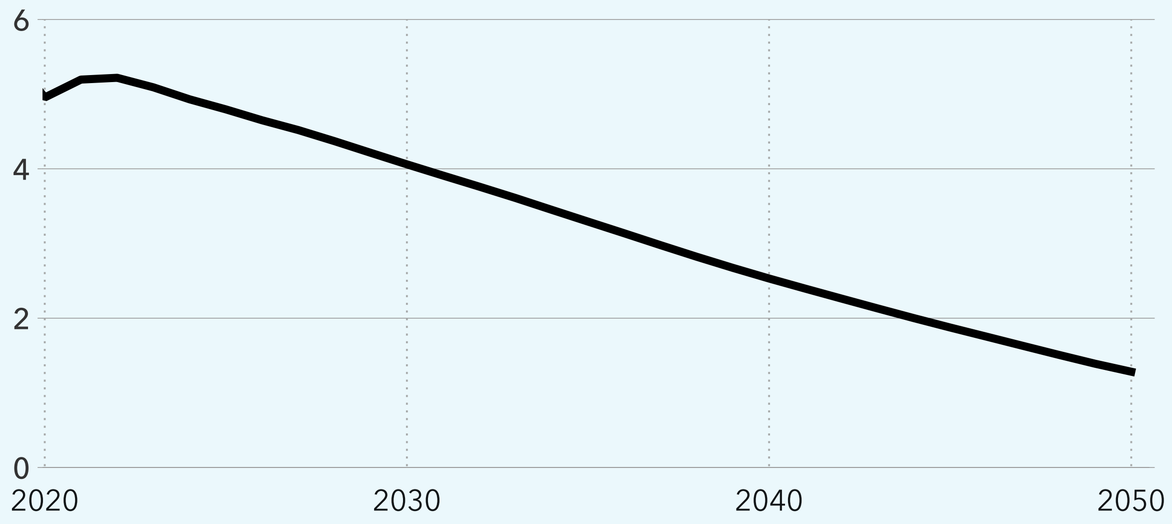
The energy transition is far from fast enough to reach net-zero

1.3 $GtCO_2$ annual emissions remain and residual presence of natural gas in the power mix prevents full power decarbonization before 2050. Electrical transmission will grow 2.5 times by 2050 to support more renewables but initial bottlenecks restrain the pace of development. Much of the existing gas grids can be retrofitted or repurposed for hydrogen and its derivatives, but more pipelines will be needed to meet climate goals, and permitting is currently challenging.

HIGHLIGHT 6

Energy-related CO_2 emissions

Units: $GtCO_2$/yr



CONTENTS

Click on the section you want to explore !

1 INTRODUCTION

About this Outlook

This *Energy Transition Outlook North America* report covers the energy future of the US and Canada through to 2050. The analysis, the model framework behind it, the methodology, the assumptions, and hence also the results lean heavily on DNV's global forecast, *Energy Transition Outlook 2023* (ETO 2023). This is important, as the energy system in North America is part of a global energy system, where technologies (learning rates, technology costs, technical solutions), economics (costs of materials, market prices, etc.) and policies are influenced by developments in other regions. The ETO model takes this into account by modelling North America as a stand-alone region linked to the other regions globally; global and regional supply and demand balances are integrated into one single model.

This report describes the development of the US and Canada combined. The energy systems between the two countries are tightly interwoven in the ETO model as well as in practice. Hence, there is merit in seeing the two countries together. There are huge differences *within* each of the two countries, not least on policy matters; we take those differences into account where possible, but use averages where necessary.

Our approach

Unlike most energy forecasters, DNV does not develop scenarios. Not because we know what the future will be like, but because not all futures are equally likely, and we see a lot of merit in giving a best estimate. Hence, our analysis produces a single 'best-estimate' forecast of the energy future for the US and Canada. This forecast accounts for expected developments in policies, technologies, and associated costs, as well as some behavioral changes. DNV also publishes a net zero 'back cast', looking into what is needed globally and in the regions to achieve a future that limits global warming to 1.5 degrees above the pre-industrial average. That *Pathway to Net Zero* is published in a separate report (DNV, 2023b), which also details the pathways of the 10 world regions in DNV's Energy Transition Outlook (ETO), including North America.

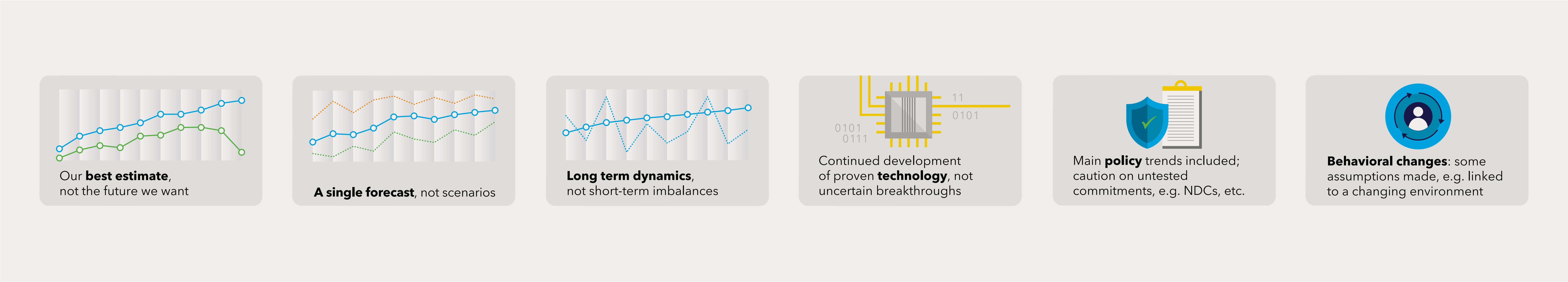
Our model simulates the interactions over time of the consumers of energy (mainly transport, buildings, manufacturing) and all sources of supply. It encompasses demand and supply of energy globally, and the use and exchange of energy between and within 10 world regions (see illustration below).

The analysis covers the period 1990–2050, with changes unfolding on a multi-year scale that in some cases are fine-tuned to reflect hourly dynamics. We continually update the structure of and input data to our model. In this report we do not repeat all the details on methodology and assumptions from the ETO 2023 report but refer readers to that open report for further details.

North America is second only to China in energy use, and is leading economic and technology developments in many areas. Therefore, what happens to this region's energy system has enormous implications for the rest of the world, including through energy exports, financing, or technology innovation and breakthroughs with powerful impacts on cost learning rates.

Chapter guide

The key policy assumptions are discussed in Chapter 2 of this report. In Chapter 3, we discuss the energy demand of the various demand sectors, and then in Chapters 4 and 5, we look at how the energy is supplied, through energy carriers like electricity and hydrogen, and by all the primary energy sources – fossil, nuclear and renewables. Chapter 6 describes the financial aspects of the transition both for the region as a whole and for individual households. Finally, in Chapter 7, we quantify and discuss the emissions from the evolving energy system we forecast.



2 POLICY

2 THE POLICY LANDSCAPE SHAPING NORTH AMERICA'S TRANSITION

The policy landscape is complex and dynamic in the North America region. Yet in recent years, key pieces of legislation have passed: in the US the emphasis is on tax credits, loans and guarantees for clean energy investment, while in Canada policies are a mixture of incentives and disincentives. Together, these are set to put the region on track to become a clean energy powerhouse.

In this chapter we present an analysis of the policy landscape in North America and conclude by describing how we integrate contemporary and expected policy developments into our long-term forecast.

Tackling climate change is a key issue both in the US and Canada. Both federal governments have set net zero GHG goals for 2050 and have intermediate reduction targets for 2030 at 50-52% below 2005 levels (US) and 40-45% (Canada). Recently, Canada also announced that it would reassess whether the long-term targets could be achieved 10 years earlier (Canadian Press, 2023). There is full focus on positioning and seizing cleantech industrial opportunities, carbon-free domestic energy developments, and encouraging economic activity in critical strategic areas for securing supply chains while addressing climate change.

The decarbonization challenge – and opportunity – is grand. Canada and the US are global players in the energy market and as top-ranked oil and gas producers, the region is a net energy exporter. The region's share of global energy-related emissions was ~17% in 2019. The energy mixes are currently dominated by fossil fuels, and energy-related emissions account for over 80% of domestic GHG emissions in both the US and Canada.

Despite the scale of decarbonization ambitions, the fossil fuel industry enjoys continued support. Amongst many stakeholders there is a deep-seated reluctance to step away from fossil fuels and the region's fossil fuel advantage, especially in the light of global energy security concerns associated with Russia's invasion of Ukraine.

Key legislative packages

Unlike the US, Canada's decarbonization regulation combines incentives as well as disincentives, such as explicit carbon pricing and internal combustion engine (ICE) phase-out policy to advance the transition (see sidebar on carbon pricing). As we detail below, the US is much more focused on incentives that are designed to boost cleantech market forces. Regardless of these differences, what the two countries have in common is the sheer scale of federal government action and decarbonization support to states and provinces' climate efforts – implying an extensive government apparatus build-out to execute plans and support schemes.

Canada

Canada's Net-Zero Emissions Accountability Act (Government of Canada, 2021) enshrines the 2030 and 2050 ambitions in law and establishes a legally binding process to set five-year national reduction targets. Targets are accompanied by credible, science-based emissions reduction plans to achieve them, such as the 2030 Emissions Reduction Plan (Government of Canada, 2022a).

The federal government accompanies the *2030 Emission Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy* (issued in March 2022) with support to achieve the outlined sector-by-sector projected contributions to decarbonization ambitions. Its 2023-2024 budget emphasizes a made-in-Canada plan underpinned by a new federal toolkit for investing in the clean economy, such as tax credits and low-cost strategic financing (Department of Finance Canada, 2023) to be competitive in the race to build clean economies. However, some business leaders have criticized what is essentially Canada's response to the IRA as 'limited' and fear that as the US builds momentum in cleantech, capital and talent may flow south from Canada (Financial Post, 2023).

Internationally, the Canadian government, with the UK, launched the Powering Past Coal Alliance at COP23 (Germany, 2017), building on Canada's domestically announced ambition (2016) to eliminate coal power by 2030.

At COP27 (Egypt, 2022), Canada, along with Chile, advanced the Global Carbon Pricing Challenge to encourage all countries to adopt pollution pricing as a central part of climate strategies and working toward a collective goal of covering sixty percent of global emissions by 2030, tripling the global coverage of carbon pricing.

United States of America

In the US, the long-term strategy *Pathways to net-zero greenhouse gas emissions by 2050* (USDS et al., 2021) was published at the time of climate negotiations, COP26, in Glasgow (November 2021). In the same year, the US returned to the Paris Climate Agreement under the leadership of President Biden and his climate envoy, former Secretary of State, John Kerry.

Several key pieces of legislation have followed with massive government support programmes. In 2021, the Infrastructure Investment and Jobs Act (IIJA) was passed, also known as the Bipartisan Infrastructure Law. It supports states and local governments on physical infrastructure development while also facilitating climate action.

Two landmark bills were passed in 2022. The CHIPS and Science Act includes about USD 53bn investment funding to the semiconductor industry (White House, 2022-08-09), and USD 1bn to carbon removal in the US and domestic high-tech research. The Inflation Reduction Act (IRA) which supports clean technology uptake and manufacturing ambitions, estimated to result in ~40% emission cuts below 2005 levels by 2030 (Rhodium Group, 2022, Jenkins et al., 2022). IRA provides unprecedented incentives to low-carbon, energy transition investments, such as tax credits, elaborated in Section 2.2, and offers long-term policy certainty to developers, breaking the cycle of development boom-and-bust that previously resulted from policy expiration and renewals.

US federal policy is almost exclusively incentive based, offering fixed subsidies towards net zero relevant technology investments, and aiming to catalyze a turning point where clean technologies take over incumbent fossil-based technologies due to lower costs. While the IRA package is presented as a nearly USD 370bn climate change investment, there is no budget cap and hence some fear a risk of over-subsidizing clean technologies. Because it lacks disincentives like explicit carbon pricing (tax or cap-and-trade), the approach also poses uncertainty about the phase out of emissions from the dirtiest sources.

> IRA provides unprecedented incentives to low-carbon, energy transition investments, such as tax credits. The IRA package is presented as a nearly USD 370bn climate change investment.

A cost on carbon? How our forecast accounts for carbon pricing

Thus far there has been no bipartisan support for carbon pricing in the US and hence there is no federal carbon tax. US carbon pricing is therefore decided at state level, except for a USD 51/tonne interim value reflecting the social cost of carbon applied by the Biden administration in federal decision making (a level established by the Interagency Working Group estimating the economic impact, or cost, of GHGs). State-level carbon pricing schemes vary in sector coverage and complement other measures for GHG emissions reductions. The Regional Greenhouse Gas Initiative (RGGI) cap-and-trade system operates across the power sector in 12 eastern states. Washington state has a cap-and-trade system with similar coverage as California, limiting economy-wide emissions. The latter is linked to the Canadian province of Québec (the Western Climate Initiative – WCI).

Canada has a federal carbon pricing policy and a Pan-Canadian, economy-wide approach covering > 80% emissions. It has a predictable price trajectory, increasing by CAD 15 per ton/year to 2030, reaching CAD 170 (USD ~127) in 2030. Beyond 2030 to 2050, we expect that Canadian carbon price levels will align with those of Europe, which is similar to expectations in the analysis by the Inter-American Center of Tax Administrators (CIAT, 2022).

In our analysis, we do not assume that additional US states will adopt carbon pricing measures. Our calculation is that about two thirds of energy currently consumed in power generation and three quarters in industry will not be subject to a carbon price. Based on research, we derive a best estimate of the trend and future price level in existing schemes. For this Outlook, the average carbon price trajectory for the North American region uses a weighted average of the different carbon prices (schemes) over the total energy consumption by state/country. Our projection for the regional average carbon level and trajectory level is USD 16/tCO_2 in 2025, USD 25/tCO_2 in 2030 and USD 56/tCO_2 by 2050.

Industrial emissions are only covered in Canada, the state of Washington, and California (WCI) but with significant free allocation as a temporary measure to protect local industries against carbon leakage risks. The effective carbon price for the manufacturing sector is thus some 50% lower than mentioned in the above trajectory and that is reflected in our forecast.

2.1 AGENDAS FRAMING THE TRANSITION

There is a complex policy agenda framing the energy transition in North America, with some policies clearly advancing progress, while others are a hinderance.

Often, policy results in funding to one or more well-intentioned goals that include addressing inequities, improving public health, boosting local economic growth, and advancing an industrial agenda. On top of those outcomes, more strategic policy aims encompass energy security, local content sourcing, and the establishment of domestic supply chains for critical minerals. Thus, for energy stakeholders, there is a need to navigate a multitude of goals and priorities when evaluating new energy projects; gone are the days when projects were judged solely on stand-alone economic criteria.

Developments advancing the transition

Climate emergency
Climate warming effects have become common and uncomfortably tangible across North America: wildfires increasing in severity and extent; mounting losses from US hurricanes; cascading power and water outages due to weather extremes; and rising heat-related illnesses and deaths. Climate effects have exposed the lack of energy system resilience ascribed to weaknesses in the centralized, fossil-dominant power system. This in turn enhances the value proposition of flexible distributed energy resources in improving grid resilience (IEA, 2022a). There is a demand from some quarters for President Biden to actually declare a “climate emergency” but so far he has insisted that the IRA and his attention to climate change across his Administration is the equivalent of such a declaration.

EPA’s new take on GHG performance standards
The US Supreme Court’s decision (West Virginia v. EPA, 2022) limited the US Environmental Protection Agency’s authority to regulate emissions unless clearly authorized by Congress. The rules proposed by the EPA (May 2023), under section 111 of the Clean Air Act, emphasize emission limits based on cost-effective and available (adequately demonstrated) control technologies, and links back to Congress’ enactment of the IRA and the IIJA support programmes which lower the cost of reducing emissions (Jenks et al., 2023). The new EPA rules are expected to push the uptake of technologies such as carbon capture and storage (CCS) and the use of low-GHG hydrogen.

Disclosure requirements for investors
The US Securities and Exchange Commission (SEC) proposed rules (March 2022) will require publicly listed companies to disclose information about their GHG emissions (Scope 1 and 2, referring to indirect emissions from purchased energy, and under certain circumstances, Scope 3 from upstream and downstream activities in value chains). Rules are expected to be finalized during 2023. Despite the contentious nature of ESG and climate disclosure in US politics and expected challenges to any SEC rule, the proposal is creating pressure on energy companies for decarbonization investments and ESG reporting (RMI, 2022). Companies are already beginning to collect and report climate-related data because of their global interconnections and obligations.

A societal transition
With US decarbonization policies based on incentives, government spending emphasizes delivering best societal value in terms of lower energy costs, pollution reduction and investment in disadvantaged communities, employment, and manufacturing (domestic content). A plethora of benefits are meant to accrue to a wide stakeholder base and boost confidence in climate as a salient, long-term policy issue. In Canada, Climate Action Incentive payments deliver carbon-pricing proceeds quarterly to individuals / jurisdictions where proceeds originated, putting affordability and fairness at the heart of decarbonization, and hence making it more politically and publicly acceptable.

Geopolitical tension unleashing cleantech supply chains
Countering China’s economic influence and dominance in the production of key goods, including cleantech areas, is common ground between the US Democrats and Republicans, boosting government funding into technological R&D, domestic manufacturing, homeshoring supply chains, and stimulating market uptake. Canada similarly invests in the clean economy and has extensive mineral wealth required for cleantech. A production ramp up in the minerals area is in the works, in collaboration between the US, Canada and Europe (Politico, 2023a), to meet cleantech manufacturing needs and the pivot towards reducing emissions.

Hurdles blocking the transition

Entrenched fossil fuel interests and policy reversals
Long-entrenched interests in the oil and gas industry dominate the lobbying agenda, and the political reach of the industry opposing climate policy is immense in both Canada (Graham et al., 2019) and the US (Nat.Clim.Chang., 2019). Climate policies are also subject to reversals from changing administrations and divided government introducing regulatory

risk for investors, as observed recently in efforts to rescind or reduce IRA clean energy incentives during the US debt ceiling negotiations.

Looming skills shortages and displacement risks
The Royal Bank of Canada (RBC, 2022) emphasizes the need for a net-zero workforce and green skills to implement existing and developing new climate technology solutions. Analysis suggests that Canada's transition to a net-zero economy could displace between 312,000 and 450,000 workers in the fossil-fuel sector through 2050 (TD Economics, 2021). In the US, the Interstate Renewable Energy Council finds that the clean energy sector will need to add more than 400,000 workers annually over the next 12 years to meet bold energy goals driven in part by recent federal climate legislation (IREC, 2023).

Energy infrastructure and permitting
The siting and permitting process of energy assets (fossil and renewable) across federal, state, and local jurisdictions is notoriously lengthy, with the development of US transmission lines facing 10 or more years to complete (WRI, 2023). As of the end of 2022, over 2,000 GW of generation and storage capacity is stuck in interconnection queues in the US (LBNL, 2023a). This is a bottleneck to leveraging the IRA's clean energy incentives. Although the IIJA (2021) and the Fiscal Responsibility Act (US Public Law, 2023) include provisions to streamline and unify the environmental review process, they are only small steps towards permitting system reform (WRI 2023, CSIS 2023). Clean energy goals in the US, such as decarbonization of power by 2035, hinge on faster permitting of projects and interstate transmission. Canada's provinces also lack integration of power systems and need build out of inter-provincial transmission lines bolstered by the federal government (Stringer et al., 2022).

Subsidy race and protectionism
Government spending in IRA has prompted a response from North America's trading partners, who perceive it as a threat to both their competitiveness and meeting their own transition targets. The EU Green Deal Industrial Plan is a direct IRA response to promote net-zero manufacturing capacity (at least 40% of EU annual deployment needs by 2030), as is relaxed State Aid Rules allowing 'matching aid' to prevent industry relocations (European Commission, 2023). A race among the deepest subsidy pockets coupled with protectionism is a race in which emerging economies with industrialization aspirations cannot compete (FT, 2023). While understandable that transition spending aims to accrue primarily domestic benefits, there is a risk that new, protectionist industrial policies will serve to shift decarbonization resources to the few rather than expanding them for the many. Furthermore, retraction from multilateral trade poses a risk of sacrificing the benefits of global cooperation in technology development and production. Such lack of cooperation is likely to push up technology costs, making the transition more costly for everyone.

TABLE 2.1

A non-exhaustive list of announced federal transition ambitions

Sectors	Country	Ambition
Power	US	– 80% renewable generation by 2030 and 100% carbon-free electricity in 2035.
	Canada	– 100% of electricity from non-emitting sources (renewables, large hydro, and nuclear) by 2035.
Oil & Gas	US	– Methane Emissions Reduction Action Plan and EPA for 75% reduction by 2030 below 2020 levels[1].
	Canada	– 31% projected sectoral contribution by 2030 from 2005 levels[2], equivalent to 42% from 2019 levels. – Reduce methane emissions by at least 75% below 2012 levels by 2030.
Hydrogen	US	– Reduce cost of clean hydrogen to USD 1/kg by 2031. – Produce 10 million tonnes clean hydrogen by 2030, 20m/t by 2040 and 50m/t by 2050.
	Canada	– Deliver 6% of Canada's end-use energy by 2030 and up to 30% by 2050[3].
CCS	US	– No concrete target. Incentives provided via 45Q tax credit. – Ongoing DOE CCS R&D and demonstrations grant programmes.
	Canada	– CCUS to capture at least 15 Mt of CO_2e/yr by 2030[4]. – Transform oil and natural gas industries to net-zero emissions.
DAC	US	– Enhance land sinks and scale up CO_2 removal technologies to deliver about 1 Gt of negative emissions[5]. – Achieve carbon dioxide removal at USD 100/t within a decade.[6]
	Canada	– No set target. Investment tax credit 2022-2030 (60% capex).
Transport	US	– No federal ICE phase out policy. Target for a 50% sales share target of EVs by 2030. – The Sustainable Aviation Fuel (SAF) Grand Challenge targets production of 3 Bn gallons per year (~11 Bn litres) by 2030, achieving a minimum 50% reduction in lifecycle GHG emissions by 2030.
	Canada	– 11% projected sectoral contribution by 2030. – 100% zero emission vehicle (ZEV) sales by 2035 (passenger), 100% commercial (light) by 2040 including mandatory interim targets on automakers / importers of at least 20% of sales by 2026 and 60% by 2030. – 10% of all aviation jet fuel used from SAF (> 1bn litres) by 2030[7], and a net-zero vision for the aviation sector.
Buildings	US	– Federal building stock: Beginning in 2025, reduce energy consumption-related emissions by 90% relative to 2003. Full decarbonization 2030 in new builds and major renovations[8].
	Canada	– 37% projected sectoral contribution by 2030 from 2005 levels.
Manufacturing	US	– Industrial Heat Shot™ aims for technology development to achieve at least 85% lower GHG emissions by 2035, and a 575 Mt/CO_2e reduction by 2050[9].
	Canada	– 39% projected sectoral contribution from heavy industry by 2030 from 2005 levels.

1. White House (2022a), **2**. Government of Canada (2022a): projected sectoral contributions outlined in 2030 Emission Reduction Plan, **3**. Ministry of Natural Resources (2020), **4**. Government of Canada (2022a), **5**. USDS (2021), **6**. US DOE (2022a) Carbon Negative Shot™, **7**. Govt. of Canada (2022b), **8**. US DOE (2022b), **9**. DOE Industrial Heat Shot™ (2023)

2.2 UNDERSTANDING KEY POLICIES

Key landmark legislative and budget initiatives are described, followed by a discussion of policy implications for DNV's forecast.

US deep dive

Infrastructure Investment and Jobs Act
In November 2021, US President Joe Biden signed the Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL), authorizing unprecedented spending on major transportation and infrastructure projects. Despite initial reports of USD 1.2trn in budget authority, the Brookings Institution (2022) calculates the IIJA's total spending will reach about USD 864bn over five years (from 2022 through 2026). With an estimated USD 591bn (or 68%) of its budget authority allocated to transportation programs, the IIJA is primarily a transportation bill. Nevertheless, the IIJA represents the largest investment in clean energy infrastructure in US history, providing funding for both clean transportation infrastructure (USD 19bn), and clean power generation, transmission, and use infrastructure (USD 75bn) (White House, 2022b).

The IIJA combines regular and extraordinary funding. First, it reauthorizes existing federal programs that are typically included in the normal, multiyear surface transportation budget bill. Second, it authorizes extraordinary funding for new transportation, energy, water, broadband and other infrastructure programs. The IIJA allocates USD 662bn (77%) to existing programs, and USD 202bn (23%) to new programs (Brookings, 2022).

The IIJA greatly expands the use of competitive federal grant-making to a broad range of eligible recipients, in both the public and private sectors. Of the 129 *new* federal infrastructure programs created by the IIJA, two-thirds of these programs (86) are competitive, meaning Executive branch leadership has wide latitude to set the program's initial rules and select recipients. The Department of Energy, for example, has 24 new competitive grant programs totaling USD 33bn, including six programs funded with USD 6.3bn to improve battery processing and manufacturing.

Fundamentally, however, the IIJA relies on traditional, formula-based budget transfer mechanisms, with USD 660bn (76%) delivered either directly to state and local governments via formula grants, or via set-asides to specific federal agencies for predetermined activities such as research or product monitoring. The law commits most of this formula spending to the transportation sector, where funds flow primarily to state highway programs and transit agencies. Formula-funding has the advantage of disbursing funds quickly, leaving project selection decisions to the local level.

Photo by, Joe DelNero, NREL 77569

Within *clean transportation infrastructure*, the IIJA funds five major programs to promote the electrification of vehicles, the two largest providing USD 7.5bn in grants to states to build a national network of 500,000 electric vehicle chargers and clean fuel stations. A USD 5bn formula grant program targets EV charging along major transportation corridors, while a USD 2.5bn competitive grant program invests in charging and fueling (hydrogen, propane, and natural gas) infrastructure both along transportation corridors and in communities to ensure deployment reaches rural, disadvantaged, and other hard-to-reach communities. In addition, it provides USD 10.9bn to states, tribes and local governments with capital investment grants to transition public vehicle fleets to electric, including transit buses, school buses, and passenger ferries.

Within *clean power infrastructure*, IIJA funding includes four major areas: delivering clean power (USD 21.3bn), clean energy demonstrations (USD 21.5bn), energy efficiency (USD 6.5bn), and clean energy manufacturing and workforce development (USD 8.6bn).

The US Administration's "all-of-the-above" policy approach to clean energy and decarbonization is evident in the IIJA, from programs to speed the development and deployment—at scale—of high-cost yet potentially high-return technologies (carbon capture, clean hydrogen, advanced nuclear, grid-scale storage), to forestalling the loss of existing non-fossil generating assets (nuclear). Top-line examples include: USD 8bn to establish four regional clean hydrogen hubs that bring together hydrogen producers, potential consumers, and connective infrastructure (§ 40311), USD 6bn for six carbon capture demonstration projects and four regional direct air capture hubs (§ 41004, § 40308), and USD 6bn in credits to existing nuclear power plants at risk of prematurely closing due to economic factors and being replaced by higher-emitting power resources (§ 40323).

The IIJA also includes non-budgetary policy provisions to address climate change, secure the grid from physical and cyber threats, streamline federal government permitting of major infrastructure projects, and impose domestic content requirements on recipients of government infrastructure funding. The "Build America, Buy America" provisions (§ 70901) stipulate that infrastructure projects receiving federal financial assistance may only use iron, steel, manufactured products, and construction materials that are wholly produced in the United States. Regarding government permitting and administrative decision-making, § 11301 codifies the so-called "One Federal Decision" process—a decision-making framework that requires federal agencies to coordinate from the outset by using a joint schedule, empower a lead agency to enforce it, require agencies to work concurrently and not wait in turn, generate a readable review document with page limits, and produce a timely decision within 90 days of finishing the review document. Although these permitting reforms are important (Rosen and Gribbin, 2021), it is debatable whether they will reduce timelines as substantially as their proponents suggest, and further reform remains a high priority of industry and the Congress.

Inflation Reduction Act

The Inflation Reduction Act (IRA), enacted in August 2022, builds on the initial climate funding in the IIJA, providing a 10-year runway for corporate and consumer tax incentives to accelerate the growth of clean energy, motivate consumer adoption of EVs and home electrification, and support decarbonization innovation across industrial sectors.

At the same time, the IRA is a socioeconomic policy tool to coax a more equitable and economic clean energy transition into being, offering substantial additional incentives to those that use American-made products, build domestic manufacturing capacity, pay labor-union rates, repurpose retired fossil fuel infrastructure, reskill and employ displaced workers, and improve work and living conditions in disadvantaged communities. In implementing the IRA, the Biden Administration has added its own social policies, with many of its programs requiring that at least 40% of the funds be allocated to disadvantaged or low-income communities.

Photo by, Dennis Schroeder, NREL

Funding mechanisms – The IRA's clean energy and climate funding is provided by two principal means: tax credits to business and individual taxpayers, and direct appropriations to federal agencies to administer various grant, loan, or direct federal spending programs. The IRA relies particularly heavily on subsidies in the US tax code to induce businesses and consumers to invest in clean energy power generation, clean energy manufacturing, carbon sequestration, clean fuels and vehicles, and energy efficiency. It restores, modifies, and expands several existing tax credits and incentives, while also creating new ones; these are described further below and enumerated in detail in (Table 2.2). In addition, the IRA creates a new marketplace for the sale and trading of tax credits; we have yet to see the fruits of this new mechanism.

To supplement the tax incentives, the IRA also makes some USD 148bn in direct appropriations to federal government programs across a multitude of agencies.

The largest is the Greenhouse Gas Reduction Fund – a USD 27bn green bank – which provides funding to support rapid deployment of low- to zero-emission technologies. Another is an additional USD 250bn in commitment authority to the Department of Energy's Loan Programs Office for loan guarantees (including refinancing) of eligible energy infrastructure reinvestment projects. The Biden Administration's "all-of-the-above" approach to energy policy is again evident, pairing policies for clean energy development with those to protect oil and gas development intended to ensure energy security. In addition, numerous programs prioritize and directly target funding for a just transition.

Clean energy generation credits account for the largest share of the IRA's climate spending. These include an extension and modification of existing clean energy investment and production tax credits (ITC and PTC) to 2025, at which point they become "technology-neutral", supporting a market-driven expansion of all zero-carbon electricity sources by not preferring one technology over the other. These will include wind, solar, geothermal, marine, hydro, biomass, etc., along with tax credits for generation from existing nuclear plants and for electricity storage technologies. The IRA extends credits at their full value for at least 10 years, followed by a phase-out period, intended to give investors, developers, manufacturers, and utilities sufficient stability and predictability to plan and build clean energy facilities well into the 2030s. Clean electricity generation projects can claim either the ITC or the PTC, but not both. Projects with high capital costs are likely to benefit most from the ITC, while those with high generating capacity would likely prefer the PTC.

Clean energy manufacturing credits – The IRA supports both clean energy development and domestic manufacturing policy through an estimated USD 30bn to production subsidies for the domestic fabrication of solar panels, wind energy components, batteries, and critical minerals processing (via the 48X credit, a PTC), as well as an additional USD 10bn in investment subsidies for establishing facilities for fabricating clean energy equipment (via the 48C credit, an ITC). Nearly USD 6bn is allocated to help existing heavy manufacturing, such as steel and cement, significantly reduce emissions.

The IRA has the potential to reshape transportation, building on the EV infrastructure investments within the IIJA and by providing EV tax credits.

Carbon capture and clean hydrogen credits – The IRA bolsters the IIJA's USD 14bn investments into carbon capture and clean hydrogen development by extending and modifying the existing §45Q carbon sequestration credit and creating a new clean hydrogen ITC and PTC (§45V). Modifications to the 45Q sequestration credit include an enhancement for direct air capture (DAC) and lowering the annual thresholds of carbon a facility must capture to qualify. The new 45V credit rewards both hydrogen produced from renewable electricity (green hydrogen) and from natural gas reforming (blue hydrogen). To qualify, hydrogen must be produced through a process resulting in lifetime GHG emissions of no more than 4 kgs of CO_2e per kg of hydrogen. The base credit is 60 cents per kg of qualified clean hydrogen, multiplied by an emissions factor depending on the GHG emissions factor of the fuel.

Consumer credits – Not only does the IRA incentivize the supply-side in terms of industry and technology development, but it also provides direct incentives on the demand-side for individual consumers to decarbonize their homes and vehicles. Individual residential clean energy incentives provide tax credits or rebates to convert furnaces and water heaters, install rooftop solar, and make energy efficiency improvements to homes. The IRA has the potential to reshape transportation, building on the EV infrastructure investments within the IIJA and by providing EV tax credits of up to USD 7,500 for individuals to purchase new or used EVs. However, the law's domestic content and assembly requirements may limit the availability and effectiveness of the incentives given current supply chains and industry dependence on critical minerals from China.

Bonus incentives and credit monetization – IRA promotes various socioeconomic policies by offering a variety of bonus credits. The most significant is a five-fold multiplier of the base credit if the project pays prevailing wages (e.g., labor union rates) and contributes to building a skilled clean energy workforce through work apprenticeships. For example, the Clean Energy PTC is increased from USD 5/MWh to USD 25/MWh. Under certain provisions, the IRA also further incentivizes the use of domestically produced materials and components (domestic content), as well as siting projects in places that will benefit low-income, disadvantaged, or so-called energy communities (i.e., areas historically dependent on fossil fuel industry, such as coal). In some cases, bonus credits are additive. Another feature is that it permits taxpayers, in particular situations, to elect a direct pay option in lieu of a tax credit, or the option to monetize the credits by transferring them to another taxpayer.

Just transition – Additionally, the IRA has specific provisions to address equity and environmental justice and to reduce pollution in low-income and disadvantaged communities. It includes a USD 3bn allocation for environmental and climate justice block grants, which can be used for community-led monitoring and remediation, mitigating the effects of urban heat islands, and facilitating community engagement in federal and state policymaking. The IRA also establishes the Greenhouse Gas Reduction Fund, a USD 27bn green bank that provides funding to support rapid deployment of low- to zero-emission technologies. Of this, USD 15bn is allocated for rooftop solar, air-pollution abatement, and financial and technical assistance for energy projects specifically benefitting low-income and disadvantaged communities.

TABLE 2.2

Details of key IRA clean energy tax incentive programs

Credit name	Tax code §	Application	Base credit	Bonus credits	Comments (credit begins 2023 and expires 2032 unless noted)
Energy Generation					
Renewable Energy PTC extension	45	Various renewables	0.3¢/kWh	1.5¢/kWh for PW&A 10% for DC, 10% for EC	Transition to 45Y credit in 2025 Direct pay & transferrable
Renewable Energy ITC extension	48	Various renewables	6%	30% for PW&A 10% for DC, 10% for EC 10% for LIC, 20% for qual. project	Expands eligibility Transition to 48E credit in 2025 Direct pay & transferrable
Clean Energy PTC	45Y	Tech-neutral	0.3¢/kWh	1.5¢/kWh for PW&A 10% for DC, 10% for EC	Applies from 2025, phase out 2032 Direct pay & transferrable
Clean Energy ITC	48E	Tech-neutral	6%	30% for PW&A 10% for DC, 10% for EC	Applies from 2025, phase out 2032 Direct pay & transferrable
Nuclear Power PTC	45U	Nuclear	0.3¢/kWh	1.5¢/kWh for PW&A	Applies from 2025, phase out 2032 Direct pay & transferrable
Energy Manufacturing					
Advanced Energy Project Credit (ITC)	48C	Production facilities for clean energy equipment	6%	30% for PW&A	Program capped at $10B max to award on competitive basis
Advanced Energy Production Credit (PTC)	45X	Production of clean energy components	Varies		Direct pay & transferrable
Carbon Sequestration					
Carbon Sequestration Credit	45Q	CC and used for EOR	$12/mt	$60/mt for PW&A	Direct pay & transferrable Cannot combine with 45V credit
		CC and sequestered	$17/mt	$85/mt for PW&A	
		DAC and used for EOR	$26/mt	$130/mt for PW&A	
		DAC and sequestered	$36/mt	$180/mt for PW&A	
Clean Fuels					
Clean Hydrogen PTC and ITC	45V	Green and blue H_2	PTC 60¢/kg ITC 6%	PTC $3/kg for PW&A ITC 30% for PW&A	PTC multiplied by an emissions factor depending on the GHG of the fuel
Sustainable Aviation Fuel Credit	40B	Aviation Fuel	$1.25/gal	1¢/gal. for each additional % lifecycle GHG reduction > 50%	Modifies existing credit Transition to 45Z credit in 2025
Renewable Fuels and Alternative Fuels Credit	Various	Transportation Fuel			Extends existing credits Transition to 45Z credit in 2025
Clean Fuel Production Credit	45Z	Transportation Fuel (TF) Sust. Aviation Fuel (SAF)	TF 20¢/gal SAF 35¢/gal	TF $1/gal for PW&A SAF $1.75/gal for PW&A	Begins 2025, expire end 2027 Credit adjusted down based on the fuel's lifecycle emission factor (full credit if < 50kg CO_2e per mmBTU)
Clean Vehicles					
Alternative Fuel Refueling Property Credit	30C	Electric charging and alternative fuel stations	6%	30% for PW&A	Max credit $100,000 per unit Direct pay & transferrable
Clean Vehicles Credit	30D	New electric vehicles (consumer credit)	up to $7500		Based on battery material & assembly origin; price & buyer income restriction
Previously Owned Clean Vehicles Credit	25E	Used electric vehicles (consumer credit)	up to $4000		Price and buyer income restrictions
Qualified Commercial Clean Vehicles Credit	45W	Commercial vehicles (consumer credit)	15%	30% for vehicles not powered by gasoline or diesel	Max credit $7500 for light vehicles, $40,000 for vehicles > 14,000 lbs.
Energy Efficiency					
Nonbusiness Energy Property Credit	25C	Home energy equip. and efficiency upgrades	30%		For energy efficiency audits & upgrades; annual limits apply
Residential Clean Energy Credit	25D	Home energy equip. purchases	30%		For energy efficiency upgrades Phase-out after 2032
Energy Efficient Commercial Buildings Deduction	179D	Commercial building efficiency upgrades	50¢/ft^2	2¢ for each % increase in energy efficiency (to max. $1/ft^2) $2.5 to $5/ft^2 for PW&A	For increasing building energy efficiency 25% or more; limits apply
New Energy Efficient Home Credit	45L	Single & manufac. home	$2500		For housing built or remodeled to reach specified energy standards
		Multi-family home	$500–$1000	$2500–$5000 for PW&A	

Glossary: **CC** – carbon capture; **DAC** – direct air capture; **DC** – domestic content; **EC** – energy community; **EOR** – enhanced oil recovery; **ITC** – investment tax credit; **LIC** – low-income community; **PTC** – production tax credit; **PW&A** – prevailing wages & apprenticeships

Canada deep dive

In 2022, Canada published its 2030 *Emissions Reduction Plan* which aims to achieve 40-45% GHG emissions reductions against 2005 levels by 2030. The Canadian Net-Zero Emissions Accountability Act enshrines Canada's commitment to achieve net-zero emissions by 2050 in law.

On March 28, 2023, the Canadian government released Budget 2023 which expands the federal commitment to the energy transition. The Budget includes funding programs and tax incentives designed to increase development and deployment of wind, solar, energy storage, and other renewables and decarbonization technologies. The Budget also includes targeted incentives to ensure a just transition, and to grow and upskill the labor force to match increased demand for energy transition projects.

Tax credit structures are similar to those contained within the 2022 Inflation Reduction Act (IRA) in the US. Of note, the Budget includes a refundable 30% investment tax credit (ITC) based on project capital cost for solar, wind, and energy storage, available from 2023 to 2034. Other tax incentives include a 15% credit available to tax-exempt entities, a 30% credit for clean manufacturing investments, and a 40% credit for green hydrogen investments. New federal funding programs include CAD 20bn for clean electricity and green infrastructure, CAD 3bn for 'smart' renewables and grid modernization, increased commitments for cleantech development and critical minerals projects, and commitments to improve intra-provincial transmission capabilities and carbon price stability within the existing carbon pollution pricing system (Canadian Renewable Energy Association, 2023).

Budget 2023 policies provide a strong foundation to support decarbonization goals; however, based on implementation trends in the US following passage of the IRA, benefits will likely take some time to be realized. Developers and financiers will need to start or adjust project planning cycles, and will also require clarifications from the government on how to proceed under new rules. In addition, action or inaction by some provincial governments may limit policy effectiveness. For example, Alberta's conservative government recently announced a temporary moratorium on regulatory approval for new renewable energy projects as a bargaining chip with the federal government on implementation of federal carbon pricing regulations (Government of Alberta, 2023). While the levelized cost of energy for unsubsidized utility-scale solar, wind, and storage are already often less expensive than conventional generation (Lazard, 2023), such policy reversals could slow project deployments.

Policy implications for our forecast

The effect of policy is discussed in supply- and demand-focused chapters. Here we outline policy implications for DNV's forecast.

The US and Canada have similar funding levels for the same identical sectors of energy with policies touching all corners of the economy and benefitting a myriad stakeholders in clean energy areas.

Overall, the 10-year window of certainty spurs:

- Frontloading of investments aided by public incentives to established technologies (e.g. solar) and more nascent industries and technologies (e.g. hydrogen, sustainable aviation fuels, carbon capture), as well as to technology adoption among households (e.g. EV, heat pump purchases, energy-efficiency measures).
- Acceleration of technology cost-learning rates through learning by doing with cost declines as the outcome in critical cleantech areas.
- Mobilization of private capital, such as companies powered by IRA committing over USD 500bn in manufacturing and clean energy investments since 2021 as reported by the US Department of the Treasury (August 2023).
- Community benefits, such as 272 clean energy projects (since the passing of IRA August 2022 – July 2023) reportedly creating more than 170,600 new clean energy jobs in 44 of the 50 states (Climate Power, 2023), with place-based and state-wide economic benefits likely positive for the acceptability of the transition, as well as countering partisan efforts to modify policies.

From DNV's forecast, we see that the 10-year window for policies and support lays the ground for:

1. **Power sector** scale-up in renewable capacities with large increases in wind and solar deployment overtaking fossil thermal plant additions, a surge in energy storage from drops in storage costs, and retainment of nuclear capacity.

2. **Demand sector electrification** assisted by power mix decarbonization:
   - In buildings with accelerated adoption of heat pumps, also encouraging efficiency improvements.
   - In transport with battery electric vehicle (BEV) uptake, resulting in a 50% market share for new passenger vehicles by 2030, and capturing a significant portion of the heavy, long-distance commercial vehicle segment.
   - In manufacturing especially when low- or medium-heat is needed, and where already a favorably substitute for natural gas, and to reduce future oil demand. Indirect electrification of manufacturing through hydrogen in high-heat processes.

3. **Fuel switching in non-road transportation** with aviation and maritime seeing uptake of low and zero carbon fuels, and almost half of the hydrogen produced in 2050 used to produce derivatives like ammonia and e-fuels for use in maritime and aviation sectors. Sustainable aviation fuel (SAF) making inroads into aviation energy demand, enabled by production capacity targets and investment support (e.g. US SAF Grand Challenge and Canada's Sky's the Limit Challenge).

4. **Relocation of energy and IT industry manufacturing** with North America regaining capacities, particularly in high value-added steps at the end of value chains.

5. **Manufacturing decarbonization** with carbon capture advancing as one of the favored options for heavy industries, and hydrogen gaining ground in meeting energy demand, and as the alternative for decarbonized processes, where carbon capture is not economically viable.

6. **Emissions capture** with IRA, IIJA and the Canadian federal budget providing CCS and carbon removal (DAC) an early development runway, the region is in the lead globally by 2030 and capturing 17% of its total emissions by 2050. But uptake could be even larger with implementation of adequate disincentives (a cost on carbon) regionally.

7. **Hydrogen production** upfront costs lowered by policy provisions to clean hydrogen supply-side investments; the support based on a CO_2 emission threshold of the hydrogen production method incentivizes electrolysis.

8. **Fossil-fuel energy supply** reducing from the present 80% to less than 50% by 2050, and non-fossil CAPEX expenditures (non-fossil energy infrastructures, electrolyzer investments etc.) overtaking fossil-fuel CAPEX in the late 2030s.

9. **Energy affordability** so that household energy bills steadily reduce from the mid-2030s onwards.

10. **Climate policy goals** being within reach, but not met. By 2030, the region's estimated reductions of energy-related emissions are: 37% for CO_2 (below 2005 levels) and 24% for CH_4 (below 2020 levels).

Photo by, Dennis Schroeder, NREL

2.3 ENERGY SECURITY AND GEOPOLITICS

The geopolitical landscape is shifting, and this influences the energy transition in multiple ways. Energy security moving to the top of the agenda is one of the changes, and we now factor into our forecast the effect of favoring domestically controlled energy.

More details around this are included in the global *Energy Transition Outlook* (DNV 2023a, forthcoming). In the global Outlook, the effect of shifts in global supply chains, diversification, and home- or friend-shoring of manufacturing, and the resultant impact on the cost of energy technologies, are described in detail.

Global context

Transition as a national security priority in the global context

Russia's war on Ukraine and its use of energy and energy infrastructure as either instruments or objects of war have shocked national, regional, and global security, vaulting "energy security" as a leading geopolitical issue, even above climate change. The war has acutely disrupted not only European but also global markets, leading to sharp increases in prices, particularly in the northern hemisphere winter, and threatening food security, with disproportionate consequences for low-income, developing countries and the most vulnerable populations.

Canada and the United States are energy exporters and hence more 'energy secure' than regions like Europe, Greater China and the Indian Subcontinent. Still, the increased energy security focus is exerting an influence across North America.

In the context of the Russo-Ukrainian war, Canada and the US have committed to intensify their collaboration with Europe to support international energy security, affordability, and sustainability, as Europe reduces its dependence on Russian energy. The EU and the US have underscored the need to accelerate the energy transition and implement more ambitious policies to reduce strategic dependence on gas and other fossil fuels as being key to achieving both shared climate goals as well as long-term energy security around the world (White House, 2022-11-07). The G7 member states – including Canada and the US – have underlined the significance of building secure, resilient, affordable, and sustainable clean energy supply chains and strong industrial bases that reduce undue strategic dependencies and benefit local workers and communities around the world (White House, 2023).

Besides immediate goals of reducing demand, ensuring short-term security of energy supply, and stabilizing energy markets, the US, Canada and its European partners have voiced a shared longer-term objective of ensuring a stable clean energy transition

as an essential tool for strengthening energy security. The US and the UK, for example, have agreed to promote civil nuclear power as a reliable part of the clean energy transition, and a secure source of energy, less dependent on unreliable sources (White House, 2022-12-07).

The role clean energy technologies play in energy security is especially prominent in the G7's Clean Energy Economy Action Plan. The Plan emphasizes scaling up investments globally into the manufacturing and installation of clean energy technologies and diversifying clean energy supply chains in a way that ensures they are secure, resilient, affordable, and sustainable, seeking to reduce and avoid undue dependency arising from geographically concentrated sources. In acknowledgement of, if not acquiescence to, the financial resources and domestic preference policies contained in the United States' IRA and IIJA, the G7's Action Plan speaks to the importance of maximizing economic incentives, support local value creation in critical minerals supply chains, including processing and refining, and supporting global partners based on a shared commitment to the multilateral trading system (White House, 2023-05-20).

Helping Europe secure gas supplies while reducing emissions – the case of methane
Following the cut-off of Russian gas supplies to Europe, the EU undertook to diversify its natural gas supplies and reduce overall natural gas demand. But for North America, supplying its EU partners meant increasing LNG production. Mindful of the environmental impact of LNG production and consumption, the US and the EU committed to increase their efforts to reduce methane emissions both in bilateral trade and at the global level. In this spirit, the EU has proposed new legislation to reduce methane emissions across the oil, gas and coal sectors, while the US IRA imposes both a Methane Emissions Fee and establishes a Methane Emissions Reduction Program (White House, 2022-11-07).

The US methane emissions fee is the only "carbon tax" enacted to date at the US federal level, is assessed on facilities that support oil and gas production, including transmission, processing, storage, and gathering, that emit more than 25,000 mt of carbon dioxide annually. The fee begins at USD 900/tCH_4 in 2024 and increases to USD 1200 in 2025 and USD 1500 in 2026. The IRA provides two carrots to this stick: it allows companies that comply with future federal methane rules to avoid paying the fee if the same levels of emissions reductions are reached, and the Methane Emissions Reduction Program provides USD 1.55bn in financial incentives (via grants, rebates, contracts, and loans) for industry to monitor and reduce their emissions and mitigate legacy air pollution (IRA § 60113).

Building on this progress, the EU-US LNG trade seeks to achieve significant reductions in flaring, venting, and leakage of methane across the oil and gas value chains. This includes purchasing frameworks to incentivize the capture of this gas brought to market, such as the EU's proposed "you collect, we buy" approach (White House, 2022-11-07).

Domestic context

Energy affordability
In the US, energy security is addressed differently depending on whether the audience is international or domestic. Domestically, the US Administration's energy security policy is nearly synonymous with energy affordability for US consumers. Here, policy actions on energy security are primarily directed at price management through use of the US Strategic Petroleum Reserve and cajoling oil majors to increase oil and gas production. Accelerating the clean energy transition is raised as an additional means to control/lower energy costs and improve national security (White House, 2022-10-19).

Infrastructure security
Cybersecurity – especially that of critical energy infrastructure – became a domestic US security priority even before the Russo-Ukrainian war broke out. In May 2021, a Russian-based ransomware attack interrupted the Colonial Pipeline – the largest pipeline for transporting refined petroleum products in the US, stretching 8 900 km (5 500 miles) from Houston to New York City. The attack shut down the pipeline's operations for five days, causing localized shortages of gasoline, diesel fuel, and jet fuel.

The incident exposed the vulnerabilities caused by the government's laissez-faire approach to cybersecurity, which had been based on private sector adoption of voluntary best practice standards without any meaningful regulatory accountability (Wood, 2023). By exposing such fragility, this high-visibility incident galvanized the US government into action, first with President Biden's Executive Order on Improving the Nation's Cybersecurity (Executive Office of the President, 2021), followed by Congress' passage of the bipartisan Infrastructure Investment and Jobs Act (IIJA), which authorized USD 1.9bn in cybersecurity funding for protecting energy and critical infrastructure.

In the power sector, electrification, digitalization and smart devices are increasing vulnerability and potential for disruption, requiring improvement in cybersecurity, and Canada and the US has strengthened network collaboration (IEA, 2022b).

2.4 IMPLEMENTING POLICY IN THE OUTLOOK

Our model is informed by the policies set out in both the US and Canada. Policy factors, as seen in Figure 2.1, span the supply- and demand sectors.

We have also factored in our own assessments of the state of play in the various sectors of the economy, based on our global energy sector knowledge, our technical and commercial expertise, and discussions with a broad range of stakeholders. On announced policy goals and pledges, such as those submitted to the Paris Agreement, we do not assume that these will be met and hence do not pre-set our Energy Transition Outlook model to achieve them.

From DNV's global *Energy Transition Outlook* (DNV, 2022a), we have a comprehensive list of the policy factors influencing the forecast, and we advise the reader to visit that source for a detailed description of how we account for policy in our forecast. The same policy factors are incorporated in the North America, but with inputs reflecting policy developments and provisions that have taken place since we issued the 2022 Outlook in October last year (Table 2.3). Please refer to the earlier highlight on carbon pricing (p.10).

FIGURE 2.1
Policy factors included in our Outlook

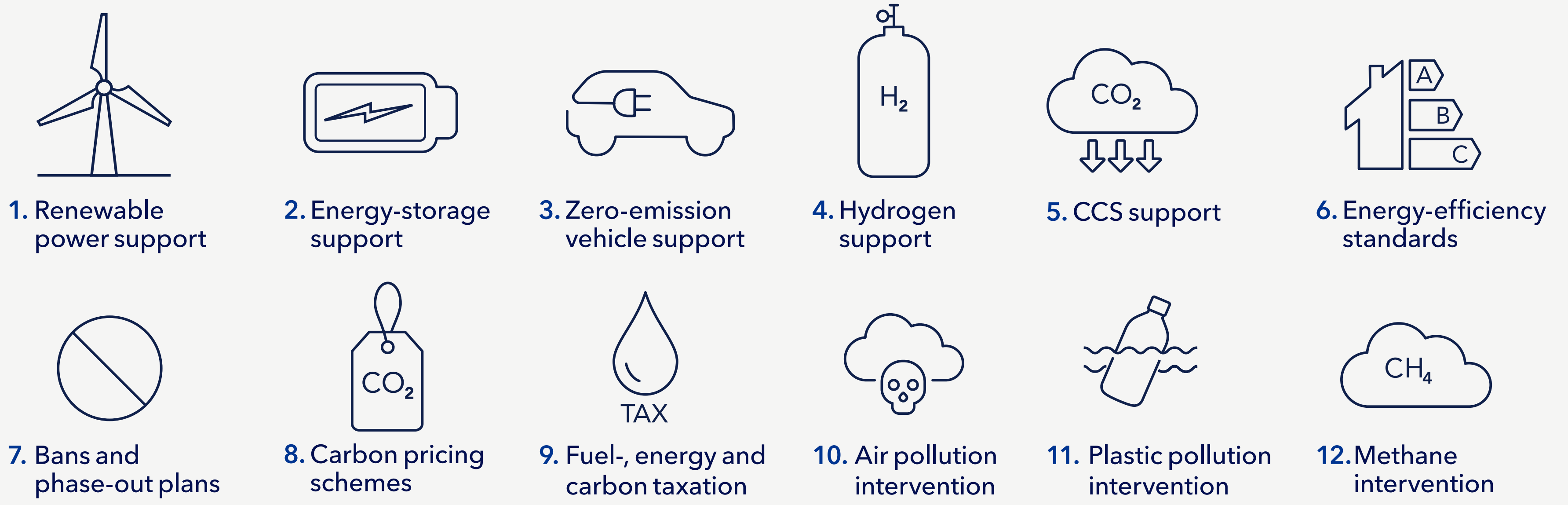


TABLE 2.3
Specific North America-related related policies implemented in our forecast and modelling

Sector	Policy
Power	– Technology-neutral production tax credit for clean energy technologies (solar, wind, nuclear, geothermal, bioenergy).
CCS	– Projects receive support reflecting government funding programmes as a percentage subsidy for the capital cost (50%) and the tax credit 45Q (US), also distinguishing between capture-storage and capture-utilization.
DAC	– Projects receive investment and operational support reflecting government funding programmes as a percentage subsidy for the capital cost (60% Canada) and the tax credit 45Q (US), also distin-guishing between capture-storage and capture-utilization.
Hydrogen	– Projects receive investment and operational support reflecting government funding programmes as a percentage subsidy for the capital cost, or the tax credits as specified by in the 45V in the US, and Canada's investment tax credit to green hydrogen. – Blue hydrogen is supported via the 45Q tax credit (see CCS) as the 45V and the 45Q tax credits cannot be stacked.
Oil & Gas	– For methane emissions from oil and gas, a weighted/composite methane fee, comprising of US's methane fee of 60 USD/tCO_2e and Canada's economy-wide carbon price, are projected, which result in a methane fee from 38 USD/tCO_2e in 2023 to 90 USD/tCO_2e in 2050.
Transport	– Zero-emission vehicle support: reflects CAPEX purchase support levels as set in IRA and state schemes (California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont, Colorado); and Canada's federal government rebates for BEVs and FCEVs, and EV support in provinces (British Columbia, Ontario, Quebec). – Higher penetration of sustainable aviation fuel (SAF) in aviation sector based on critical policies such as Clean Fuel Production tax credit and the SAF Grand Challenge in the US and Sky's the Limit Challenge in Canada.
Buildings	– Tax credits for heat pumps, and electric cooking equipment. – Higher retrofitting rates of buildings and envelopes based on tax credits for insulation and weatherization of buildings.

3 ENERGY DEMAND

3 ENERGY DEMAND

Energy demand in North America will undergo a sea-change in the coming decades, spurred by the US Inflation Reduction Act (IRA) and similar legislation, and by the cost-efficient economics of renewables. In 2022, three-quarters of final energy demand was fossil-based. By 2050, this will shrink to less than half, driven by electrification of all major demand segments.

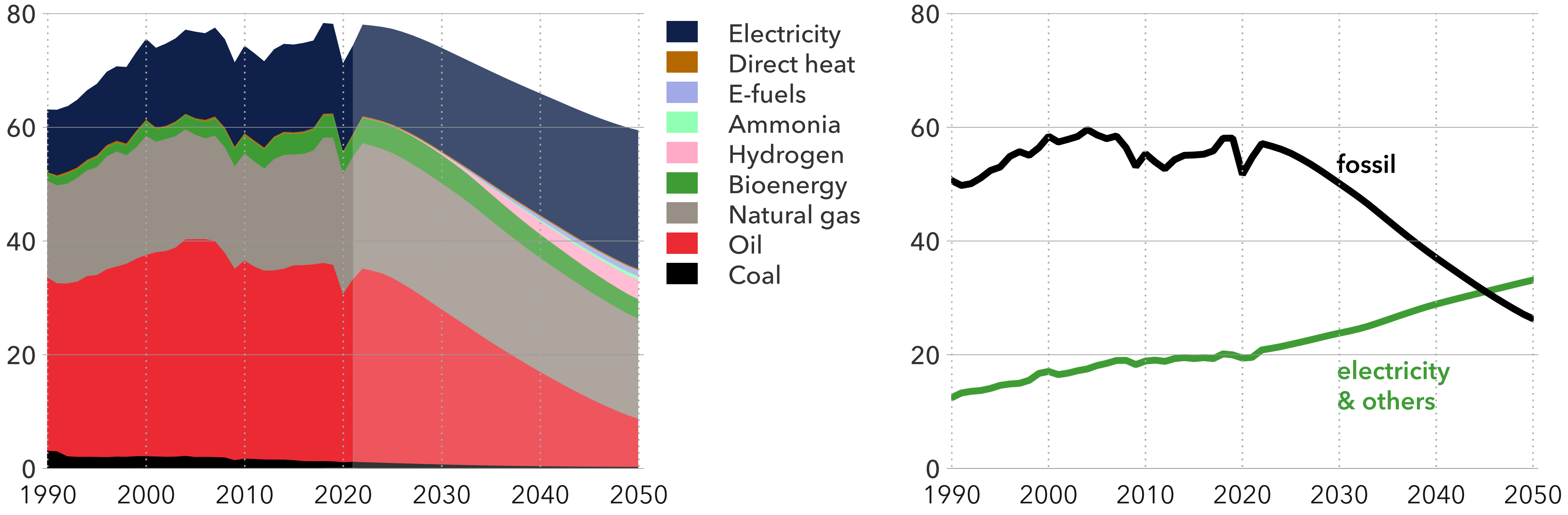
Final energy demand in North America reduces from 78 EJ in 2022 to 59 EJ in 2050, aided by electrification and energy-efficiency improvements (Figure 3.1). This is a compound annual reduction of just over 1% despite useful energy demand rising from 58 EJ per year to 67 EJ over the period, and regardless of increasing GDP and population in the region.

As Figure 3.1 shows, fossil fuels met 73% of final energy demand in 2022. Given that little more than half of today's grid-connected electricity generation is also from fossil fuels, their combined share in the energy mix is in reality considerably more. But by 2046, electricity and other energy carriers such as hydrogen and its derivatives will overtake fossil energy demand. By 2050, with an almost completely decarbonized power grid, the fossil share in final energy demand will be 44%.

FIGURE 3.1

Final energy demand by carrier

Units: EJ/yr



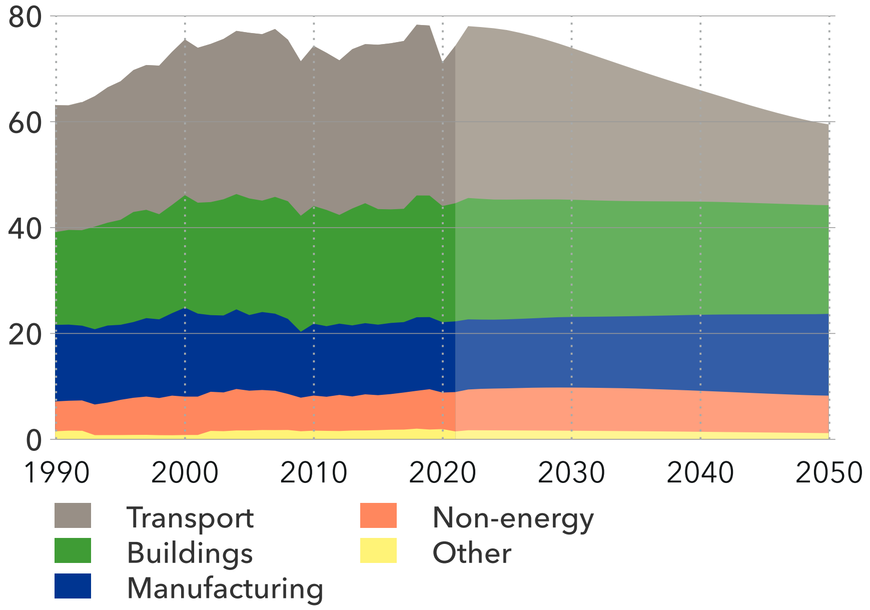
Historical data source: IEA WEB (2023)

The transport, buildings, and manufacturing sectors together accounted for almost 90% of final energy demand in North America in 2022. Transport was the biggest source of annual demand (33 EJ), followed by buildings (23 EJ) then manufacturing (13 EJ). Our forecast suggests a reshuffling of this order by 2050, when buildings will be the largest demand segment (21 EJ per year), followed by transport and manufacturing at about 15 EJ each (Figure 3.2).

FIGURE 3.2

Final energy demand by sector

Units: EJ/yr



Historical Data: IEA WEB (2023)

Other sources of demand (agriculture and military) and non-energy uses (e.g. as industrial feedstock) account for the other 11% of final energy demand in 2022. The shrinking energy demand for transport and buildings in absolute value terms implies that, by 2050, feedstock's share in demand will be marginally higher from 10% in 2022 to 12% by 2050.

In buildings – despite growing prosperity and building stock, electrification of space and water heating, and improved insulation efficiency, lead to final energy demand reducing by 13% between 2022 and 2050.

In manufacturing, homeshoring of industries, and the ensuing restructuring of the economy with growth in the secondary sector, leads to demand growth of 15% from 13 EJ in 2022 to 15.5 EJ in 2050. This also means that instead of plateauing, energy demand for manufacturing increases continuously and gradually until mid-century.

In transport, although transport services will grow in North America, electrification of the road transport subsector will lead to dramatic energy demand reduction overall, from 33 EJ in 2022 to 15 EJ in 2050. Electrifying road transport also instantaneously improves efficiency as battery-electric vehicles are more efficient, especially when charged from a grid in which most of the power is from renewables.

3.1 TRANSPORT

Transport energy demand reduces from 33 EJ in 2022 to 15 EJ by 2050, with direct and indirect electrification, and low-carbon fuels.

Current developments
It is in transportation that the energy transition will be most visible and consequential. Over the next three decades some 3,000 million barrels of oils per day will disappear from North American roads. The main reason for this is the displacement of combustion vehicles on North American roads because the uptake of EVs is poised to accelerate – the region will see a 50% market share for new vehicles by 2030. Commercial vehicles will follow some years later. Aviation and maritime are harder to electrify but they will nevertheless switch to a variety of low- and zero carbon fuels. The result of these changes is that energy demand for transportation will decrease to 15 EJ by 2050.

This shift is meaningful in global terms – transportation in the US and Canada alone accounted for 27% of global transport energy demand in 2022. This share will fall largely due to the energy efficiency of its electric fleet in 2050 and has also implications for emissions as transport activities in the two countries are primarily fueled by fossil fuels at present.

Figure 3.3 shows how oil dominated and will continue to dominate the energy consumption in the transportation sector, representing 88% of the total energy used today and 40% in 2050. Natural gas and biofuels accounted for 4% and 8% respectively and will be at 5% and 14% in 2050. While electricity contributed only 0.3% in 2022, its share will grow significantly to 26% in 2050.

Measuring energy; joules, watts and toes

EJ, TWh, or Mtoe? The oil and gas industry normally presents its energy figures in tonnes of oil equivalents (toe) based on m³ of gas and barrels of oil, whereas the power industry uses kilowatt hours (kWh). The main unit for energy, according to the International System of Units (SI), is, however, joules, or rather exajoules (EJ) when it comes to the very large quantities associated with national or global production. EJ is therefore the primary unit that we use in this Outlook.

So, what is a joule? Practically, a joule can be thought of as the energy needed to lift a 100 g smartphone 1 metre up; or the amount of electricity needed to power a 1-watt LED bulb for 1 second (1 Ws). In other words, a joule is a very small unit of energy, and, when talking about global energy, we use EJ, being 10^{18} J, or a billion billion joules.

While we use J or EJ as the main unit of energy, in a few places we use Wh. For measurements of quantities of energy production, we use tonnes, m³, and barrels.

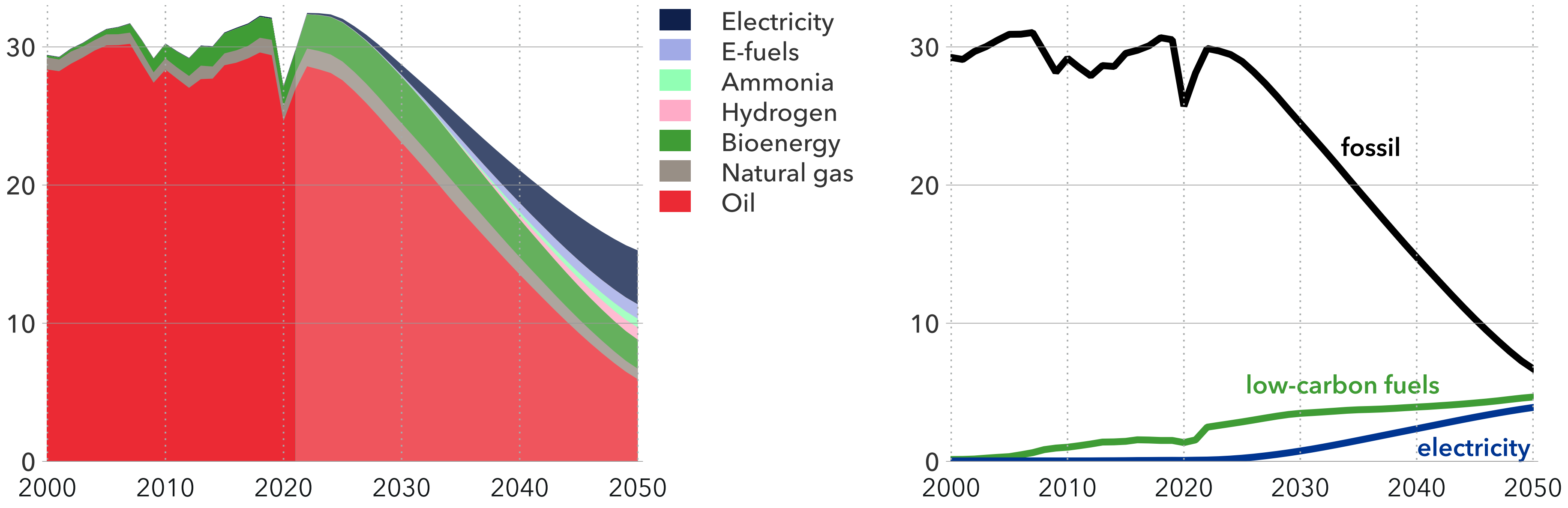
For ease of comparison, conversions are:

1 EJ = 277.8 TWh
1 EJ = 23.88 Mtoe

FIGURE 3.3

Transport sector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

Road

The level of prosperity measured by GDP per person significantly impacts the density of vehicles per person. This relationship is influenced by various regional factors such as geography, culture, technology, infrastructure, environmental conditions, and the availability of alternative transportation options. However, the situation in North America is somewhat special. In fact, the US and Canada are effectively car dependent nations. As shown in Figure 3.4, road vehicle density by region is by far highest in North America, and these levels will not be reached by other regions despite growing GDP per capita. Canada allocates the most space per capita to automobiles, with 734 square meters per person, followed by the US with 573 square meters. The percentage of total land area used for cars reflects population density and economic intensity, while land area per capita figures indicate the level of car dependency. In the US, approximately 155,000 square kilometers are designated for car use, constituting 10% of all available arable land. Although the overall land area used for roads and parking facilities may not be vast, their concentration is predominantly in urban areas (The Geography of Transport Systems, 2020).

Within the road transport subsector, we categorize vehicles into three main types: passenger vehicles, commercial vehicles, and two- and three-wheelers. The term "passenger vehicles" includes vehicles designed to carry three to eight passengers, including typical sedans, vans, SUVs and pick-up trucks, encompassing also most taxis. "Commercial vehicles" refer to buses and to non-passenger vehicles with at least four wheels, primarily used for commercial purposes.

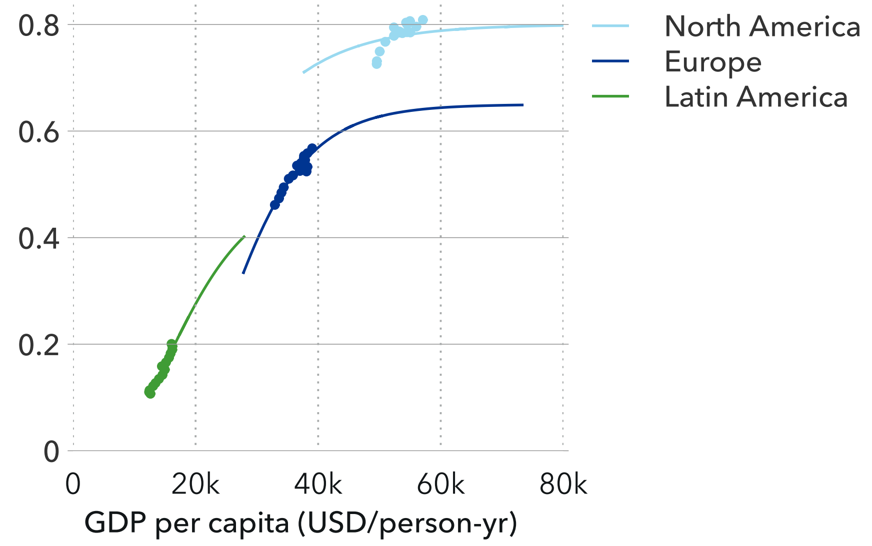
The increasing adoption of digitally-enabled transportation options, such as automation and ridesharing, may come at the cost of traditional public transportation, walking, and cycling. While there may be potential changes in modal preferences, we anticipate that various factors will offset each other – for example ride sharing reduces kilometers driven, but automation may increase kilometers driven per vehicle due to higher utlilization. As a result, we assume that the overall distance traveled by vehicles, measured in vehicle kilometers, will not be significantly affected by the implementation of automation or the sharing of cars.

The adoption of electric vehicles (EVs), starting with passenger EVs, is expected to experience rapid growth. Within our approach, prospective buyers have the option to choose between EVs, which are becoming more affordable and offering increased range over time, internal combustion engine vehicles (ICEVs) and FCEVs (fuel cell electric vehicles) in passenger and commercial vehicle segments. When considering passenger vehicles, potential buyers primarily prioritize the purchase price, while placing less emphasis on the favorable operating costs. In contrast, owners of commercial vehicles, typically fleets, attach greater importance to the advantages of EV operational costs.

FIGURE 3.4

Road vehicle density

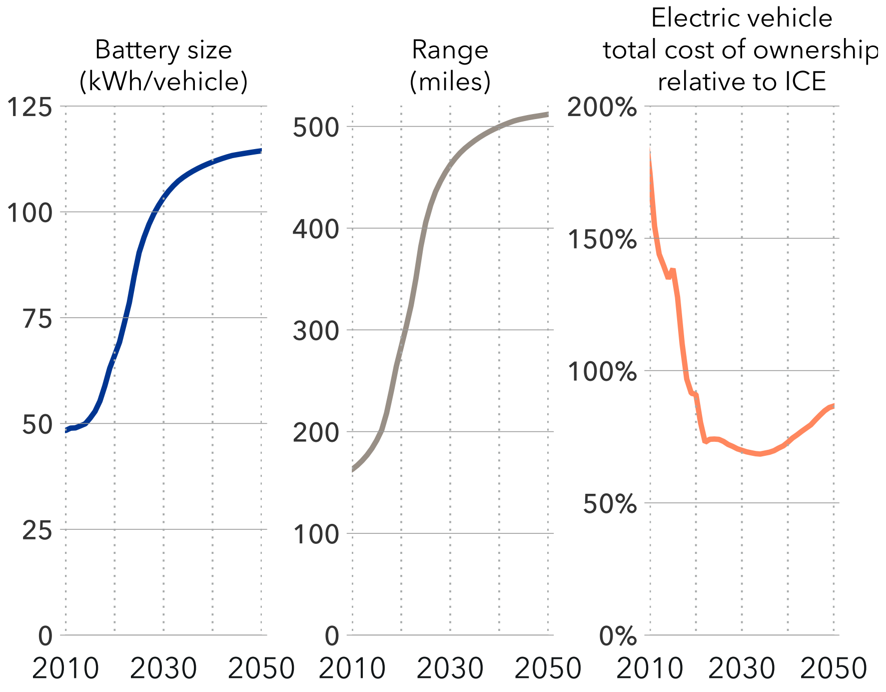
Units: Vehicles per person



Lines show model estimates from 1980 to 2050. Excludes two and three-wheelers. Points show historical data from 2000 to 2015 (OICA, 2016)

FIGURE 3.5

Development of key parameters of electric vehicles in North America



Insufficient charging infrastructure is currently a significant obstacle to the widespread adoption of electric vehicles (EVs) in North America.

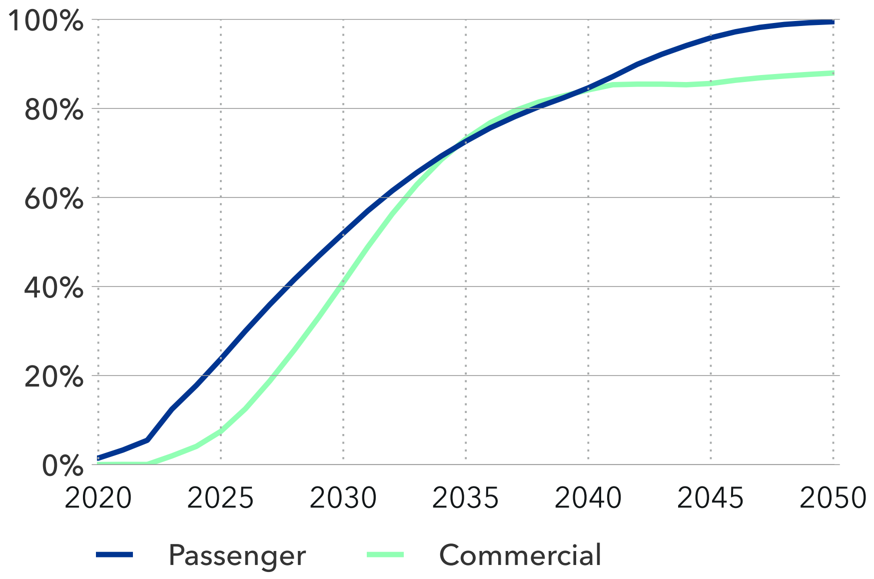
In order to achieve substantial EV uptake, both the average range of EVs and the density of charging stations need to increase and will increase. In North America, the average battery size per vehicle is expected to increase from the current 74 kWh to approximately 110 kWh in 25 years, resulting in extended vehicle range and making EVs even more appealing (Figure 3.5).

Figure 3.6 reflects our forecast that EVs will reach 50% of new passenger vehicle market share in North America in 2030 and globally by 2033. This milestone is central in our forecast and has not changed significantly between our Outlooks over the last five years. Electrification will be more prolonged for commercial vehicles. North America will see 50% of commercial vehicle sales being electric by 2032. In Figure 3.7, we present a comprehensive projection of North Americas vehicle fleet considering the influence of increased car sharing and automation on demand. The number of passenger vehicles is expected to decrease from 317 million currently to slightly over 235 million by 2050. However, the dominance of ICEVs is anticipated to decline significantly, plummeting from 97% at present to below 20% by the middle of the century.

FIGURE 3.6

Market share of electric vehicles

Units: Percentages

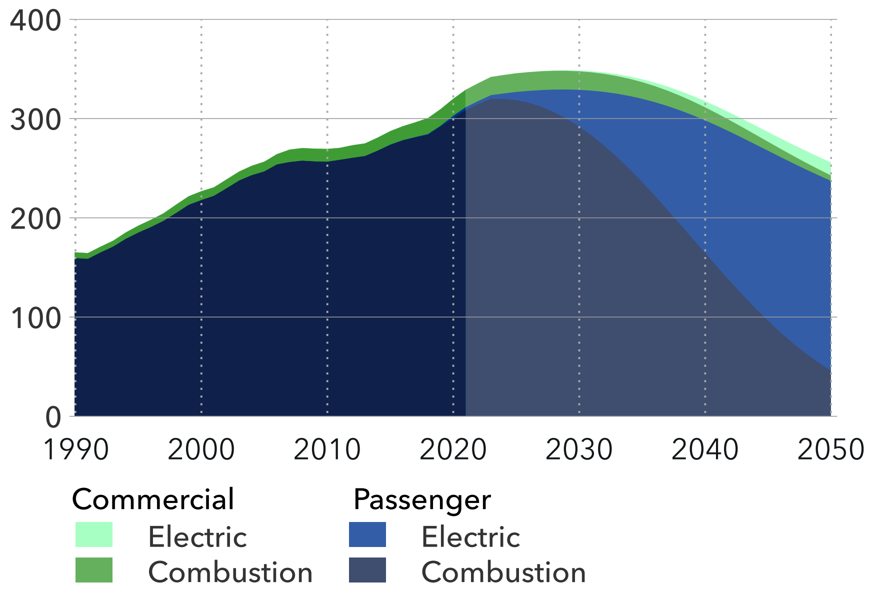


Electric vehicles include BEVs and FCEVs.
Historical data source: Marklines (2022), IEA EV Outlook (2022), EV Volumes (2022)

FIGURE 3.7

Number of road vehicles by type and drivetrain

Units: Million vehicles



Historical data source: Marklines (2022), IEA EV Outlook (2022), EV Volumes (2022)
Combustion vehicles include ICEs and PHEVs.Electric vehicles include BEVs and FCEVs

The acceleration of EV uptake in North America is supported by consumers now having a broader selection of vehicles to choose from, given that manufacturers have introduced a more extensive assortment of BEVs into the market, including the highly sought-after large-size vehicles. Until recently, compact cars such as sedans and hatchbacks were practically the sole EV choices available, despite trucks and SUVs comprising approximately 78 percent of new vehicle sales in the US in 2021. However, the range of options is poised to grow even further, with numerous new models anticipated to debut by 2024. However, offering more affordable EVs, around the 25,000 USD mark, is also essential for a further widespread uptake, in combination with a sufficient charging network build-out. Both, home charging, which will be the main option to charge your private EV, and a further roll-out of public charging options will also significantly support the EV uptake growth in North America (JD Power, 2023). Mainly for two primary reasons, namely, (1) enhanced convenience and accessibility through an increasing number of charging stations in public places, workplaces, and commercial areas to alleviate "range anxiety" concerns among potential EV owners, and (2) more rapid chargers, in particular, will encourage more people to adopt EVs as their primary mode of transportation, as they can charge up quickly and efficiently while running errands or during short stops. In the near-term future, V2X will enhance the utility of EVs even more through grid stabilization, provision of backup power source, and demand response and load management services.

Our projections indicate that fuel-cell electric vehicles (FCEVs) will have a limited and local role in North American road transportation. Due to cost and energy-efficiency disadvantages compared to BEVs, FCEVs are unlikely to experience widespread adoption, except in one market segment: heavy, long-distance commercial vehicle transport. Even in this segment, battery electric trucks will also capture a significant portion of the non-fossil transport market, competing with FCEV-powered trucks. Combustion technologies, including the use of biofuels, will continue to be utilized in this category as well.

Policy support is crucial for the uptake of hydrogen in various sectors, and some countries like Japan and South Korea strongly promote FCEVs as part of their automotive emission-reduction plans, as well as California. Nevertheless, significant barriers hinder the widespread adoption of hydrogen in road transport.

The conversion of power to hydrogen incurs a considerable energy loss (approximately twice the input), and additional efficiency reduction occurs when converting hydrogen back to electricity in the vehicle. Consequently, FCEVs can only achieve an overall well-to-wheel efficiency of 25% to 35%, significantly lower than the 70% to 90% range for BEVs. Additionally, FCEV propulsion is more complex and costlier compared to BEVs. Due to these factors, almost all major vehicle manufacturers focus solely on introducing BEV models.

California has installed one of the most generous governmental support schemes for fuel-cell electric vehicles (FCEVs). Consequently, the sales of passenger FCEVs in the past seven years have experienced a remarkable surge, resulting in a total of 11,956 vehicles sold in the state by the end of 2021, compared with only 188 in 2015, an increase of over 6,000%. However, despite this growth, FCEVs still constitute just 0.025% of California's total vehicle population. This notable increase in FCEV sales has been accompanied by a corresponding expansion of retail hydrogen refueling stations. Presently, approximately 56 stations are operational, from six in 2015, with several more under development, indicating a significant growth in infrastructure to support FCEV refueling.

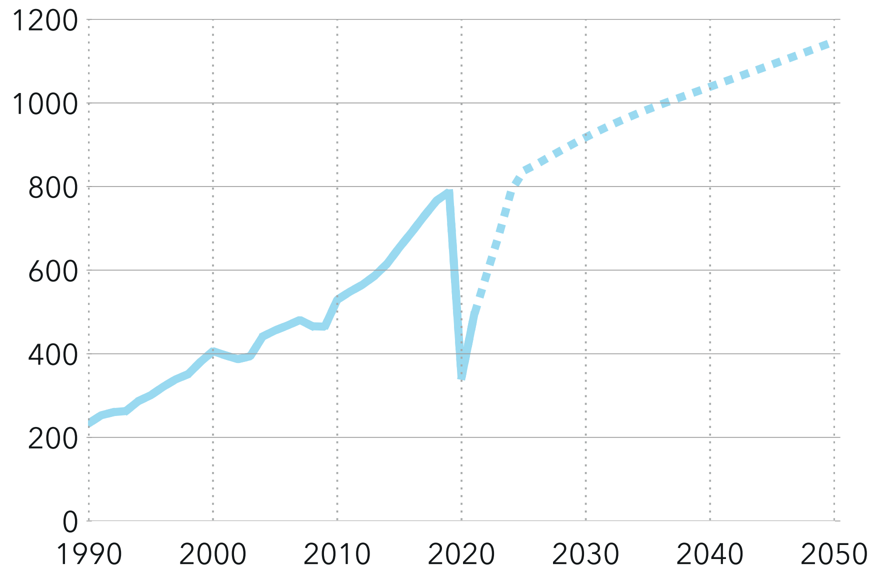
Aviation

Despite the significant impact of COVID-19 on air travel, which resulted in a more than 50% decrease since the start of the pandemic, the number of passenger trips continues to grow. Figure 3.8 illustrates the projected passenger flights for North America reaching 1,150 million flights by 2050, which represents a 45% increase compared to the levels before the pandemic. However, the recovery has been slower compared to other industries. Although we expect leisure travel to return to normal, the pandemic has introduced new work patterns that will have a lasting effect. As a result, we anticipate a 20% reduction in business travel throughout the forecast period, indicating a long-term impact.

FIGURE 3.8

Air passenger demand

Units: Million passenger-trips/yr



Historical data source: ICAO (2020), Airbus GMF (2018)

Technologically, aviation faces challenges in finding alternatives to oil-based fuel, making it a more difficult sector to decarbonize than road transport for example. However, due to its manageable stakeholder landscape and international governance structure, implementing and monitoring the adoption of low-GHG emission technologies and fuels could be relatively feasible. Nonetheless, even with advancements in non-fossil fuel alternatives, their high cost and limited supply and infrastructure availability remain significant barriers.

Due to the weight of batteries and their energy density, electrification is currently a viable option for propulsion only in short-haul flights. The deployment of electric airplanes is expected to begin before 2030, starting with very small aircraft carrying fewer than 20 passengers. In the 2030s, this trend is likely to expand to slightly larger short-haul planes in leading regions such as North America. Hybrid-electric solutions will become relevant for medium-haul flights. Considering that a small portion of aviation fuel is consumed in short-haul flights, electricity is projected to constitute only 3% of North Americas aviation fuel mix by 2050.

The aviation industry is exploring two alternative routes to transform the fuel mix: pure hydrogen and sustainable aviation fuels (SAF). This includes biomass-based fuels from first- and second-generation sources, as well as power-to-liquid (PTL) or e-fuels derived from hydrogen. It is important to note that all these alternative solutions will incur higher costs compared to current oil-based fuel, both in the short-term and towards 2050. Consequently, regulatory and consumer-driven factors are expected to drive the adoption of these fuel and technology changes.

> Bio-based sustainable aviation fuels (SAF) are already being implemented on a small scale. However, with regulatory support and consumer demand, SAF is expected to rapidly scale up.

The US government has initiated the "SAF Grand Challenge" to achieve cost reduction, enhance sustainability, and expand the production and utilization of sustainable aviation fuels (SAF). The primary objective of this initiative is to scale up SAF production to 3 billion gallons per year by 2030, ultimately reaching 35 billion gallons by 2050. This collaborative effort involves multiple government agencies coordinating investments in research and development, demonstrations, and support for the SAF supply chain.

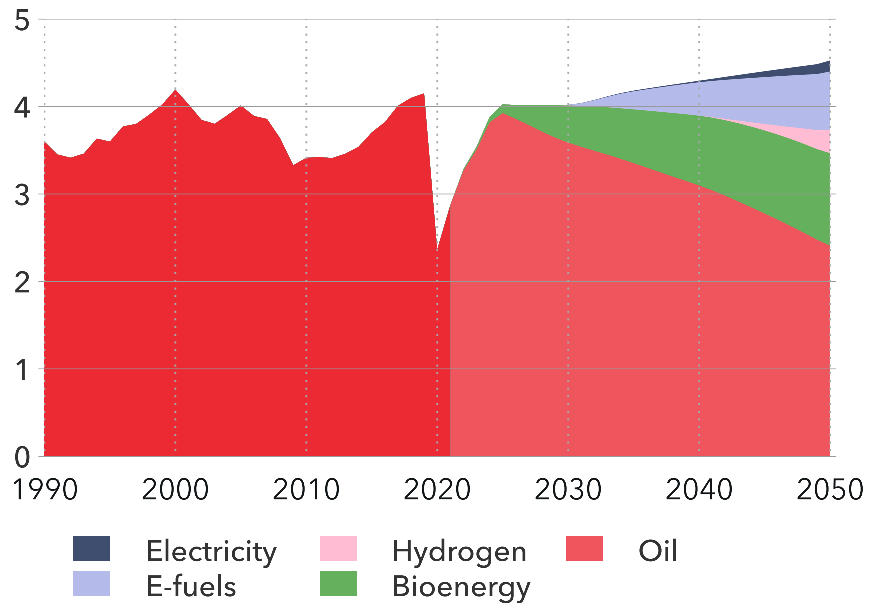
The US Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA) both provide support for creating demand and supply of SAF. The IRA offers a production tax credit of up to USD 1.75 per gallon for very low life-cycle GHG fuels until 2027. The IRA also includes tax credits for carbon capture, direct air capture (DAC), clean hydrogen, and clean electricity production, indirectly reducing the cost of SAF feedstocks. Collectively, these policies have the potential to significantly decrease the overall cost of SAF. Similarly, the creation of credits for SAF with the Canadian federal Clean Fuel Regulation will also boost the uptake of SAF.

In the short and medium term, biofuels are likely to dominate the SAF composition. Comparing the advantages of hydrogen and e-fuels, the aviation subsector in North America is projected to have 2.5 times more e-fuels, accounting for a 15% share in the fuel mix, compared to pure hydrogen. This is primarily because e-fuels can be used as drop-in replacements for all types of flights, while pure hydrogen is mainly limited to medium-haul flights. Nevertheless, oil will remain the primary fuel source for aviation, representing a 53% share in 2050, albeit with a 47% reduction in absolute terms compared to present levels (Figure 3.9).

FIGURE 3.9

Aviation energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

Maritime

The maritime industry in the United States and Canada plays a vital role in their respective economies due to their extensive coastlines and reliance on international trade. Additionally, the intercoastal highway, inland waterways system, and the Great Lakes also move significant tonnage of agriculture products, dry and liquid bulk commodities to and from the international gateway ports. The movement of cargo on the waterways is most efficient mode in terms of emissions per ton-mile, but ships are capital intensive assets with 20+ years expected lifetime, and towards 50 years for US and Canadian domestic vessels operating in the rivers and Great Lakes. As the shipping industry aims to achieve decarbonization, one of its primary concerns revolves around the supply of carbon-neutral fuels and port infrastructure to deliver these fuels to the ships. This concern arises due to the industry facing competition from other sectors of the limited supply and the expected higher cost of the carbon-neutral fuels.

In January 2023, multiple federal agencies in the US together created a roadmap aimed at reducing emissions from the transportation sector, including maritime. The maritime roadmap encompasses various initiatives such as research and innovation, engagement with international and domestic stakeholders, infrastructure investment, as well as enhancements in design and planning. As outlined in our recently released Maritime Forecast to 2050 (DNV, 2023d), it is our view that in the foreseeable future, it is improbable that the US or Canada will add specific regulations on international ships operating in their ports or waters, and just ensure that ships calling the ports are in compliance with the environmental and GHG regulations adopted by IMO for international shipping as per the MARPOL convention. The recently revised International Maritime Organization (IMO) strategy on close to zero emission shipping around 2050 is just another sign of the mounting pressure to decarbonize in maritime sector.

However, individual states, like California, have already implemented specific mandates. For instance, since 2014, California has required increased utilization of shore power at berth for cruise vessels, container, and reefer ships at major ports. Furthermore, the state intends to extend these mandates to include tankers and vehicle carriers in the coming years.

In addition to governmental and regulatory efforts to decarbonize maritime sector, it is the response to the decarbonization demands of cargo owners, that will enable the implementation of zero-emission shipping services, thus generating a market demand for e.g., sustainable biofuels in the short-term. Our recently released white paper *Biofuels in Shipping* sheds light on areas such as biomass availability, biofuel refinery capacity, and ship and engine fit regarding biofuel use (DNV, 2023d).

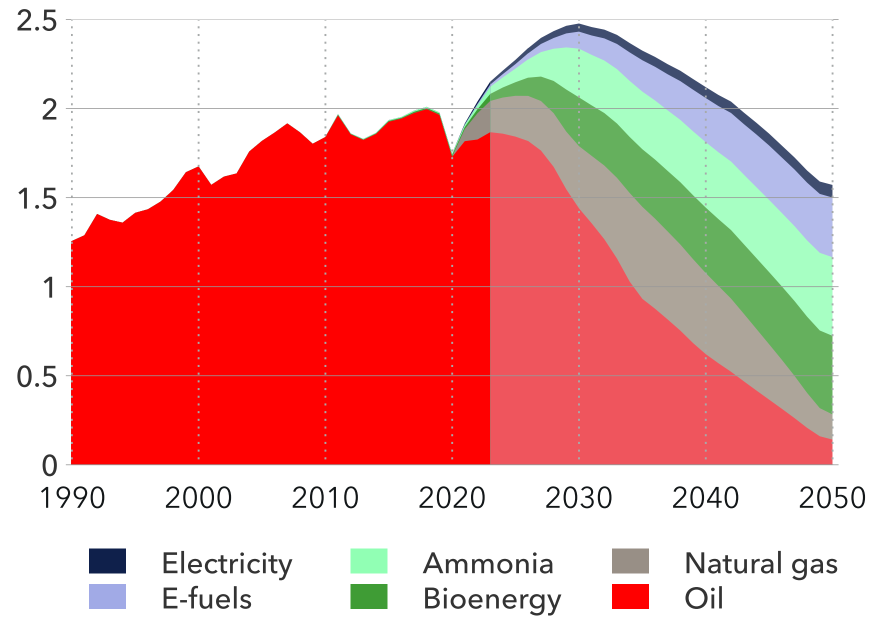
A recent and emerging trend we now observe is that some cargo owners are setting ambitious decarbonization goals for their operations. To achieve these targets, especially so-called scope 3 emissions reduction, which involve transportation of cargo, access to low- and zero-emission shipping services is crucial. In response to this demand, shipping companies have already begun offering "zero-emission services", and we anticipate further growth in this sector to meet cargo owners' demands.

Currently, certified biofuels are utilized to achieve zero emissions, but new options like e-fuels and other low- and zero-carbon fuels from the 2030s on, will also contribute to this goal. This will go in hand with the emergence of green corridors, reliably supplying low- and zero-carbon fuels to both domestic and international shipping.

FIGURE 3.10

Maritime energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

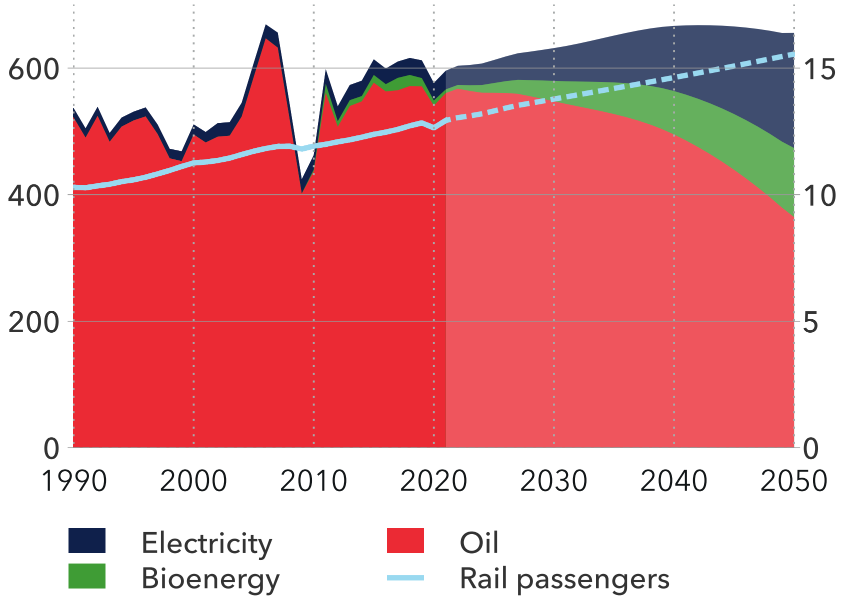
Rail

When it comes to passenger transport, particularly in urban regions, rail transport offers superior space efficiency compared to other alternatives. Additionally, the ease of electrification further enhances its attractiveness as a means of decarbonizing transportation. This particular segment encompasses all forms of transportation that utilize rail, including urban rail systems. In 2022, rail accounted for 2% of the overall energy demand for transportation and approximately 0.7% of the total energy demand. It is projected that passenger numbers will continue to grow in the coming decades, reaching slightly above 15 billion passenger-kilometers (Figure 3.11).

FIGURE 3.11

Rail energy demand by carrier and rail passengers

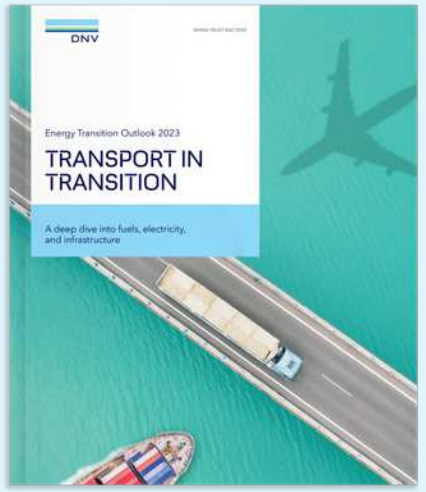
Units: PJ/yr (left); Billion passenger-km/yr (right)



Historical data source: IEA (2023), IEA UIC (2019)

Despite numerous advantages over diesel-powered locomotives, electric locomotives are not as widespread in the US. In the past, US railroads were at the forefront of innovation and technology adoption. However, they have fallen behind many other advanced nations that have long invested in electric-powered railroads. In the early to mid-20th century, electric locomotives and diesel-electric locomotives replaced steam engines, with US railroad companies choosing diesel due to its lower initial costs. Although electric systems are more cost-effective to operate and maintain, US railroads faced challenges in financing electrification upgrades compared to building diesel-fueled systems. Unlike many other countries where railroads were government-owned, US railroads have always been regulated private sector entities. As a result, less than 1 percent of US railroad tracks currently utilize electrification, while globally, electricity powers over one-third of trains.

Hydrogen has the potential to serve as a substitute for diesel in rail systems without electrification. The first hydrogen-powered passenger train is set to begin operation in 2024 under the aegis of San Bernadino County Transit authority in the US (Hydrogen Central, 2022). Similarly, numerous electric battery-powered and hydrogen fuel cell powered demonstration projects have been carried out in the US and Canada (Delphi Group, 2022). Nevertheless, several barriers hinder large-scale implementation, including limitations in pulling power for rail freight, the requirement for government support, and the absence of a hydrogen refueling infrastructure along primary rail routes.



TRANSPORT IN TRANSITION

A deep-dive into availability, technology development, costs, policy drivers, and likely uptake of sustainable energy sources in transport sectors through to 2050.
Download

3.2 BUILDINGS

One of the three main demand categories in North America, building energy demand shrinks marginally, from 23 EJ in 2022 to 21 EJ in 2050, despite increasing prosperity leading to higher useful energy demand, larger building area to be served, and climate change impacts in the region.

We are entering an era when the overall energy intensity of buildings in North America declines. Final energy demand from buildings shrinks while useful energy demand in US and Canada grows from 30 EJ in 2022 to 38 EJ in 2050, spurred on by electrification and higher-efficiency appliances, thus reducing the overall energy intensity of buildings (Figure 3.12).

The relative share of buildings within total final energy demand in the region grows from 29% in 2022 to 35% by mid-century, mostly due to the much faster demand reduction in transport through electrification (Figure 3.13).

In our forecast, we separate buildings energy demand into five end-use categories: space heating, water heating, space cooling, appliances and lighting, and cooking. We also separate commercial and residential buildings in the model because the drivers of useful energy demand in the two building types differ.

Of the 23 EJ of buildings energy demand in 2022, residential buildings accounted for 55% and commercial buildings the remaining 45%, but by mid-century both residential and commercial buildings will have equal demand. In terms of building area to be serviced by energy, residential area typically dominates with a 70% share throughout the forecast period. But, due to faster adoption of heat pumps, in both space and water heating in residential buildings, its share in building energy demand shrinks.

Space heating accounted for 46% of the total buildings energy demand in North America, followed by appliances and lighting (29%). By mid-century, space heating will have been displaced by appliances and lighting (39%), with prosperity in the region driving greater use of appliances. Moreover, space heating requirements will diminish in a gradually warming climate.

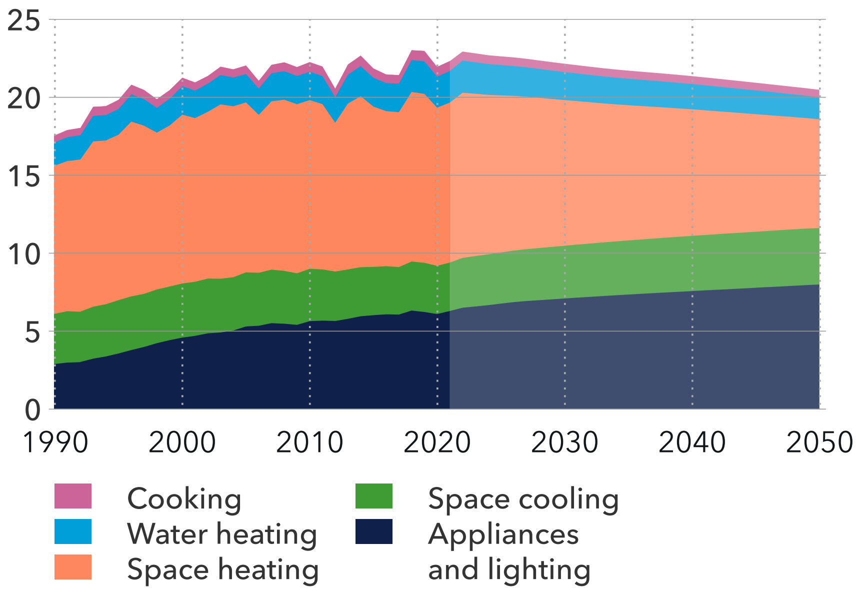
Even in 2022, electricity constituted 51% of total building energy demand, with the majority of that used to power electric appliances and lights, and air-conditioners. In contrast, space and water heating rely heavily on natural gas and other fossil fuels. By mid-century, electricity starts to make in-roads into these difficult-to-electrify end-use categories to reach 70% of the total final energy demand of buildings.

Hydrogen, both blended into natural gas grids, and as a stand-alone fuel gains traction in the US and Canada in the buildings sector. By 2050, 5% of the total energy demand, 0.94 EJ, in buildings will be supplied by hydrogen, spurred on by the IRA clean hydrogen incentives making hydrogen cost-effective.

FIGURE 3.12

Buildings energy demand by end-use

Units: EJ/yr

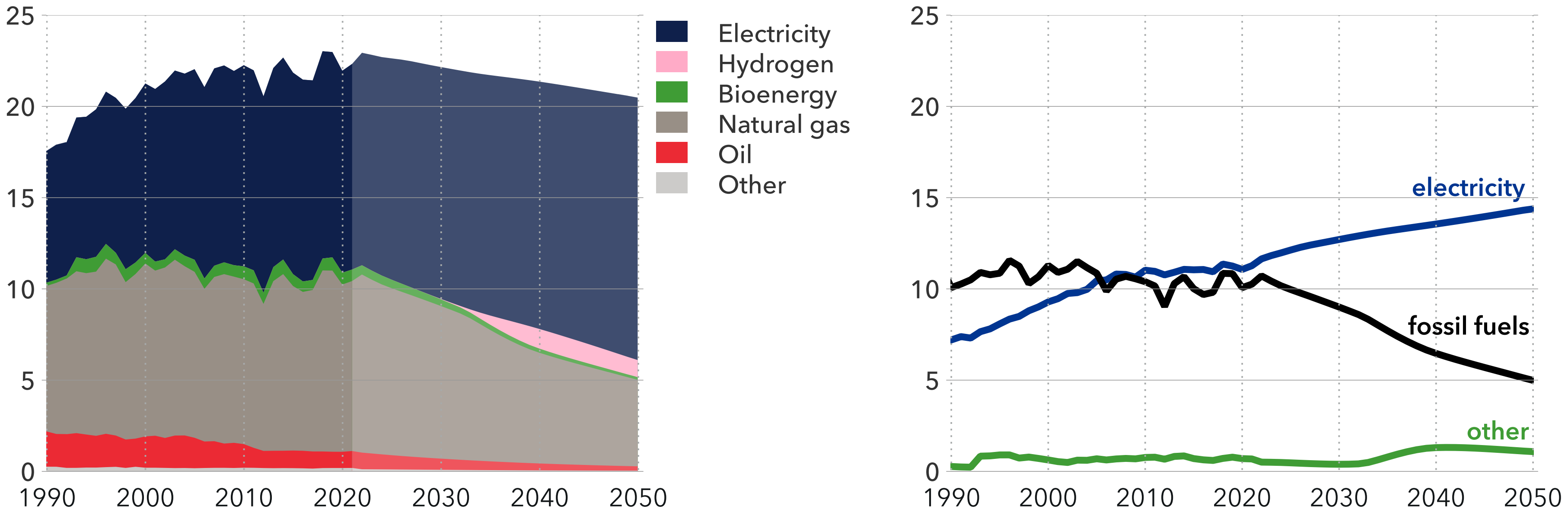


Historical data source: IEA (2023), EIA RECS (2020), DNV analysis

FIGURE 3.13

Buildings energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

1 Useful energy demand is the services demand in buildings, and final energy demand is the energy expended to provide the services demand.

Drivers of building energy demand

Overall, GDP per capita and tertiary sector GDP drive or increase the useful energy demand for all end uses, in residential and commercial buildings, respectively.

Additionally, each of the end uses has distinct factors which either increase or decrease the useful energy demand. This is shown in Table 3.1, where the arrows indicate an increase/decrease in a factor resulting in a corresponding change in useful energy demand.

Elaborating the effect of changing climate characteristics and policy

In our forecast, the building area to be served in the US and Canada increases from 35,000 square km in 2022 to 44,000 square km by 2050, driven by continuously increasing GDP per capita. Throughout our forecast horizon, residential building area is the clear majority, accounting for about 70% of the area to be served even in 2050. There is evidence that the post-pandemic office occupancy has not rebounded

TABLE 3.1

Factors affecting the useful energy demand in buildings

	Commercial				Residential				
	Space heating	Water heating	Space cooling	Appliances and lighting	Space heating	Water heating	Space cooling	Appliances and lighting	Cooking
GDP from tertiary sector per capita	↑	↑	↑	↑	↑	↑	↑	↑	↑
Floor area of buildings	↑		↑		↑		↑		
Heating degree days (HDD)	↑	↑			↑	↑			
Cooling degree days (CDD)			↑				↑		
Building thermal characteristic improvement and retrofitting	↓		↓		↓		↓		

in cities in North America (CNN, 2023). Despite this, we forecast a modest increase in commercial building square meterage, since the category includes all non-residential buildings such as manufacturing facilities and industrial plants. With the home- and friend-shoring boost due to the IRA and IIJA, more manufacturing and adjacent buildings are expected, and this is accounted for in our forecast.

The characteristics of a building envelope and the insulation provided by windows etc. determine the overall space heating and cooling loads of buildings. In our forecast, building thermal characteristics (BTC) are influenced by the building code standards and the improvement in BTC due to retrofitting of buildings. There are push and pull forces at play, which determine the dynamics of change of BTC in North America. Pushing better BTC are the building codes and standards set by the International Energy Conservation Code, which are applicable to both new residential and commercial buildings, adopted to varying degrees by the different states in the US (PNNL, 2021a). Pulling towards better thermal insulation and building energy efficiency are financial incentives available as tax credits through the IRA, mainly for households to improve their energy efficiency (IRS, 2023a).

Another pull strategy which has energy justice and equity dimensions, in addition to energy demand implications, is the Weatherization Assistance Program (US DOE, 2023b) run by the Department of Energy in the US, where financing is made available at very low costs to low-income households to reduce their energy expenditures, mainly through building envelope improvements.

Space heating and cooling demand is dependent on the prevailing weather and longer-term climate trends in the US and Canada. Heating degree-days (HDD) and cooling degree-days (CDD) determine how much space heating and space cooling demand will be present, and is defined as the cumulative positive difference between daily average outdoor temperature and reference indoor temperature of 21.1 °C. In 2022, for example, the cumulative daily total temperature running below this reference level amounted to 3,020 °C. This number is arrived at by multiplying a single day by the positive difference between 21.1 °C and the average temperature of the day, and then summing these over 365 days of the year.

With a warming climate in North America, our forecast assumes that HDD decreases from 3,020 °C-days/year in 2022 to 2,900 °C-days/year in 2050. Owing to more frequent extreme heat events which are forecast due to a warming climate in North America, CDD increase from 455 °C-days/year in 2022 to 620 °C-days/year in 2050.

Space and water heating

Space and water heating accounted for 55% of total building energy demand in 2022 but by mid-century their importance will reduce somewhat, accounting for only 41% of the total building energy demand.

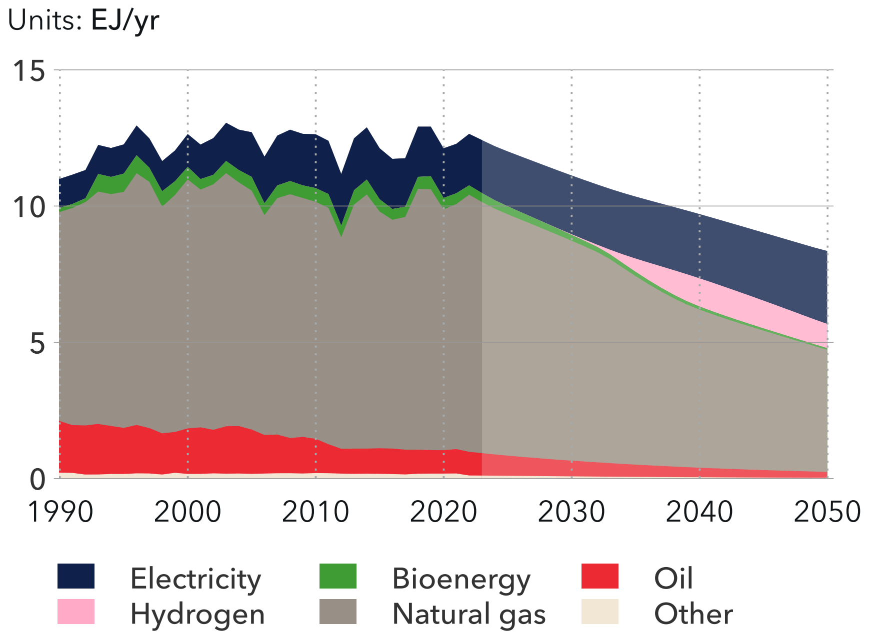
This is due not only to a reduction in HDD (when less energy is required for heating space and water) driven by a warming climate but is also due to the uptake of heat pumps, which because of their higher energy efficiency than gas boilers, results in a reduction in final

energy demand. In addition, steady improvements in building insulation and thermal efficiency also exert downward pressure on the energy demand for space heating. By 2050, 108 million households in US and Canada will be kept warm by heat pumps.

With all these factors at play, the energy demand for space and water heating reduces 25%, from 12.6 EJ in 2022 to 8.5 EJ by 2050. Of this, the share of hydrogen is significant, at about 11% in 2050, both in blended form in piped gas and in hydrogen boilers (Figure 3.14). With the IRA and Canadian Clean Hydrogen tax credit provisions incentivizing the production of hydrogen through low carbon means, the offtake of hydrogen in building heat provision becomes meaningful in the 2030s.

FIGURE 3.14

Space and water heating energy demand by carrier



Historical data source: IEA (2023), EIA RECS (2020), DNV analysis

While the energy demand for space and water heating supplied by electricity is modest in North America by 2050, our forecast shows that heat pump adoption in new buildings will be high. Figure 3.15 shows the decadal average adoption shares of space heating technologies, for residential and commercial buildings separately. In residential buildings even now the adoption of heat pumps is higher than fossil fuel boilers (mainly running on natural gas). By 2050, almost 65% of residential buildings will have heat pumps providing space heating.

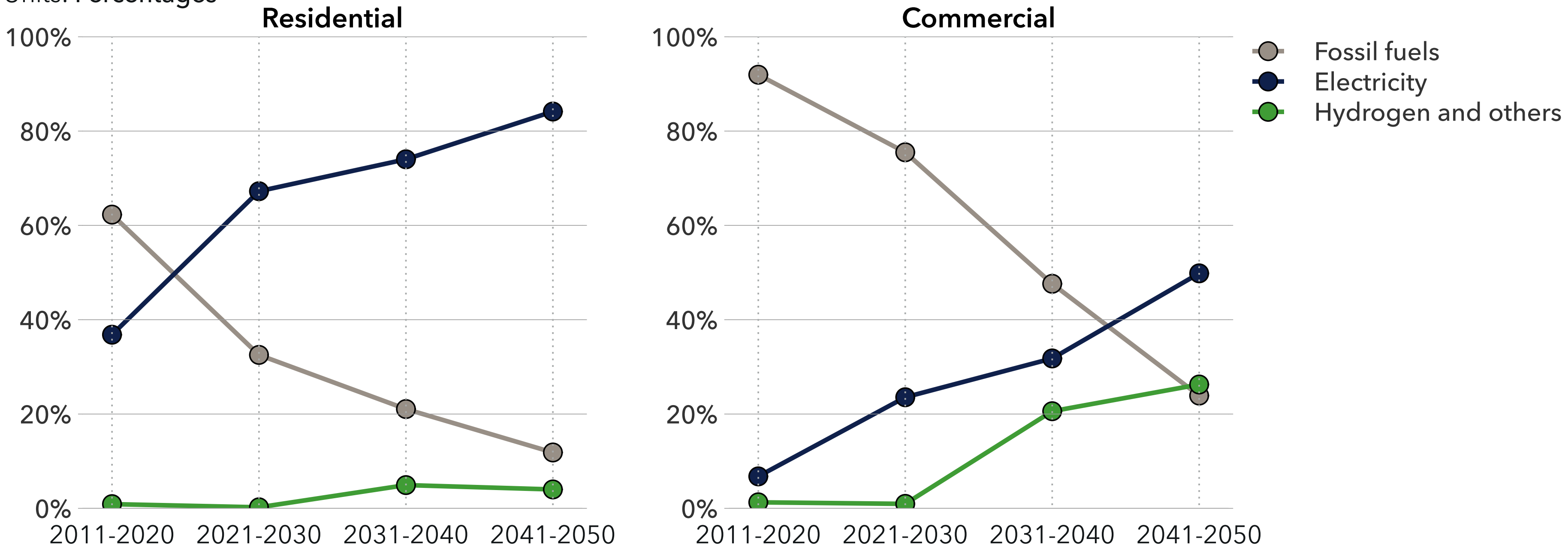
For commercial properties, the share of adoption of heat pumps lags natural gas boilers. One of the reasons for this is that the tax rebates that are available for heat pumps for residential buildings are not the same for commercial buildings. Rather, incentives relate to the overall energy efficiency standards in commercial buildings (IRS, 2023b), and these may be reached while preserving fossil-fuel based heating methods. Furthermore, most commercial buildings are not owner-occupied and hence the split incentive at play between who benefits from efficiency upgrades is more pronounced in the commercial space.

However, for commercial buildings, hydrogen blending into natural gas grids will be higher than for residential buildings (Figure 3.15). Up to 13% of commercial buildings will consume hydrogen for heating purposes by mid-century. With the inclusion of other marginal heating technologies such as direct heat, bioenergy boilers and solar thermal heaters, this other category provides up to 16% energy demand.

FIGURE 3.15

Space heating technology adoption by energy carrier

Units: Percentages



Space cooling

Extreme heat events are occurring with increasing frequency (Canadian Climate Institute, 2023) in many places across North America (NYT, 2023). This underscores the importance of space cooling, and how access to space cooling technology will be vital for climate change adaption in US and Canada. Hence, despite improving energy efficiency standards, cooling energy demand will increase 0.5% year on year from 2022 to 2050, reaching an energy demand of 4 EJ in 2050.

Appliances and lighting

Despite the year-on-year improvement of 0.6% cumulative energy efficiency of appliances and lighting in North America, the energy demand for this end-use category will continue to grow, driven by GDP per capita growth. The total growth from 2022 to 2050 is expected to be 27%, which signifies a year-on-year growth of 0.8%. In absolute terms, the energy demand grows from 6.5 EJ to 8.1 EJ during the same period.

Of this growth, a significant portion is also for energy used to run data centres and cryptocurrency mining and transaction activities. Overall, we estimate the energy demand for data centres to be about 7% of the total commercial appliances and lighting energy demand in 2050.

Cooking

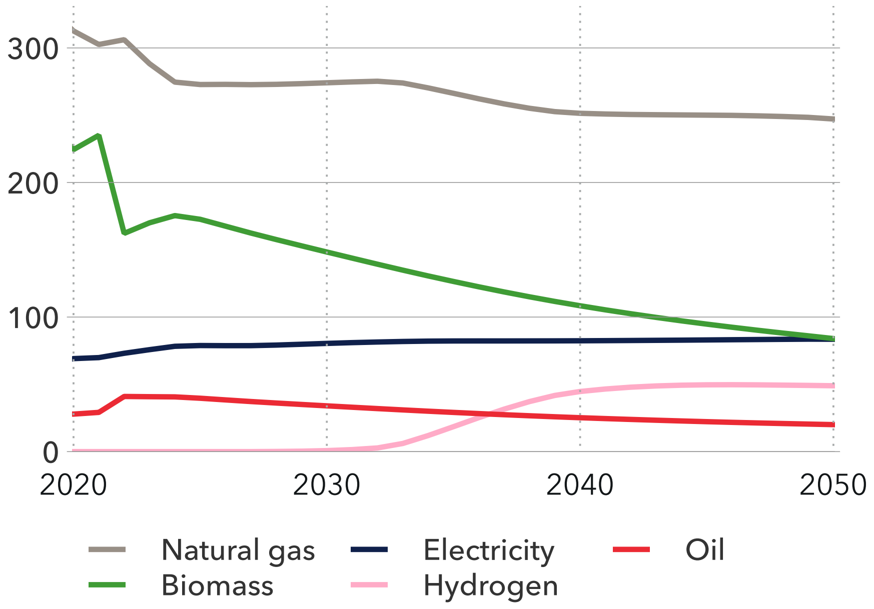
Cooking is often an overlooked end-use category in buildings, especially with respect to energy demand. But it often has an oversized impact on the health and wellbeing of the people, especially with the overwhelming evidence pointing to leakage of natural gas even when the stoves are not in use (Lebel et al. 2022).

Our forecast shows that while there will be a reduction in the share of cooking energy demand provided by natural gas in North America, a still-significant portion, about 50%, will remain even in 2050. Electric ranges and hydrogen blending will make inroads, but despite some counties and states mandating electric hook-up ready new buildings (California Energy Codes and Standards, 2023), it will take many years before natural gas cookstoves are eliminated (Figure 3.16).

FIGURE 3.16

Cooking energy demand by carrier

Units: PJ/yr



Historical data source: IEA (2023), EIA RECS (2020), DNV analysis

3.3 MANUFACTURING

A rebound in manufacturing in North America sees manufacturing energy demand increase from 13 EJ in 2022 to 15 EJ in 2050, a 15% increase.

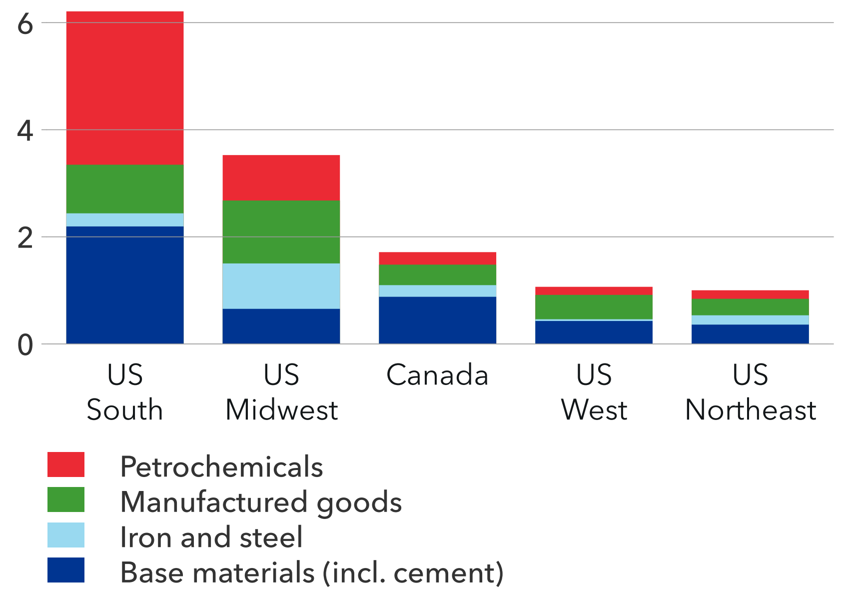
A manufacturing stronghold sustained by affordable energy

North America used to be a leader in manufacturing, representing around a quarter of global manufacturing energy demand in the early 1980s. With the rise of China as a low-cost manufacturing hub, North America progressively turned to higher value-added production.

FIGURE 3.17

Regional manufacturing energy demand, in 2018

Units: EJ/yr



US regions according to US Census Bureau. Historical data source: EIA (2023)

However, the abundance of competitive energy has been a decisive factor in shielding North America from a deindustrialization seen in other high-income regions. The access to valuable natural resources, and especially fossil fuels, has also deeply influenced the geographical distribution of the manufacturing subsectors shown in Figure 3.17.

Heavy industries (e.g. cement, iron and steel, petrochemicals) are the most energy demanding, but also have the lowest value-added and usually tight cost margins. In these subsectors, affordable energy is a decisive factor in deciding if a product is competitive or not. The location of these fossil fuel-intensive industries consequently tends to be correlated with the local supply of the desired energy source, whether it is coal, oil, or natural gas. Local manufacturing hubs also have a role; for example, a large share of steel production is in the Great Lakes region where the car industry has also been historically located.

Less energy-intensive industries, grouped under the 'manufactured goods' subsector, are more evenly distributed and their locations are more dependent on other considerations, like local agricultural production for the food industry (which represents more than 40% of energy demand in this subsector).

A future shaped by geopolitics

The future for manufacturing in North America cannot be decoupled from global geopolitics. The US in particular is used to adopting drastic measures to protect its own industrial interests. Trade tariffs on Chinese steel and solar PV panels are spectacular examples of this behavior. The IRA and the IIJA (see Chapter 2 on policy) have additional protectionist measures, such as domestic content requirements (see Section 5.4), that will also restructure the current manufacturing capacity by making a clearer case for decarbonized energy.

Relocation of industrial production, especially for critical equipment like solar panels, batteries, and silicon chips will result from the continuing increase in geopolitical tension and associated protectionist policies. Demand for locally sourced base materials (cement, steel, etc.) will increase to support these new industries. Although this rebound in manufacturing will provide additional revenues, this will not necessarily translate into a tremendous increase in energy demand. Indeed, some of the most energy-intensive components (e.g. manufacturing of polysilicon for solar PV, or electrodes for EV batteries) will still mostly be manufactured in other regions, namely China and South East Asia. North America will instead apply its capacity to high value-added steps at the end of value chains.

After a decade of energy demand plateauing, we nevertheless forecast that it will increase by 17% between now and 2050, back to a level last seen in the early 2000s. Coupled with improved energy efficiency, this will correspond to a significant increase in manufacturing output.

A decarbonizing fuel mix

The pace of decarbonization will not be the same in all parts of the North America region. The distribution of manufacturing subsectors highlighted in Figure 3.17, coupled with important variations in local policies, will lead to different speeds in transition. For example, differences in carbon pricing are prevalent within the region. Canada and California are expected to have carbon prices above 100 USD/tCO_2e, while industry-heavy states (US Southeast & Texas) will most likely not implement any. This already has a visible impact, as much of the new heavy-industry projects will be located in these more fossil fuel-friendly states. There will be a significant risk of intra-regional carbon leakage, where businesses, for reasons of costs related to climate policies, transfer production to locations with laxer emission constraints. Job preservation and local industrial strategies will also affect the speed of the transition. However, there is a regional consensus around some decarbonization solutions in manufacturing.

Carbon capture will be one of the favored options to decarbonize heavy industries. As detailed in Section 7.2, significant uptake in manufacturing will result from:

- Transferability of competence from the oil and gas sector
- Regional production of fossil energy
- The possibility of retrofitting existing installations
- Strong governmental policy support (e.g. IRA, 45Q tax credit).

Carbon capture will be especially relevant where large industrial production allows hub creation, and where there is access to infrastructure to transport CO_2 for sequestration or an end-use such as enhanced oil recovery.

The uptake of carbon capture (15 $MtCO_2$/yr of direct emissions by 2030) will preserve demand for fossil fuels, especially for already popular natural gas, for which demand will slightly increase by 16% by mid-century. Conversely, oil and coal will continue to decline, by 80% by 2050, as older industrial plants are progressively phased out and new low-carbon competitive technologies are preferred for new plants.

Hydrogen will be an alternative for decarbonized processes when carbon capture is not economically viable, but also for new industrial installations. We forecast that the sector will be using 2 MtH_2/yr by 2030, aided by the window of certainty provided by the US IRA and the Canadian Clean Hydrogen Investment Tax Credit. By mid-century, this will rise to 12 MtH_2/yr, equating to 10% of manufacturing energy demand.

Electrification will also play an important role in decarbonizing manufacturing, especially when low- or medium-heat is needed, and where it can already favorably substitute for natural gas. Some possibilities for electrification will also appear for high-heat processes, like steam crackers, but long asset lifetimes and difficult retrofitting will favor carbon capture instead. Overall electricity demand will increase from 1,000 TWh/yr now to 1,400 TWh/yr in 2050.

Transition dynamics will vary across manufacturing

As shown in Figure 3.18, the petrochemicals, manufactured goods, and base materials subsectors are the most energy-hungry in North American manufacturing, each accounting for around a quarter of the sector's energy demand.

The petrochemicals subsector has an important share in both manufacturing sector energy use and revenues. Although local oil and shale gas supply will decrease, North America will still make use of its abundant resources to extract the most value from fossil fuels. We forecast a 12% increase in energy demand by 2030 in the subsector, and 23% by 2040 before a slow decrease. This is tightly linked to non-energy demand presented in the next section.

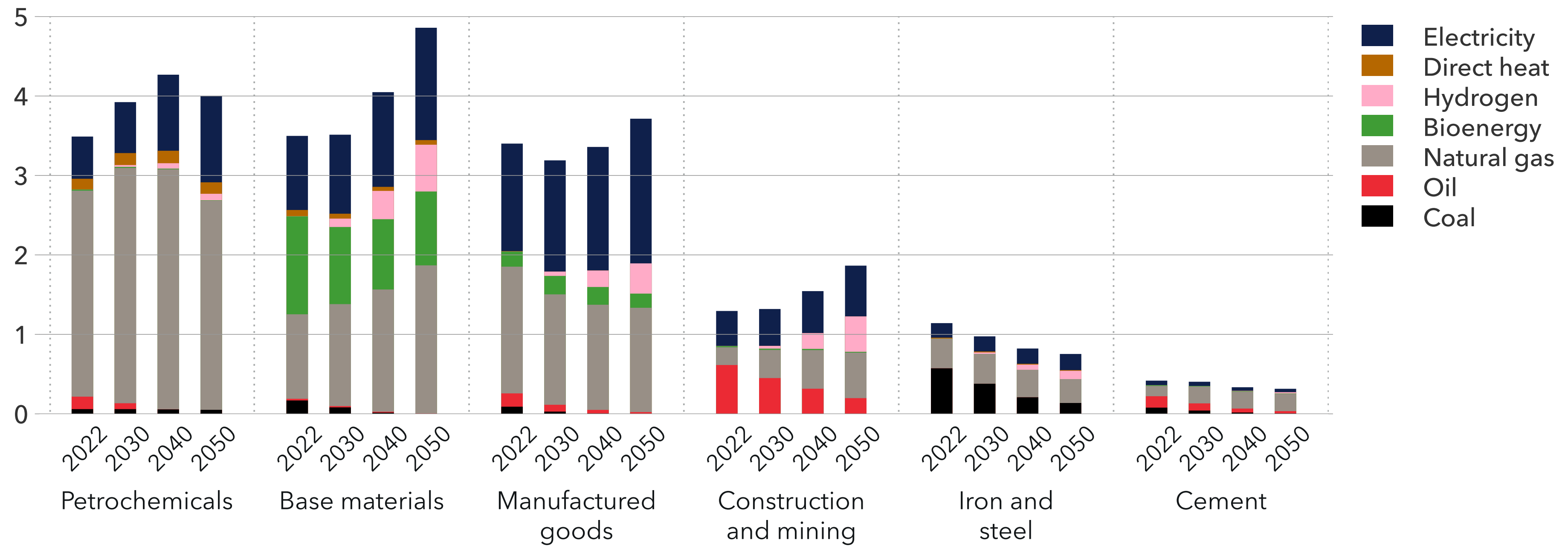
The manufactured goods subsector is economically important in North America. Natural gas (48%) and electricity (40%) currently cover most of its energy demand, mostly for low- and medium-heat processes. Total demand will remain fairly stable towards 2050, but electricity's share will increase to meet half of the demand while natural gas (35%) will partially be replaced by and blended with hydrogen (10%).

The base materials subsector is currently dominated by the energy-intensive pulp and paper industry, the

FIGURE 3.18

Manufacturing energy demand by subsector and energy carrier

Units: EJ/yr



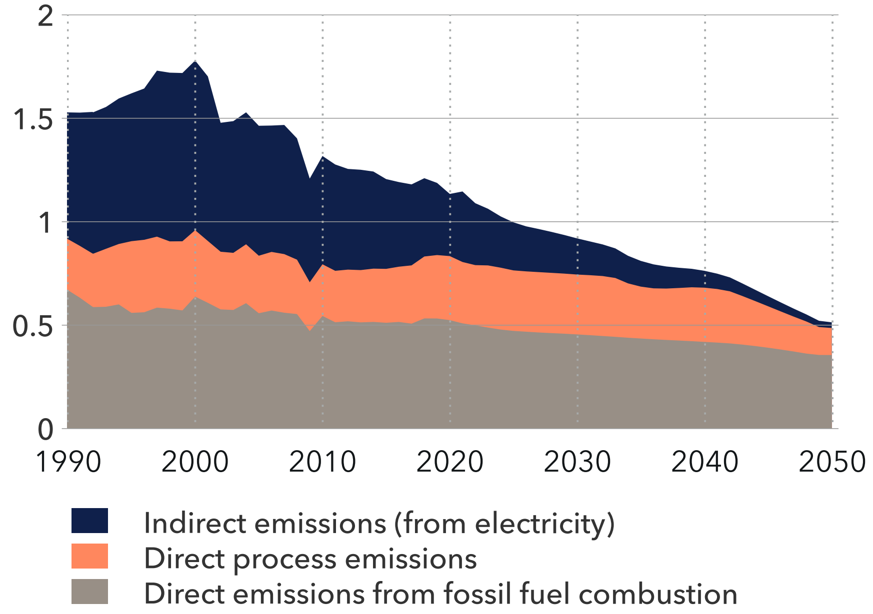
primary user (84% of total demand) for bioenergy in manufacturing. Bioenergy meets a third of base materials' energy demand, the rest coming mostly from electricity and natural gas in similar shares. Demand for pulp and paper is not expected to increase, but other base materials, like aluminum and other metals, will be an essential part of the new renewables value chains. Production and thus energy demand will increase, mostly supported by natural gas, electricity, and hydrogen (5 MtH_2/yr by 2050).

Although steel production has progressively declined over recent decades, North America is still a major steel-producing region, with 92 Mt/yr in 2022, mostly for domestic use. Steel production is located in specific regions, with US states like Indiana dominating. Electric arc furnaces (EAF) are already widespread for processing scrap steel. We also expect the natural gas-based direct reduced iron version (DRI-EAF) to expand and become the preferred solution for steel production from virgin iron ore, with an option for retrofitting to use future decarbonized hydrogen when competitive.

FIGURE 3.19

Manufacturing sector CO_2 emissions by source

Units: $GtCO_2$/yr



Historical data source: IEA WEB (2023)

A clear cut in emissions

The significant transformation that the manufacturing sector will undergo, supported by decarbonization of the power mix, will lead to a halving of manufacturing emissions, as shown in Figure 3.19. At the same time, energy demand and manufacturing output will be increasing. As a result, emission intensity will decrease even more, highlighting the profound transition that North America's manufacturing sector is about to undergo.

Though the rebound in manufacturing in North America will provide additional revenues, this will not necessarily translate into a tremendous increase in energy demand.

3.4 OTHER & NON-ENERGY DEMAND

Other energy demand reduces from 1.8 EJ/yr in 2022 to 1.2 EJ/yr in 2050, driven by increasing electrification in agriculture, fisheries, and the military. Driven by the petrochemical industry, non-energy demand will continue to increase in the coming decade, before slowly declining.

Other energy demand
Other energy demand – from agriculture, fisheries, and the US and Canadian military at home and abroad – is driven by secondary and tertiary sector GDP. So, despite the region's GDP growth, greater energy efficiency and electrification imply a one third (33%) reduction in other energy demand between 2022 and 2050.

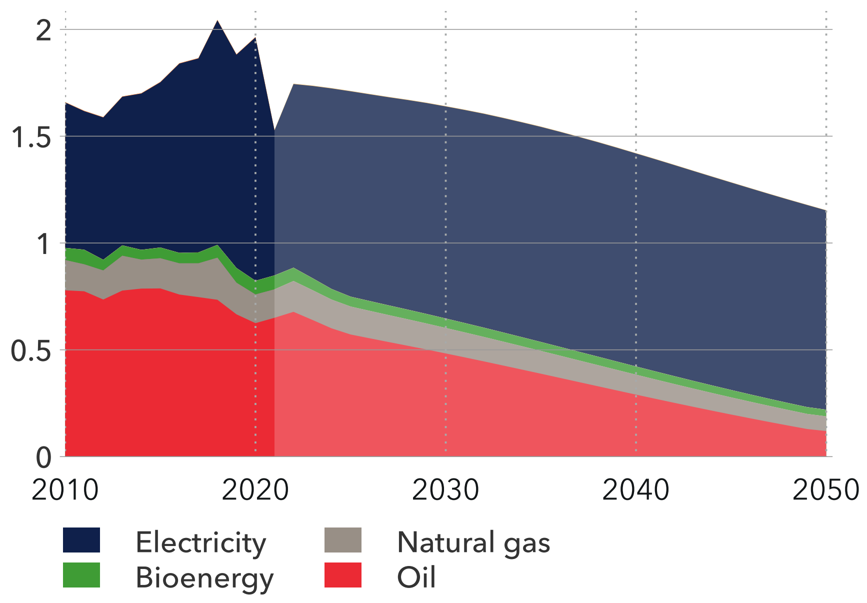
In North America, 'other' covers just 2% of total energy demand and retains more or less the same share in 2050. Electricity meets most (54%) of other energy demand. Increasing electrification of agricultural vehicles and machinery will see this share rise to 81% by mid-century (Figure 3.20).

Almost 42% of other energy is for the military in North America, and due to reporting procedures, regardless of the way electricity was produced, the energy carrier is reported as electricity. Nevertheless, there is an established history of renewable energy use among deployed military forces. For example, even as early as 2011 the US Marines installed solar-based microgrids in one of their bases in Afghanistan (NPR, 2011), reducing diesel consumption of their electricity generator by almost a tenth.

Non-energy demand
Non-energy use reflects consumption of coal, oil, natural gas, or biomass as industrial feedstock, and typically results in tangible products like plastics, paints, or fertilizers. In 2022, 7.7 EJ (about 9%) of North America primary fossil-fuel supply was used for non-energy purposes.

FIGURE 3.20
Other energy demand by energy carrier

Units: EJ/yr



Historical data source: IEA WEB (2023)

Slowly decarbonizing ethylene crackers

Steam cracking is usually the first step in the petrochemicals value chain. It converts ethane, LPG or naphtha into primary petrochemicals (mainly ethylene) that are further processed into other chemicals. In North America, almost all plants are located close to oil and gas production and refining facilities, - Texas and Louisiana in the US, and Alberta in Canada.

The process is energy- but also emission-intensive, representing around 1% of North America emissions. Energy- and conversion-efficiency has however greatly improved over the past decades. While a few large-scale projects are in the pipeline, other decarbonization options are being considered within the industry, boosted by the recent policy packages.

Carbon capture is a first option, as plants are usually located close to existing or planned CO_2 infrastructure. For example, Dow's project in Fort Saskatchewan in Alberta will rely on carbon capture to achieve net-zero emissions.

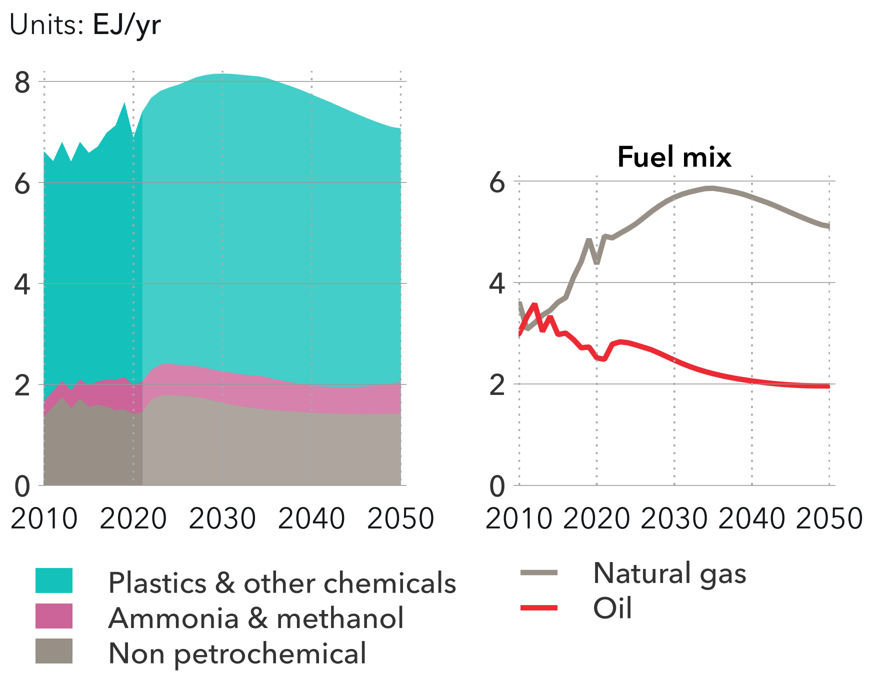
Another one is the use of decarbonized electricity and further electrification. Electric crackers are still in a development phase, but petrochemicals plants already have important electricity as well as high temperature steam needs. Renewables can cover the electricity needs. But the petrochemical industry might also be one of the first industrial clients for small modular nuclear reactors, as this technology can provide both electricity and steam, like the current onsite gas- or coal-fired power plants. This is an approach selected by Dow, which has partnered with X-energy for the installation of four 80 MWe units at its Seadrift plant in Texas, for an operational start by 2030.

Plastics production represented 3.3 EJ (42%) of total non-energy demand in 2022. Global plastics demand has grown significantly in recent decades, and North America is currently the second largest producer of plastics and a large exporter. This growth is expected to continue in the coming decades, as plastics consumption is strongly related to the global increase in GDP per capita.

North America is lagging other high-income regions when it comes to plastics recycling and has historically exported a significant share of its waste. But tighter regulations or outright bans in importing countries (e.g. China in 2018) will force local recycling solutions.

FIGURE 3.21

Non-energy demand for energy carriers by end use



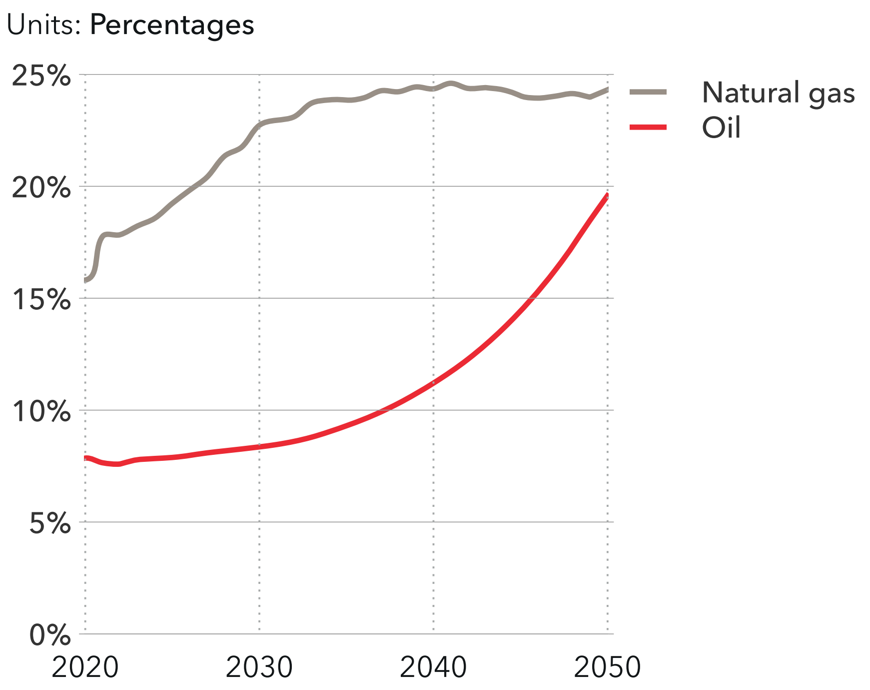
IEA WEB (2023), DNV analysis

The need for virgin fossil feedstock will then decrease, enabled by technological development in advanced recycling. One interesting development is the uptake of chemical recycling via pyrolysis and similar technologies. It will create a stream of recycled fuel that could be directly fed into traditional steam crackers as a replacement for oil. By 2050, 0.15 EJ of this recycled fuel will be produced each year in North America, covering above 1% of oil primary energy demand (Figure 3.21).

Demand for ammonia as a feedstock, mainly driven by fertilizer consumption, is expected to remain stable around 22 Mt/yr in our forecast period. Natural gas is currently used to provide hydrogen for ammonia production. Ammonia manufactured from electrolytically produced hydrogen could reduce the non-energy demand, but subsequent reuse of CO_2 in the process to produce urea will limit interest in this alternative. Thus, natural gas (with and without CCS) will still feed 95% of ammonia production in 2050. Non-energy demand will be stable at 0.5 EJ/yr over the coming decades.

FIGURE 3.22

Share of non energy use in oil and natural gas demand



Demand for other chemicals (methanol, paints, cosmetics, pharmaceuticals) is expected to stay stable around 2 EJ/yr towards 2030 before a continuous decline. Non-chemical uses include applications for asphalt (bitumen), lubricants, and solvents. Demand for these purposes is expected to increase slightly in the next five years, driven by increased infrastructure buildout, but will then return to today's level and remain stable to mid-century.

Fuel mix

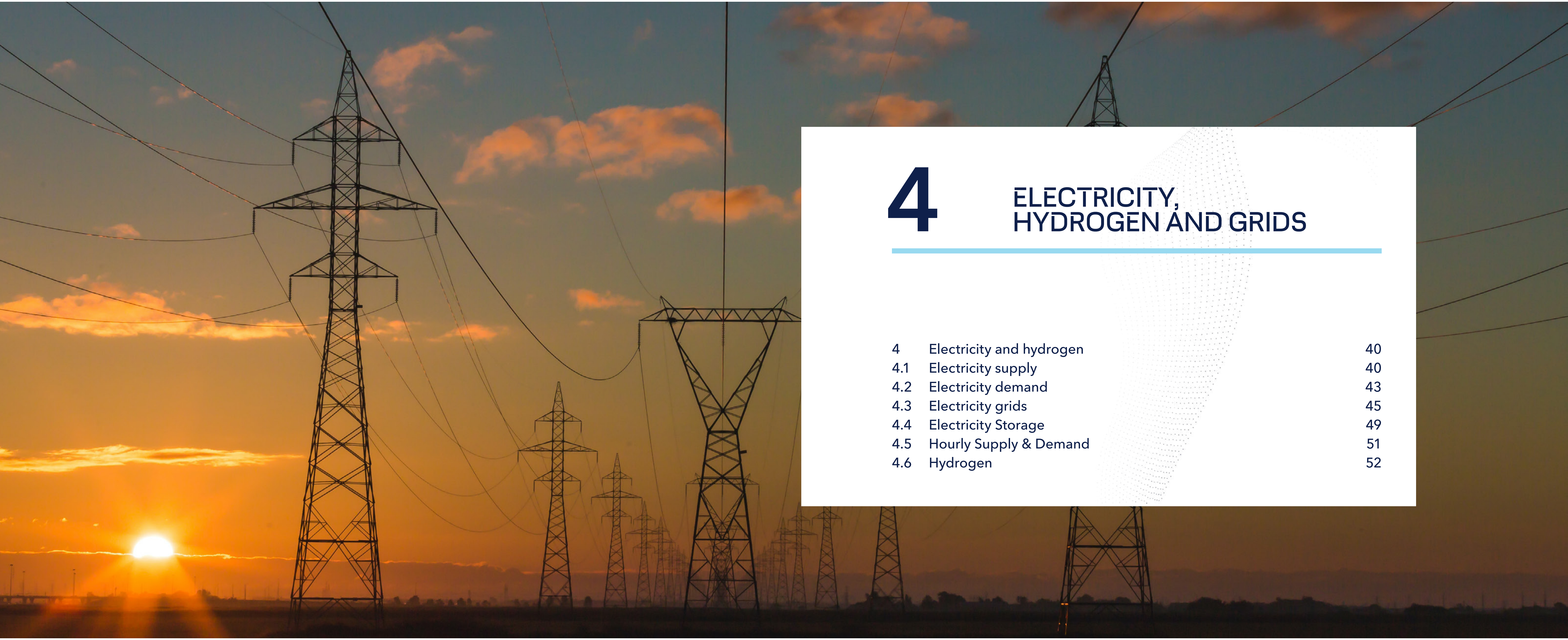
Oil and natural gas dominate today's fuel mix for non-energy use, meeting 36% and 64%, respectively, of North American demand in 2022.

Plastics production requires primary chemicals like ethylene or propylene, which can be obtained from cracking oil or from natural gas. Since the US shale boom, North America has increasingly relied on natural gas due to the abundance of ethane, a by-product of gas extraction. In 2022, two-thirds of plastics feedstock demand was covered by natural gas and the rest by oil (especially its naphtha fraction). The share of natural gas is expected to continue growing to almost 90% by 2050.

The fuel mix for other chemicals is closely related to that for plastics, given that in most cases (but not for methanol), the same primary chemicals obtained via steam cracking are used. Non-chemical uses are and will be covered by oil; for example, bitumen is essential for roads.

Non-chemical uses include applications for asphalt (bitumen), lubricants, and solvents. Demand for these purposes is expected to increase slightly in the next five years, driven by increased infrastructure buildout, but will then return to today's level and remain stable to mid-century.

Overall, non-energy demand for oil will slowly decrease, while demand for natural gas will increase until the mid-2030s before returning to today's level by 2050. As Figure 3.22 shows, non-energy use will represent an increased share of natural gas demand, reaching a quarter of the total. For oil, the share of non-energy demand will also gradually increase from 8% in 2022 to 22% in 2050 as energy demand will decline faster than non-energy demand. Feedstock use will therefore be a key driver for oil demand in the coming decades, with the caveat that total demand will steadily decline.



4 ELECTRICITY, HYDROGEN AND GRIDS

4 ELECTRICITY AND HYDROGEN

Electricity and hydrogen and its derivatives will reach 50% share of final energy demand by mid-century, greening and decarbonizing the energy sector along the way.

Electricity and hydrogen are the twin pillars of decarbonizing the energy system and will grow immensely in the next 30 years. Variable renewable energy sources (VRES) in particular are set to transform the electricity system, but not far enough to satisfy the decarbonization objectives of carbon-free electricity set for 2035 by the US and Canada, as highlighted in Chapter 2.

By 2050, electricity's share in final energy demand will grow to be 41%, from 21% in 2022. Similarly, the share of hydrogen and its derivatives will increase from almost zero in 2022, to 9% by 2050 (Figure 4.1).

A high penetration of VRES needs a corresponding buildout of the power grid. This is where there is a risk of a bottleneck developing; however it is also the key to a cheaper, more efficient power system in North America and hence a major commercial opportunity.

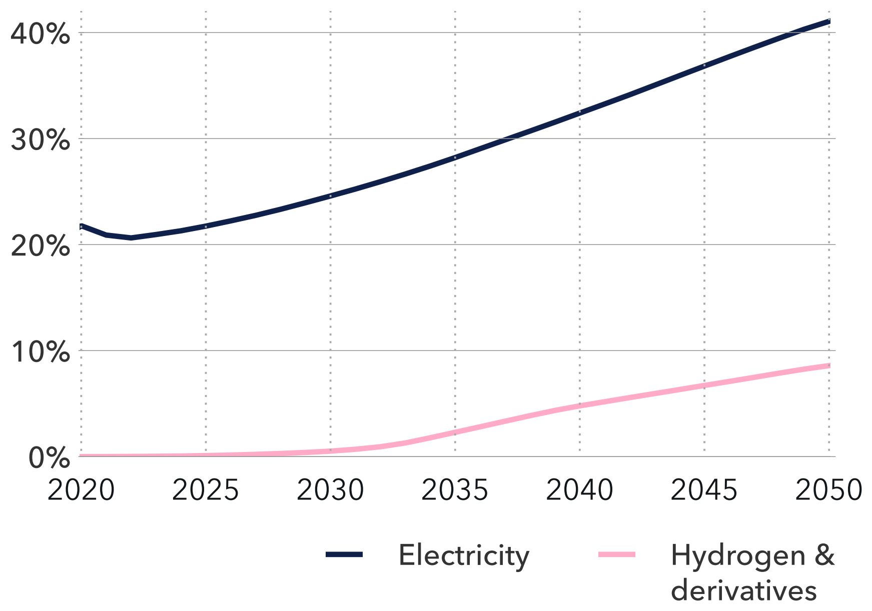
Green hydrogen demand in North America will require 521 GW of dedicated renewables capacity by 2050.

Electricity, hydrogen and its derivatives together will account for half of the North American final energy in 2050.

FIGURE 4.1

Electricity and hydrogen share in final energy demand

Units: Percentages



4.1 ELECTRICITY SUPPLY

Spurred on by new demand categories and the electrification of major existing demand segments, electricity supply in North America nearly doubles from 5,000 TWh/year in 2022 to 9,000 TWh/year in 2050, a 2% increase year-on-year.

This is remarkable when you consider that the US and Canada already have near-universal access to electricity. The electrification of many sectors means, however, that enormous growth and change in the power sector is going to happen in the next two decades, encompassing renewables, storage, and grid development.

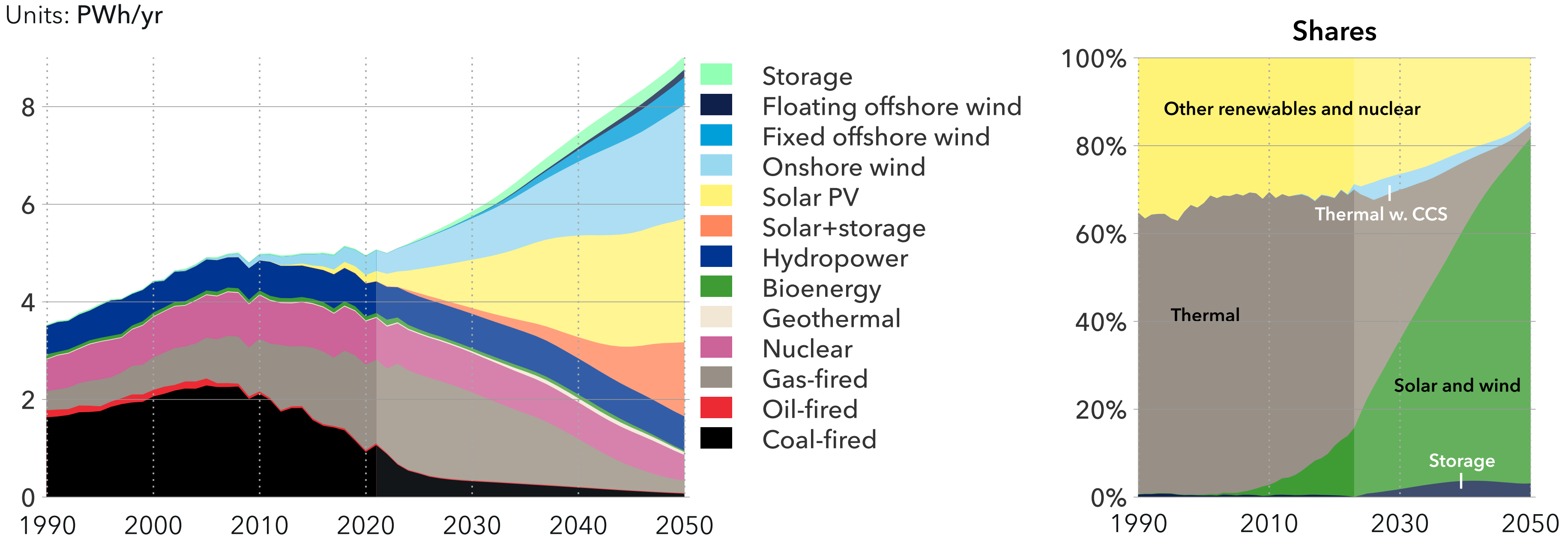
Figure 4.2 presents the historical and forecast development of electricity supply in North America, categorized by different supply sources.

Grid-connected electricity generation dominates electricity supply at present, especially at the yearly timescale. Currently, almost all the electricity is grid supplied, matching demand and supply instantaneously.

FIGURE 4.2

North America electricity supply by source

Units: PWh/yr



Historical data source: IEA (2023); GlobalData (2023)

This is set to change in the US and Canada, with storage and hybridization playing a critical part, due to the rising VRES penetration. With more and more solar and wind coming online, storage will increasingly play an important role in balancing generation, and by extension supply and demand of electricity.

Added-up over the 12 months in the year 2050, electricity storage supplies about 3% of the supply, but at a finer granularity – daily and hourly – electricity storage plays a critical role in ensuring a continuous supply of energy. This is covered in further detail in our section on storage.

Grid-connected electricity generation

In 2022, grid-connected electricity generation accounted for almost all of the electricity supplied; it will almost double from 5,000 TWh/year at present to 8,800 TWh by mid-century. Of the electricity generated in the grid in 2022, 53% was from fossil thermal, mostly supplied by natural gas (35%) (Figure 4.2).

A surge of legacy investments in natural gas-fired power plants from the 2000s through to as recently as this year has given considerable impetus to natural gas in the electricity mix – masking the considerable growth of solar and wind, which have been the cheapest form of electricity in many parts of the US since 2020. In fact the momentum behind gas-fired power continues for the next few years, increasing its share from 35% in 2022 to 38% in 2025, slowing the transition to renewable power sources in the short term.

This short-term reliance on gas-fired generation is exacerbated by the geographical disparity of solar and wind in North America, that does not affect gas-fired power plants. The places with high wind and solar resources are often far away from the demand centers. The physical process of getting the electrons produced cheaply but remotely to population and industrial centers is often riddled with bureaucracy and market disincentives associated with the transmission of electricity. This means that despite the incentives given to solar and wind through the US Inflation Reduction Act (IRA) and the Clean Electricity Investment Tax Credit of Canada, the lack of effective transmission between the power plants and demand centers places a drag on the transition to clean energy in the region. This is discussed in detail in the Section 4.3 on grids.

Nevertheless, we do forecast a moderate short-term increase in electricity generated through solar and wind in the North American grid in the period from 2023 to 2030. From generating 14% of the grid-connected electricity in 2022, solar and wind's share grows to 35% in 2030, and reaches an astonishing 81% by 2050 (Figure 4.3).

Correspondingly, with the vast growth in solar and wind, fossil thermal generation in the North American grid sees a remarkable decline. By 2050, the fossil share in grid-connected generation will be a paltry 4%, and a year-on-year decline of 8.5% from 2030 to 2050 (Figure 4.3).

Other electricity generation sources include: bioenergy-fired power plants, nuclear, geothermal and hydropower. Their share remains generally stable until 2040s, with a slight decline to mid-century, mostly due to crowding out by solar and wind, and the use of bioenergy in other hard-to-decarbonize demand segments such as aviation, rail, and heavy road transport.

Grid-connected capacity

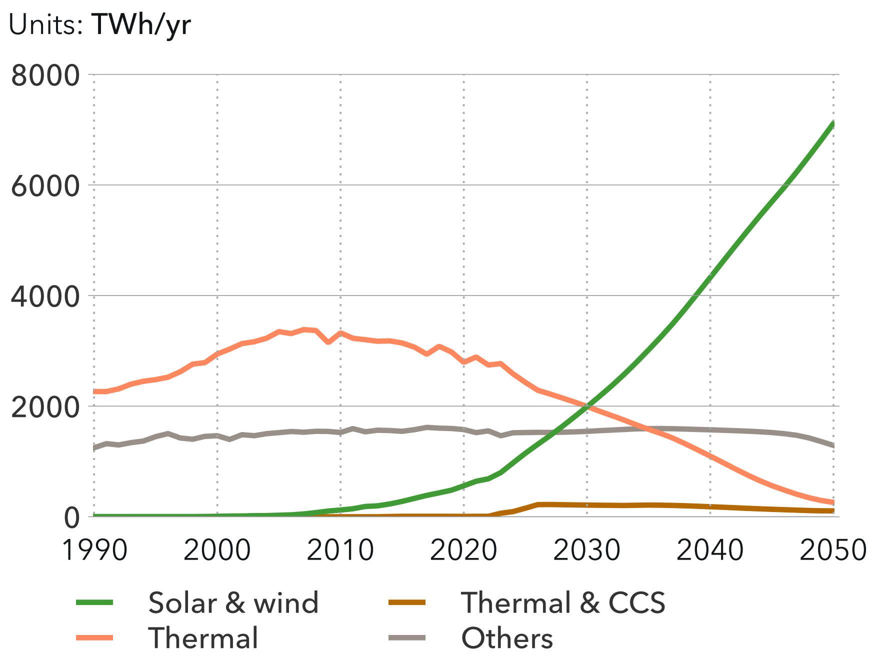
Total grid-connected capacity in US and Canada was 1,476 GW in 2022, with solar and wind each taking 11% of this. At 57% of total capacity (844 GW), fossil fuel thermal power plants provided most of the capacity needed. Other power plant types, such as nuclear, hydropower, and bioenergy-fired power plants provided the remaining capacity.

This situation will change fundamentally in the coming decades in North America. The need for new capacity because of increasing electrification and capacity retirements of aging fossil fuel-fired power plants will all be satisfied by new solar and wind. In Figure 4.4 we present the average capacity additions per decade. In the decade preceding 2021, the majority of additions were fossil thermal power plants (15 GW/yr), mostly gas-fired power plants. In comparison, solar and wind were lower than fossil thermal power plants.

In the current decade, we already see a complete reversal. Both solar and wind will overtake new fossil thermal power plants, with 21 GW/yr of solar expected and 6 GW/yr of wind capacity expected.

FIGURE 4.3

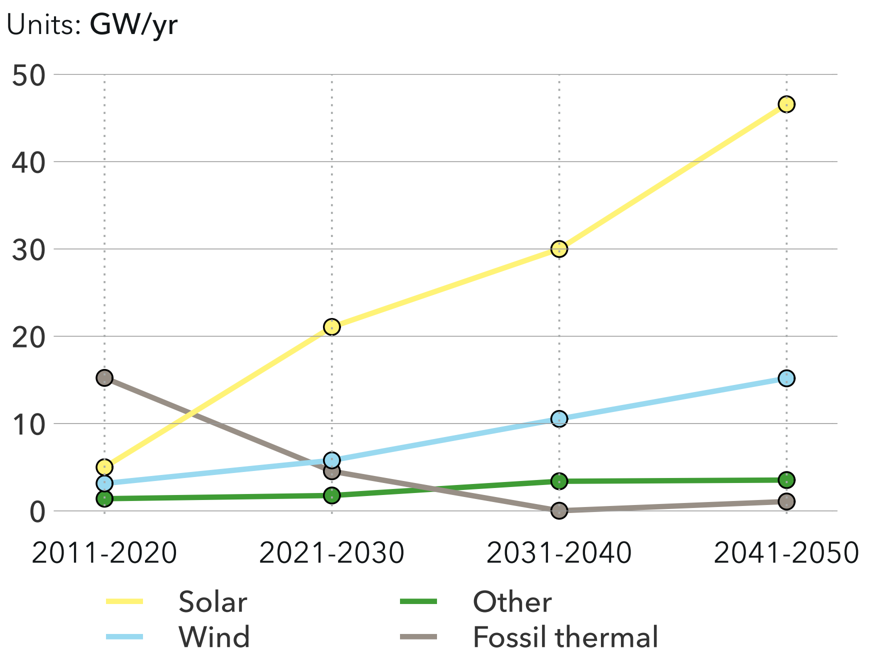
Grid-connected electricity generation in North America



Historical data source: IEA (2023); GlobalData (2023)

FIGURE 4.4

Average grid-connected capacity additions



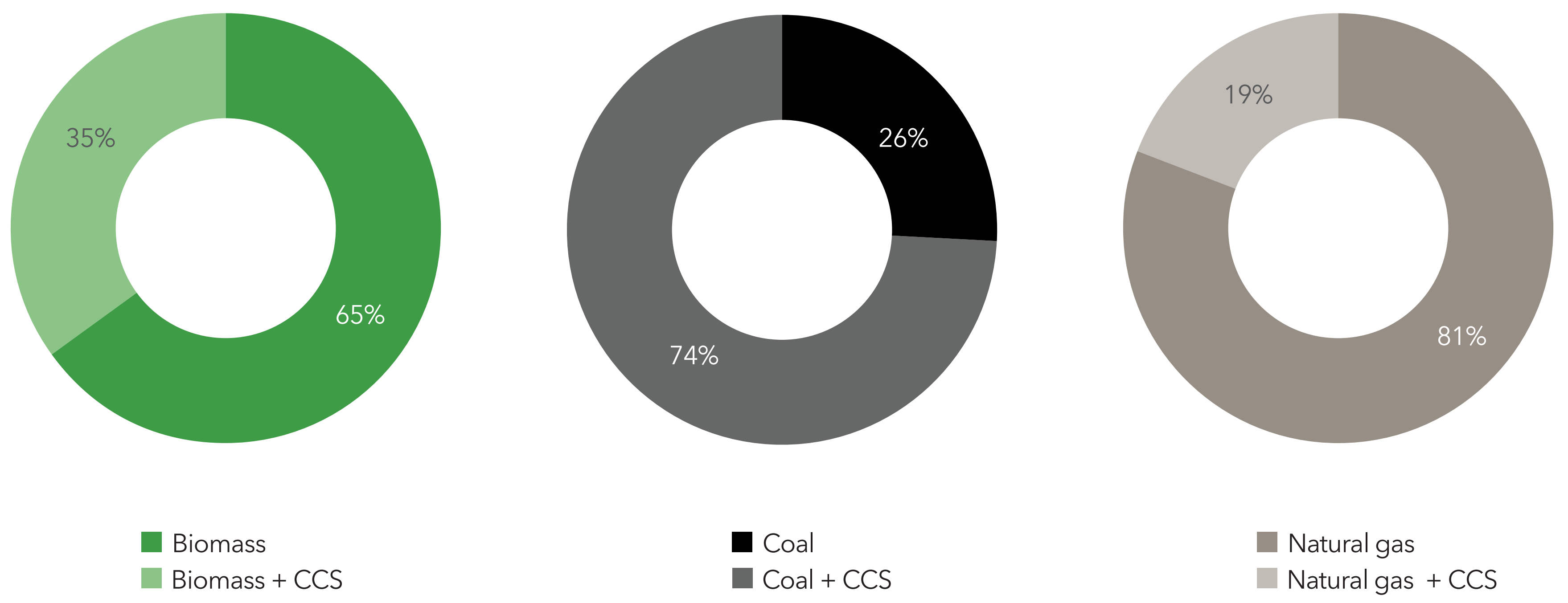
Historical data source: GlobalData (2023)

Despite the grid constraints, which slows the solar capacity additions noticeably in the decade leading up to 2040 compared to the current decade, we do not foresee fossil thermal generation being added in significant quantities in North America. While the remaining fossil thermal plants will operate, with CCS units helping them decarbonize, we foresee massive amounts of wind and solar capacity being added, simply because they are the cheapest form of electricity in most places in North America already.

The additional location based sweeteners in IRA help install VRES even in locations where renewables have hitherto faced resistance due to vested fossil fuel interests.

FIGURE 4.5

2050 CCS share in power supply



Carbon capture and storage in power generation

Spurred on by financial incentives for carbon capture and storage (CCS) through the IRA and Canadian electricity decarbonization plans coupled with carbon prices and regulations in certain provinces and states, CCS is expected to play a vital role in fossil fuel and biomass (thermal) electricity supply. A little more than 30% of the thermal generation will be from plants outfitted with CCS units in North America by 2050, with some variations in terms of the fuel used in the power plant.

By 2050, three-quarters of coal electricity generators will be outfitted with CCS plants, while for natural gas and bioenergy, this is one-fifth and one-third, respectively (Figure 4.5). Such thermal generation coupled with CCS enables some of the newer coal power plants to keep functioning, despite the other externalities such as local air-pollution from coal being eliminated through the complete transition to renewables.

Hydrogen in power generation

Unlike some other regions such as Europe and OECD Pacific (DNV, 2022a), hydrogen is expected to play a limited role in electricity generation in North America. Despite projecting a maximum volumetric blending fraction of 60% based on the price differential between methane and hydrogen, by mid-century, only about 8% of gas-fired electricity is from hydrogen. There are two main reasons for this. Firstly, given the high demand for hydrogen in other hard-to-electrify sectors, it is not economically efficient to use to hydrogen in power generation. Secondly, for decarbonization there are again more-cost effective methods such as CCS on thermal power plants or early-decommissioning and replacement by renewables.

Off-grid capacity for hydrogen

In addition to grid-connected capacity for electricity generation, there will be dedicated renewable capacity for hydrogen production via electrolysis. We forecast 5 GW of solar and 2 GW of wind capacity for hydrogen production by 2025 in North America, reaching about 521 GW (total) by 2050. These capacities also add to the cost learning reductions, especially for solar+storage and offshore wind. Such high renewable capacities for hydrogen production are made possible by the generous USD 3/kgH_2 renewable hydrogen production tax credit under the IRA, and also due to the Investment Tax Credit under the Canadian Clean Hydrogen Program.

Photo by Ellen Jaskol, NREL

4.2 ELECTRICITY DEMAND

With the exception of isolated communities in the far north of Canada, there is near-universal access to the North American grid in Canada and the US. Both countries are already among the top ten countries globally in terms of electricity consumption per capita.

From the mid-20th century, electricity consumption in the region rose steadily almost every year all the way through to 2007. Since then – essentially over the last two decades where combined GDP has increased by more than two thirds – electricity consumption has levelled off at around 5 TWh a year. Most of this flattening in demand can be explained by energy efficiency improvements (including the switch to LED lighting) and by the absence of any major or significant developments in new electricity demand categories. But this is set to change in the next three decades, with the emergence of new demand categories such as electrified road transport, electrolysis for hydrogen production, and the use of heat pumps in buildings and manufacturing.

In 2022, the cumulative electricity demand reached 5,000 terrawatt-hours (TWh) per year. Our forecast indicates that this demand will escalate to almost 9,000 TWh per year by 2050, with an average annual growth rate of 2.1%. This annual growth rate is slightly higher than the annual growth rate from 1990 to 2010. By 2050, electricity will account for 41% of the overall energy demand, while the current contribution stands at 20% of the final energy demand.

Figure 4.6 illustrates the changing patterns of North American electricity demand across various sectors. It is evident that these demand sectors do not follow identical growth trajectories.

Currently, electrolysis demand from dedicated on-grid production is negligible. However, by 2050, it is projected to represent 6.6% of the total electricity demand. Similarly, the transportation sector presently accounts for a mere 0.6% of the demand, but this figure is expected to surge to 12% by 2050, initially driven by the electrification of passenger vehicles and later by commercial transport and the partial electrification of maritime and aviation.

The residential segment, encompassing space and water heating as well as cooking, accounted for 9% of electricity demand in 2022, and is projected to decrease to 6% by 2050. That decrease in overall share masks growth in absolute terms: the electrification of cooking stoves, space heating, and water heating drives an increase in electricity demand within this segment, as well as in commercial space and water heating. The demand from this residential segment is anticipated to rise from 465 TWh per year in 2022 to 550 TWh per year by 2050.

The demand for space cooling, both in residential and commercial buildings, which currently accounts for a combined demand of 920 TWh per year, is expected to grow slightly by 2050. This growth can be attributed to the increasing number of cooling degree-days (CDD) due to a gradually warming climate and the ongoing installation of air-conditioners. The electricity demand for appliances and lighting in residential and commercial buildings is projected to decline by 12% from the present to 2050.

In the manufacturing sector, electricity is predominantly used for industrial heat and operating machines, motors, and appliances (MMA). The MMA segment dominates, accounting for 22% of total electricity demand – by far the largest single source of demand. However, by 2050, improvements in energy efficiency within this segment, coupled with the growth in electricity demand from the transportation sector, leads to a relative decrease in its share to 21%, despite an absolute demand increase from 960 TWh per year in 2022 to 1,400 TWh per year.

FIGURE 4.6

Grid-connected electricity demand by sector

Units: PWh/yr

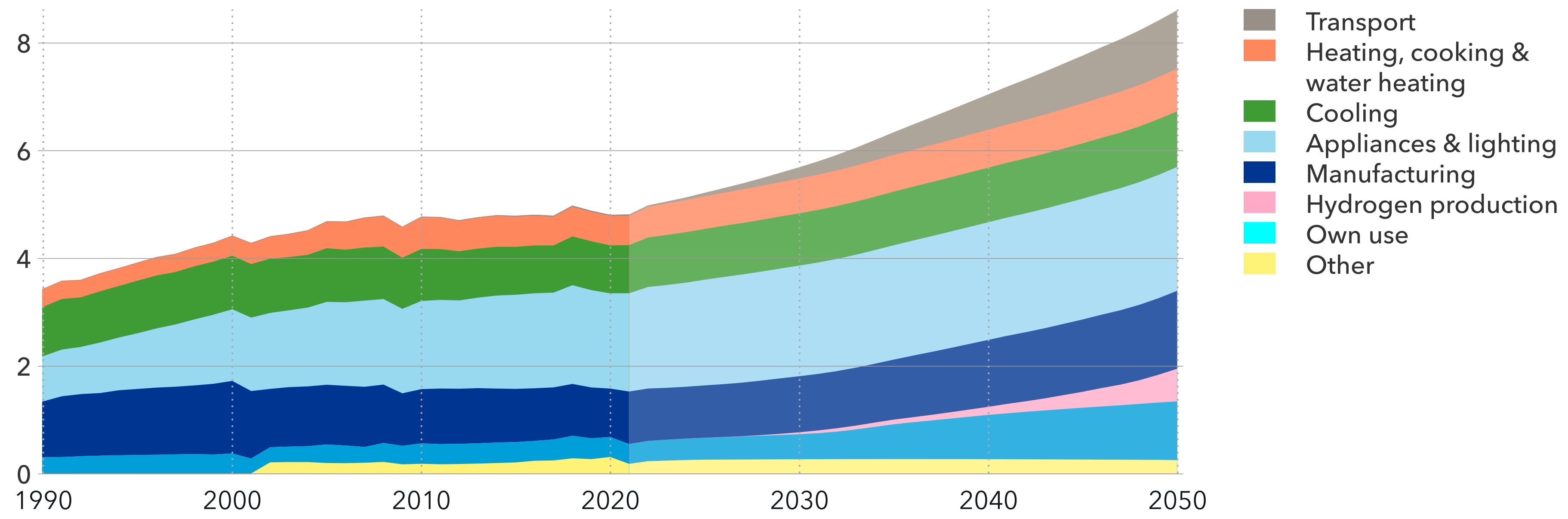


Photo by Dennis Schroeder, NREL

Power demand

In this Outlook, the term "peak power demand" refers to the highest level of electricity demand experienced by each region on an hourly basis throughout a given year.

According to our forecast, peak power demand is expected to increase annually for North America. The total peak power demand reached 730 terawatt-hours per hour (TWh/h) in 2022. By 2050, it is estimated to rise to 1200 TWh/h, reflecting an average annual growth rate of slightly above 1.5%. This growth rate is similar to that of overall electricity demand.

Nonetheless, the increase in peak power demand has implications not only for power generators but also for the physical transmission and distribution grid within each region. The grid infrastructure must be designed and reinforced to facilitate the swift transfer of this peak power from generators to consumers. Consequently, there is a need for strengthening and expanding the transmission and distribution grids, even if one has achieved 100% electrification levels at present.

Excess electricity

The intermittent and variable nature of renewable energy sources introduces challenges in matching electricity generation with demand. During periods of favorable weather conditions or high renewable energy availability, renewable power generation can surpass electricity demand. This situation commonly occurs when there is a high penetration of renewable power, meaning a significant proportion of the electricity supply is derived from renewable sources such as solar, wind, or hydroelectricity. This excess electricity needs to be managed effectively within the power system.

Ensuring the security of power supply in the face of a significant proportion of variable renewable energy sources (VRES) in a power system is a concern frequently raised today. However, the integration of digital grid infrastructure solutions, battery storage, and dispatchable backup capacity can effectively address the challenge of grid instability even at 100% VRES penetration.

To manage hourly and daily fluctuations, key sources of flexibility include pumped hydro, battery storage, dispatchable generation, demand-side response management, and interconnections between power systems. In extreme scenarios where high electricity demand coincides with low wind and solar generation, low-capital expenditure (CAPEX) natural gas combined-cycle power stations will play a critical role in providing backup capacity to ensure system reliability. To encourage further investment in VRES, it is crucial to incorporate flexibility measures and ensure sufficient availability of dispatchable power (as highlighted by IRENA, 2019). Power-to-hydrogen technology will also play a vital role by utilizing surplus renewable electricity and reducing situations with extended periods of low or zero electricity prices.

4.3 ELECTRICITY GRIDS

Given the near-doubling of electricity demand and supply, the North American electricity grid will undergo vast expansion, increasing 2.5 times in capacity from 2022 to 2050, a 3% year-on-year growth. This would mean doubling the average growth in capacity (1.5%) from the decade preceding 2022, every year from now to 2050. Timing, however, is critical, and our forecast takes into account the current bottleneck in transmission line buildout which places a restraint on the pace of renewable energy integration in the coming decade.

Electricity grids are an under-appreciated piece of the energy transition puzzle. Electric grids are the backbone of industrial North America: the US grid is effectively the largest machine in the world (PNNL, 2021b), transporting electricity across vast swathes of land, over waterways and through rough terrain.

The electric grid consists of two parts; low voltage (LV) and medium voltage (MV) lines which make up the distribution grid, and high, extra high, and ultra-high voltage (for brevity classed together as HV) lines which make up the transmission grid.

In 2022, the total length of the North American grid was about 13 million circuit-kilometers (c-km). We forecast this increasing to about 24 million c-km. Of this, 8% is for transmission and 92% for distribution, a ratio more or less preserved in 2050. The ratio is very different when it comes to grid capacity, measured in TW-km (Figure 4.7). Most grid capacity is for transmission, approximately 87% in 2022, with the rest for distribution. This ratio is also preserved through to 2050. The flipped ratios in grid length and capacity between transmission and distribution reflect the long distances associated with North American distribution, and the sheer capacity needed for transmission. Given the increase in electricity demand, especially the distributed demand loads due to EV charging, the transmission and distribution grids need to grow in tandem.

The North American grid has not experienced any major growth spurt in the last decade, as expected with the stagnant electricity demand and supply in the region within the same timeframe. But with vast amounts of renewables set to come online thanks to the potent incentives through the US IRA, this is set to change. Often, the windiest and sunniest sites are far from population or demand centers, and therefore require connection to existing or new transmission lines to transport electricity to where it will be used.

Similarly, with more electrification in all major demand sectors, electricity and power demand grow over time in North America, requiring stronger distribution grids. Also, more distributed solar generation feeding to the grid requires distribution lines with power electronics and other grid-enhancing technologies that can handle intermittency and weather-induced, large-scale voltage fluctuations.

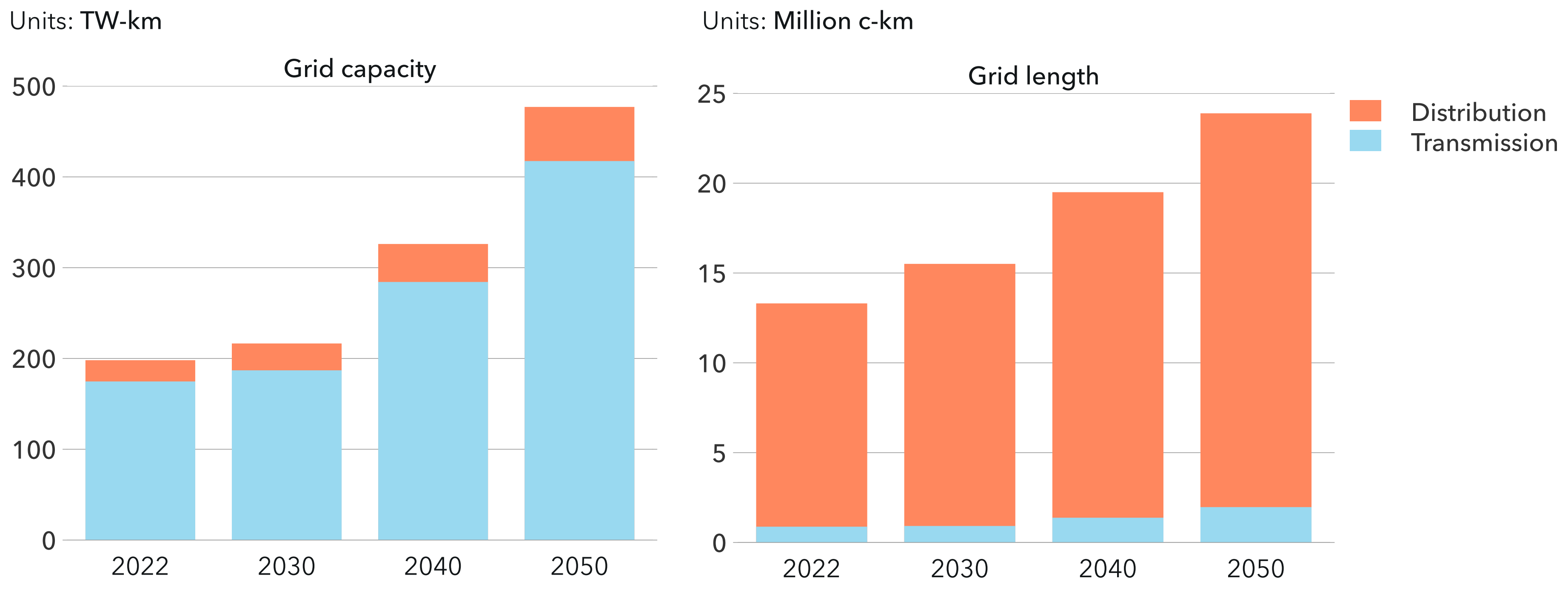
Additionally, there is an increased need for resilience in the grid as it is vulnerable to physical impacts of extreme weather such as wildfires and deep freezes, and to cyber-attacks (Bipartisan Policy Center, 2021). This would imply sustained effort and investment in upgrading and maintaining the grid, assisted by real-time and/or drone-assisted monitoring and analysis using tools such as digital twins. Transmission and distribution grids each face distinct challenges, and the electric grid needs to expand in both capacity and length to be able to support North America's decarbonization objectives. In fact, the successful uptake of renewables in North America is predicated on the grid also keeping up (McKinsey Sustainability, 2023).

Transmission grid

'No transition without transmission' is both a terse slogan and a well-understood fact (Andersen, 2014; HeatMap, 2023). We recognize this in our energy transition forecast for North America.

FIGURE 4.7

North American grid expansion



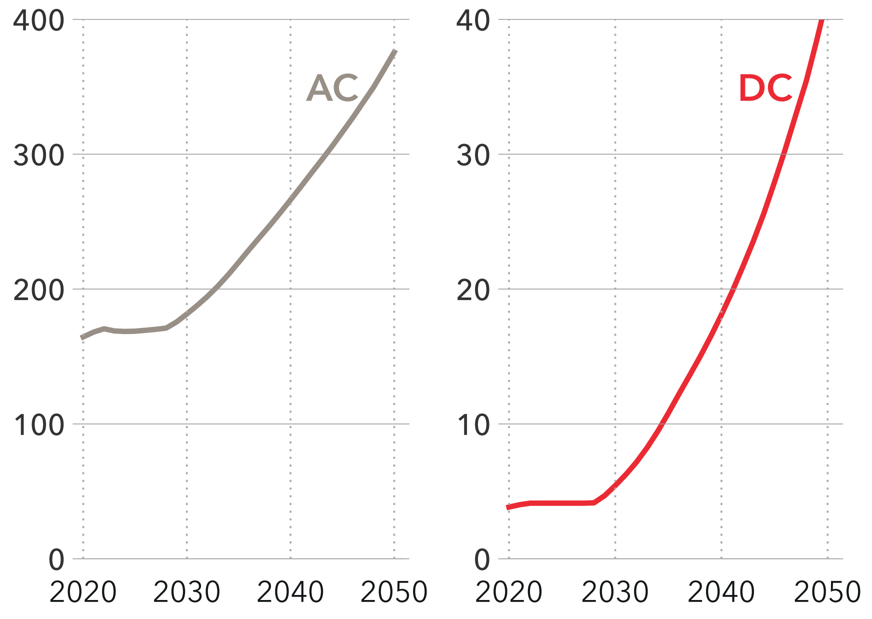
The transmission grid capacity of North America more than doubles from 175 TW-km in 2022 to 417 TW-km in 2050, equating to 3% annual growth throughout. This growth rate is higher than for electricity demand (as detailed in Chapter 4). The difference is due to a greater than proportional increase in new renewable capacity coming online in the decades up to 2050, which will be further away from urban cities and require transmission over longer distances. The transmission grid is essentially made up of lines connecting the power plants to the main grid and then lines transmitting the electricity to a lower-voltage distribution grid.

Figure 4.8 illustrates the growth in alternating current (AC) and direct current (DC) transmission capacity.

FIGURE 4.8

HVAC versus HVDC transmission grid in North America

Units: TW-km



Almost all (98%) transmission lines in North America today are HVAC, but by 2050 their share will reduce to 90%, with the other 10% being HVDC. DC lines are less expensive than AC for long-distance energy transmission and are beneficial in terms of transmitting high voltages at low levels of loss, especially undersea cables connecting offshore wind.

In the short term, our model results reflect the challenges underpinning the transmission grid buildout, both for AC and DC lines (Figure 4.8). In the near term, there is alarmingly little transmission-grid buildout in the US and Canada. This jeopardizes the intended stimulus effect of the IRA and other policies – if you cannot connect clean electricity to the grid, you cannot decarbonize. More worryingly, it reduces the attraction of renewables as a commercial venture, due to cost increases associated with delays to starting revenue-generating operation. This drives away investors and project developers, with severe long-term consequences for the renewables market in North America.

Many reports (e.g. LBNL, 2023a) have highlighted long delays in interconnecting solar and wind projects to the transmission grid, due to delays in laying transmission lines. Similarly, new interstate transmission lines which connect VRES projects in remote yet profitable sites to demand centers face multi-year multi-agency review processes which often end up dissuading the project developers (HeatMap, 2023). Nevertheless, actions are being taken to ease this transmission chokehold, as the following North American examples show.

Transmission lines near Pimm, Nevada carrying electricity from the Hoover Dam to Los Angeles. HVAC lines on the left and HVDC lines to the right of this image. Courtesy, AARoads.com

Policies addressing North American transmission-grid expansion challenges

We list below some of the key challenges facing transmission grid expansion in North America along with corresponding mitigatory policy actions.

Onerous delays for interconnection of VRES plants to grids

- Grid operators to adhere to stringent deadlines in approving or rejecting interconnection requests (FERC, 2023a).

Delays in getting environmental reviews for transmission projects

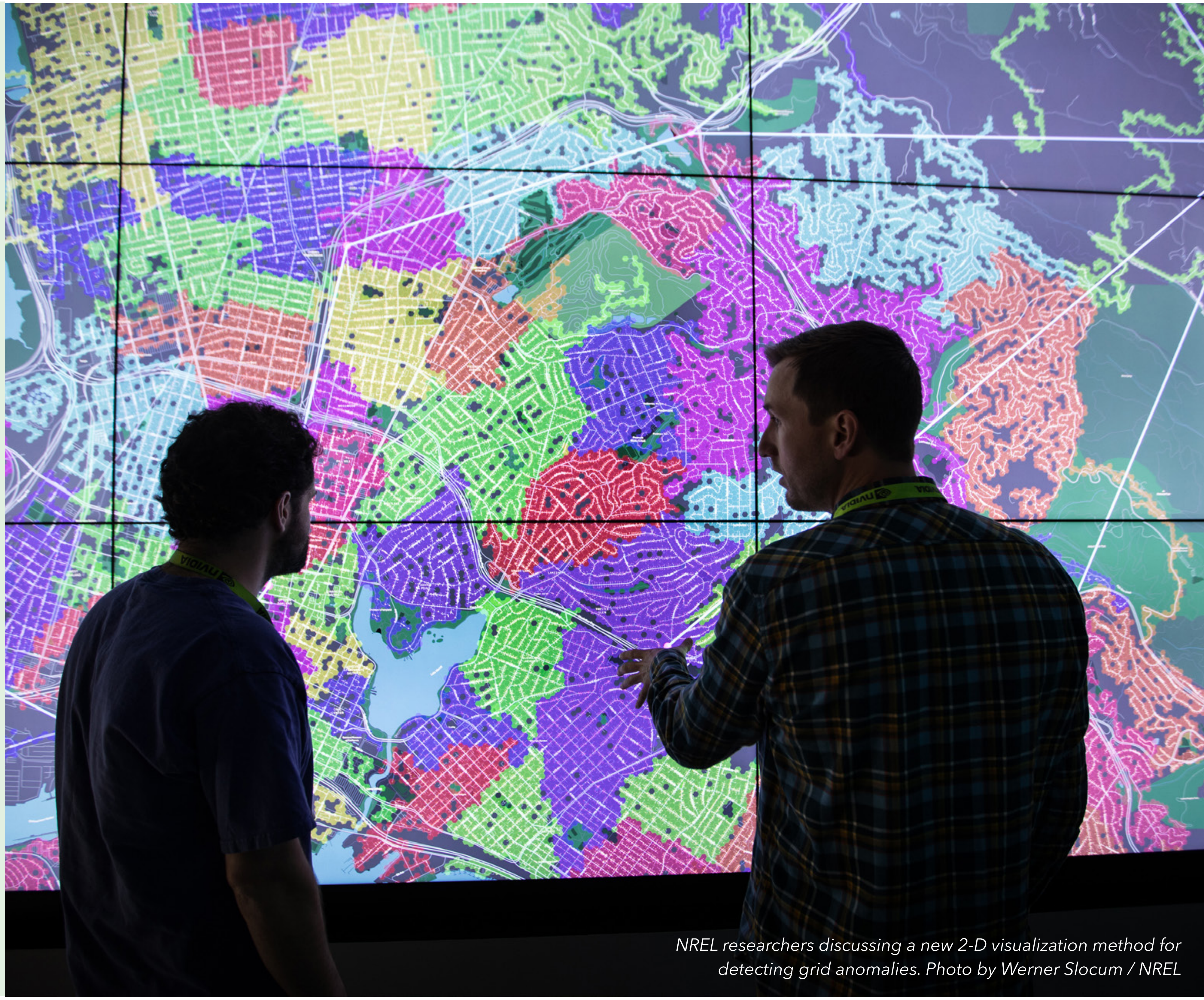
- Setting deadlines and page limits for the review and ensuring a unified bureaucratic process that reduces the number of reviews under the National Environmental Policy Act (NEPA), thus streamlining federal permitting (White House, 2022b).
- Designation of route-specific transmission corridors where the Federal Energy Regulatory Commission (FERC) has authority, as designated in IIJA, to issue permits for construction and modifications of the transmission grid (White House, 2022b)
- Coordinating federal project permitting in Canada through a single central federal office (Electricity Canada, 2023)

Burdensome transmission planning involving multiple institutions

- Enhanced single-point coordination between disparate and multiple authorities and stake-holders, through the Building a Better Grid initiative (US DOE, 2022d).
- National transmission planning studies under-taken by US Department of Energy and chosen National Laboratories (Federal Register, 2022), thus reducing the burden on utilities and grid operators.
- 'One Project, One Approval' framework described in the 2023 Canadian Federal Budget, cutting away multiple administrative steps transmission projects have to go through.

Resolving cost and budget allocation

- New financing and loan programs authorized to facilitate upfront funding for transmission infrastructure projects, under the IIJA (White House, 2022b) and Building a Better Grid initiative.
- Department of Energy authorized to serve as an anchor (or proxy) customer for new or upgraded transmission lines.



NREL researchers discussing a new 2-D visualization method for detecting grid anomalies. Photo by Werner Slocum / NREL

Despite the policies detailed above, challenges still remain. Some of these challenges are:

- Limited ability of the state and/or the federal authorities to leverage 'eminent domain' to acquire/lease land for transmission line construction
- 'Not in my backyard' – NIMBYism stopping transmission lines predominantly connecting clean power between generators and cities (Council of State Governments, 2022)
- Lack of qualified, trained and skilled labor to plan and construct these transmission lines (Electricity Canada, 2023)
- Supply chain disruptions at the back-end of transmission construction, with shortage in distribution side transformers, and other needed construction raw materials (Utility Dive, 2022)
- Elevated cost of capital in the short to medium term.

The lines that connect new power plants to the transmission grid may be overhead, underground, or undersea cables. Figure 4.9 breaks down these categories in our most likely forecast. Prior to 2030, with limited uptake of offshore wind in North America, undersea cables can barely be seen in the graph. Between 2030 and mid-century, they increase rapidly with the growing installed capacity of both fixed and floating offshore wind.

FIGURE 4.9

Transmission grid by power line type

Units: TW-km

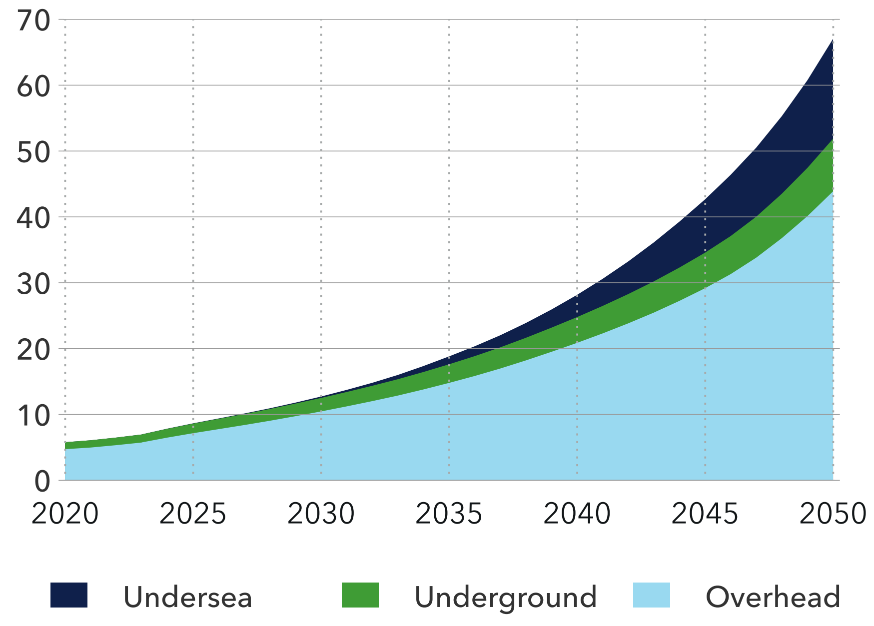
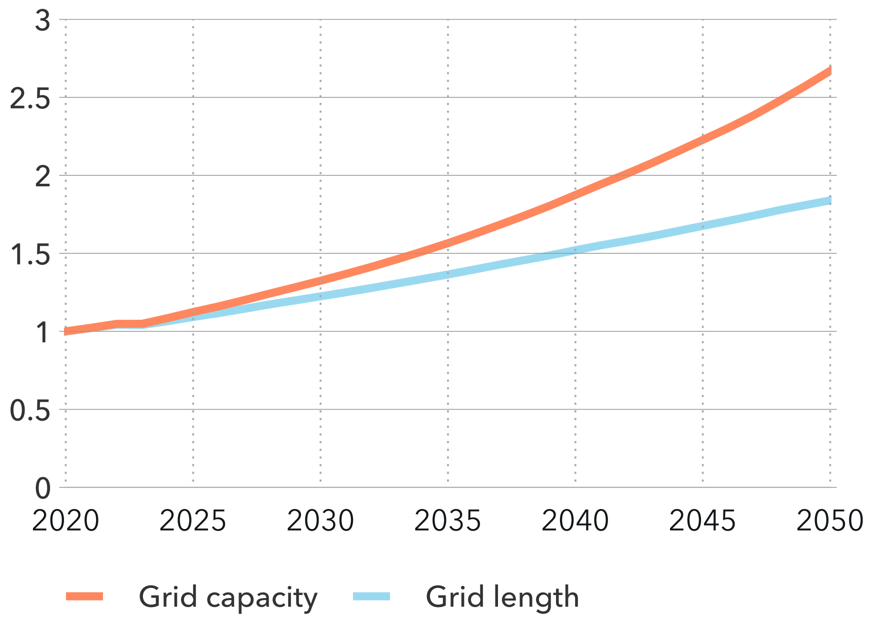


FIGURE 4.10

Distribution grid growth in North America

Units: Unitless, 2020 value =1



Distribution grid

The distribution grid, made up of LV and MV lines, is about 12 million circuit-kilometers (c-km) long in North America in 2022, bringing electricity to almost every home, school, and factory. This is set to almost double by 2050, to about 22 million c-km.

However, distribution grid capacity almost triples from 23 TW-km in 2022 to 60 TW-km in 2050. The higher growth in distribution grid capacity is due to increasing power demand (discussed in Chapter 4) in the North American grid with increasing electrification of buildings, transport, and manufacturing (Figure 4.10).

Conclusion

The challenges discussed in this section are all surmountable, and the US and Canada are poised to overcome them. We are already seeing welcome signs of grid expansion, even though not at the levels we require them to be (Bloomberg, 2023a). Similarly, the slew of legislation that acknowledges the grid and allocates funding to its expansion is heartening, also signaling to utilities, investors and to renewable project developers that it is a bottleneck that is being taken seriously. The fact that we forecast a more-than-doubling of grid capacity in the next three decades is not a matter of faith that policymakers will introduce the legal framework required as much as it is an acknowledgement that the vast market for renewable power creates an historically unprecedented opportunity for transmission- and distribution-system operators.

4.4 ELECTRICITY STORAGE

Energy storage is crucial to balancing the supply and demand of the evolving grid and market dynamics driven by accelerating deployment or renewable energy. While the dominant technology may shift over time, the magnitude of the deployments will be dominated by lithium-ion which will grow from 2022 capacity by 11 times by 2030 and another 72 times by 2050. This growth is supported by cost reductions, EV deployment, and new Investment Tax Credits made available under the Inflation Reduction Act of 2022.

Historically, power generation plants have consumed fuel and provided energy in response to real time demand. While these dispatchable plants (e.g. hydro, coal, gas) made room for intermittent renewables, we are entering a period where the higher proportion of lower cost renewables will challenge the grid and produce surplus electricity. The need to store clean energy when it is abundant, produce it when it's needed, and balance fluctuations can be achieved by using energy storage.

The region has used pumped hydro as storage since the 1930s, However, a new and accelerating energy storage market has blossomed in just the past decade. The USA was an early adopter, with commercial lithium battery systems beginning to appear in California and the PJM market in 2014 and growing from less than 100 MW at that time to above 10 GW operating by end of 2022. While the rapid growth of this new asset class sounds impressive, it is just getting started. We expect continued growth to achieve 1 TW of energy storage capacity to be operating in 2050 in North America.

In addition to mere growth, we also expect the industry will change over time as innovation, both technical and commercial, adapt to the market needs. While widespread and affordable lithium EV batteries have created the technology that kicked off this industry, changes to the EV battery (such as solid state or sodium replacing lithium), and competing technologies (e.g., flow batteries, thermomechanical systems), will likely push the choice of equipment to the most economic, long lasting, flexible, and safest technology in the future.

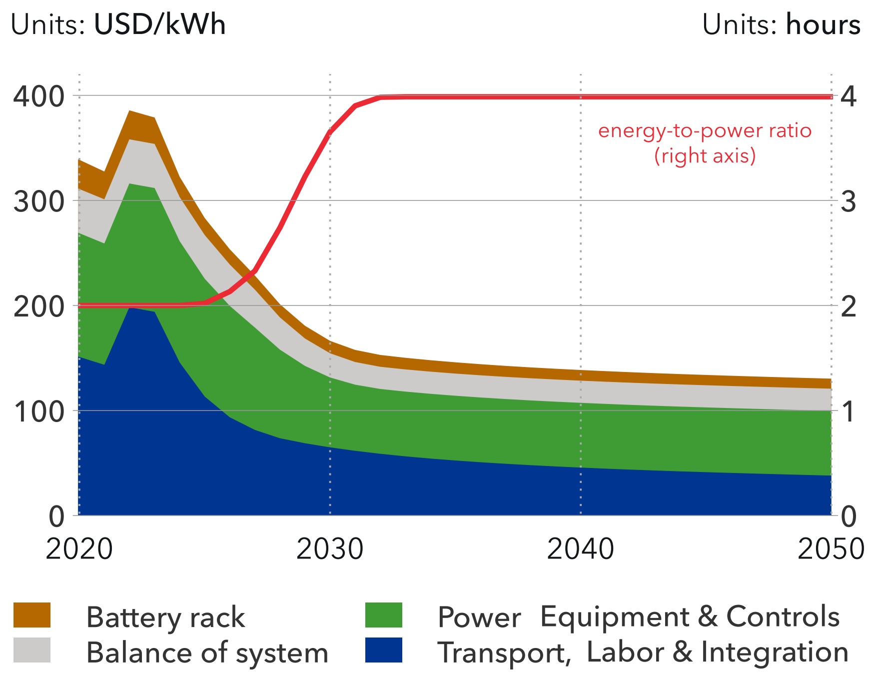
Trends

The electricity storage market in North America is being driven primarily by the rapid decline in costs of storage technologies, especially lithium-ion batteries, the surge in renewable energy adoption, and grid reliability concerns. As renewable sources like wind and solar become integral to the energy mix, the need for storage solutions to address their intermittency has risen. Additionally, policymakers and utilities are now revising the definition of a power generator to explicitly include storage, enabling stand-alone storage to be considered as a capacity resource, which become particularly critical when considering extreme weather events and the evolving demands of a modernized grid.

Market incentives such as ancillary service revenues and price arbitrage, supportive regulatory frameworks including a 30% investment tax credit (ITC) for both stand-alone and hybrid battery storage in the Inflation Reduction Act (IRA), and an increasing awareness of the need for energy independence have further bolstered the growth of storage solutions in the region. Recent policy changes aimed at promoting energy storage include the introduction of a fast-track process for projects up to 5 MW, designed to reduce interconnection delays for electric storage devices

FIGURE 4.11

Average size utility-scale Li-ion battery system cost



(FERC, 2023a). Additionally, co-located or hybrid storage systems can now be interconnected under the existing agreement of the original generator, eliminating the need for a separate administrative process. Furthermore, interconnection feasibility studies have been updated to no longer assume that electric storage systems will charge during peak demand periods. Storage activity in North America has been mainly in the USA so far. However, Canada has now begun to head towards a GW sized market in the coming years via several contracted utility scale assets in Ontario under construction, and a growing pipeline of uncontracted storage projects in Alberta which will participate in the AESO market.

Costs

In the coming years, we anticipate the cost of utility-scale Li-ion battery systems, with 2–4-hour capacities, to drop below 200 USD/kWh by 2030, further decreasing to around 130 USD/kWh by 2050 (Figure 4.11). Meanwhile, longer duration storage systems that offer 5–24-hour capacities – encompassing technologies like flow batteries, compressed air, liquid air, liquid CO_2, and gravity-based solutions – will also experience cost reductions due to technological advancements and scaling benefits.

A key trigger for the adoption of long duration technologies will be revenue streams that value the incremental addition of longer duration such as wider arbitrage periods or capacity reliance on storage. Thus, with increased adoption of variable renewable energy sources, the demand for these longer-duration batteries grows.

Growth to 2030

We expect a surge in the development of utility-scale electricity storage capacities in North America towards the end of this decade. Lithium-ion capacity co-located with utility-scale solar will see a rapid rise from 7 GW / 15 GWh in 2022 reaching about 43 GW / 167 GWh by 2030. This significant increase signals an average growth rate of over 4 GW/yr (Figure 4.12) and is due in large part to the co-location of storage enabling utility-scale solar to participate in capacity and frequency regulation markets. As more solar PV is added to the grid, price arbitrage and profitability increasingly favors storage co-located with generation than without. For example, in 2021 in California (a renewable-heavy region), 80% of the battery storage that came online was used for price arbitrage (S&P Global, 2022). Utility-scale lithium-ion capacity in stand alone or solar + storage hybrid configuration, is predicted to shoot up substantially from 10 GW / 21 GWh in 2022, achieving approximately 118 GW / 375 GWh by 2030, marking a remarkable average growth rate of nearly 13 GW/yr or 44 GWh/yr.

Long duration storage capacity is also projected to grow, reaching about 11 GW / 85 GWh by 2030, with an average annual growth rate of around 1.5 GW/yr.

Pumped hydro capacity, historically the dominant storage technology, will experience only slight growth from 23 GW today, ending the decade at roughly 25 GW / 308 GWh.

Growth from 2030 to 2050

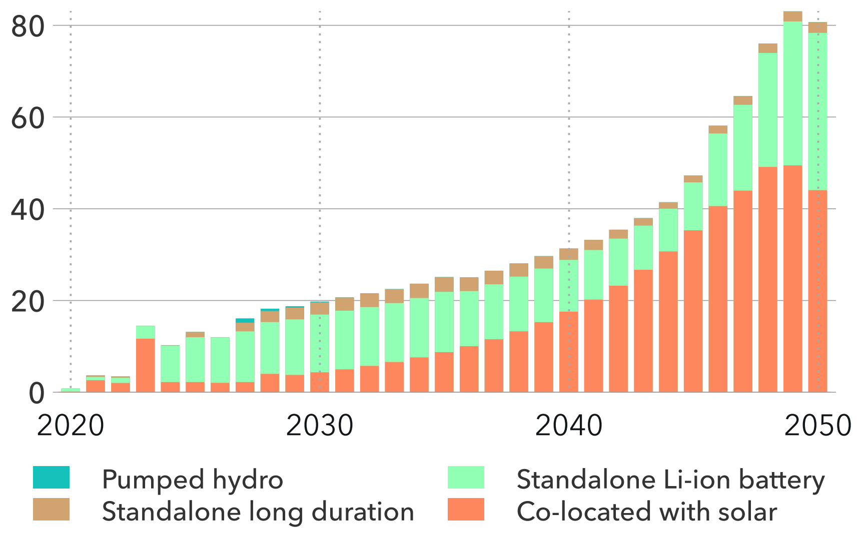
The trajectory from 2030 to 2050 indicates a robust, continued growth in storage capacities, albeit with changing dynamics. By 2050, lithium-ion capacity co-located with utility-scale solar will soar to about 520 GW / 2 TWh, translating to an average annual growth of about 24 GW/yr or 96 GWh/yr from 2030. This will make it the most substantial contributor to the storage mix.

The combined growth in stand-alone and hybridized lithium-ion capacity will decelerate but remain strong, reaching approximately 750 GW / 2.9 TWh by 2050, an average yearly growth rate of about 32 GW/yr or 130 GWh/yr from 2030. This stabilization of growth in storage is correlated to grid-connected electrolyzers coming online, providing a balancing of supply and demand, and conversion of electrons to molecules.

FIGURE 4.12

Utility-scale storage power capacity additions

Units: GW/yr



Does not include behind-the-meter storage. Long duration storage includes 8-24 hours storage such as flow batteries, compressed air, liquid air, liquid CO_2 and gravity-based solutions. Historical data source: GlobalData (2023), US DOE (2022).

Long duration storage capacity will continue its growth but at a decelerating rate, landing at around 38 GW / 370 GWh by mid-century. Pumped hydro, having shown minimal growth till 2030, will remain relatively stagnant due to limitations of available sites, with a total capacity hovering around 25 GW / 310 GWh by mid-century.

Vehicle-to-grid

The projected ascent of vehicle-to-grid (V2G) capacity in North America, reaching 43 GW by 2030 and 255 GW by 2050, marks a significant shift in the perception and utility of electric vehicles (EVs). Increasingly, EVs are being considered as not just a mode of transport, but as vital grid assets that can act as a flexibility provider on par with utility-scale stand-alone batteries in 2050. This transformation is driven by financial incentives provided by net metering programs, state and provincial incentives for installing V2G-capable charging equipment and demand response programs for EV owners. EV owners are expected to be incentivized to sell stored energy back to the grid during peak demand periods, creating a revenue stream that helps offset EV ownership costs and encourages clean energy adoption. However, the lack of interoperability and standardization between systems, limited charging infrastructure and grid capacity, potentially high implementation costs, and public concerns about battery degradation still stand as challenges. Nonetheless, we expect these challenges to be overcome gradually with standardization and scale and have assumed in our analysis that 10% of the EV fleet will be available for V2G at any time from early 2030s.

Long Duration Storage

An assortment of companies are offering technologies that compete well against lithium battery systems for long durations including novel compressed air, heat storage, flow batteries and gravity systems. Historically, the ETO has modeled the most commercially ready long duration energy storage (LDES) with costs and performance similar to vanadium flow batteries. These technologies are well suited for 8-24 hr applications and show potential for cost savings over lithium-ion. Some emerging 'very-long duration' technologies have even higher cost-saving potential over lithium-ion or the previously mentioned LDES. These emerging technologies have not been modeled in the 2023 ETO, as most of these have not demonstrated commercial viability. We expect this to change in the coming years as successful demonstrations and early sales provide confidence that they can effectively scale and become part of the energy mix of the future.

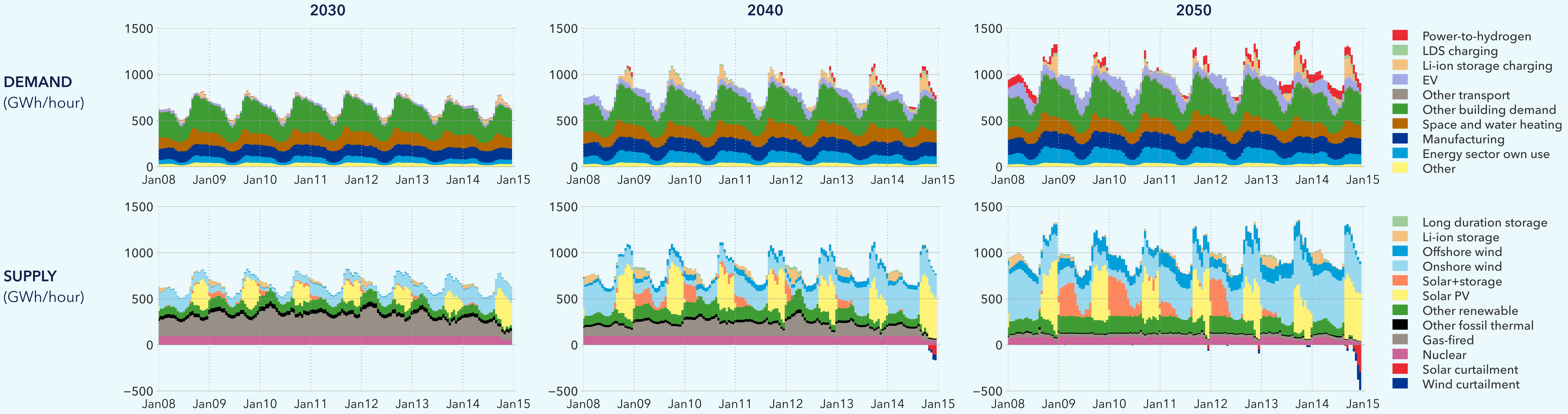
4.5 HOURLY SUPPLY & DEMAND

The supply and demand characteristics of the North American electricity system are going to fundamentally transform in the next three decades. This can be seen by looking at illustrative examples of the same winter week in three different years (2030, 2040, 2050). We draw particular attention to changing roles of renewables, storage, and hydrogen.

In 2030, nuclear and gas-fired power plants supply half of the demand. However, solar satisfies a large share of the peak demand spikes, while in the twilight hours solar+storage takes over from waning solar PV. Stand-alone grid-connected Li-ion batteries also discharge to the grid during this critical time. During night hours with plentiful wind and relatively cheaper power prices, stand-alone Li-ion storage is charged back. In 2030, the power system is dominated by demand, i.e. electricity supply changes to balance the demand, rather than demand changing to balance supply.

In 2040, gas-fired power is lower, despite higher peak demand in North America. The difference is largely supplied by solar PV, solar+storage and wind, coupled with grid-connected stand-alone storage. For example, in the early morning hours of Jan 14th 2040, grid-connected Li-ion storage is able to provide electricity, especially for overnight EV charging, despite low wind and no solar power. By 2040, the change to a supply-dominated power system will have begun in North America; i.e. electricity demand changing to match the supply in the grid.

By 2050, an almost fully decarbonized grid adequately serves North America, in the same winter week, despite almost double the peak-electricity demand compared with 2030. Grid-connected electrolyzers, and charging of grid-connected stand-alone storage (Li-ion batteries and long duration storage (LDS)) absorb the supply of electricity during peak hours of solar production, while LDS and stand-alone Li-ion batteries provide electricity during low solar and wind periods. The power system has fundamentally transformed from a demand-dominated one to supply-dominated one. Load is optimally distributed to overcome the supply variability of renewable electricity, and the electricity system is adept at supply-matching, due to flexibility and responsiveness of grid-connected electrolyzers and storage.



4.6 HYDROGEN

From near zero in 2022, hydrogen and its derivatives will have a share of 9% in North America's final energy demand, about 5 EJ (exajoules), by mid-century.

While this may not seem significant, hydrogen and its derivatives such as ammonia and e-fuels are critical pieces of the energy transition puzzle in sectors which are hard to electrify, such as long-distance trucking, maritime, aviation, high heat processes in manufacturing, and the heating of buildings.

The importance of hydrogen in the energy transition is recognized by both US and Canada. Both countries have made provisions for significant financial incentives in dedicated legislation and budgets.

As an essential component of decarbonization, substantial developments in hydrogen are needed in the coming five to ten years. These will be driven by:

- Funding opportunities and subsidies
- The need to replace, retrofit, and expand existing energy infrastructure to accommodate hydrogen.
- Societal demand for clean fuels

The main challenges that hydrogen and its derivatives face are:

- High CAPEX. Electrolysis equipment dominates the cost structure.
- Lower capacity factors for electrolyzer utilization resulting from intermittency of renewable power and hence cost to produce hydrogen.
- Access to financial support favoring known players with a track record over new entrants.

Policy incentives for clean hydrogen

The Inflation Reduction Act (IRA) introduced a clean hydrogen production tax credit (PTC) or an investment tax credit (ITC), based on the CO_2 emission thresholds of hydrogen, under its 45V provision. The ITC and PTC are not stackable, implying that a production facility would only qualify for one of them. The CO_2 emissions thresholds and the corresponding ITC and PTC are presented in Table 4.1. These incentives apply to production facilities between 2023 to 2034.

In addition to the 45V ITC and PTC provisions, blue hydrogen – produced through steam methane reforming (SMR) coupled with carbon capture storage (CCS) – qualifies for CO_2 tax credits of USD 85 per ton of CO_2 captured, under provision 45Q.

The above provisions are spurring interest in the production of H_2 and have led to several project announcements. However, very few projects are reaching final investment decisions (FID stage) due to lack of offtakes for hydrogen. As a consequence, the US Department of Energy (US DOE, 2023f) has issued a request for information on end-use cases for hydrogen offtake with an intention to support developments up to USD 1bn.

TABLE 4.1

US Inflation Reduction Act 45V Investment and Production Tax Credits for clean hydrogen

CO_2 (kg) per H_2 (kg) ratio	IRA ITC	IRA PTC (USD per kgH_2)
Greater than 4	0%	0
2.5 - 4	20%	0.6
1.5 - 2.5	25%	0.75
0.45 - 1.5	33.4%	1.0
Less than 0.45	100%	3

Canada has allocated funding in its federal budget for 2023 for an ITC for clean hydrogen. Table 4.2 gives the assigned CO_2 emission thresholds and their corresponding ITC levels.

In addition to the specific provisions addressed above, the US DOE has announced USD 8bn in funding to support Hydrogen Hubs – a concept where an entire hydrogen value chain (production, transport/storage and end-use) can be demonstrated, with funding intended for four to six hubs. There is an additional funding of USD 1bn to advance research and development for electrolyzers for green H_2 production, and USD 500Mn for end-of-life recycling of electrolyzer components (White House et al., 2023).

TABLE 4.2

Canadian Clean Hydrogen Investment Tax Credit

CO_2 (kg) per H_2 (kg) ratio	ITC
2 - 4	15%
0.75 - 2	25%
Less than 0.75	40%

In a similar fashion, the Hydrogen Shot program initiated by the US DOE establishes a framework and foundation for clean hydrogen deployment, which includes support for demonstration projects with a goal to achieve clean hydrogen production at USD 1/ kg in one decade (White House et al., 2023).

Taken together these various initiatives will help lower the production cost of hydrogen and help expand its production and use in new areas. More importantly, the IRA and other provisions give a longer window of certainty for hydrogen, for electrolyzer manufacturing scale up, required power generation matching and subsequently anticipated cost reductions that perhaps would not require subsidies in the future. It is important to note that stacking of tax credits should be carefully considered to meet the provisions under different categories, such as impacts on fossil fuel-reliant communities.

Hydrogen demand

In 2022, hydrogen demand was 15 Mt in North America. Most of this demand (65%) was for use in refineries, for upgrading of oil products (Figure 4.13). A further quarter was for producing ammonia as a precursor to fertilizers. The remaining 10% of the demand was mostly as a raw material for chemicals such as methanol. Compared with these feedstock sources of demand, the demand for hydrogen as an energy carrier was negligible in 2022.

With additional offtake policy support expected, this is set to change. While hydrogen demand as a feedstock will be stable from now until 2030, it will start declining in absolute terms due to declining oil demand, and in relative shares due to the increase in demand for hydrogen as an energy carrier. The demand for hydrogen as an energy carrier will overtake feedstock demand by 2030s (Figure 4.14). Hydrogen demand for energy will reach 53 Mt by mid-century. Here, feedstock includes the demand for hydrogen for production of ammonia, and other chemicals such as methanol. Energy source includes hydrogen demand for direct use in energy sectors or to produce e-fuels and ammonia as a fuel.

Hydrogen demand as energy

Hydrogen used for energy purposes grows from practically zero at present to about 53 Mt per year in 2050. Almost half of that production (46%) will be used to produce derivatives like ammonia and e-fuels used in the maritime and aviation sectors (Figure 4.15).

Of the remaining half, by mid-century, half again will be used in the manufacturing sector, with transport and building sectors splitting the remainder almost equally. While the major demand sectors –manufacturing, transport and buildings – have almost equivalent hydrogen shares in 2050, they are phased very differently in the buildup to mid-century.

The first meaningful offtake will be in the manufacturing sector due to decarbonization incentives in North America. This initial use will lead to cost learnings which in turn will make hydrogen competitive enough to

Photo by Dennis Schroeder, NREL

be blended into natural gas distribution grids, which provide the majority of space and water heating, as well as cooking. Following that, the direct use of H_2 will start to make inroads in long-distance trucking and aviation from the late 2030s, and 2040s, respectively. This phased development is visible in Figure 4.15. It should be noted that the initial and most of the ongoing offtake in transport will be in the form of hydrogen derivatives such as ammonia and e-fuels/sustainable aviation fuels and not hydrogen in its pure form.

> Hydrogen energy demand as an energy carrier grows from near zero to 53 Mt by 2050, overtaking existing feedstock demand by 2030

FIGURE 4.13

Hydrogen demand in North America

Units: MtH_2/yr

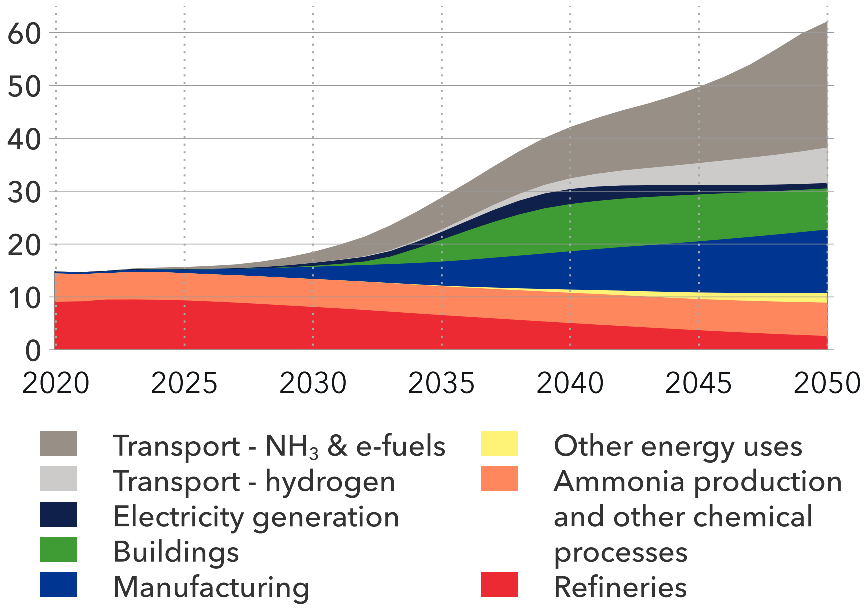


FIGURE 4.14

Hydrogen demand as energy and feedstock & additives

Units: MtH_2/yr

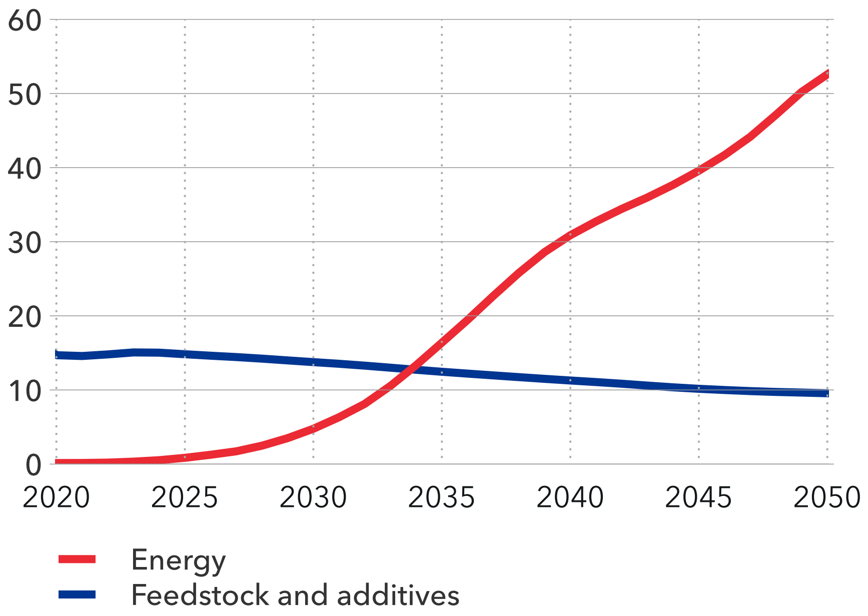
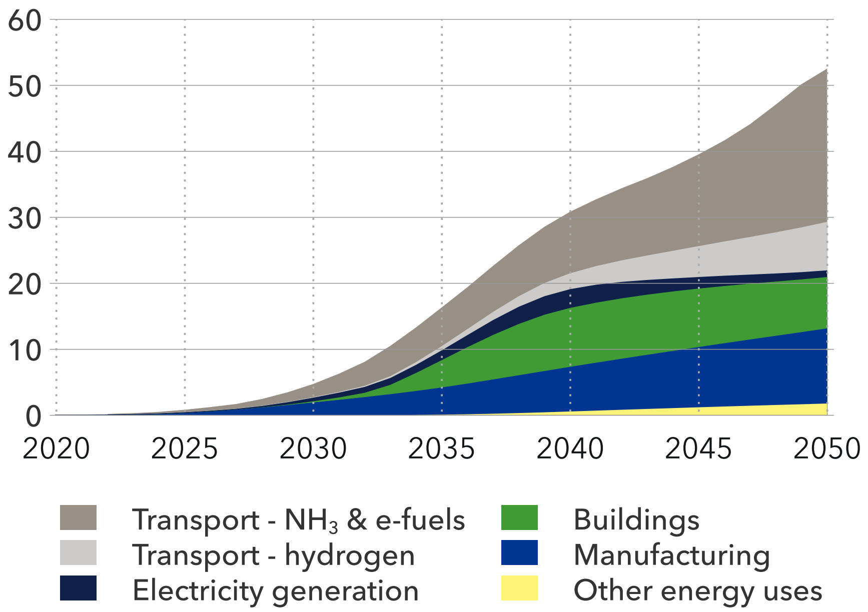


FIGURE 4.15

Demand for hydrogen and its derivatives as energy carrier by sector

Units: MtH_2/yr



Manufacturing

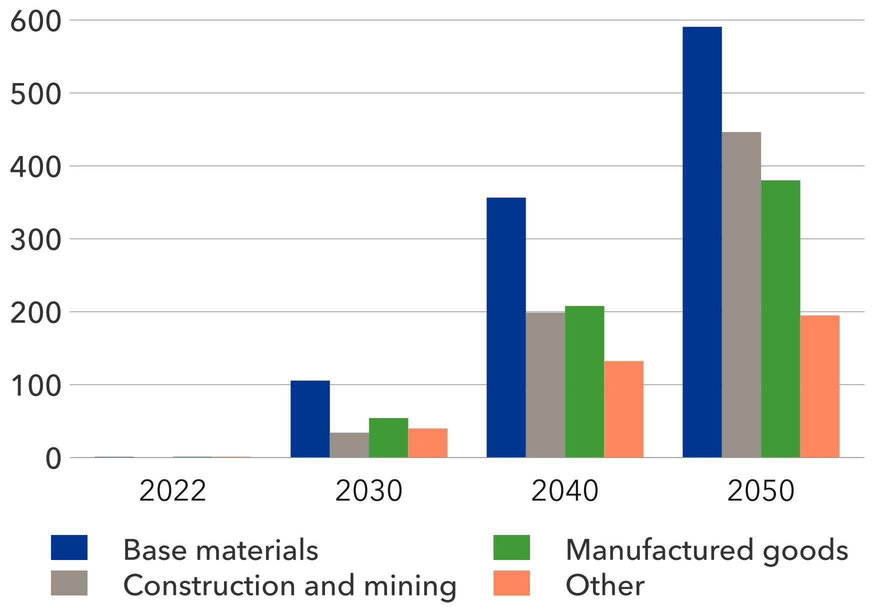
Hydrogen's share in manufacturing energy demand is expected to increase to 10% by mid-century. If only considering provision of heat, it is expected to be even higher, at 13% – larger than electricity's share (8%) in 2050.

The base material segment will have the highest use of hydrogen, around 0.6 EJ in 2050 owing to high-heat processes, especially in industries such as aluminum production and pulp and paper. Manufacturing of goods also requires some provision of high-heat, which again can be supplied by hydrogen (Figure 4.16). By 2050, 1.6 EJ of energy demand within manufacturing will be from hydrogen.

FIGURE 4.16

Hydrogen demand in manufacturing

Units: PJ/yr



Buildings

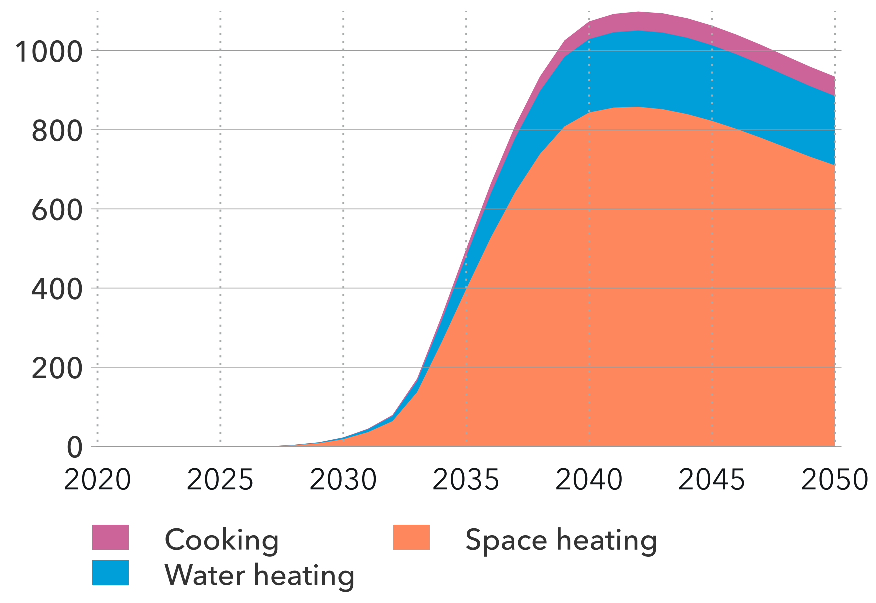
Hydrogen for building energy demand will reach a share of 5% by 2050, delivered as a blend with natural gas in the gas distribution grids. This will only occur once the levelized cost of hydrogen in North America falls to levels acceptable to end consumers – a development expected in the wake of the IRA and other tax credit mechanisms and the associated cost learning effects. On the demand-side, the decarbonization policies of counties and cities will provide a market for the blending of hydrogen into natural gas grids.

The dynamics of hydrogen demand in buildings is presented in Figure 4.17. By 2050, the hydrogen demand is about 0.9 EJ, reducing from a maximum of 1.1 EJ in 2040s. This is due to the rise of heat pumps and the replacement of natural gas – and the H_2 blended with it – for heating buildings.

FIGURE 4.17

Hydrogen demand in buildings

Units: PJ/yr



Transport

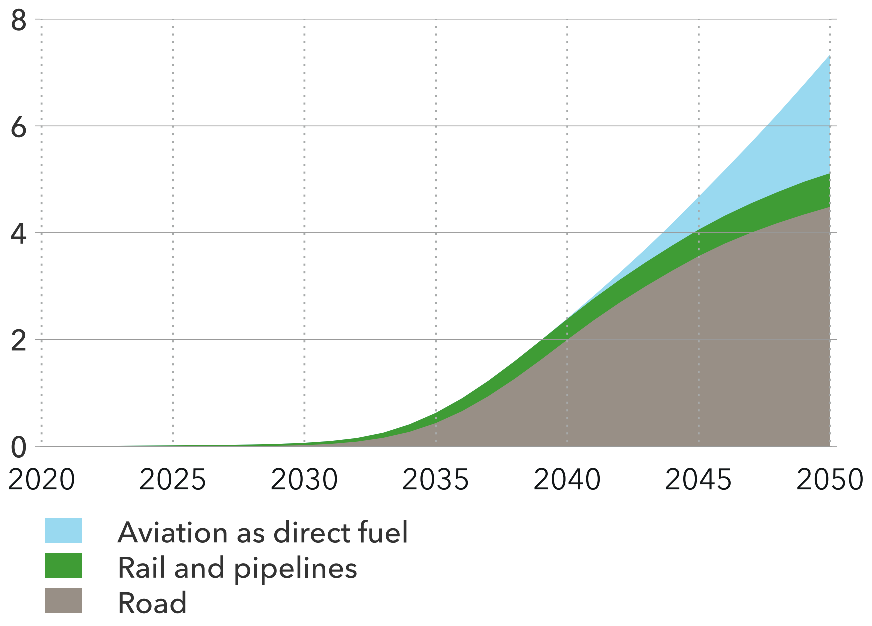
Figure 4.18 shows the direct use of hydrogen in the transport sector, which will reach 0.9 EJ by 2050, with most of that used for road transport. In total, hydrogen reaches a share of 6% by 2050 in transport energy. However, this increases to 16% when including ammonia and e-fuels.

The role of pure hydrogen in commercial transport, especially long-distance trucking will begin taking off in the mid-2030s, spurred on by the affordability of clean hydrogen due to the IRA support, and the slight delay in the establishment of appropriate electric charging infrastructure for long-distance trucking.

FIGURE 4.18

Direct use of hydrogen in transport

Units: PJ/yr



Direct use of hydrogen in aviation will also start scaling up in the 2040s, aided by the willingness of the aviation industry to decarbonize and policies requiring decarbonization.

In addition to direct use of hydrogen in transport, there is also the considerable use of ammonia in maritime, as well as e-fuels in maritime, aviation and rail in North America. By 2050 around 0.64 EJ of energy through ammonia will be expended in the maritime segment, amounting to 36% of maritime energy demand. Such a high share is likely due to the decarbonization regulations of the International Maritime Organization (IMO). Similarly, hydrogen-derived e-fuels will meet 19% of maritime energy demand by 2050.

In addition to maritime transport, e-fuels will also supply a significant share (15%) of aviation energy demand in North America by mid-century.

Uptake of ammonia and e-fuels in both maritime and aviation transport will start as early as the late 2020s, which feeds the virtuous cost learning cycle of hydrogen production through both methane reforming with CCS and electrolysis. This has the added benefit of providing an early offtake market for hydrogen.

Hydrogen supply

Hydrogen supply for energy will grow from minuscule amounts in 2022 to 31 Mt in 2050. In 2022, most of the hydrogen for energy was produced through methane reforming. It is our expectation that hydrogen for energy will not be produced using carbon-intensive production routes such as coal gasification or methane reforming but would exclusively be produced through electrolysis or fossil-fuel production routes coupled with CCS (blue hydrogen).

Figure 4.19 presents the dynamics of hydrogen production routes in North America. Even at present, blue hydrogen in very small quantities is being produced for use in refineries and in iron and steel production. In the near term, through to 2030, blue hydrogen will be preferred in North America. In fact, the existing knowledge base of steam methane reforming (SMR) plays a vital role in catalyzing and inducing the demand for hydrogen. This is because of abundant domestic availability of natural gas and North American oil and gas industry's experience with CCS (for enhanced oil recovery).

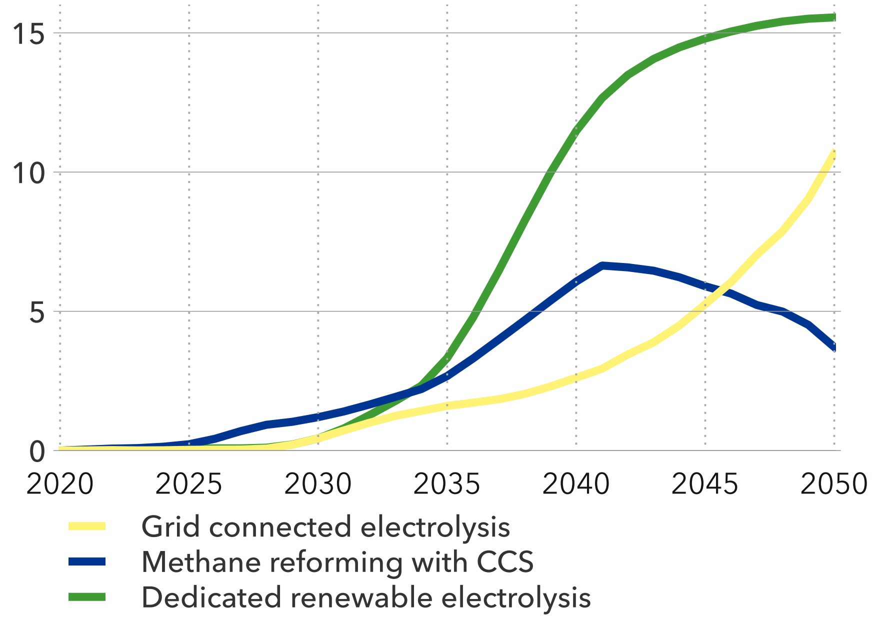
Green hydrogen from both dedicated renewables and from grid-connected sources will follow fast on the heels of blue hydrogen, spurred on by the beginning of IRA support for electrolysis. Dedicated renewables-based hydrogen overtakes blue hydrogen in the mid-2030s, and plateaus. Owing to its ability to optimize the running time of electrolyzers in synchrony with electricity price arbitrage opportunities, grid-connected electrolysis increases over time, overtaking blue hydrogen in the 2040s.

The selection of production route in this forecast is primarily influenced by the levelized cost of the production routes of course, which is discussed in detail in the following section.

FIGURE 4.19

Hydrogen supply by production route

Units: MtH_2/yr



Levelized cost of hydrogen

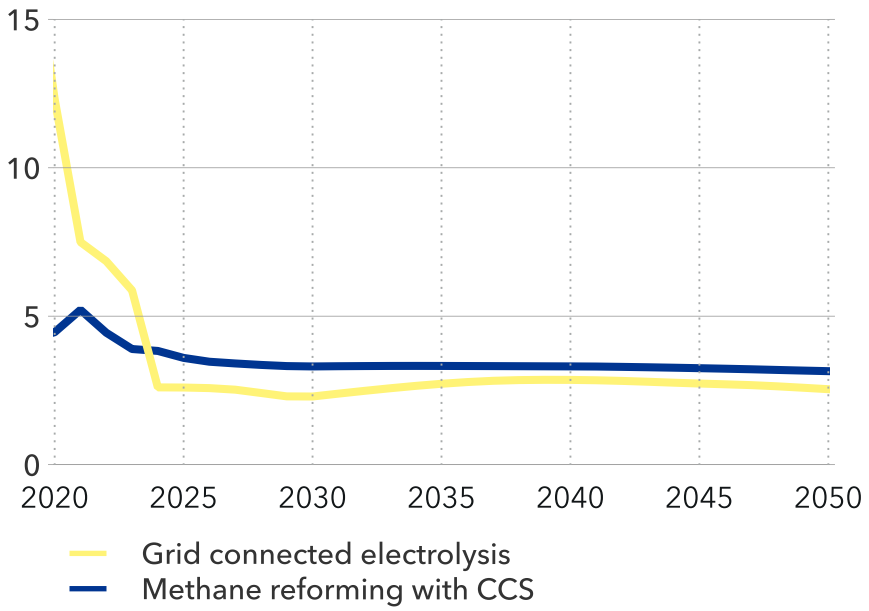
Figure 4.20 compares the levelized cost of hydrogen (LCOH) of grid-connected electrolysis and blue hydrogen in North America and how it changes over time. What is included in the LCOH is documented in our dedicated *Hydrogen Forecast to 2050* (DNV, 2022d). Prior to the support given through the IRA, grid-connected electrolysis has one and half times the levelized cost of blue hydrogen. However, owing to the high level of support for grid-connected electrolysis and relatively lower level of support for blue hydrogen based on the 45Q support for CCS, the levelized cost of grid-connected hydrogen reduces well below that of blue hydrogen from 2024. Despite the phasing out of support in early 2030s, grid-connect hydrogen never increases to the level of blue hydrogen. This influences the production route mix as shown in Figure 4.20.

Figure 4.21 shows the dynamics of LCOH of the different dedicated renewables-based ('green') hydrogen production routes expected in North America. The four expected green hydrogen production routes are electrolyzers running on electricity generated by dedicated solar PV plants, onshore wind farms, solar+storage plants and some fixed offshore wind farms.

FIGURE 4.20

Levelized cost of hydrogen – grid-connected versus blue hydrogen

Units: USD/kgH_2



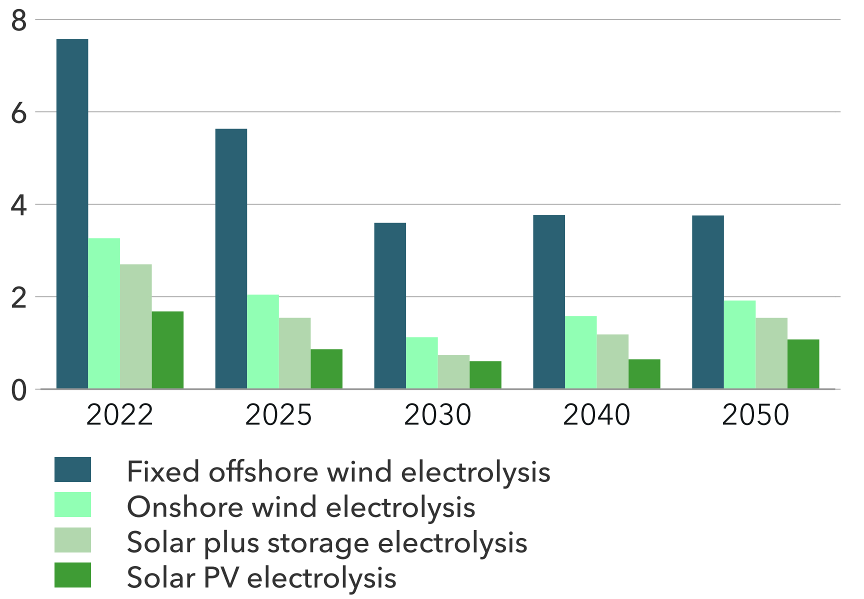
The LCOH from solar PV will be cheapest in North America, followed by solar+storage, onshore wind and then fixed offshore wind. The cost order is preserved throughout the IRA and Canadian hydrogen support years, despite the fast reduction observed in LCOH of fixed offshore hydrogen, mostly due to volume effects.

These LCOH figures reflect the average across the region and not individual projects. There will be individual fixed offshore wind projects, especially for export purposes, situated on the Eastern seaboard of Canada and US. By mid-century, we forecast about 9 GW of fixed offshore wind producing about 1 Mt of H_2.

FIGURE 4.21

Levelized cost of green hydrogen in North America

Units: USD/kgH_2



All sources are dedicated hydrogen production.

Gas grids

Leveraging existing gas infrastructure to support low-carbon fuels and feedstock is vital and has the potential to accelerate the energy transition. Much of over 5 million km of natural gas and 9,500 km of CO_2 existing transmission and distribution pipelines could be retrofitted or repurposed. However, new pipelines will also be required, and permitting and public acceptance is currently a challenge.

Natural gas

There is a potential for repurposing natural gas networks to store and transport hydrogen at low blend ratios. This will be required in the near term for hard-to-abate sectors that will depend on a chemical fuel such as steel, fertilizer, glass, ceramics, metals and other heavy industry. Natural gas may not be as prominent as it is today in residential applications but it's probably the best backup to renewables during cold winters or when there is extremely high demand to produce power. The key is to blend H_2 up to 20% and therefore minimize the need for new equipment consuming the fuel. However, due to vast property differences between hydrogen and natural gas, conversion of an energy-system requires thorough examination of their impact on pipeline networks and end use applications in modified engines, boilers, oven burners, stoves and fuel cells. The advantages of using hydrogen as a zero-carbon fuel needs to be balanced with the safety of blended gas, such as over pressure and leakage. Short term hydrogen-embrittlement studies with low blend ratios have shown little degradation in metal tensile properties (example - HyDeploy), however long-term embrittlement is still under investigation (example - HyBlend). Another way to leverage existing infrastructure is adding more renewable natural gas (RNG) such as, from agriculture, a preferred net negative route. Land fill natural gas, although a larger source, is not as powerful a reduction as regulations requires large landfills to combust the methane onsite through flares and/or power production.

Carbon dioxide

ransport and storage infrastructure for CO_2 is essential to realize low carbon fuels, such as methanol, synthetic methane and sustainable aviation fuel (SAF). There are encouraging announcements globally for increased storage capacities to potentially reach 420 Mt CO_2/year by 2030, a strong step towards balancing demand and supply, but perhaps insufficient to meet net zero goals which require 1200 Mt CO_2/year by 2030. Nevertheless, increased storage and clean fuel production capacity will require substantially more connecting pipelines.

North America currently has nearly 9,500 kms of CO_2 pipelines but will require 70,000 miles of new CO_2 pipelines to reach the decarbonization goals. Approximately 50% of offshore pipelines could be repurposed for CO_2 transportation, with onshore requiring purpose-built infrastructure. Industries such as the cement industry (a heavy emitter), requires a high amount of CO_2 transportation and storage to reduce emissions. Ethanol manufacturers in the will likely consider CO_2 transportation as it would position them as a feedstock provider for new transportation fuels (methanol, SAF).

Common between these two trends is public resistance to new pipelines and lengthy permitting processes, particularly for pipeline going across state lines. Legacy regulatory agencies are setup to limit the impact of industry on the environment but do not have the means to accelerate plans to benefit the climate. New policies are required to support permitting or prioritizing certain infrastructure.

5 ENERGY SUPPLY

5 ENERGY SUPPLY

The energy mix in North America will undergo rapid and dramatic changes over the coming decades, with fossil energy reducing from the present 80% to less than 50% by 2050. The two most noticeable changes are the growth of solar and wind as they start dominating the power mix, and the decline of oil as electric vehicles will be outcompeting internal combustion engine (ICE) passenger vehicles and light trucks.

Primary energy supply is the total amount of energy needed to meet energy demand, and the details of counting and a description of energy losses are included in the main ETO (DNV, 2023a).

Figure 5.1 shows the historical and forecasted changes in US and Canada primary energy consumption. Overall energy consumption peaked in 2007 at 112 EJ, stands at 104 EJ today, and will decline to about 77 EJ by mid-century. The decline is mainly attributed to more efficient electric engines in road transport, but heat pumps and general efficiency improvements are also important.

A changing primary energy mix is nothing new. In fact, the dramatic turnaround has already started, with coal's share of the energy mix falling by two-thirds over the last 15 years, from 22% in 2007 to 9% today, and natural gas increasing from 26% to 36% at the same time. The decline of coal is forecast to continue, while natural gas consumption will remain high this decade and then start to reduce from around 2030.

The main decline of gas is in power, whereas cheaper and more competitive solar and wind will grow strongly. Compared with 2022, solar and wind energy will grow 15-fold and 8-fold, respectively. Nuclear has been stable in the US for 20 years, and we forecast a stable supply from nuclear this decade, followed by a small decline of about 25% to 2050.

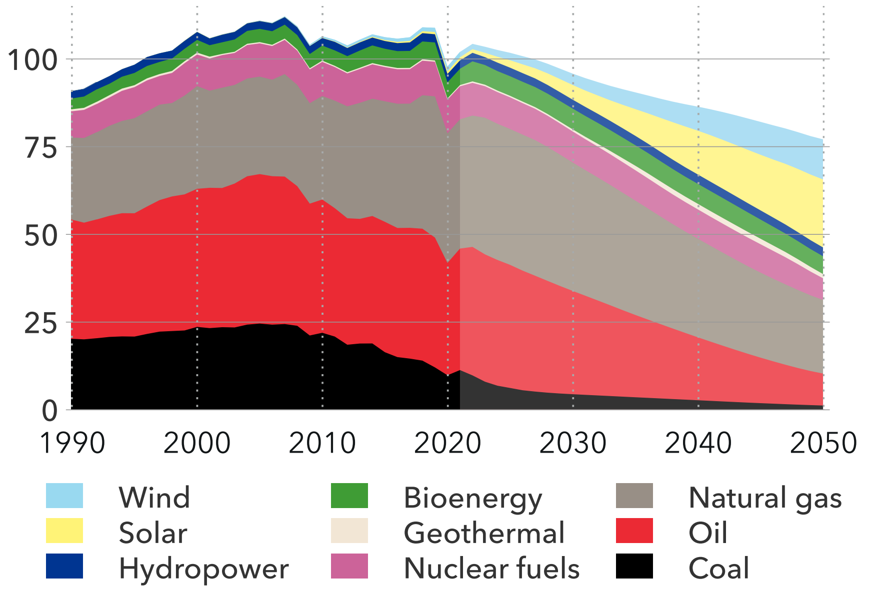
As electricity in road transport increases and EVs take over from ICE passenger vehicles, light trucks, and part of the heavier trucking segment, US and Canada oil use is reduced by more than two-thirds, from 37 EJ today to 9 EJ in 2050. For the 'land of big oil' this change is dramatic, but oil use will remain in feedstock and in aviation and long-distance trucking.

Bioenergy use, currently having a 6% share, is relatively flat, and mostly used in manufacturing and transport. In transport, the use of first-generation bioethanol and biodiesel for road transport will decline, while sustainable bioenergy use will grow significantly in aviation and shipping. Hydropower remains relatively small in the region, though the share in Canada alone is much larger.

FIGURE 5.1

Primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2023)

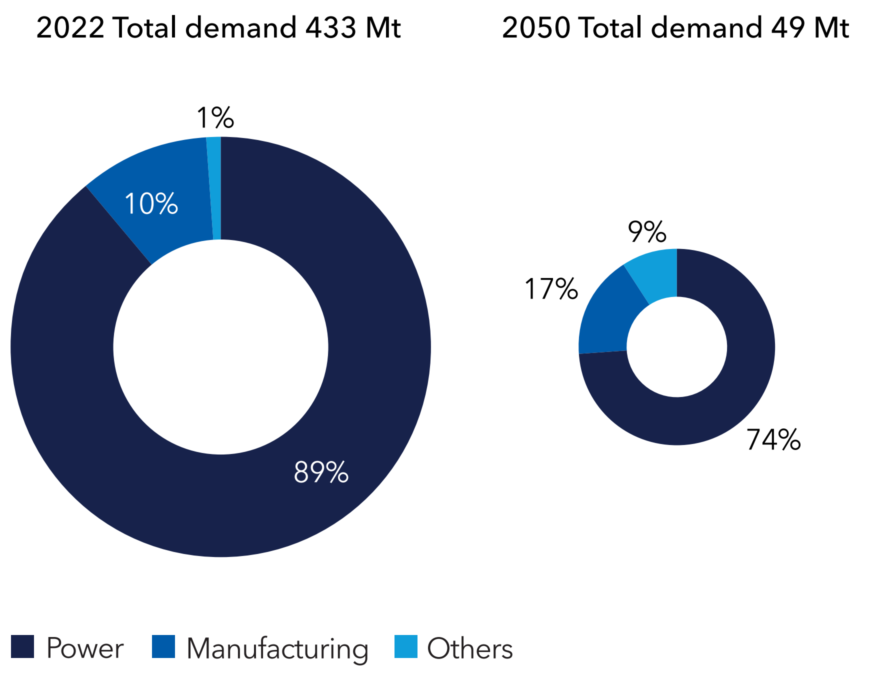
5.1 COAL

Historically, coal has been a significant energy source in North America, with states such as Wyoming and West Virginia, and the British Columbia province in Canada benefiting from abundant coal reserves.

Over the past thirty years, the power generation sector accounted for 90% of coal consumption, while manufacturing represented 10% of coal usage. Within this 10%, approximately 40% was used in industrial coke plants (for high-heat manufacturing), with 20% used in industries with low-temperature needs.

FIGURE 5.2

Coal energy demand in North America



Long the dominant source of electricity generation in North America, coal was surpassed by cheaper, cleaner natural gas in 2015 and is now increasingly giving way to policy-supported growth in wind and solar generation. By 2050, electricity generated by coal will be one fifth of its current amount. Figure 5.2 compares coal energy demand in 2022 and 2050. The phase down of coal in power generation and low-heat processes, easily substituted with electricity, is relatively straightforward. However, due to the complexity involved in shifting away from coal in high-temperature processes like cement, iron, and steel production, coal is likely to remain the preferred option in these hard-to-abate sectors.

In 2022, North America produced a total of 530 Mt of coal, consisting of 193 Mt of brown coal and 337 Mt of hard (metallurgical) coal. Canada accounted for approximately 9% of the region's coal production, while the remainder was produced in the United States, principally in Wyoming. Coal consumption during the same year reached 433 Mt, equal to 9.8 EJ.

By 2050, both coal production and consumption are projected to decrease by 86% and 89%, respectively, compared with 2022 levels.

TABLE 5.1

Coal production, demand, and export in North America

Year	Production			Export	Demand			
	Total (Mt)	Brown (Mt)	Hard (Mt)	Hard (Mt)	Total (Mt)	Electricity (EJ)	Manufacturing (EJ)	Others (EJ)
2000	1063	495	568	7	1056	22	2	0.2
2022	530	193	337	96	433	8.7	1	0.1
2050	79	19	60	30	49	0.8	0.2	0.1
2000 vs 2022	-50 %	-61 %	-41 %	1271 %	-59 %	-60 %	-50 %	-50 %
2022 vs 2050	-85 %	-90 %	-82 %	-69 %	-89 %	-91 %	-80 %	0 %

In 2022, the region exported 96 Mt hard coal to primarily China and India. Canada's export volume alone accounted for around 30 Mt, representing more than two-thirds of its production (Statistics Canada, 2023a). As the region is the largest exporter of metallurgical coal after Australia, the share of exported coal is expected to increase from 18% in 2022 to 37% in 2050, reaching 30 Mt out of a total production of 79 Mt. Table 5.1 summarizes and compares coal production, demand, and export in 2000, 2022 and 2050.

The economic impact of reduced demand and therefore coal production on local communities is notable. 142 coal mines have closed in the U.S. since 2000, and, according to FRED (2023), the number of employees in the coal mining industry in the United States has reduced from 90,000 to 40,000 from 2012 to 2022. Both US and Canada have specific initiatives targeted towards coal-dependent communities. For example, the IRA has introduced an 'energy community bonus' for developers locating clean power projects in historical energy communities, including areas with shuttered coal mines or power plant. This mechanism is likely to help increase the social acceptability of coal phase down within these communities, while incentivizing clean energy investments and their associated economic benefits – including local economics and health benefits to communities which hitherto have been placed at risk by the energy transition (Energy Institute at HAAS, 2023).

The IRA includes tax credits for carbon capture technologies in coal-fired plants, but these incentives have been met with limited enthusiasm (Politico, 2023b). Only one in 10 of the utilities with the largest coal-fired fleets has active plans to adopt the technology. Additionally, this is a costly and inefficient GHG abatement strategy compared with alternative options like solar and wind energy.

5.2 OIL

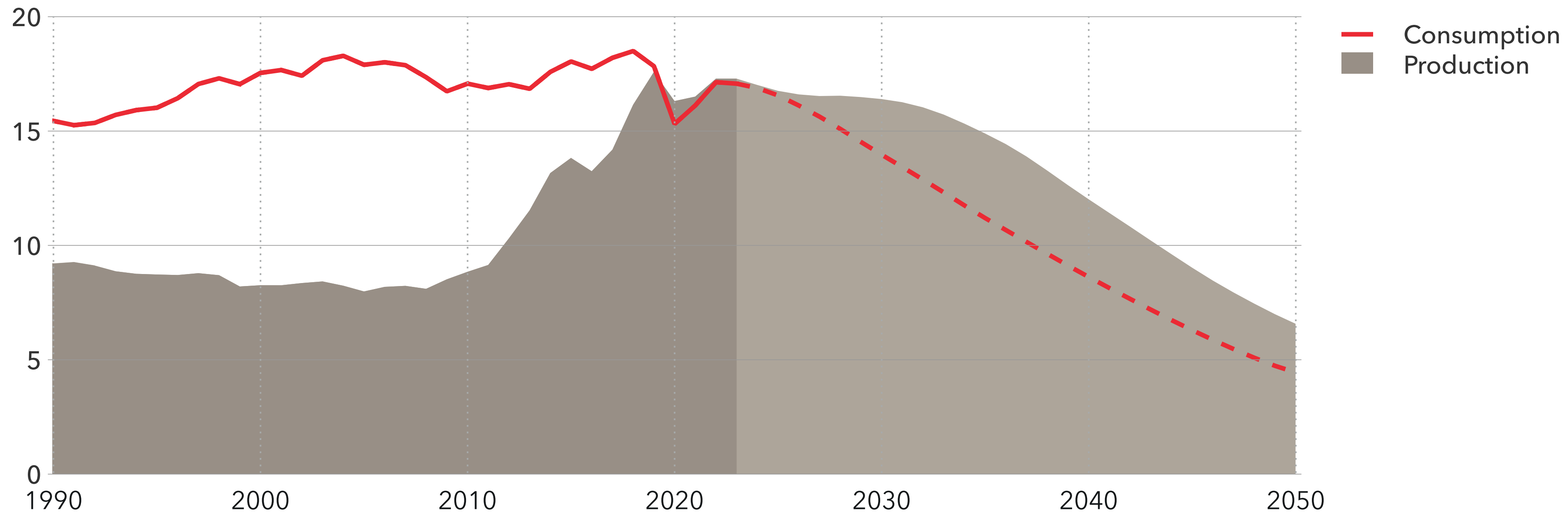
The US is by far the largest user of oil globally. On a barrels-per-capita basis, Canada outstrips even the US and is on a par with several of the Arab states. Oil has long been the dominant contributor to primary energy supply in North America with a 35% share in 2022. Though consumption is forecast to decline to 12% by 2050, production remains stable, leading to a tripling of exports by 2050.

The decline in North America's crude oil production between 1985 and 2008 was reversed with the 'shale gale' oil revolution – itself a product of a combination of technical advancements, low interest rates, and government policy. Subsequently, oil production increased almost every year from 2009 to 2019, so much so that the US was the world's top crude oil producer in the four years leading up to 2022. Oil production in North America was about 17 million barrels per day (Mbpd) in 2022, and our forecast foresees it plateauing until 2024 then declining to 7 Mbpd by 2050. Figure 5.3 provides an overview of production and consumption trends.

FIGURE 5.3

Oil production and consumption

Units: Mb/d



Historical data source: IEA (2023); GlobalData (2023); Rystad Cube (2022)

North America's oil demand has remained relatively flat for two decades but is projected to decrease to one third of current levels by 2050, from 17 to 4 Mbpd, mainly due to the electrification of road transport. Despite falling domestic demand, production does not reduce until 2030, propped up by continued exports, mostly to Europe, Latin America, and China. As the ratio of oil demand to production in the region continues to decline, our forecast indicates a tripling of exports to 2050. These higher exports are not sufficient to stop production levels reaching one third of 2022 levels by 2050

In Canada, annual growth in oil exports has averaged 6.2% since 1990 while the share of production going to export more than doubled from 38% in 1990 to 87% in 2022 (Statistics Canada, 2023b). The US became a net exporter of oil in 2020, exports reached 1.26 Mbpd in 2022, and the country is expected to remain a net exporter (EIA, 2023a).

North America's oil demand is projected to decrease to one third of current levels by 2050.

Oil demand by sector is shown in Figure 5.4. Transport, which historically accounted for the largest share of oil demand, is expected to use substantially less going forward to 2050. The sector's share of oil demand grew from 60% in 1980 to 82% in 2022, but its use of energy from oil is forecast to plummet from 29 EJ in 2022 to 6 EJ in 2050. This decline is due to the replacement of ICEVs by more efficient EVs.

Electrification of the manufacturing sector reduces its oil demand from 1.1 EJ to 0.3 EJ, less than a third of its current level. On the other hand, the non-energy (feedstock) and building sectors are expected to show relatively stable oil demand throughout the forecast period.

Driven by the rise of car sharing and automation, the decrease in vehicle ownership from 85% of households in 2022 to 57% in 2050 will also have a significant impact on oil demand per capita.

Nevertheless, there are key differences in the oil demand transition for transport subsectors. Oil demand per capita in the road transport is expected to decrease nine-fold, from 62 GJ (ca 10 barrels) in 2022 to 7 GJ (ca 1 barrel) (Figure 5.5).

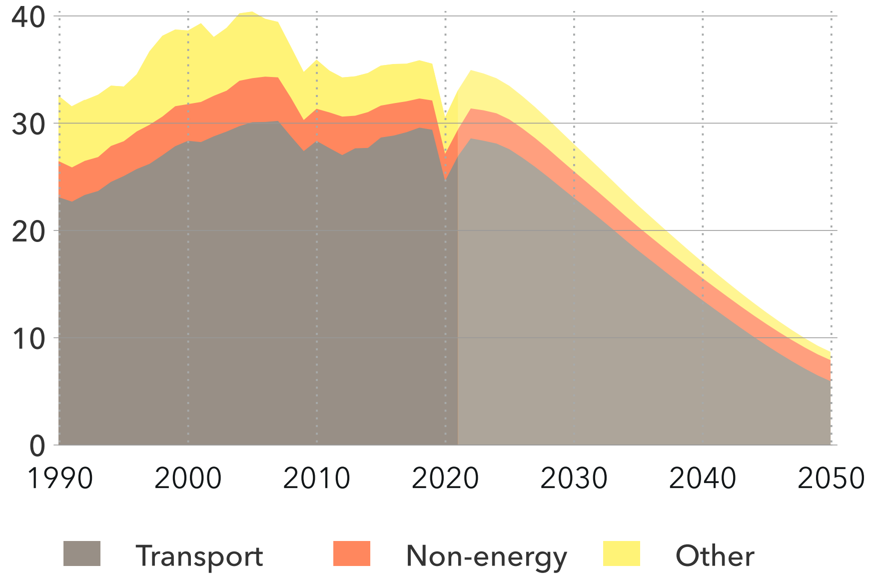
The change in aviation oil demand will not be so marked. North American oil demand in aviation has been more than twice that of other regions in the last few decades. Aviation is well correlated with GDP per capita, which has consistently been higher in the US than even OECD-Europe, during the same period. Despite sustainable aviation fuel (SAF) making inroads into the subsector's energy demand, conventional aviation fuel is still needed when producing SAF. Regulations require that conventional jet fuel and SAF are mixed to assure the correct chemical properties are maintained for safe operation of jets. Unless technology advances, we will not be able to retire conventional jet fuel production. Thus, aviation oil demand in the US and Canada, on average, is currently 9 GJ (ca 1.5 barrels) per capita, and although this will reduce to 6 GJ (ca 1 barrel) per capita, North America will remain the highest consumer of oil per person for aviation (Figure 5.5).

Electrifying road transport in North America leads to a dramatic reduction in oil demand.

FIGURE 5.4

Oil demand by sector

Units: EJ/yr

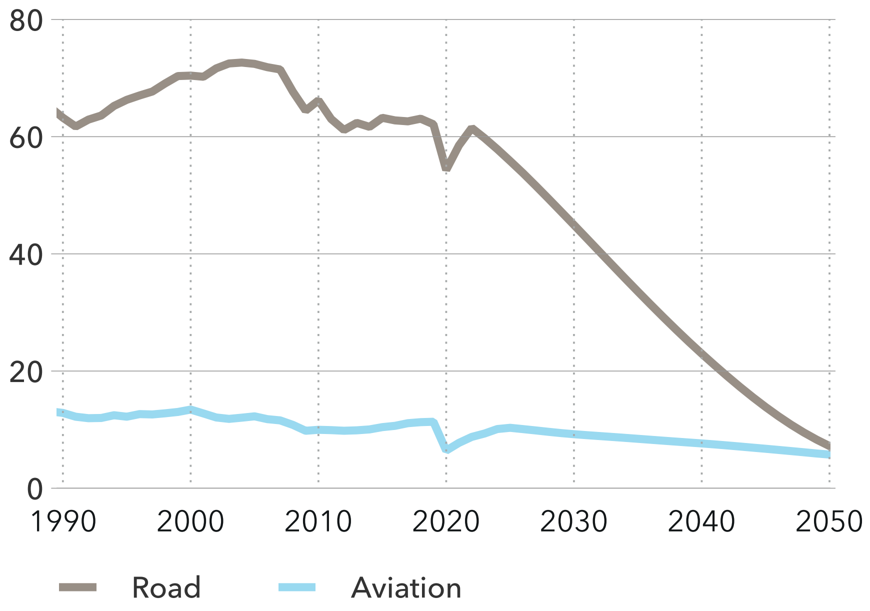


Historical data source: IEA WEB (2023)

FIGURE 5.5

Oil demand in road and aviation per capita

Units: GJ/person/yr



Historical data source: IEA WEB (2023)

5.3 NATURAL GAS

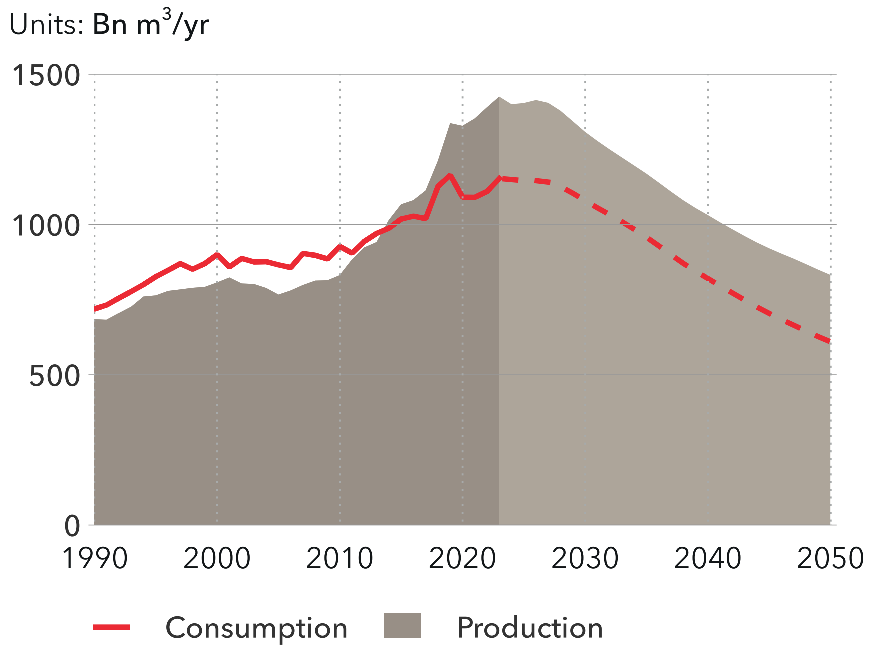
The US produces six times more natural gas than Canada. Over the past two decades, while Canada's natural gas production remained relatively stable, US production has nearly doubled.

The first surge in the US started in 2006 with the advent of hydraulic fracturing. The second boost came with the opening of the first large-scale LNG export terminal on the Gulf Coast in 2016, and the most recent leap involved exports to gas-starved Europe from mid-2022. In 2022, natural gas production in North America reached a record high of 1,390 Bn m³. We forecast that natural gas production in North America will continue to grow gradually to a plateau of about 1,400 Bn m³ until 2028 before gradually declining to 832 Bn m³ by 2050. Figure 5.6 provides an overview of production, consumption, and export trends.

In 2022, demand for natural gas in North America reached approximately 1,110 Bn m³, 20% higher than a decade ago. As shown in Figure 5.7, there has been a shift in natural gas usage over the years in different sectors. Since 2012, the power sector has surpassed the buildings and manufacturing sectors as the primary user, accounting for 32% of natural gas consumption in 2022.

FIGURE 5.6

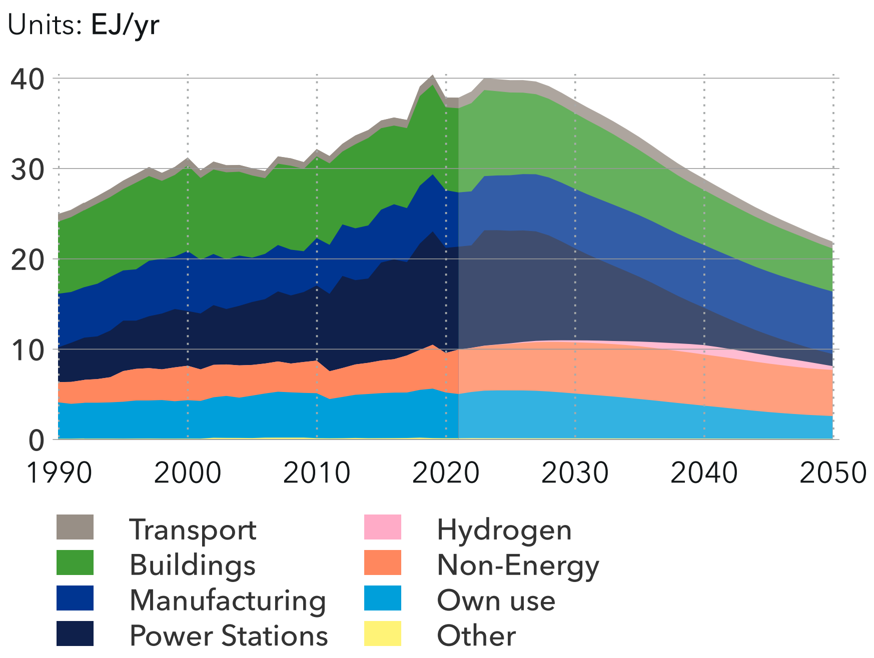
Gas production and consumption



Historical data source: IEA (2022); GlobalData (2021); EIA (2023)

FIGURE 5.7

Gas demand by sector



Historical data source: IEA WEB (2023)

Total domestic demand for natural gas is projected to grow to 1,150 Bn m³ by 2024, mainly due to its expanding role in electricity generation, replacing coal-fired power plants. Thereafter, it will decline gradually to 610 Bn m³ by 2050. This decline will be, driven by factors such as improved energy efficiency; much greater shares of renewable energy sources in the power sector; blending of biogas and hydrogen into the natural gas stream; and, by electrification of various sectors including buildings and the energy industry's own-use. Compared with 2022, gas demand for power, buildings, and own-use decreases by 88%, 51% and 52%, respectively, through to 2050.

This decline is partly offset by higher demand in hydrogen and ammonia (non-energy sector) production. In 2050, gas demand for manufacturing and non-energy use will be 16% and 4% higher, respectively, compared with 2022.

The share of natural gas in primary energy supply in North America surpassed oil in 2018 and maintains a steady share of about a third until 2050. Low production costs, ample availability, and modest carbon pricing allow natural gas to remain relatively cheap. Indeed, it remains more price-competitive than renewables until the early 2030s. Higher carbon prices in some US states and Canada does not change this general picture. Additionally, natural gas has established infrastructure and distribution networks in place, making it convenient and cost-effective to use, especially for demand in buildings. However, the infrastructure can also be repurposed for storage, transportation, and distribution of renewable gases like biomethane or hydrogen.

In 2022, 65% of the hydrogen produced in North America was from natural gas reforming in large central plants. In our ETO forecast, we forecast that natural gas demand for hydrogen production would increase to 22 MtH_2/yr in 2050 (95% blue) as the low-carbon hydrogen market accelerates owing to clean energy policies, including US provisions in the IRA and the IIJA, as well as Canada's federal investment tax credits (see Chapter 2), which incentivize carbon capture and storage (CCS) after the methane reforming process (White House et al., 2023).

LNG production

North American gas exports were mainly piped intra-regionally and to Mexico, but in recent years these volumes have been eclipsed by LNG exports. With gas demand/supply patterns changing and energy security becoming increasingly important, LNG demand is high and continued growth is expected in the coming decade. Despite Kenai LNG exporting LNG from Alaska since 1969, the first LNG plant in the US lower 48 states, Sabine Pass, began operations with a capacity of 4.5 million tons per annum (Mtpa).

Since then, six new projects have been initiated, bringing the total LNG capacity in the US to 101 Mtpa in 2022. Canada's LNG Canada project, with an initial capacity of 14 Mtpa, is scheduled for commissioning in 2025. In North America, the total liquid regasification plant capacity is 143 Mtpa, but the plants are hardly in use, and Figure 5.8 illustrates the rapid shift in the region from LNG imports to LNG exports.

Natural gas trade

Canada trades natural gas almost exclusively with the US via pipelines. Canada exports its surplus natural gas across the international border from British Columbia, Saskatchewan, and Manitoba to the US, while importing smaller amounts from the US into Central Canada. In 2022, Canada's natural gas exports declined to 85 Bn m³, 8% less than in 2010 (Statistics Canada, 2023c). This decrease is due to greater demand within western Canada and the rise in natural gas production in the US. Trade volumes are expected to remain stable in the coming years.

US gas export is via pipeline or trucks to Canada and Mexico, or by LNG vessels to other regions. While the export volume to Canada remained relatively stable at around 26 Bn m³ (EIA, 2023b), the volume to Mexico experienced remarkable growth, about 60 Bn m³ in 2022, more than six times the level seen in 2010. As shown in Figure 5.9, we forecast the export to Mexico via pipeline stays the same to the end of the forecast period. Figure 5.10 illustrates North America export volumes to world regions in 2022, 2030, 2040 and 2050. There's an increase and then a decrease in LNG exports to Europe, Greater China, and OECD Pacific, while an increase is expected in the Indian Subcontinent and Latin America.

Underground gas storage

Natural gas is injected into underground storage (salt caverns, aquifers, or depleted fields) when demand is lower (summer) and withdrawn when gas demand for space heating increases (winter). As the demand for gas for space heating starts to decline in North America, the need for seasonal natural gas storage will peak within five years. By mid-century, 172 Bn m³ of methane storage capacity will be present.

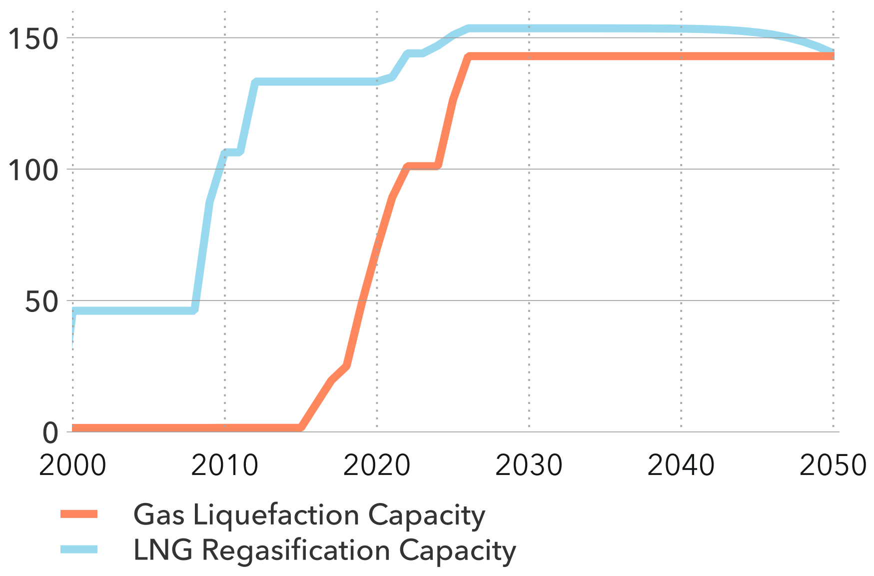
In contrast, about 52 Bn m³ of hydrogen storage will be developed by 2050, about 85% of which will be repurposed methane storage sites. Figure 5.11 demonstrates historical and projected underground storage volumes.

North American LNG exports have eclipsed piped exports in recent years.

FIGURE 5.8

LNG liquification and regasification capacity

Units: Mt/yr

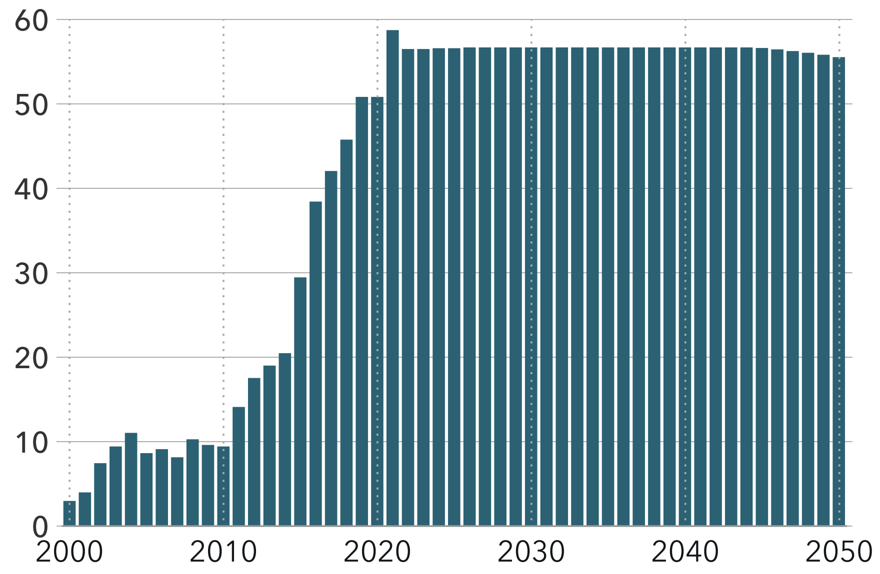


Historical data source: Global Data (2020), IGU World LNG Report (2018), EIA (2023)

FIGURE 5.9

US Gas Export to Mexico via pipeline

Units: Bn m³/yr



Historical data source: EIA (2023)

FIGURE 5.10

North America LNG exports by importing region

Units: Bn m³/yr

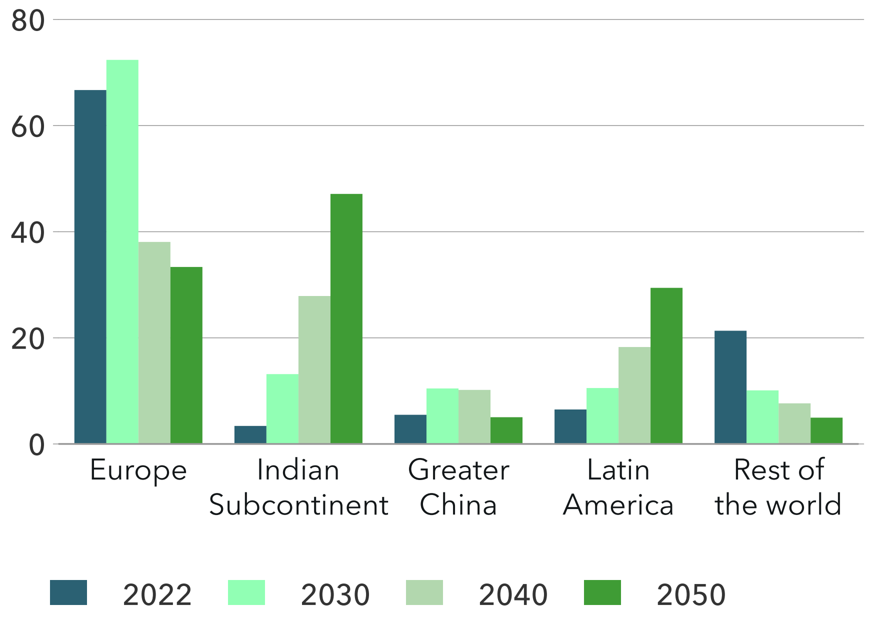
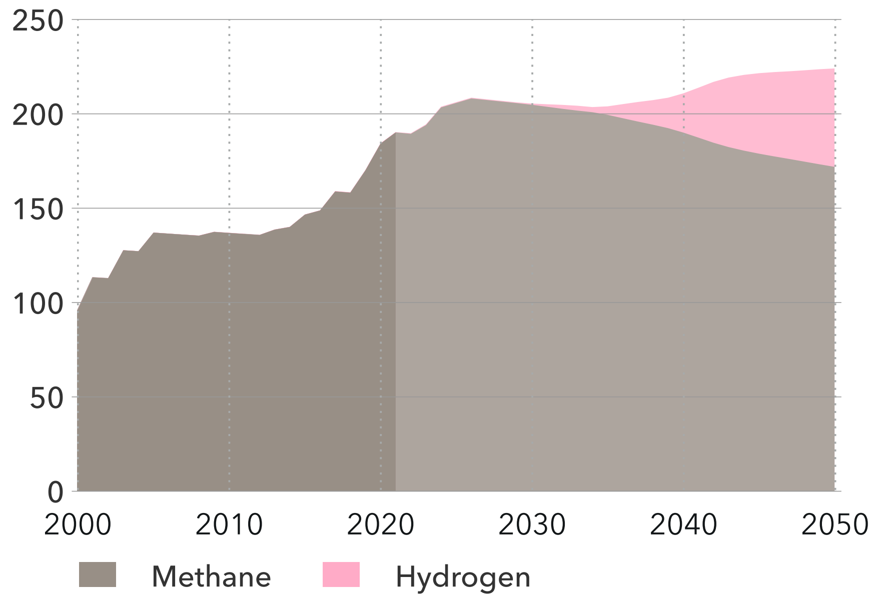


FIGURE 5.11

Underground gas storage by gas type

Units: Bn m³/yr



Historical data source: Cedigaz (2022)

5.4 SOLAR

We forecast that renewable generation from solar PV will overtake all other types of generation by the mid-2030s and account for almost half of all electricity produced in North America. About a third of solar capacity installed will be combined with storage, mainly batteries. Such growth will be driven by favourable economics and enhanced policy support in the region.

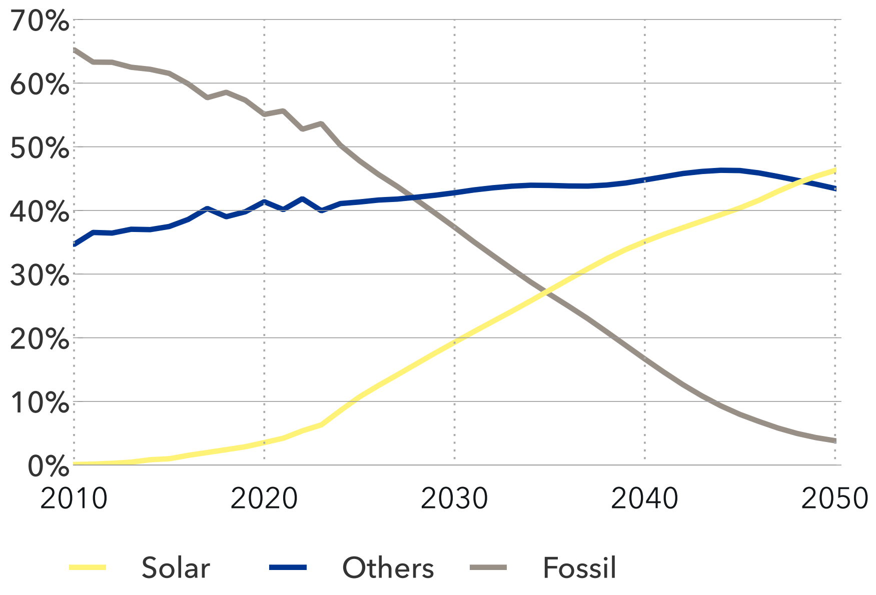
Generation and capacity

The share of solar PV in grid-connected electricity generation in the region has increased moderately in the past 10 years, from less than 1% in 2013 to around 5% presently. Given that electricity demand has been more or less constant over the same period, this is a five-fold increase in a decade, albeit from low levels. At present, solar is the third largest renewable source in the power sector after hydropower and wind. However, we forecast that renewable generation from solar PV will surpass all other types of renewables by 2027 and will see even higher growth. By 2050, solar PV will have grown 15-fold from today's levels, and will account for almost half of all electricity generated in North America.

FIGURE 5.12

Share of solar and fossil fuel in grid-connected generation

Units: Percentages



Historical data source: IEA WEB (2023)

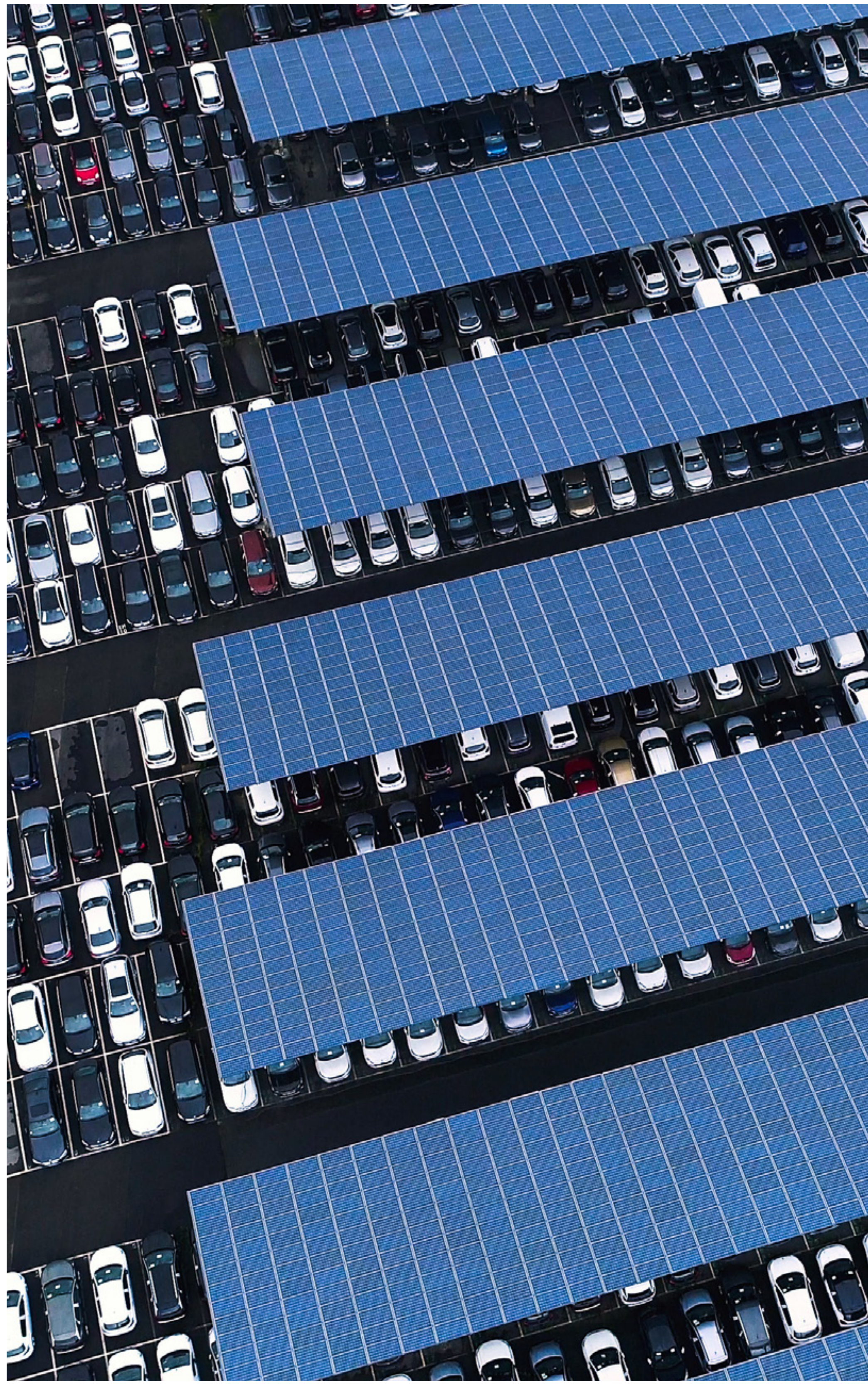
Thanks to the 10-year window of certainty created by two policies – the clean energy production and investment tax credit provision in the IRA, and the clean energy tax credit from the Canadian federal budget – we forecast that solar PV will overtake all other types of generation by the mid-2030s. By 2050, solar will be generating around 4,000 TWh/yr.

By mid-century, more than a third of this will be combined with storage, mainly battery, providing greater asset values, flexibility, and cost advantages. While solar will reach nearly half of total generation in 2050, other non-fossil plants including wind together contribute almost as much. In other words, the share of fossil-fired generation is due to reduce dramatically (Figure 5.12), leaving the North America region with one of the cleanest (and most efficient) electricity mixes globally.

Such growth is possible first and foremost due to rapidly increasing electricity demand – driven by electrification of all major demand segments, such as road transport, buildings, and manufacturing, and by the establishment of new demand segments such as grid-connected electrolysis. This expected growth in electricity demand will drive commensurate investment in new power plant capacity.

The growth in new capacity has been driving the increase in solar generation. Solar will account for 65% of the new capacity coming online between now and 2030. To give a sense of the scale, for each 1 GW of new capacity added in the years 2023 to 2030, 0.65 GW of will be solar. This is because, on average, solar has the cheapest levelized cost of energy (LCOE). Favorable economics will see solar continue to propagate into many major grids and markets. In addition to the cost learning curve effects applicable globally for solar energy, the improving economics of solar is driven by three main factors in North America: production and investment tax credits under the IRA; the aging coal power plant fleet that is increasingly difficult to operate due to dwindling profitability; and the clean power and climate goals of states and provinces.

In 2010, new capacity additions exceeded 1 GW/yr for the first time and grew increasingly thereafter, breaking through 10 GW/yr in 2016 and 20 GW/yr in 2021. Accordingly, the total installed grid-connected capacity in 2022 exceeded 150 GW compared with just above 3 GW in 2010. We forecast that annual solar capacity installations will continue to rise, nearing 130 GW by 2050.

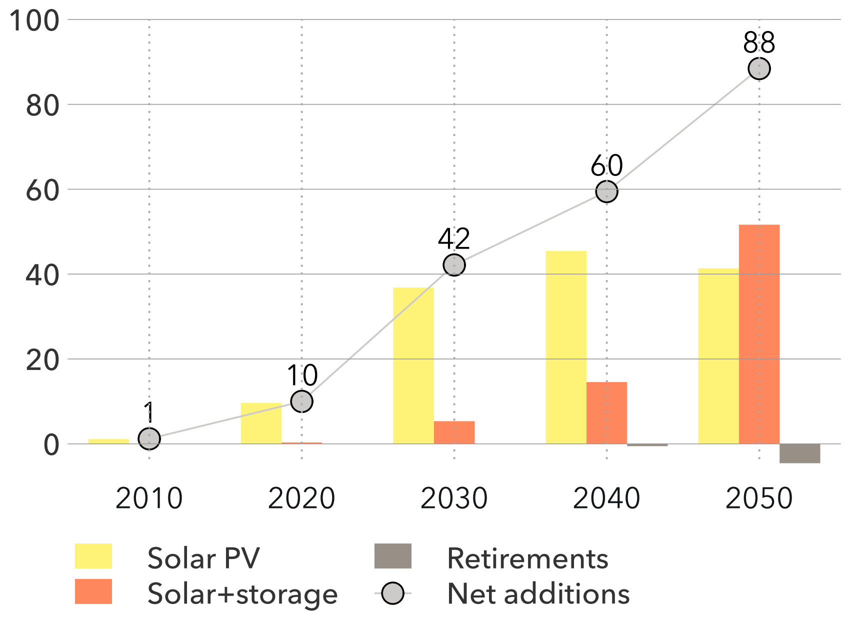


As storage costs become cheaper with more storage capacity being added worldwide, helping to drive cost learning, the share of solar PV systems with dedicated storage will rise to about 13% of all solar installations by 2030. It will continue rising to reach about 24% in the 2040s and 56% by 2050 (Figure 5.13). As increasing amounts of solar PV electricity are grid-connected, the additional benefits of a near-fully flexible storage system co-located with solar PV generally outweigh the limited benefits of clipped solar generation (Müller et al., 2019). These benefits may also enable solar+storage investments to maximize the value of the assets and interconnection capacities in markets that will become increasingly more dynamic.

FIGURE 5.13

10-year average solar capacity additions and retirements

Units: GW/yr



Historical data source: GlobalData (2023)

By mid-century, total installed capacity will reach 1.8 TW for solar PV and 0.7 TW for solar+storage. The 2.5 TW of combined solar capacity projected for 2050 is 15 times the level seen in 2022. More than half of all installed capacity in the region in mid-century will be solar (Figure 5.14).

In addition to grid-connected solar, we expect about 500 GW of off-grid capacity dedicated to satisfying electricity demand for hydrogen production through electrolysis; a dramatic increase from only about 1.5 GW installed now.

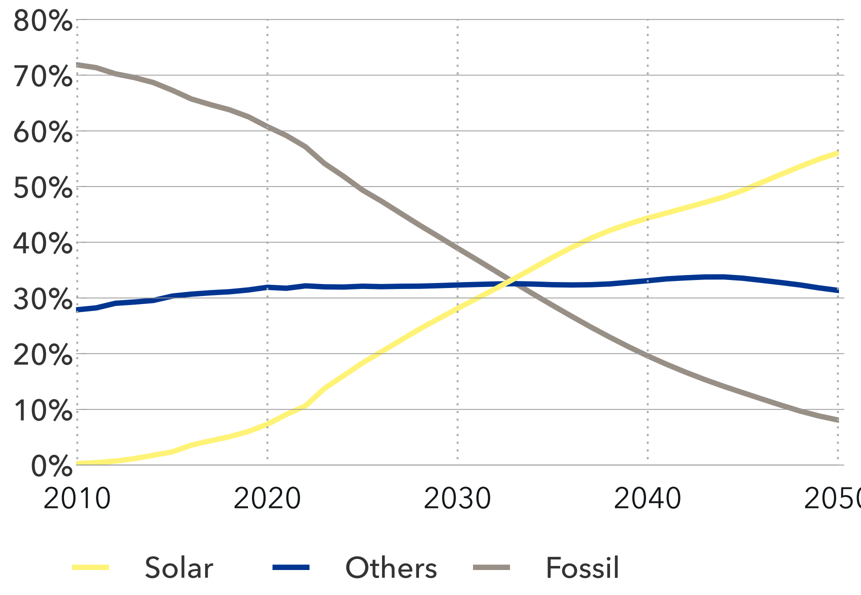
Economics

Favorable economics underpins continued growth in solar capacity. LCOE for solar PV is currently around

FIGURE 5.14

Share of solar and fossil fuel in grid-connected installed capacity

Units: Percentages



Historical data source: GlobalData (2023)

USD 34/MWh, the lowest among all fuel options in the power sector. For solar+storage, it is almost twice as much at USD 60/MWh, though this is more competitive than all other power generation options except onshore wind. As installations continue increasing both in the region and globally, powerful cost learning effects will drive down unit investment cost and reduce solar LCOE still further. Even more importantly, battery costs are also being driven down by the learning effect, further reducing the levelized costs of solar+storage. By 2050, we expect LCOEs as low as USD 20/MWh and USD 36/MWh for solar PV and solar+storage, respectively. For the period 2023 to 2034, an additional cost advantage will come from IRA support, using investment tax credit (ITC) and production tax credit (PTC) mechanisms to incentivize solar, solar+storage, and stand-alone energy storage development.

There is more to the story of solar economics, however. Our ETO model follows levelized profitability accounting for both price and costs. This approach better reflects the competitiveness of generation technologies as investment choices, given that some, such as solar PV, are fundamentally variable. Solar PV currently receives a capture price of slightly under USD 55/MWh, higher than for any non-solar generation technology. Solar+storage has only a minor capture price advantage over regular solar PV today. But over time, as the share of variable renewables in the power mix increases, the capture price advantage of solar+storage increases, and surpasses the cost disadvantage. Figure 5.15 shows the widening gap between capture prices and the narrowing gap between LCOEs for the two solar technologies.

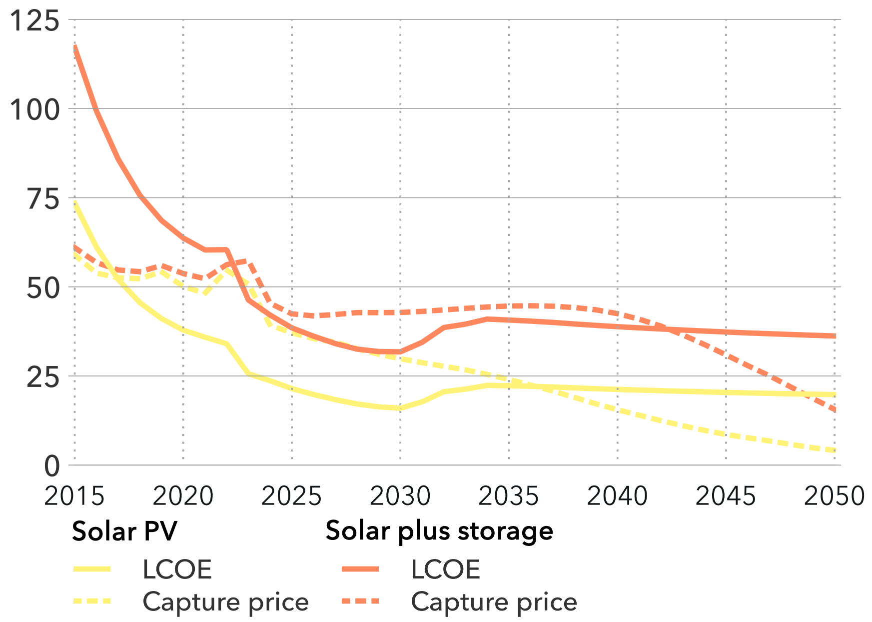
Driven by decreasing electricity prices, capture prices for solar are declining and heading towards levels below LCOEs. The eventual crossovers in capture prices and LCOEs happens in the mid-2030s for solar PV and in the early 2040s for solar+storage.

Low capture prices will not, however, hinder the strong growth of solar PV. Figure 5.15 portrays prices and costs that are averaged across the projects in the region, and with prices reported on an annual rather than hourly basis. Therefore, individual

FIGURE 5.15

Solar levelized cost of energy and capture price

Units: USD/MWh



project costs can be well below the average values, thus yielding higher profitability. Moreover, PV and storage systems are increasingly designed as a 'package' that can produce energy on demand, just like hydropower, nuclear, or combustion plants. New business models will therefore incentivize capacity, reliability, and flexibility aspects of such combined systems for solar project investors.

Due to the intrinsic variability of solar, its average capacity factors are currently the lowest compared with other generator assets. However, as more solar capacity is installed and more flexibility options are developed (i.e. energy storage, new markets, and demand-response solutions), capacity factors will increase steadily in the next decade. At higher penetration levels of solar towards mid-century, the capacity factor of solar without storage will decline due to more capacity being online during hours when solar generation is plentiful and cheap and electricity demand is not proportionally as high. Yet, as the role of solar+storage in providing flexibility becomes even more important with the rising share of renewables in the power mix, its capacity factor will continue increasing to reach 25% in 2050.

Our ETO forecast does not spatially distinguish the placement of solar projects; nor do we analyze LCOEs at project-level granularity. Nevertheless, an important profitability mechanism that is a part of the IRA provision is the stackable tax credits added to the basic ITC and PTC, based on 'placement' of the projects. Projects placed in energy communities, or former coal or fossil-fuel communities, have additional financial incentives that push the project profitability calculus considerably (DOE, 2023e). Such tax incentives also have the co-benefit of renewable projects having a higher marginal impact in decarbonizing the grid compared with an additional project in a nearly decarbonized grid.

Optimizing solar asset value across the lifecycle

A solar asset's value is evaluated and optimized across multiple stages: project development including siting, permitting, interconnection planning, the design or configuration, and the financing of the solar asset; construction and commissioning; the operation of the solar asset through continuous monitoring and maintenance to ensure the asset performs as expected throughout its expected useful life; and finally end-of-life decommissioning of the asset. At each of these stages, the asset value may be optimized to increase electricity generation over the asset's lifetime, thus increasing revenue, reducing costs or both.

Site selection and configuration of the arrays and other components can have a long-lasting impact on the capacity factor of the project and minimize the LCOE while maximizing generation. Carefully designed siting/location can set the project up for optimized performance within the same boundaries of cost.

Similarly, automated digital twins can provide real-time monitoring of asset performance and help to quickly characterize losses, reduce system downtime, and improve asset performance and profitability. Furthermore, aerial imaging of solar assets gives an invaluable insight into the system health, which is becoming increasingly relevant in O&M practices as well as in the face of supercharged climate events such as hail, wind, and wildfires that are disruptive to the operation and safety of the asset or people working on-site.

Especially relevant for the forecasted increase in variable renewables, projects with storage benefit from power forecasting, real-time pricing, and price arbitrage to maximize revenue while also ensuring that 'clean' electricity is provided to any offtake customers.

Over the lifetime of these assets, software services that provide optimization system value and performance will have a significant impact on the revenues and profitability, through maximizing capacity factors, reducing downtime through agile maintenance and through monitoring through via digital twins. Businesses such as Raptor Maps and HST service needs in the solar market for optimizing the value of solar assets and clean energy contracts, while helping enable the critical technical and commercial knowledge to deliver the full potential of these solar assets.

Even though the ETO forecast presents the most likely future over an entire region, at a project level asset optimization allows the industry to develop and operate projects that perform as designed over their modeled useful life, thereby delivering value to the investors, offtakers, and grids they are powering for decades to come.

Solar market challenges

The US IRA's tax credits and the tax incentives in the Canadian budget provide potent incentives for deployment of new solar capacity in North America in the coming decade. Notably, the legislation also takes a new approach to addressing domestic content requirements (DCR).

In recent years, the DCR regime has relied on a 'stick' approach, with the 'stick' being import tariffs against solar PV modules and parts from China. Instead, the IRA uses a country of origin as a 'carrot' by offering an additional 10% bonus stacked on top of available tax credits for projects that meet specified DCR. According to further guidelines released by the US Department of the Treasury and Internal Revenue Service in 2023 (Norman, 2023), both PV and steel components for projects must comply with DCR to qualify for those additional benefits. For PV modules and other manufactured products there is a 40% requirement on domestic production for projects that begin construction before the end of 2025. Starting in 2026, this requirement rises to 55%. For steel and iron components, the requirement is 100%. While lower DCR until 2026 can encourage funding of new projects, stricter requirements in place afterwards may risk creating additional market challenges, adding urgency to the deployment of solar.

Despite these favorable conditions for solar PV expansion, significant interconnection delays are a major challenge (LBNL, 2023a), as covered more fully in Section 4.3 on grids. Long, slow interconnection queues reflect a complex landscape of factors affecting solar deployment. For example, locations with favorable conditions for solar insolation and cheap, available land are often far from existing infrastructure or major transmission lines. Similarly, solar farms are typically sited further away from populations and demand centers. Planning and building new interconnection capacity through transmission and distribution lines can take many years due to bureaucratic processes and time lags in deciding on locations and financing new lines. Many solar projects have been waiting many years for interconnection approvals. Recent rule changes to the US National Environmental Policy Act (NEPA), such as time limits to come to a decision regarding transmission lines, may ease this time lag (Canary Media, 2023). In terms of the grid's technical capability to connect to variable solar PV capacity, being co-located with storage capacity may expedite the process.

Future developments

Role of floating solar: Meeting climate targets in North America will likely require innovative solutions, which also need to consider a region undergoing climatic changes. One example of such solutions is floating solar PV systems, often referred to as 'floatovoltaics'. Unlike regular solar PV projects mounted on land or rooftops, floating solar PV systems are constructed and installed on a contained body of water, such as ponds, reservoirs, and lakes. Floating solar can be an optimal choice of renewable project when additional space for solar installations needs to be accessed, especially since it can often be combined with other uses of water bodies (i.e. hydropower generation and storage).

Furthermore, floating solar has environmental benefits as it can reduce water evaporation rates and thereby help to conserve water. In regions of drought-prone western North America, such as California and Utah, floating solar could have many advantages. Examples include conserving arable/productive land for other uses and reducing evaporative losses from water reservoirs, while still producing the energy needed locally.

In DNV (2022b), we assess that as of April 2022 more than 10 MW of floating solar PV capacity has been installed in North America and 2.7 GW globally, mostly in Asia Pacific, led by China, and in Europe. We foresee the overall installed capacity to be within the range of 10 to 30 GW by 2030, much less than for solar PV on land, but nevertheless showing substantial growth over present levels.

What does this mean for the future of floating solar in North America? Given global estimates of installed capacity, it is unlikely that this type of solar will comprise a significant share of total solar PV in the region. However, even at a comparatively low scale, floating solar will likely play a role in cases where installation space or environmental aspects are of concern.

Automated solar site building: The prolific deployment of solar PV expected in the coming decades will require commensurate human resources. Yet the industry has already reported difficulties in hiring more labor (IREC, 2022). Further labor shortages risk hindering the continued roll-out of solar capacity. Some companies in the region began exploring solutions to this problem through automation, which combines robot technology and AI. Since the nature of solar farm construction is consistent and predictable, it lends itself well to automating processes such as trenching, laying foundations, and assembling and installing solar panels. Several start-ups are targeting automated, robotic installation and/or on-site manufacturing of PV systems (Smart Energy USA, 2023). Beyond tackling labor shortages, automation in large-scale solar projects has the potential to enhance the quality of installed products and promote further innovation, speed improvements, and cost reduction.

5.5 WIND

Much of the answer to North America's clean energy ambitions have been, and will continue to be, achieved through wind power. We predict the wind development boom that has occurred in the last half-decade to accelerate due to policy support, despite interconnection challenges and the impact of inflation on supply chains. By 2050, wind is forecast to generate 35% of the region's electricity.

Wind energy played a minor role in North America's electricity supply up until the early 2000s. A mere 10 gigawatt-hours (GWh) of wind electricity was generated in 2000, enough to power about 1,000 average homes. By 2009, wind energy had grown 10-fold to 100 GWh/yr or approximately 2% of all electricity generation. In the US, wind energy development has largely been driven by the Production Tax Credit (PTC) originally enacted in 1992 and renewed in fits and starts in one- to two-year increments until 2015.

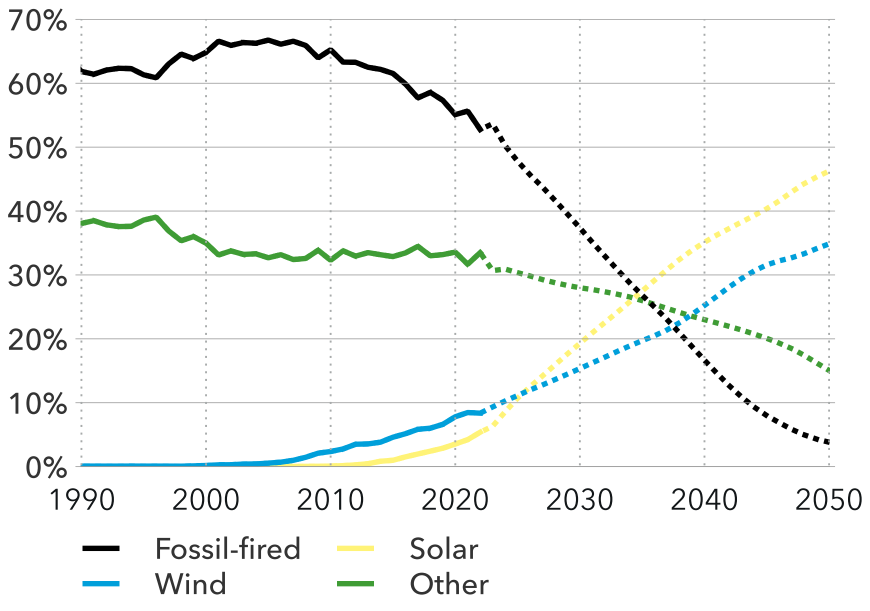
In late 2015, the PTC was extended for five years, phasing down the value by 20% each year. In addition, the 2015 legislation established a framework for partial repowering of ageing wind farms, allowing them to requalify for the PTC (10-year term) on condition that sufficient capital was reinvested in the project. The resulting boom in wind development brought wind energy across North America up to 8% of electricity supply by 2022, and as high as 55% of in-state generation in Iowa. Texas leads the region in cumulative installed wind capacity at nearly 36 GW (US DOE, 2022c).

With the enactment of the IRA in August 2022, which brings a 10-year certainty window on the PTC in the US, and the 2023 Canadian Clean Energy Plan, which brings an Investment Tax Credit to support renewable energy in Canada, we forecast 1 million GWh and 17% of electricity from wind in North America by early 2030s. By 2050, we forecast wind power to be 3.1 million GWh and 35% of total power generation in the region (Figure 5.16).

FIGURE 5.16

Share of technologies in grid-connected generation

Units: Percentages

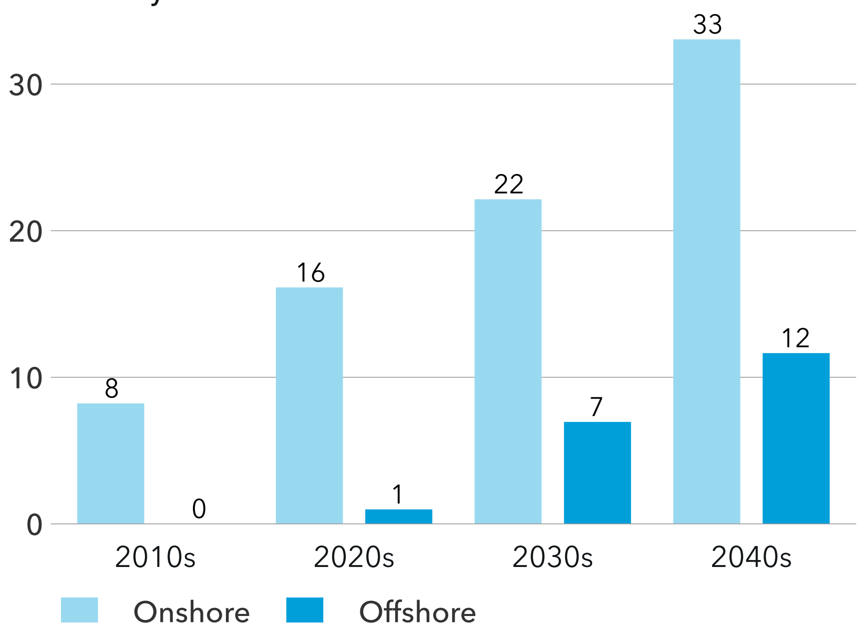


Despite the struggles with interconnection queue delays (LBNL, 2023a) and interstate transmission line siting, this Outlook foresees a robust growth trajectory for wind power in North America. Up until 2022, the growth has been primarily due to robust wind regimes in areas where land was available, the Production Tax Credit (PTC) that was renewed multiple times, and more recently local decarbonization and renewable energy targets. We foresee continued growth, despite the recent supply-chain constraints, with the IRA expected to significantly increase local manufacturing capacity in coming years.

FIGURE 5.17

Average wind capacity additions by decade

Units: GW/yr



We predict robust growth in capacity throughout our forecast period. As Figure 5.17 shows, from 2010 to 2020, about 8 GW of wind capacity was added on average to the grid every year. This rate of addition is expected to increase to 16 GW/yr of onshore wind capacity between 2020–2030, rising further to 22 GW/yr and 33 GW/yr in the 2030s and 2040s, respectively. Offshore wind capacity development follows a similar trajectory, albeit with a delay.

The acceleration of wind power capacity is driven on the demand side by the electrification of major demand sectors coupled with growth in grid-connected electrolysis. A doubling of the electricity demand in North America is expected from now to mid-century. On the supply side, wind power is already the cheapest form of new power generation available in many locations, and the IRA in particular provides developers certainty in the coming decade.

Onshore and offshore development

In this Outlook, we distinguish between onshore and offshore wind power, and within offshore, fixed-bottom and floating foundations. Fixed-bottom foundations are usually used for offshore wind wherever feasible, while floating foundations are typically used in deeper waters.

In North America, onshore wind is expected to be the primary form of wind power generation through 2050.

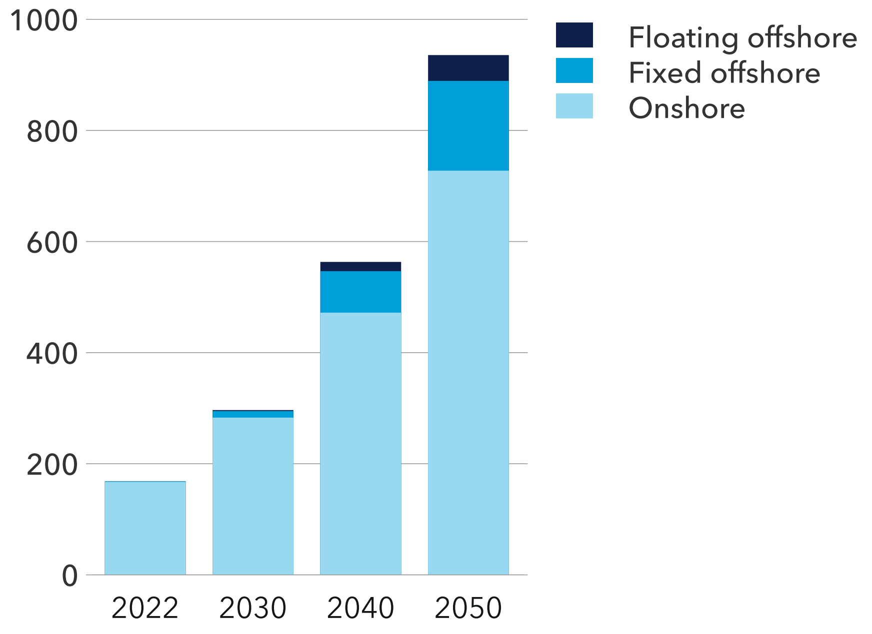
Quite favorable onshore wind regimes, the lower cost of onshore versus offshore, and availability of both public federal and private land with historically limited public opposition, mean that even by mid-century, onshore wind will make up 78% of total wind power (Figure 5.18). Of the remainder, 80% is expected to be fixed-bottom offshore generation, mostly off the US East and Gulf coasts. In total, 940 GW of wind power is forecast to be installed in North America by 2050.

Without national and state-level policy to incentivize offshore wind development, the high relative cost would limit its economic feasibility to only a handful of very specific geographic locations in North America.

FIGURE 5.18

Onshore and offshore wind grid-connected capacity

Units: GW



However, many US states now have offshore wind targets and policy in place which dictates periodic competitions to award an offshore wind development the contractual arrangement to sell power at a relatively high price compared with traditional onshore renewable generators. These state-led offshore wind 'solicitations' have been driving the market for the last five to ten years and will continue to do so into the future until state targets are met.

Choosing between fixed-bottom and floating projects is primarily a function of water depth. For example, apart from Maine and sites very far from shore, the relatively shallow and wide continental shelf along the US East Coast and Gulf of Mexico allows for fixed-bottom designs, while the relatively deep US west coast will potentially require floating ones.

Capacity for wind dedicated to hydrogen electrolysis

In addition to grid-connected wind capacity, DNV forecasts off-grid wind capacity dedicated to hydrogen production by electrolysis. We forecast that almost all this capacity will be either onshore or fixed offshore wind. Given the IRA support (USD 3 / kgH_2) for 'green' hydrogen or hydrogen produced within a low threshold of associated CO_2 emissions, we expect about 6 GW of dedicated onshore and 1 GW of dedicated fixed offshore capacity by 2030. We see this increasing to about 19 GW of onshore and 9 GW of fixed offshore by 2050. We expect the majority of the offshore wind capacity to be placed on the Eastern seaboard of North America, with some of the hydrogen exported to Europe.

Wind-turbine capacity factor development

The capacity factors of wind turbines play an important role in wind power profitability and feasibility. Historically, we have seen considerable growth in the size of wind turbines, initially in terms of rotor diameter and more recently power rating as well. The rapid growth of rotor diameters has supported significantly higher capacity factors. Class III turbines with large rotors have also made some lower-wind sites economically feasible to develop, contributing to a reduction in capacity factor driven by lower wind speeds. Furthermore, consolidation of turbine platforms around machines with larger, more flexible power ratings in more recent years has slowed the capacity factor growth of previous years. That said, the drive among wind original equipment manufacturers (OEMs) to lower levelized cost of energy (LCOE) in recent years has had some consequences on reliability. Many major OEMs have been impacted by quality issues that can be linked to the rapid product development cycle driving LCOE lower, partly through expansion of wind-turbine size.

Hence, DNV expects a slowdown of this LCOE trajectory in coming years, with the focus partly shifting to quality and industrialization to minimize reliability concerns and produce more from existing manufacturing facilities, thus boosting their profitability.

We do expect the capacity factor growth for onshore wind turbines to plateau around 2025. This is due to a combination of factors including turbines with larger power ratings, increasing technical and logistical challenges with larger components, and an overall reduction in average wind speeds in sites being developed. Further increases in capacity factor could be realized if distant load centers can take advantage of the vast wind resources available in areas with low population density through transmission development or energy arbitrage via hydrogen-based molecular energy sources.

Fixed offshore capacity factors are expected to see continuous improvement, even after mid-century, and floating offshore wind capacity factors will overtake fixed offshore in the 2040s due to more favorable wind conditions off the US West Coast.

Without national and state-level policy to incentivize offshore wind development, the high relative cost would limit its feasibility in North America.

Levelized cost of electricity

Figure 5.19 presents the dynamics of LCOE for onshore and fixed offshore wind in North America at final investment decision (FID) years. The LCOEs are for new wind power coming online. At a regional level, DNV has seen the LCOE of wind increase in 2022, countering the trend of continuous declines in the previous decade.

The effect of cost learning rates on turbine and other component costs led to rapidly decreasing levelized costs for onshore wind in the period from 2012 to 2022. This trajectory was temporarily stalled with increasing costs for turbines and other components due to supply-chain issues, pushing LCOE up in 2022. However, the IRA takes effect from 2023, contributing to the declining LCOE trajectory seen in Figure 5.19, until 2034.

We forecast levelized costs for onshore wind in North America reducing from 5.5 US cents (US¢) per kWh in 2022 to about 3 US¢/kWh in 2030. But the phasing out of IRA support in the early 2030s results in a marginal increase in LCOE from 3 US¢/kWh to 3.5 US¢/kWh in 2034. Over time, we expect the LCOE to reach the 2030 level by the mid-2040s. The cost reductions that are possible start levelling out in the future, also due to reasons explained under capacity factor development. DNV forecasts a stable and slightly decreasing LCOE for onshore wind, around 2.5 to 3 US¢/kWh by mid-century.

It is important to note here that the LCOE trajectories presented are annual LCOE averaged over the entire region. Some individual projects will have lower LCOE over a given year at the timescale of hourly or daily capture prices. These projects will be profitable. Especially given the important role solar is set to play in North America, wind becomes more important in the hours when solar electricity is unavailable. In those periods, wind power will command a premium price.

Figure 5.19 compares the LCOE of onshore and fixed-bottom offshore wind in North America. The cost trajectory of offshore wind does come down rapidly from 2012 to 2022, and the gap in LCOE between onshore and fixed offshore narrows considerably in the same period. However, fixed offshore wind will on average have twice the LCOE of onshore wind even in 2050.

While the turbine costs for both onshore and offshore wind are not significantly different, other fixed engineering costs such as construction and assembly, civil works, and grid-connections costs are considerably higher. While these do also reduce due to learning and volume effects and capacity factor improvements in fixed offshore sites, they do not completely compensate for the LCOE differential between onshore and fixed offshore.

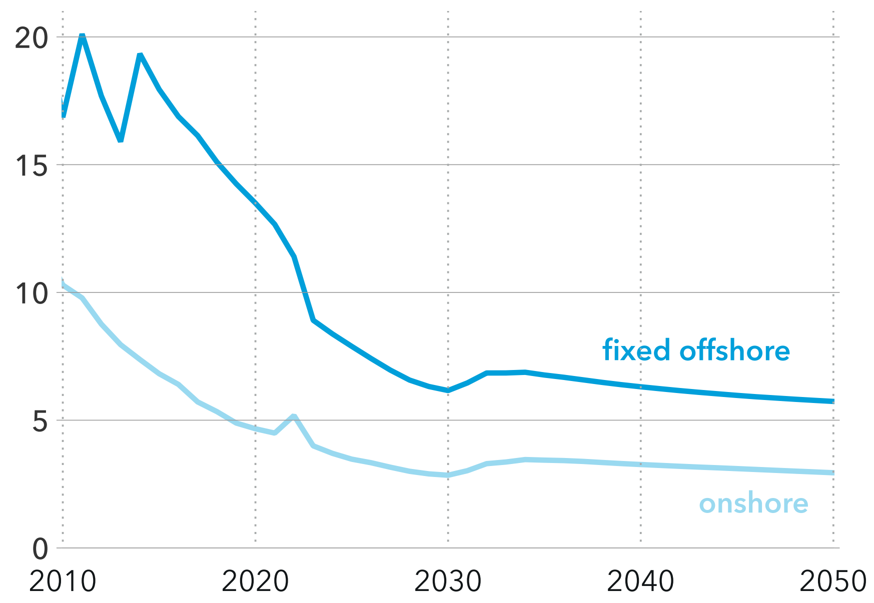
Nevertheless, where demand centers are close to the coast, such as US East Coast cities, there are offshore wind sites that would be profitable since land is either not easily available or is prohibitively expensive, with local ordinances/regulations against siting onshore wind farms close to these cities. In such cases, these states are also willing to pay a premium for clean energy. This makes such offshore wind projects even more desirable.

Figure 5.20 compares the LCOE for floating and fixed offshore wind. Floating structures are 3.5 to 4 times more costly than fixed structures, and also had twice the grid-connection cost in 2022. This results in the LCOE of floating offshore wind being about 4 times as high as that of fixed offshore wind. While this gap narrows rapidly with powerful cost learning and volume effects, even in 2050 there is a 30% cost difference between the two.

FIGURE 5.19

Onshore and fixed offshore wind levelized cost of energy

Units: US ¢/kWh



Historical data source: Global Data (2023)

FIGURE 5.20

Offshore wind levelized cost of energy, by technology

Units: US ¢/kWh

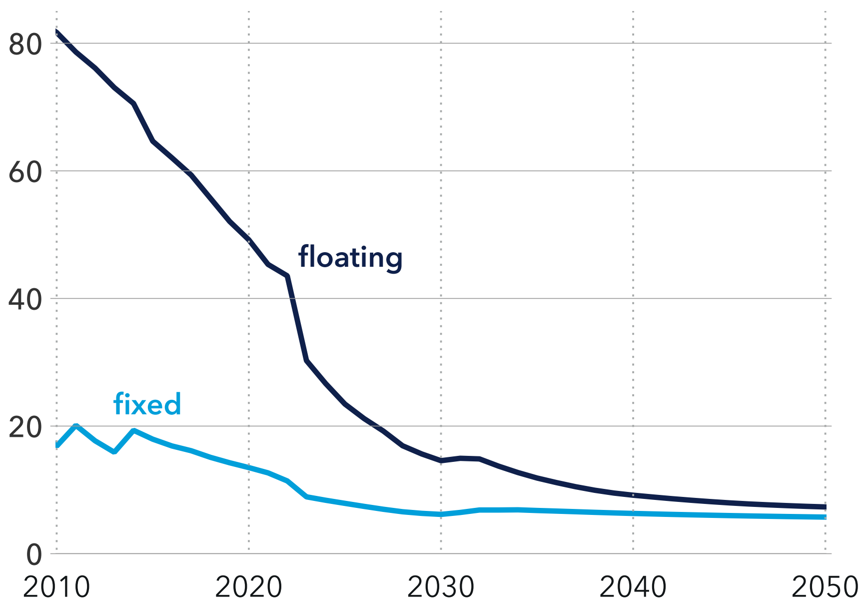



Photo: Stefanie Bourne

Challenges for wind power

Short-term cost increases
In the short term, persistently high inflation, and consequently high interest rates and cost of equity and debt, higher prices of steel and wind turbine components, and increasingly low margins for OEMs have led to challenging times for wind power in North America and globally. The IRA support in the US mitigates the impacts somewhat starting from 2023. However, these inflationary and cost pressures do shift the cost trajectories further out in time, delaying the expected cost reductions and thus reducing the attraction of investing in wind power projects.

The IRA incentivizes local manufacturing of turbines and other components, and nudges hiring policy towards local labor through the incentives. Due to these added incentives, there is movement towards local production, with manufacturing supply chains moving to North America. While in the long term these incentives will end up driving down the cost of wind power, especially offshore wind, they may in the short term add to temporary cost increases as more and more projects get built.

Transmission and interconnection line buildout
Some of the best wind resources on the continent (both land and sea) are in remote locations with low population and energy demand. These regions have long been 'locked' with no means to move potential green energy to areas of high demand. Recent legislation such as the US Infrastructure Investment and Jobs Act (IIJA) and the IRA have spurred momentum on long-distance transmission (including HVDC) as well as production of green hydrogen and its derivatives. For example, our forecast shows that the offshore wind development will need about 9,500 km of HVDC undersea transmission cables by mid-century.

The feasibility of long-distance transmission lines built, or interconnecting these projects, faces many fiscal and regulatory hurdles. There are instances of wind projects waiting for several years in interconnection queues (LBNL, 2023a). There can also be multi-year environmental review processes for inter-state transmission lines as states negotiate over who pays what for the clean wind energy and getting it to where it will be used.

Opposition to wind
While in the past two decades there has been some opposition to the siting and operation of wind power plants, this has intensified in recent years, whether justified or not. There are different kinds of opposition to wind:

- State or county level opposition – some counties restrict projects as they could be considered a safety threat to land users and/or because of limited land availability (Eisenson, 2023).
- Bad faith protests – some opponents wrongfully attribute environmental calamities to offshore wind; for example, a group protesting offshore wind in New Jersey, US, have claimed it kills whales (NJ, 2023).
- NIMBYism – (Not In My Back Yard) there is evidence that residents are amenable to the idea of wind power as long as it comes from somewhere else (Smith and Klick, 2007).

Leading wind power players are attaching high strategic importance to demonstrating viable co-existence with other industries (particularly offshore) and to demonstrating minimal environmental impact (DNV, 2022c and Energy Monitor, 2022). Such efforts are critical in competitive auctions where these criteria carry weight. But the decisive factor appears to be early, extensive, and meaningful stakeholder engagement by wind developers.

5.6 NUCLEAR

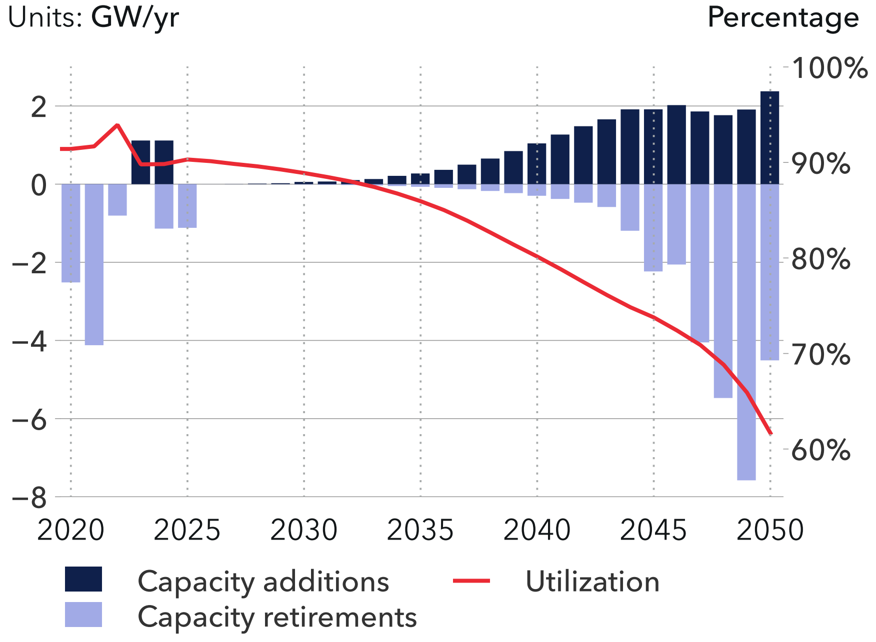
In 2057, nuclear energy will celebrate its centenary as a source of electricity in North America. In the intervening years from the present until then, however, nuclear generated power is unlikely to experience a resurgence. Crowded out by much cheaper renewable sources of power, electricity from nuclear power is likely to decline by one third by 2050, even though small modular reactors (SMRs) will start to enter commercialization during our forecasting period.

North America has added only two new nuclear plants since 1996, one in 2016 and again in 2023 with the Vogtle plant in Georgia coming online. With its addition, the region's nuclear capacity now matches Europe's, the world's largest. As of 2022, nuclear power generated approximately 17% of North America's electricity, accounting for about 7% of its grid-connected power capacity. Most of the region's nuclear reactors are aging, with an average age of over 40 years (IAEA, 2023). The Infrastructure Investment and Jobs Act (IIJA) from 2021 (see Chapter 2) included a USD 6bn program to provide grants to nuclear reactor owners or operators and stave off closing them (US DOE, 2021). However, even with the program in place, many existing plants will reach end of life before 2050.

New capacity coming online will only partially make up for those plants being retired. We expect capacity to rise from 105 GW today to peak at 110 GW in 2045 then decline slightly to 97 GW in 2050. Many of the new plants being built are expected to be of the Small Modular Reactor type (see factbox). Starting from around 2030, they will account for around 2 GW of annual capacity additions by 2045 (Figure 5.21).

FIGURE 5.21

Nuclear additions and retirements in GW (left axis) utilization in percentage (right axis)



Historical data source: World Nuclear Association (2023)

North America has the world's highest nuclear fleet utilization, with a capacity factor over 90%. Its nuclear fleet is thus operating for 1,400 hours more per year than Europe's fleet running at a capacity factor of about 75%. Going forward, utilization will be challenged by the 60-180 GW/yr of renewable energy capacity that North America will add over the next 30 years. Large-scale solar PV and wind will be the cheapest forms of electricity generation throughout many hours of the year, forcing nuclear and other power plants to reduce operating hours. Initially, this will have only a marginal effect; but by 2040, the capacity factor becomes 80%, and by 2050, the nuclear fleet is likely to operate only 60% of the time (Figure 5.21). Thus, annual electricity generation from nuclear will decline from more than 800 TWh today to 530 TWh in 2050, affecting the cost per TWh.

Overall, nuclear will remain expensive compared with renewable electricity (including renewable electricity with storage), but we see specific use cases emerging. These include areas that are remote or unsuitable for large-scale renewables deployment; commercial shipping unable to use cheap renewable energy; and, large sources of manufacturing demand, such as steel, cement, and petrochemicals. These industries will need to secure a supply of electricity, combined with heat and possibly hydrogen. In all these use cases, a SMR could support energy supply as a cheaper alternative to hydrogen derivatives, or through flexibly supplying electricity to the grid or factory depending on availability of cheap wind or solar energy. At other times, it could divert to increase its production of hydrogen.

Energy security is less of a concern domestically in both the US and Canada than in many other regions. Hence, North America does not have to consider nuclear to be a factor in national stability and security, and nuclear expansion will mostly be driven by its ability to compete with other energy sources.

Small modular Reactors (SMRs)

Small Modular Reactors (SMRs) are expected to be the technology for which the nuclear industry will find its next major market growth. Especially so in western developed economies such as Europe and North America, where the latest nuclear plants have suffered significant budget and schedule overruns. SMRs are characterized by their scalable nature, reduced capital costs, and potential for expedited deployment. But just like existing nuclear plants, SMRs still need to demonstrate high safety levels and solve non-proliferation and waste-management challenges.

So far, US regulators have approved only one SMR design, by NuScale Power Corporation. But many companies are lining up designs for approval in both the US and Canada, planning construction towards operational start-up around 2030. Companies such as Westinghouse and GE Hitachi are focusing on deploying designs similar to NuScale's water-cooled reactor. Others – for example TerraPower, Terrestrial Energy, and X-energy – are notably pushing the boundaries of SMR technology in the region, using different cooling designs, with more uncertainty on operational start dates.

There are large uncertainties in future construction costs for SMRs. With limited public information, the one company required to report on break-even costs, NuScale, has recently increased estimates from USD 55/MWh in 2020 up to USD 89/MWh in 2022, which includes a USD 30/MWh subsidy in the US Inflation Reduction Act (IEEFA, 2023). With many years still before operation starts, cost hikes and delays are not unlikely based on experience with recent nuclear projects.

While SMRs hold the promise of providing stable, carbon-neutral energy, especially in areas unsuitable for large-scale renewable deployments, their widespread adoption is contingent on numerous factors, including public acceptance, regulatory agility, and economic viability.

Mockup of the upper one third of the NuScale Power Module™. Courtesy of NuScale/Oregon State University/Flickr

5.7 BIOENERGY

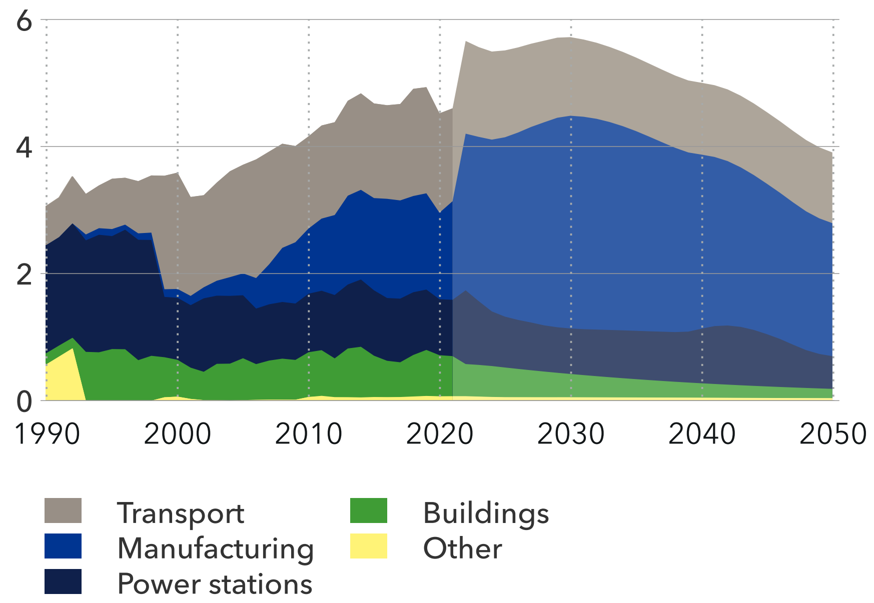
North America has closely tracked the uptake of bioenergy globally, which has seen a near-doubling since 1980. Bioenergy use in North America will continue to grow until 2030, thereafter declining to reach a level by 2050 that resembles today's use.

The main driver behind this rise and fall of bioenergy use in the region is the transition in road transport. As of today, the road transport sector accounts for approximately 99.5% of bioenergy use in North American transport, primarily in the form of blends with traditional gasoline (ethanol) and diesel fuels (biodiesel). The fossil fueled vehicle fleet will continue to grow towards 2030, spurring further growth in bioenergy. But, by 2030, the growing presence of BEVs on North America's roads will start to displace gasoline and diesel demand, and, by extension, biodiesel and ethanol demand as well.

FIGURE 5.22

Bionergy demand by sector

Units: EJ/yr

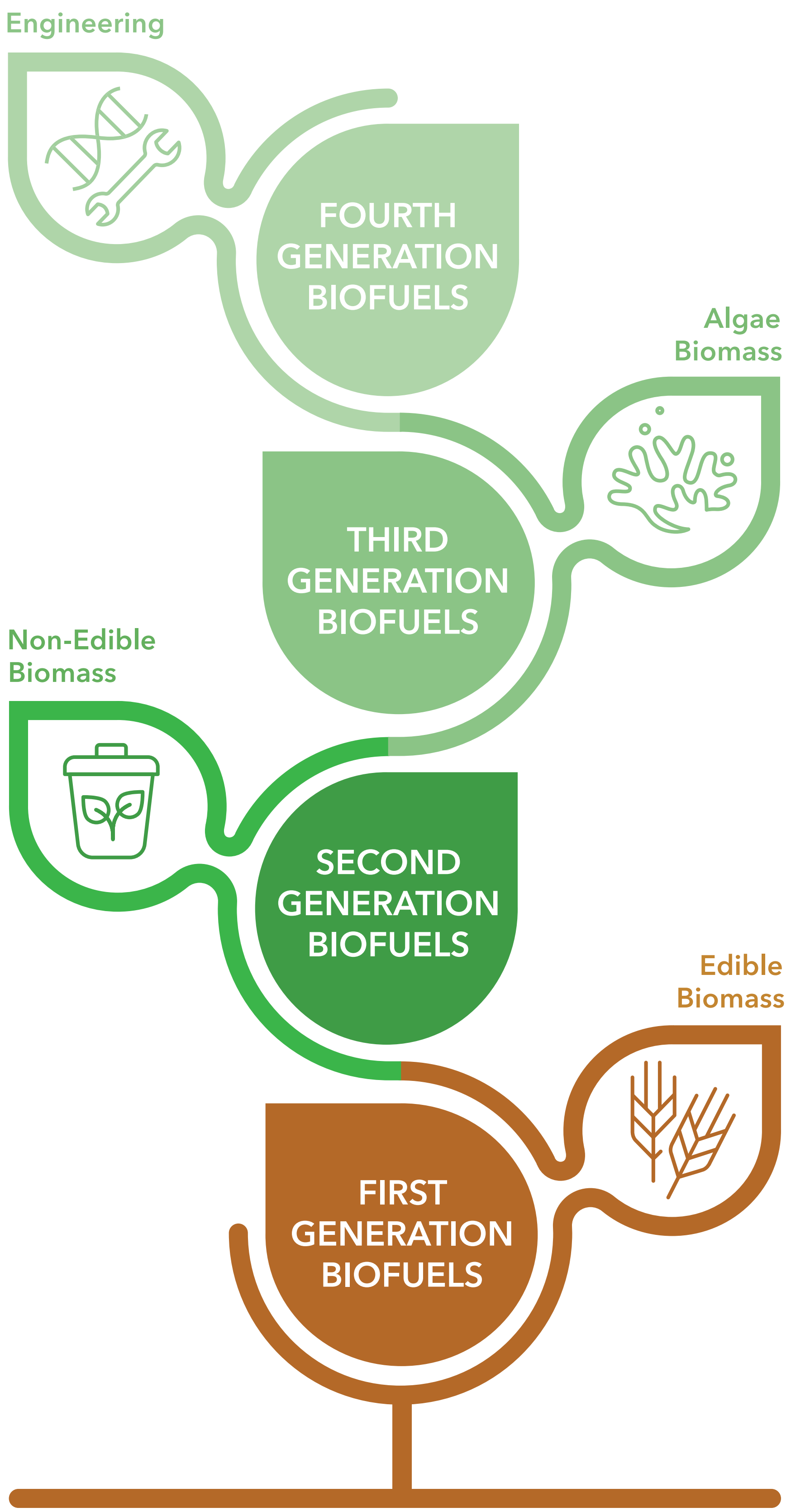


Historical data source: IEA WEB (2023)

But the story for bioenergy does not end there. Biofuel use in aviation in North America will grow from virtually zero today to more than 1 EJ by mid-century. Small shares will also be used in rail transport and likely maritime.

Bioenergy use in buildings will reduce by about two thirds by 2050, mainly due to increased use of heat pumps. Biomass in manufacturing declines slightly over the coming decades despite growth of the sector itself.

In sum, use of biofuels in other demand sectors (except buildings) will not compensate the drop-off in biofuel use in the road transport (Figure 5.22).



Towards sustainable biofuel

Currently, much of the bioenergy used in North America is sourced unsustainably. Crop-based, 'first generation' biofuels are difficult to defend from an overall carbon accounting perspective and are also subject to concerns about land-use changes and biodiversity loss. The future focus is shifting to non-food-based sources (second generation biofuels, derived from biowaste and residues). However, in North America it is market forces – effectively the rise of EVs – that will push first generation biofuel out of the energy mix, although policy changes promoting second-generation biofuel use will play a role, as we discuss below.

IRA`s effect on bioenergy in the US

The IRA introduces a range of strategic measures to support and incentivize the use of sustainable aviation fuel (SAF), clean transportation fuels, and clean hydrogen within the bioenergy sector.

This forward-thinking approach aligns with the evolving priorities of both the European Union (EU) and the United States to significantly bolster the adoption of renewable fuels.

Under the IRA framework, the tax credit for eligible fuels commences at USD 1.25 per gallon. However, the credit has the potential to increase up to USD 1.75 per gallon based on the level of GHG reduction achieved. Further, it includes the establishment of a technology-neutral Clean Fuel Production Tax Credit, designed to provide support to produce low-emission transportation fuel sold during the years 2025, 2026, and 2027. Continuity and support beyond the previous pattern of one- to two-year extensions provides confidence for developers and financiers. In addition, IRA credits are sufficient to cover the costs of carbon capture, utilization and storage (CCUS) for ethanol production from corn to help such ethanol to qualify as a sustainable aviation fuel (SAF) feedstock. This would enable SAF producers to select ethanol over used cooking oils for a more reliable and cheaper feedstock. Organizations are actively scoping the ethanol industry for CCUS as the CO_2 stream from ethanol production has high purity making it a good candidate for this infrastructure.

Prospects for renewable natural gas in North America

Biomethane, also frequently called Renewable natural gas (RNG) in North America, is pipeline-quality gas that can be blended with conventional natural gas and thus piped and used in the same way as natural gas. The majority of RNG projects involve the bio-digestion of agricultural waste and subsequent refining of the biogas to produce biomethane. There is also a growing number of landfill-based RNG projects.

Biomethane from landfills involves very little net gain in emissions reduction because for most large landfills the biogas is already flared to reduce GHG emissions. Even so, landfill gas could still be an important feedstock for SMRs (steam methane reformers) to produce hydrogen which can be used to decarbonize other industries. In contrast, biomethane derived from wet manure can produce GHG savings in excess of 100% compared with alternative manure management. As such, blending 15% RNG sourced for example from dairy farms could potentially achieve net zero for a natural gas pipeline system, and consequently, gas utilities are setting ambitious goals for blending RNG into their pipeline systems. With multiple federal and state programs promoting biomethane, the market is poised for significant growth, as reflected in our forecast. By 2050, Renewable Natural Gas will substitute close to 3% of North Americas methane demand by then.

Renewable natural gas could be an important feedstock for steam methane reformers, to produce hydrogen which can be used to decarbonize industries.

5.8 GEOTHERMAL AND HYDROPOWER

Hydropower has the biggest share (45%) in renewables-based electricity generation in North America today. Its share is 14% in on-grid electricity generation. Geothermal makes up slightly less than 1% of all renewables-based generation in 2022, and less than 0.5% in total generation. Nevertheless, these two renewables will have two very different trajectories in the North American power system, due to climate change, resource depletion, and incentives.

By mid-century, hydropower will generate more or less the same amount of electricity, but its share in electricity generation will fall to about 8% due to crowding out by cheaper and more plentiful solar PV and wind. Geothermal on the other hand sees deployment of capacity and, with it, increasing generation, though its share in generation is still about 1% in 2050. Nevertheless, in terms of capacity, geothermal and hydropower coupled with pumped hydro provide valuable firm capacity.

Geothermal

The US currently has the highest installed capacity (4 GW) of geothermal energy in the world. Aided by the IRA's technology-agnostic Clean Energy PTC and ITC, we forecast an uptick in the installed capacity of geothermal from now until the 2040s, reaching about 20 GW in the US and Canada by mid-century.

Natural geothermal energy systems need three key components: heat, fluid, and rock permeability. There are only a handful of countries, the US among them, where all three are present. Thus, natural geothermal energy is very much site-dependent.

Of late, there have been breakthroughs where the absence of one of the three components is not a showstopper for harnessing geothermal energy. Enhanced geothermal systems (EGS) is one such energy harnessing process, where even in sites with viable heat and fluid and no rock permeability, fluid is injected deep into wells to fracture the rock and create permeability, thus allowing heat to be converted to electricity. In Nevada, such an EGS system was recently scaled to a commercial pilot plant that has a commercial offtake agreement with a data center (Bloomberg, 2023b).

Another emerging geothermal technology is advanced geothermal system or closed loop geothermal, where water or other fluids flow through pipe systems engineered for the specific area instead of through subterranean rocks (CleanTechnica, 2023). This technology potentially makes geothermal technically feasible almost anywhere. Even if electric power is not economically viable, low-grade heat provision through geothermal systems, especially at the neighborhood/block scale, has potential for future development.

Geothermal systems are presently niche and geography dependent. But given the IRA incentives, more states adopting clean energy targets, and dedicated commercial offtake agreements, geothermal will have a role to play in the North American energy system. However, there is uncertainty regarding its potential role, due to regulatory barriers such as lengthy delays in site permitting and environmental review, which oil fields do not suffer from (BCG, 2023).

Hydropower

The total installed capacity of hydropower in North America today is 184 GW, 100 GW of which is in the US and the remaining in Canada. Given the size of the installed capacity base in both the countries, hydropower plays a much bigger role in electricity generation in Canada. Our forecast sees this installed capacity in North America increasing only marginally to about 200 GW by 2033 and thereafter staying constant in the region.

The main reason for the lack of capacity additions is that most of the viable hydropower resources have already been developed in both countries. While some small megawatt-scale plants may come up, given the changing climate and more drought and dry conditions, hydropower will not be significantly developed in the future in North America.

5.9 ENERGY EFFICIENCY

Doubling electrification and energy amplifying technologies such as heat pumps see useful energy demand overtaking final energy demand by 2043 in North America.

Energy-efficiency trends

In the years to 2050 from now, GDP per capita will rise by around 30% in the US and Canada. Higher output per person would historically have been accompanied by greater energy use. But that is not the case for the next three decade where overall primary energy use will fall by 20%. This dramatic switch in the energy intensity of the North American economy illustrates the power of energy efficiency, which in turn will be driven – as we discuss in this section – primarily by much higher levels of renewables-based electrification.

The future dynamics of our energy panorama are significantly influenced by the patterns and determining factors of energy use. Figure 5.23 illustrates the historical and projected progressions in North America's primary, final, and useful energy consumption.

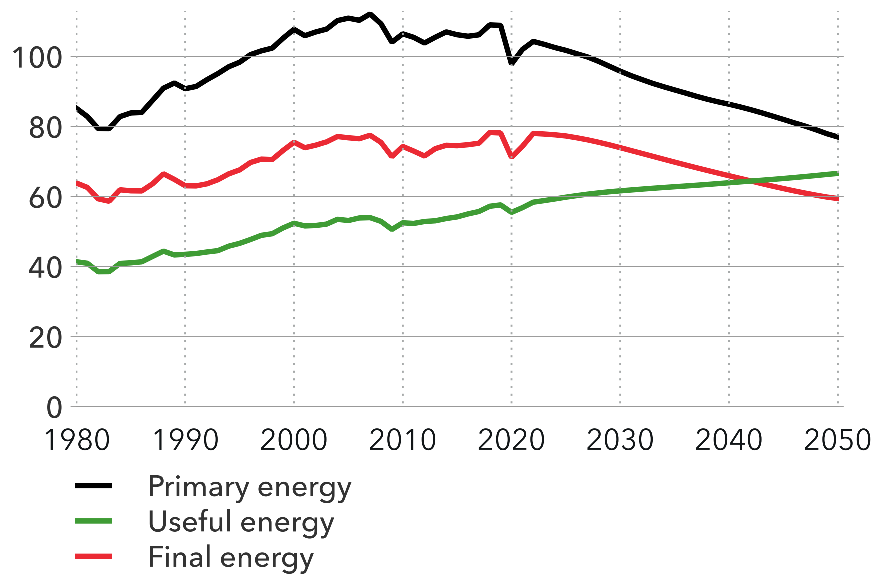
Useful energy is synonymous with tangible services procured from energy sources – light, heat, and transportation – and operating various appliances and machinery. We are witnessing a shift in energy consumption across sectors such as transport, buildings, and manufacturing. This shift is indicative of our perpetual progression toward greater energy efficiency.

However, discussing the nuances of energy would be incomplete without delving into the concept of 'final' and 'primary' energy. The energy directly consumed by end users is defined as 'final energy', whereas 'primary energy' designates the original, unrefined form of energy, pre-conversion or transformation. While certain energy sources like fossil fuels and bioenergy lend themselves to direct final consumption, albeit with a majority conversion loss, secondary energy forms such as electricity and hydrogen necessitate a transformation process from primary energy, which could be sourced from either fossil or renewable resources.

FIGURE 5.23

Energy consumption 1980-2050

Units: EJ/yr



Historical data for primary and final energy: IEA (2023)
Useful energy estimated by DNV

The efficiency of energy used by engines, motors, or appliances is determined by the conversion ratio of final to useful energy. A high ratio indicates efficient conversion, while a low ratio signals energy waste during the conversion process. For example, an EV typically has an efficiency of over 90%, while a similar sized internal combustion vehicle will usually have a tank-to-wheel efficiency of 25 to 35%. Interestingly, there is an intriguing anomaly – devices such as heat pumps, which can 'amplify' the input energy into a greater output of useful energy by extracting ambient environmental energy, can potentially drive this ratio beyond 100%. Rising heat pump adoption for air conditioning and space heating will likely tip the balance, making useful energy consumption greater than final energy by the 2040s in North America.

Strategies targeted at decreasing the demand for energy services, like insulating buildings or levying congestion charges on vehicles, act not by enhancing the ratio of final to useful energy, but by curbing useful energy consumption, or by eliminating the need for useful energy.

Historically, conventional electricity generation from sources such as coal, gas, and oil bore the brunt of inefficiencies, squandering a significant slice of primary energy as heat. In stark contrast, the migration toward renewable sources, predominantly solar PV and wind, has ushered in a new era of dramatically improved efficiency levels. Since all captured energy is directly converted into electricity without heat loss, solar and wind power generation are considered virtually 100% efficient in terms of energy accounting as their electricity is considered a form of primary energy.

This renewable revolution magnifies the final to primary energy ratio, implying a more effective use of raw energy to fulfill our needs. In the past two decades, while 80% of final energy consumption was attributed to the direct use of fossil fuels and bioenergy, a meager 20% came from electricity, which is susceptible to conversion losses. However, with the projected rise of electricity's share to over 40% by 2050, the continued increase in the final to primary energy consumption ratio hinges on the increased share of renewables. This trend is being spurred by breakthroughs in renewable energy technology; declining costs; policies such as the IRA in the US and Canada's Clean Energy Tax Credit granting incentives to renewables; and, by a burgeoning awareness that a low-carbon energy transition is necessary for environmental sustainability.

It is worth noting, however, that the energy efficiency of end-use appliances and machinery should not be sidelined. Sustained improvements in this area can inflate the useful to final energy ratio, augmenting the benefits arising from the shift toward renewables. This convergence of structural efficiency enhancements and electrification holds the key to achieving substantial future energy-efficiency gains.

Challenges and policies

Energy efficiency is often hailed as 'the first fuel'. This reference is attributed to its potential for reducing the overall energy demand, thereby outpacing the need for additional energy production. Furthermore, energy-efficiency measures typically prove to be the most cost-effective solution over both the investment and asset's lifetime. Amory Lovins (2023), arguably the leading expert on energy efficiency, recently pointed out that energy efficiency has already delivered half the decarbonization achieved globally over the past two decades, and using energy more productively through integrative design could deliver 40% to 70% of future decarbonization.

However, investing in energy efficiency faces various challenges. A lack of upfront financing is a significant hurdle, as the initial cost of energy-efficient technologies can be higher than less-efficient alternatives. There is also the issue of foresight and planning. Energy efficiency often requires a long-term perspective, which may not align with the shorter-term objectives of some stakeholders. The problem of split incentives often arises, particularly in rented properties where the costs and benefits of energy-efficiency investments are not shared equally between landlords and tenants. Finally, the long lifespan of existing energy technology stock often means that it takes years, if not decades, to replace older, less-efficient technologies.

For instance, while new building codes and regulations require adherence to specific local, state, or regional energy-efficiency standards, existing structures are often exempt. As a result, improvements in energy efficiency take as long as the turnover of the building stock, which could span decades because of the patchwork of building codes at various levels of government.

Several solutions can help overcome these barriers. Prioritizing energy efficiency at the design stage can help reduce long-term operating costs and minimize environmental impacts. Financial incentives, such as tax credits for installing insulation or heat pumps and/or utility incentive programs, can encourage homeowners and businesses to retrofit existing properties. Utilities may also offer on-bill financing with a low or zero interest rate.

The IRA is a testament to the growing focus on energy efficiency. The Act commits substantial investments to disadvantaged communities, promoting projects to repurpose retired fossil-fuel infrastructure, employ displaced workers, and ensure a fair and equitable clean-energy transition. The legislation expands upon the IIJA, supporting many projects including EV charging, power infrastructure, and climate resilience. Additional financial provisions, such as expanded production tax credits and investment tax credits for clean-energy manufacturing, further support the US energy industry.

American families are also incentivized under the IRA to reduce their carbon footprint, for e.g. through rebates for heat pumps. Similarly, Canada Greener Homes Grant Initiative has grant reimbursement for homeowners' making efficiency upgrades (Canada.ca, 2023).

The IRA prioritizes the transportation sector. By providing tax credits for electric vehicles, the legislation intends to transform the automotive landscape, with expectations of a significant surge in electric vehicle adoption by 2031.

6 FINANCING THE ENERGY TRANSITION

6 FINANCING THE ENERGY TRANSITION

North America will see seismic shifts in energy expenditure over the next three decades. The fact that investment in solar outstripped fossil thermal power CAPEX in the US in 2022 is a sign of the shift to come.

The good news for the average North American household is that cleaner energy will also mean cheaper. The energy bill of an average North American household was USD 2,600 for the year in 2022. We forecast that this will fall by 12% by 2030, and the benefits of cheap electricity, thanks to solar and wind, will continue to accumulate. While household energy expenditures, such as buying electric heat pumps, will lead to a temporary increase in energy-related spending from 2022 until 2030, by 2050 not only would that bump in expenditures be eliminated, the household energy expenditures would be half of what they are now.

The Inflation Reduction Act (IRA) and the Federal Budget of Canada give cause for measured optimism among a myriad of stakeholders in clean energy due to the 10-year window of certainty it provides. However the prevailing transmission gridlock could hobble the energy transition, unless the opportunity it provides is tackled by North American enterprise and by bold policymaking.

6.1 NORTH AMERICAN ENERGY TRANSITION HEADWINDS AND TAILWINDS

In accordance with the aim of the Paris Agreement, the US and Canada have charted ambitious goals towards cutting greenhouse gas emissions (GHG) from economy-wide sectors, as detailed in Chapter 2. The Biden administration set US goals of achieving a carbon-pollution-free power sector by 2035 and a net-zero emissions economy by 2050. In addition, the IRA was passed to support the furtherance of these goals. Eighteen US states, in conjunction with the District of Columbia and Puerto Rico, have passed 100% clean-energy standard goals; a further eleven states have adopted renewable power standards. Similarly, Canada aims to achieve a 40-45% reduction in emissions compared with 2005 levels by 2030, and net-zero emissions by 2050. It targets 90% of electricity to be generated from zero-emitting sources by 2030, and 100% by 2035.

Finance is a key component for enabling this energy transition. According to some estimates, USD 1.1-1.5 trillion investment in US wind and solar projects alone will be needed to achieve the US power-sector decarbonization goal, with further hundreds of billions required to support a commensurate build out in the transmission system (Princeton University, 2020 & Electric Power Research Institute, 2021). More investment is needed – and quickly. And this must be accompanied by increased rates of clean energy development, expanded global and domestic manufacturing capabilities, and a massive cohort of skilled workers positioned to install and maintain these projects.

Against these lofty goals, the energy transition in North America has recently been buffeted by economic and regulatory challenges on multiple fronts: supply chain snarls, labor scarcity, trade restrictions, inflation, elevated costs of capital, and interconnection gridlock to name but a few. Although the renewable-energy sector has proven to be largely resilient to these challenges – mainly owing to organized industry groups and multiple stakeholders finding enterprising solutions to each of them – their impact has nevertheless been felt. For the first time in more than a decade, the levelized cost of energy (LCOE) of North American solar and wind generation projects increased in 2022.

While deployments of renewable energy projects remained near historic highs, capacity additions fell year-on-year (the US added 32.5 GW of renewable energy capacity in 2022, compared to 37.6 GW in 2021) (BloombergNEF, 2023a). Similarly, overall investments in renewable energy have shrunk from pre-COVID highs; between 2021 to 2022, solar and wind investments reduced by 8% and 25%, respectively (ACORE, 2023).

Tailwinds – cause for measured optimism

Passed in 2022, the IRA is making a substantial impact in 2023 and represents a potential inflection point in unlocking new sources of financing for renewable energy. Canada responded in echo: Budget 2023 (Department of Finance Canada, 2023) will provide billions of dollars of tax benefits for clean energy projects over the next decade. New regulatory disclosure requirements that have been adopted or proposed by the European Union, Canada, US, and the wider global community will align investments with domestic and global climate goals while simultaneously providing the impetus for long-term climate-risk management. Large corporates, as well as residential customers, have continued to demand more renewable energy, with 2022 being a record year for both corporate offtake agreements (BloombergNEF, 2023b) and residential solar installations (SEIA/Wood Mackenzie, 2023). Uncertainty in both international relations and supply chains, coupled with the IRA's bonus incentives allotted for projects with sufficient equipment manufactured within the US (domestic content), is spurring more interest in North American manufacturing and also driving LNG exports to new heights. Together, these trends point towards a historic, coordinated expansion in financing availability, demand for clean energy projects, and a need for a larger enabling workforce with a resilient supply chain to match.

Expanded long-term incentives and new monetization options

Last year's passage of the IRA in the US and Canada's Budget 2023 provides a long-term measure of certainty compared with previous versions of support. Many analyses reveal that these major policy packages unlock opportunities for historic deployment of clean-energy generation, associated reductions in greenhouse gas emissions (GHG), and support for locally manufactured components that will reduce supply chain and international-trade restriction risks. In addition, they will bring a new cohort of skilled workers into the industry.

Inflation Reduction Act

The IRA makes considerable investments into the energy transition, with a long-term, durable signal to the market. Investment- and production-based tax credits announced via the IRA, linked to actual reductions in GHG emissions, are projected to last into the 2030s (Credit Suisse, 2022). A decade of opportunity provides the certainty that is necessary to attract new sources of finance and give long-term confidence to developers of renewable-energy projects.

Although only indicative, these efforts nevertheless appear to be paying immediate dividends. A 2023 survey conducted by the American Council on Renewable Energy (ACORE), demonstrated that all developers, and the overwhelming majority of investors, plan to increase their activities and investments in the US renewable-energy sector compared with 2022 (ACORE, 2023). A similar overwhelming

Photo by Drew Angerer, Getty Images

majority of the investors surveyed expected the attractiveness of renewable-energy investments to moderately or significantly increase compared with other potential asset classes in their portfolios over the near term (ACORE, 2023).

According to four independent analyses regarding IRA's potential impacts within the US, its provisions may result in 65-95 GW of annual new-build utility-scale wind and solar (almost three times previous record deployments) and 1.2-1.7 million additional jobs by 2030 (Energy Innovation Policy & Technology, 2022). The stand-alone storage investment tax credit, coupled with a recent Federal Energy Regulatory Commission (FERC) ruling that modifies how transmission owners consider storage, is poised to expand the US battery energy-storage market significantly (FERC, 2023a).

In order to meet the unprecedented demand unlocked by the IRA, the tax equity market must increase by two-and-a-half times, from approximately USD 20bn per year to over USD 50bn per year (ACORE, 2023).

Tax credit transferability and direct-pay options provide a new pathway for financiers to enter the US market. Both investors and developers expect transferability to play an outsized role in the market. However, the impact of transferability is uncertain; the associated tax mechanisms are complicated for new entrants, and transferred tax credit beneficiaries are unable to claim accelerated depreciation (unlike traditional tax equity). Indeed, the IRA is likely to expand the number of tax equity players as large corporates and other sophisticated entities rush to take advantage of lucrative incentives and opportunities to demonstrate sustainability bona fides. It remains to be seen how these dynamics will play out over the coming years.

Direct investments in advanced domestic manufacturing (Advanced Energy Project Credit, Advanced Energy Manufacturing Credit) coupled with domestic content bonuses for investment tax credits (ITCs) and production tax credits (PTCs) will provide a significant boost to the availability of US-manufactured components. Although LCOE impacts are likely to be net neutral over the next five years, we anticipate that expanded manufacturing will improve supply-chain uncertainties. Large renewable energy developers and operators are likely to integrate vertically. According to ACORE, 39% of developers plan either to open, or invest in, domestic manufacturing plants (ACORE, 2023).

Budget 2023

The recently published Budget 2023 expands Canada's commitment to the energy transition. Like the IRA, Budget 2023 provides long-term (through to 2034), predictable tax incentives to zero-emission energy projects, clean-technology manufacturing, clean hydrogen, and carbon capture and storage (CCS). These are coupled with targeted incentives that aim to ensure a just transition while also expanding the labor force and arming them with the skills necessary to meet increased demand for energy-transition projects (Department of Finance Canada, 2023).

Increased sensitivity to extra-financial impacts of investments

Despite top-down climate-change disclosure regulations being yet to materialize in the US, the impact of climate risk-averse "Environment, Social, and Governance" (ESG) investing practices, ratcheting regulatory pressures, and shifting desires of consumers towards sustainable practices are already driving financiers towards investments in the energy transition. While the US's adoption of climate-risk disclosure requirements faces delays and mounting political pressure, many North American investment managers have bond mandates that are beholden to the European Union's Sustainable Finance Disclosure Regulations and its associated evaluation framework (the EU Taxonomy). Additionally, late last year, Canada's Sustainable Finance Action Council (SFAC) unveiled their Taxonomy Roadmap Report that adapts already developed global taxonomy efforts to Canada's unique economy and culture (SFAC, 2022).

These disclosure frameworks are not merely a regulatory burden. For financiers with "green" or "sustainable" mandates, straightforward taxonomies are a critical tool for evaluating the real climate value of investments with the aid of credible, predictable, science-based analysis methodologies. These frameworks provide long-term value to financiers by arming investment committees with the tools to identify and mitigate asset climate-risk exposure.

The overall impact of ESG disclosure frameworks is to direct sustainable investment activity towards proven, durable solutions to combat climate change.

The IRA's place-based incentive mechanisms add further momentum to energy transition. Lucrative energy equity adders awarded to projects sited within historically underserved or historically fossil-industry focused communities offer compelling signals to developers and to invest in these areas. At the same time, they also support environmental justice and economic development in low-income communities as well as energy communities that historically had high employment rates in the fossil-fuel industry.

Tax transferability is expected to play an outsized role.

Headwinds remain, and volatility is increasing

Despite this confluence of public and private support unlocking tremendous opportunities, macro-level trends in project development, power delivery, supply chains, and insurance will all challenge the clean energy industry's growth potential.

– **Interconnection hurdles and uncertainty:** A key component of project feasibility is interconnection. Projects seeking to connect to the electric grid undergo a multi-phase study process that analyzes potential grid impacts and ultimately determines which new transmission equipment or system upgrades are required before a project can be built. This study process may take years. According to a series of studies published by Lawrence Berkeley National Laboratory, over 2,000 GW of total generation and storage capacity are locked in this interconnection study process (LBNL, 2022-2023). Study timelines have ballooned, rising from an average of three years in 2015 to five years today, with some markets reaching a seven-year backlog. The Federal Energy Regulatory Commission (FERC) recently issued a final ruling with many reforms (cluster studies, strict timeline requirements, guidelines to consider the impact of storage projects on grid reliability) which aim to alleviate interconnection timelines. As detailed in Section 4.3 on grids, we look forward to evaluating the ongoing impact of these reforms, in conjunction with developers, financiers, and industry partners.

– **Transmission constraints:** As the electrons flowing through our electric grids are increasingly generated by intermittent, distributed technologies like wind and solar, balancing the demand and supply for electricity is becoming more complex. According to a recent study conducted by Energy Innovation Policy & Technology, unlocking the full benefits of the IRA will require the historic pace of transmission development in the US to double (Energy Innovation Policy & Technology, 2022). This aligns well with DNV's forecast, as observed in the section on grids of this publication. Transmission development is a tortured process. On average, siting and permitting alone require seven years for approval. Lack of inter-regional transmission planning coordination has also slowed development. While there are recent causes for optimism – FERC's recent ruling introduced inter-regional planning requirements – the IRA did not allocate funds commensurate with transmission's importance. Until transmission receives enhanced support, financiers must consider uncertainties in project cost (interconnection upgrades), transmission congestion, and generation curtailment that may suppress investment returns.

– **Strained supply chain:** While the worst COVID-induced supply-chain constraints have now largely been alleviated, procurement still poses elevated risks to clean-energy deployment. Heightened international tensions and commendable commitments to supply-chain traceability and human rights may reduce the suite of options available to project developers. Domestic manufacturing will take years to ramp up and provide an alternative for a large percentage of the growing need.

– **Long term insurability challenges:** During the summer of 2023 climate instability touched nearly every corner of North America, introducing elevated risks and increased public acknowledgement of extreme weather hazards. Insurers pulling out from the California and Florida residential markets is concerning for renewables as it indicates a shrinking appetite to insure against risks associated with a changing climate. The industry will be challenged to accurately identify risks while developing and demonstrating enhanced mitigations to protect projects against acute, extreme weather events – and to clearly articulate these benefits to insurers. The emerging climate vulnerability risk assessment field, driven by global sustainability taxonomies, is shedding new light on these long-term risks and driving towards solutions.

– **Potential for policy reversals:** Despite verifiable climate and economic benefits to communities throughout North America, programs of sufficient scale to address North America's emissions footprint have generated anxiety – and some controversy – regarding a transition away from legacy power generation. Within the US, Texas's defunct Senate Bill 624 is an early example of efforts to hinder solar and wind development. Twenty US states have adopted some form of "anti-ESG" rules, restricting the ability for public investments to consider ESG risks, including acute risks associated with climate change. The Heritage Foundation Project 2025's "Mandate for Leadership: The Conservative Promise" proposal aims to unwind the energy transition and has found a receptive audience in Republican presidential hopefuls. In Canada, Alberta's conservative government recently announced a temporary moratorium on regulatory approval for new renewable-energy projects as a bargaining chip with the federal government on implementation of federal carbon-pricing regulations (Government of Alberta, 2023). Although the LCOE for unsubsidized utility-scale solar, wind, and storage are already often less expensive than conventional generation (Lazard, 2023), such policy reversals could slow project deployments.

Summary

Supply chain and macroeconomic factors from the depths of COVID lockdowns are improving. Developers and financiers in the US have largely adapted to procurement hurdles introduced by supply-chain traceability legislation. In this interim period between COVID-induced delays and storm clouds gathering on the medium-term horizon, it may be tempting for the risk averse to discount recent shifts in support of the energy transition.

Policy, regulatory, technological, and economic spillover effects are washing over the US and Canada in tandem. There is a confluence of funds and forces: easing of international macroeconomic logjams; long-term incentives offered by the IRA and Budget 2023 driving global financiers towards North America; ESG investment disclosure requirements ensuring investments are disproportionately targeted in support of the energy transition; and compelling benefits to local communities that have been historically marginalized, or fossil-fuel focused, ensuring a just energy transition.

Taken together, these developments are fueling a virtuous cycle that promises to drive the energy transition to unprecedented heights over the coming decade. However, there are challenges ahead, as detailed in the discussion on headwinds above. Nevertheless, drivers of the energy transition have proven themselves to be nothing if not innovative, resilient, and capable.

We find ourselves collectively at a historic inflection point. Despite the near-term challenges and opportunities ahead, we are still taking our first steps in a long journey towards decarbonization.

The confluence of headwinds and tailwinds influencing the energy transition will have far-reaching consequences for US and Canada in the medium- to long-term future. As this forecast reveals, the region can expect an unprecedented energy transition through to mid-century. But despite this transition, the region is likely to fall short of achieving the levels of decarbonization that are required to secure the 1.5-degree future envisioned by the Paris Agreement.

There are challenges ahead. Nevertheless, drivers of the energy transition have proven themselves to be innovative, resilient, and capable.

6.2 EVOLUTION OF COST OF CAPITAL

An important decision-making factor in our ETO model, and which underpins this most likely forecast for North America, is cost. The investment decisions in most of the sectors in our model are primarily made on the basis of LCOE. One parameter that determines this levelized cost is the cost of capital (CoC).

In the real world, CoC is one of the key cost drivers for capital-intensive purposes; for example, new power generation projects, investment in power grids and gas infrastructure, equipment in buildings, and infrastructure for zero-emission vehicles. We use levelized costs to compare competing technologies, where the ratio of lifetime costs to lifetime generation (e.g., electricity or hydrogen production) is discounted back to a common year using a discount rate that reflects the CoC. With lower discount rates, the break-even price that satisfies equity and debt returns is reduced. Hence, predicting the competitiveness of, for example, competing power-generation technologies now and in the future requires accurate CoC predictions. We therefore continue to focus on the granularity of the different CoC inputs for the different energy technologies.

To forecast the CoC development toward 2050, DNV makes assumptions about today's cost of capital per technology category, and about the speed and direction of capital allocation up to 2050.

In the short term, the inflationary pressure on interest rates is reflected in our CoC predictions. The increased policy rates in 2022 and 2023, in both the US and Canada, have increased the cost of borrowing (or debt) and thus the CoC. However, the impact of the increased cost of borrowing does not have a uniform effect on technologies, not least because the debt-to-equity ratio is different for technologies at different stages of their product life cycle. Mature technologies typically have more debt financing than equity financing, and hence the increase in CoC will be higher than for less mature technologies that generally have more equity financing. Nevertheless, there is a short-lived impact on the CoC associated with all energy technologies in North America.

In the long term, our CoC should accurately reflect the impact of debt and equity costs on intra-technology competition and the opportunity cost and risk associated with the investment choice. Ultimately, our forecast is mostly dependent on CoC levels varying between the different technology categories.

ETO cost of capital categories

We categorize our inputs under two major categories of technologies: mature and emerging technologies.

Mature technologies may then be further considered under the following groups:

- Oil and gas upstream, midstream, downstream technologies - including grey and brown hydrogen and gas and oil-fired power generation.
- Coal-fired power generation and production
- Mature renewable technologies; solar and solar + storage, onshore and bottom-fixed offshore wind, biomass, hydropower
- Nuclear power

Emerging technologies, often targets of energy transition funds, are:

- Floating offshore wind,
- Grid-connected and dedicated electrolyzer-based hydrogen.
- Production of green ammonia, e-fuels, and SAF
- Geothermal power

Figure 6.1 presents the CoC for energy technologies assumed in ETO for North America. For all technologies, a short-term increase in CoC from 2022 to 2023, due to inflation, can be seen. For both emerging and mature renewables and nuclear, following the temporary increase in CoC in 2023, the CoC levels are predicted to decrease towards 2050, with the perception of risk reducing. The opposite trend is forecast for fossil fuels.

Mature renewables

In the short term, the increase in risk-free rate is due to rises in steering rates by federal reserve/central banks. This also elevates the CoC. As mature renewables have a higher debt-to-equity ratio, the increase in CoC, from 2022 to 2023, is 1%, which is in contrast to that of emerging renewables. Following the public forecasts on policy rates by the federal reserve/central banks, we predict an inflationary impact until 2025 that then tapers off in 2030. Our forecast assumes that the CoC for these technologies will reach 5% by 2030 and then stay constant until mid-century. Compared with any other category of technology, mature renewables have the lowest CoC in 2022 at 5.5%

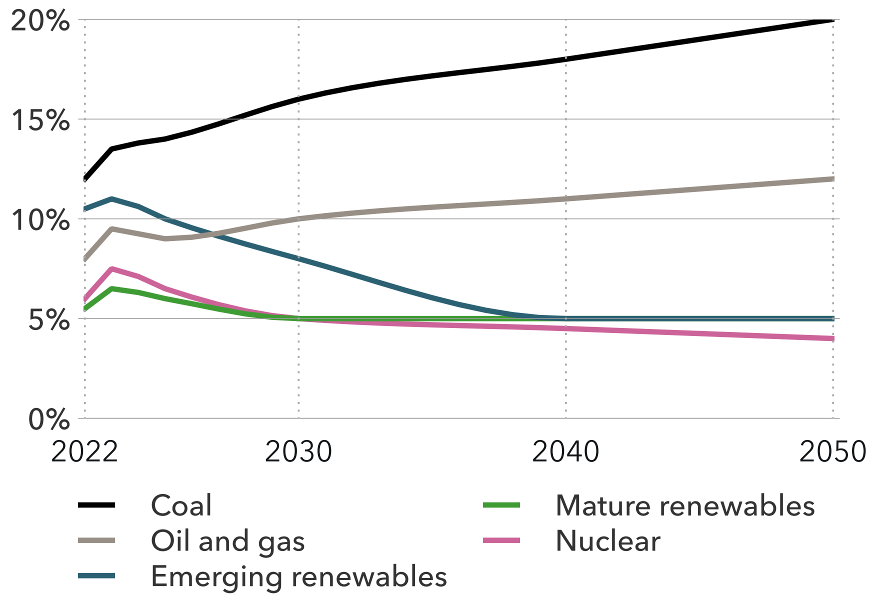
Emerging renewables

Unlike mature renewables, emerging renewables have a higher risk premium, and hence their average CoC is 10.5% in 2022.

FIGURE 6.1

Cost of capital for energy technologies

Units: Percentages



Nevertheless, since they rely on equity financing, rather than debt financing, their inflation-based increase from 2022 to 2023 is only 0.5%. From 2023, the CoC for these technologies gradually decreases and we expect them to mature and attain parity with mature renewables by 2040.

Oil and Gas

We expected that oil and gas would have a lower CoC in 2022 than emerging renewables in North America, mostly because it was still perceived as less risky than emerging renewables. Successive administrations have not been opposed to selling licenses for new oil and gas development, and we also expect considerable staying power for natural gas infrastructure. This is also recognized by the financial markets. Additionally, LNG exports to Europe are likely to increase in the short- to medium-term. However, we also expect the CoC to slowly increase for oil and gas, becoming higher than that of emerging renewables by 2028. The CoC for oil and gas is forecast to increase from 8% in 2022 to 12% by 2050.

Coal

Investors already perceive coal as being a significantly higher risk than other fossil-fuels or renewable energy projects, as evidenced by a clear increase in loan spreads over the past decade. We expect a rapid upward trend in CoC due to reduced availability of capital. We forecast the CoC for coal to increase from 12% in 2022 to 20% by 2050.

Nuclear

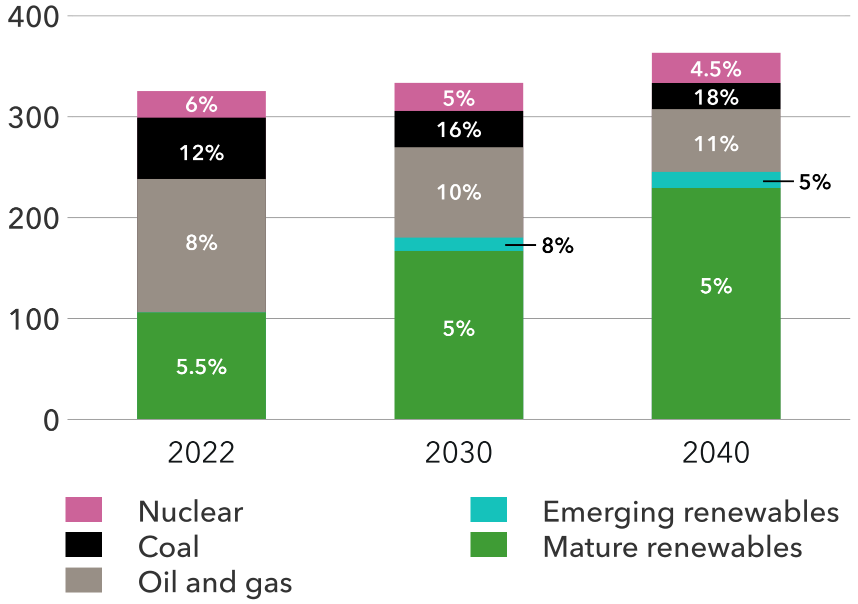
We expect the nuclear-power CoC to be low, stable, and to reduce slightly over time, supported by the expectation that the market will increasingly move towards becoming low-risk, and returns will be regulated. The CoC for nuclear is forecast to decrease from 6% in 2022 to 4% by 2050. Additionally, part of the funding in nuclear investments is also public. This is due to the nature of nuclear technology and associated concerns of safety, thus securing lower CoC.

Figure 6.2 presents the spread of expenditures in power in selected years based on the CoC technology categories. As expected, we see that those categories whose CoC is expected to reduce over time, such as mature and emerging renewables, will begin crowding out coal and oil and gas expenditures.

FIGURE 6.2

Expenditure spread of power sector and cost of capital

Units: billion USD/yr



Percentages show cost of capital for the technology

Cost of capital inputs to the ETO

CoC is largely determined by two cost variables, and the ratio between them:

- The cost of debt: i.e., the combination of the risk-free rate and the risk premium (or 'margin'), together often referred to as borrowing costs
- The cost of equity: i.e., the equity return required by investors
- The ratio between cost of debt and cost of equity, above; i.e. the 'leverage'

The main driver for these variables is risk perception

For example, a greenfield coal-fired power plant project in North America would have been less risky, with a final investment decision, in 2002, than such a project coming online in 2022. Given the decarbonization plans of both the US and Canada, such a project would risk being left with stranded assets should it begin operations in 2025. Thus, financial debtors of such a project would be taking on more risk, driving up the cost of debt, in 2022 than two decades earlier.

In contrast, financing green-hydrogen production, for example, would be perceived as riskier today than in 2040, by which time the technology is likely to have matured and been proven in both production and end-use sectors. In addition, by then the market for green hydrogen would be mature, and this would result in less risk, cheaper borrowing costs, lower equity-return requirements from investors, and higher leverage, all driving down the cost of capital.

These two examples above illustrate both the difficulty of setting assumptions on the CoC and also the dynamic nature of CoC.

Photo by Werner Slocum, NREL

6.3 ENERGY EXPENDITURES

In this section, we show how much money is predicted to flow between the different sectors of the North American energy system.

This knowledge is important for various reasons, including:

- To determine the impact of the energy transition in monetary terms, and to understand where finance and capital are being directed.
- To determine how much money is needed in order to reach the most likely future of the North American energy system.
- To understand the relative size and transformation in size of the different energy sectors.

Supply-side energy expenditures
We analyze supply-side energy expenditures of North America under three major categories: fossil expenditures, non-fossil expenditures, and grid expenditures. Expenditures include both capital expenditures (CAPEX) and operational expenditures (OPEX). Fossil expenditures includes coal, oil, and natural gas, while the rest, are classified as non-fossil (inclusive of nuclear). Power grids are treated separately.

In 2022, total energy expenditure was about 4% of North America's GDP. Between 2023 and 2026, energy expenditure in relation to the region's GDP will be higher than in 2022. Owing to increased investments in energy infrastructure, and the expenditures in oil and gas due to elevated production, and supply export demand, expenditures are stable and high until 2030. In the long term, however, GDP growth in the region will outpace the rise in energy expenditures. The fraction of energy expenditure in GDP will reduce to around 2.5% by mid-century (Figure 6.3).

The main reason for energy expenditures declining as a fraction of GDP in our forecast is the transformation that the energy sector is set to undergo in the North American region (Figure 6.3). Based on expenditure, it can be seen that renewables and other low-carbon energy are cheaper to extract, produce, and transmit than fossil-based energy, even without taking into account negative externalities associated with fossil-based energy. Export of oil from North America will fall over time, whereas export of natural gas will stay relatively stable. The cumulative effect will be that export of fossil-based energy will decrease over time, which will also contribute to a reduction in fossil expenditures.

Expenditure definition

There are various descriptions of 'energy expenditure' available, and we have chosen to use a relatively strict definition. We have therefore included only fossil-fuel extraction, transport, and refinement processes, such as liquefaction, regasification, refineries, and conversion to hydrogen and electricity.

Similarly, all costs in the power sector are incorporated (including power grids, storage capacity, and the installation and operation of renewable energy plants). However, we have excluded investments in energy-efficiency measures. In addition, we do not incorporate costs related to end-use spending (in manufacturing, transport, and so on).

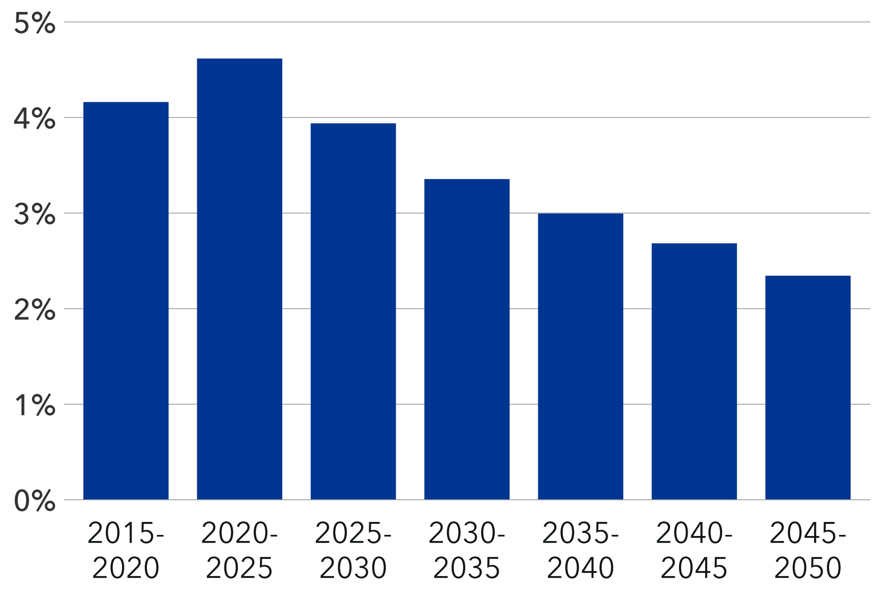
What actually constitutes a subsidy deserves a chapter in its own right, and we have therefore decided to adopt a simplified approach. We have modelled subsidies as support that benefits consumers and are not counted as energy expenditures. Likewise, fuel taxes are not included.

Although the simulated decision making in our model discounts expected future cash flows, in this section we report annual sectoral outlays in terms of CAPEX and OPEX.

In 2022, total energy expenditure was about 4% of North America's GDP. This fraction of energy expenditures will gradually reduce to around 2.5% by mid-century.

FIGURE 6.3
Fraction of energy expenditure in GDP

Units: Percentages



Fossil versus non-fossil expenditures

We estimate that for every dollar spent on non-fossil expenditures in 2022, around 7 dollars were spent on fossil expenditures. Our forecast finds that this ratio will increase to about 9 in 2024, because of the expenditure on natural gas and oil infrastructure, mostly geared towards oil and gas exports filling the vacuum from North East Eurasia. After 2024, this ratio will start declining rapidly, reaching about 5 in 2028, 3.5 in 2032, and almost achieving parity by mid-century.

Although non-fossil expenditures are always lower than fossil expenditures, the picture is starkly different regarding CAPEX alone (Figure 6.4).

As previously mentioned, there will be fossil-fuel capacity additions in the years leading up to 2026. Subsequently, however, fossil-fuel CAPEX will reduce rapidly, with sustained investments into non-fossil energy infrastructure, both in terms of power capacity and, after the 2020s, increasing electrolyzer investments. We foresee non-fossil CAPEX overtaking fossil-fuel CAPEX in North America in the late 2030s.

Oil and gas expenditures

Figure 6.5 shows the expenditures in oil and gas, and how DNV forecasts their changes over time. The power sector that contributes as the largest share of natural-gas demand in North America, will experience a remarkable transition to renewables by 2050, resulting in a relatively large reduction in natural-gas expenditures. Oil demand, however, will continue due to the hard-to-electrify demand segments, such as aviation and maritime. As a consequence, we estimate a greater reduction in expenditures in natural gas from 2022 to 2050 (-41%) than for oil (-24%).

However, a factor that will feed into continued oil and gas expenditures, even into the 2040s, is exports. Despite a gradually decreasing domestic demand, the region will continue to export both oil and gas, and therefore upstream expenditures will be maintained. For example, while domestic consumption of natural gas is predicted to be 1,000 Bn m^3 in 2032, the production is predicted to be 1,300 Bn m^3. This means that upstream activity related to export is continued, and this feeds into the expenditures in natural gas.

Solar and wind expenditures

More than half (56%) of the non-fossil expenditures in North America in 2022 were for solar and wind. This will keep increasing, reaching 58% by 2030 and up to 80% by 2050. In absolute terms, solar expenditures in 2022 were about USD 30bn, and these will increase to USD 147bn by 2050. About 90% of expenditures will be CAPEX. Similarly, wind will grow from USD 43bn in 2022 to USD 124bn by 2050, with about 70% of these wind expenditures being CAPEX.

FIGURE 6.4
Fossil versus non-fossil CAPEX

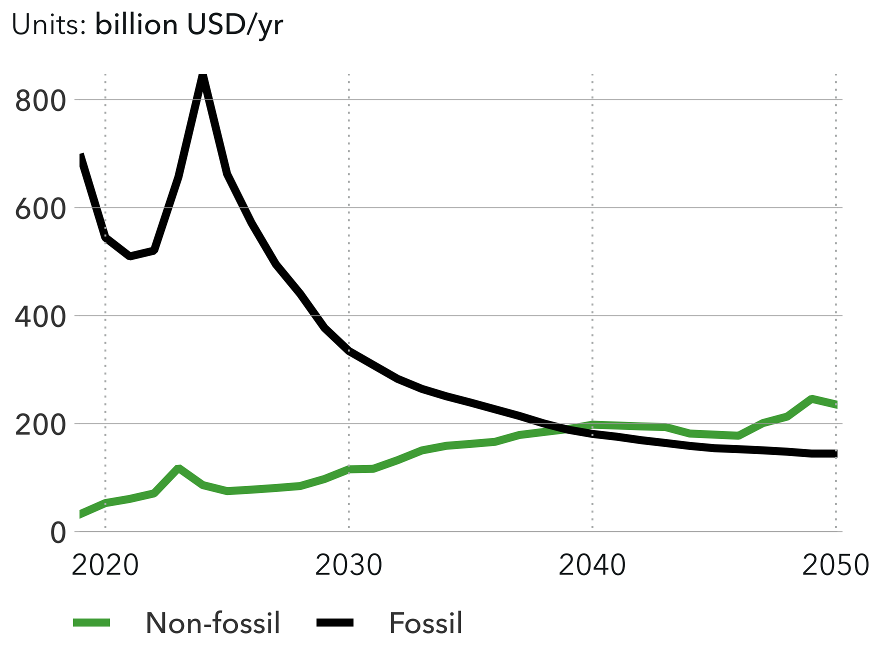
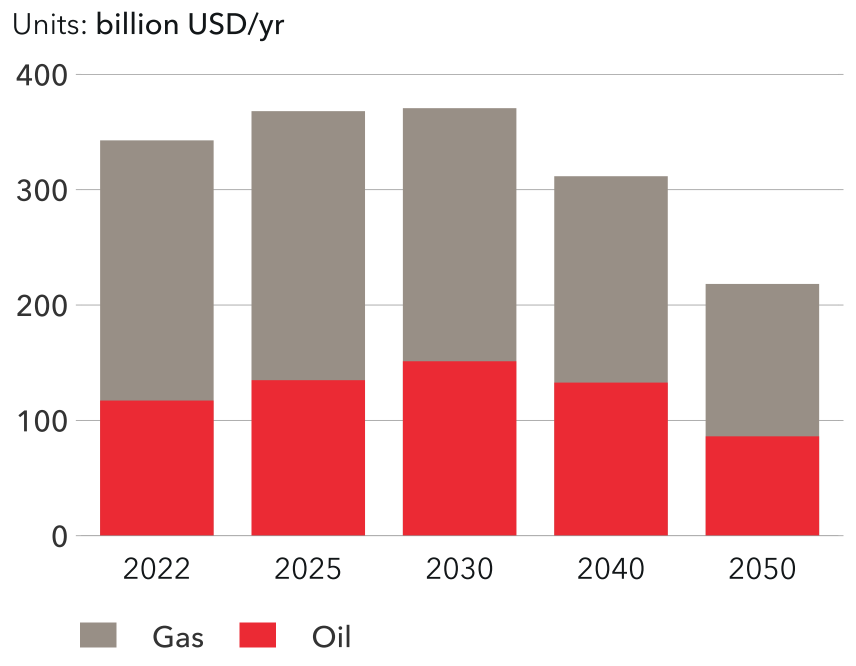


FIGURE 6.5
Oil and gas expenditures



Grid expenditures

In the decade leading up to 2022, grid expenditures were about 11% of total energy expenditures. Given that electricity demand was near-stagnant during this period, this was expected. However, with the vast transformation that we are forecasting, this is set to change.

In the near term, as shown in our results and also documented by many other sources (e.g., Quartz (2023) and Financial Times (2023a)), there will definitely be under-investment in grids. For every dollar expended in grids in 2022, 10 dollars was expended on fossil and non-fossil activities. In relative terms, in the period 2023 – 2025 the average investment in grids will fall to 8% of energy expenditures (down from a 11% average in the previous decade).

We have detailed the many reasons for this under-investment in Section 4.3 on grids, where we have also explained how this jeopardizes the entire decarbonization and transformation that is intended to be achieved by the policies enacted in the region.

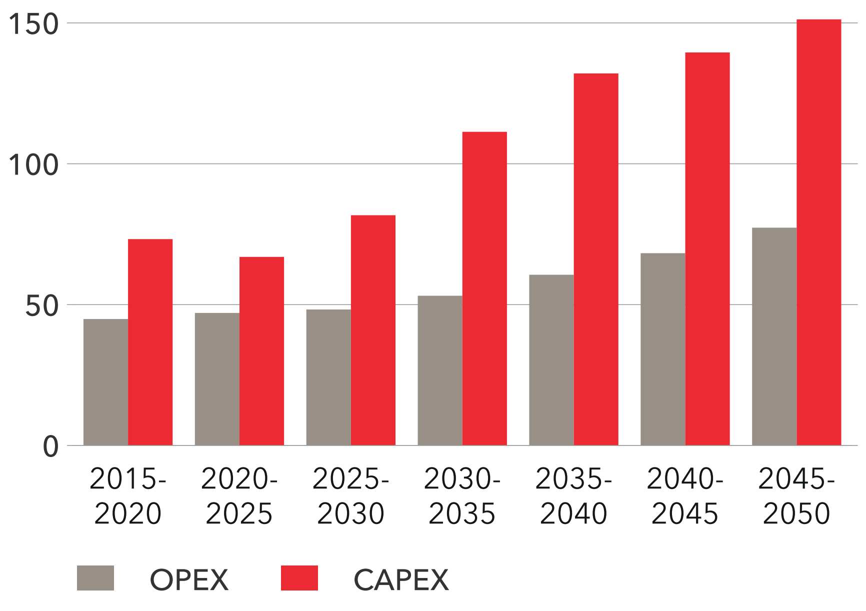
After this period of under-investment, we foresee that grid expenditures will expand rapidly to accommodate the renewables coming online, and to transmit and distribute electricity for new demand categories, such as road transport, space and water heating, manufacturing and electrolysis of hydrogen, and for new load centers. The electricity demand and supply almost doubling will lead to higher and higher expenditures in both absolute and relative terms. From being 9% of energy expenditures in 2022, grid expenditures will reach a 14% share by 2030, 20% by 2040, and 26% by mid-century. From 2022 to 2050, the increase in grid expenditure will outpace all other expenditures.

Figure 6.6 shows the dynamics of power-grid OPEX and CAPEX, averaged over five-year periods. In the period leading up to 2025, both OPEX and CAPEX of power grids stay stable. However, starting from 2025, CAPEX will increase more than OPEX, with infrastructure investments necessary in order to connect power generators with demand-centers across the vast land and sea areas of US and Canada. Although power-grid OPEX does increase in the decades after 2020, the majority of expenditure will be CAPEX.

FIGURE 6.6

Power grids OPEX and CAPEX

Units: billion USD/yr



Cost of support

There is overwhelming interest in understanding the actual cost to the region's governments and tax payers under the support schemes such as IRA in the US and 2023 Federal Budget of Canada.

Similarly, given that we are presenting DNV's forecast of the most likely energy future for North America, it is important to understand how much the cost of support is estimated to be in this forecast, and determine whether this figure can be reconciled with the cost of support mentioned elsewhere, such as by the White House (2023).

FIGURE 6.7

Cumulative cost of support 2022-2031

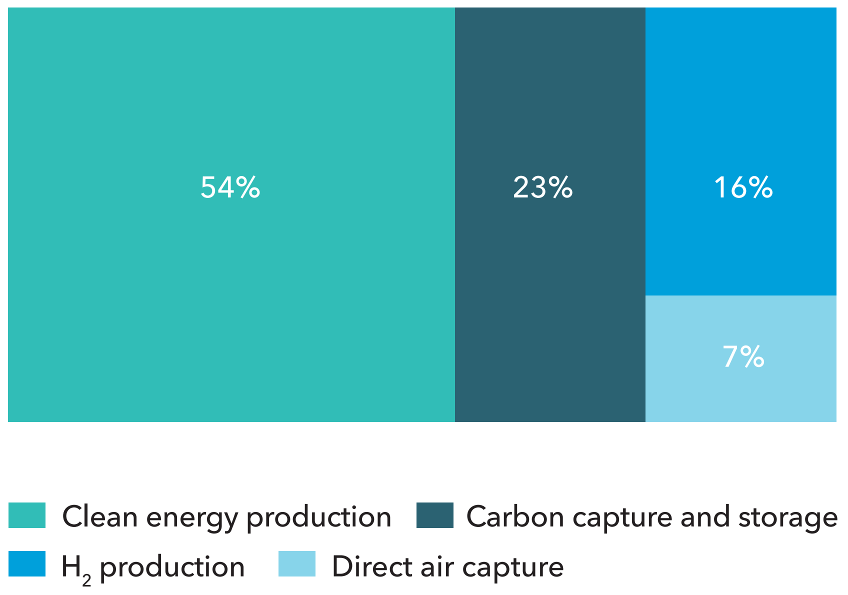


Figure 6.7 presents the expected cumulative cost of support for the period 2022 - 2031 according to the four main energy segments: clean electricity production, hydrogen production, Direct Air Capture (of CO_2), and CCS.

In DNV's forecast of the most likely energy future for North America, the cumulative cost of support from 2022 – 2031 is estimated to be USD 144bn, including the costs from Canada. These numbers agree with the allocation and split between these four categories detailed in Visual Capitalist (2023).

According to our forecast of the total cost of support, the lion's share (54%) is allocated to clean energy production; essentially electricity derivation from renewables and nuclear. The next highest share goes to CCS, which also includes support for hydrogen produced with steam methane reforming, combined with CCS.

Electricity demand and supply doubling will lead to higher and higher grid expenditures, in both absolute and relative terms.

The costs of support in the ETO-model were estimated using some simplifications, as explained below:

The cost of support figure is for both USA and Canada – Our North American region includes both USA and Canada. For the most part, the IRA allocates funding for the energy sector for the US. As previously elaborated in the relevant chapters, Canada has similar funding levels for the same energy sectors. Similarly, there are also spillover policies both ways. Thus, for simplification purposes, we input regional average support levels that are reasonably representative of USA and Canada.

The stackable local content Production Tax Credit (PTC) is not included – We have only input the basic production tax credit (PTC) and investment tax credit (ITC) for solar- and wind-energy production. This simplification is justifiable as the uncertainty regarding the percentage of renewable electricity production that will actually qualify for the stackable tax credits is very broad.

Grid-connected electrolysis-based hydrogen receives two thirds of the support for dedicated renewable hydrogen – As elaborated in the Hydrogen Section 4.6, the IRA has a CO_2 threshold-based support for hydrogen. Under the IRA 45V provision, dedicated renewables or nuclear electrolysis-based hydrogen qualify for USD 3/kgH_2, whereas the support level for grid-connected electrolysis depends on the CO_2 threshold of the grid at that hour. While grid-connected electrolysis-based H_2 producers may have individual power-purchase agreements that guarantee that the grid at the relevant hours will be below the CO_2 threshold, it is not always a given. We have therefore assumed that two thirds of the grid-connected electrolysis H_2 are produced below the CO_2 threshold that qualifies for the USD 3/kgH_2 support.

Support for methane reforming coupled with carbon capture and storage (CCS) (or blue H_2) is accounted for in CCS – Support for blue H_2 could either be through IRA 45V provision or 45Q, and these two are not stackable. As a generalization, support for blue hydrogen is accounted for in CCS in our model, as that support is calculated to be higher than the support that blue H_2 would receive under 45V (see Hydrogen Section 4.6 for detailed explanation).

Household energy expenditures

The previous section elaborated on upstream energy expenditures, and how money is moved around between fossil, non-fossil, and power grids in the most likely energy future of North America. However, it is also important to understand what the energy transition entails for the end consumer in the US and Canada. The acceptability of the energy transition is a relevant indicator of its success, and household energy expenditures will have a decisive impact on whether the transition is considered socially acceptable.

Figure 6.8 presents the average household energy bill in North America, where this is the average annual household cost for various energy carriers and fuels (such as natural gas and electricity), which are needed to run the household energy equipment.

In 2020, the average household energy bill in US and Canada (combined) was USD 2,100 per household-year in our analysis, which generally aligns with publicly available data for household energy bills in US and Canada.[1]

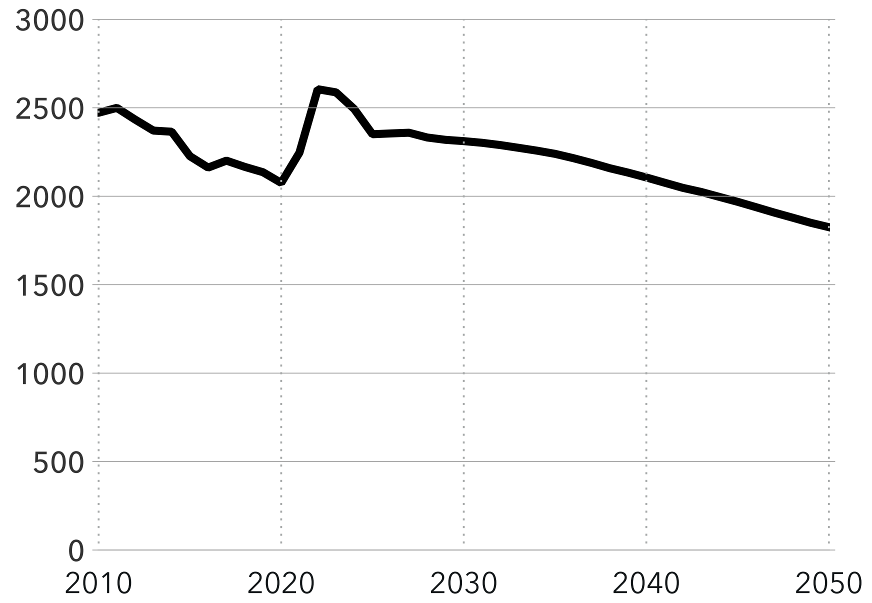
In 2022, however, the average North American household felt the impact of the present high energy prices, with the household energy bill being USD 2,600 per household. While energy prices are presently falling, we forecast that household energy costs will show only marginal reductions from 2022, mostly driven by more electricity demand for appliances and lighting in the average North American household. Similarly, relatively higher electricity prices will keep the average household energy bill at stable levels throughout the 2020s.

Nevertheless, starting from around the mid-2030s, we foresee the size of household energy bills steadily shrinking, dropping from around 2,250 USD per household-year down to around 2,000 USD in the mid-2040s.

FIGURE 6.8

North American household energy bill

Units: USD/household/yr



1 This is slightly higher than the data published by the US Energy Information Administration (EIA, 2023c), which was USD 1,884 / household-year for 2020. Considering that the average Canadian household energy bill is higher (around USD 2,200 /household-year) (Canada Energy Regulator, 2023), and the US EIA did not include the cost of bioenergy, direct heat, solar thermal, and coal in their calculations, the divergence between the two numbers is negligible.

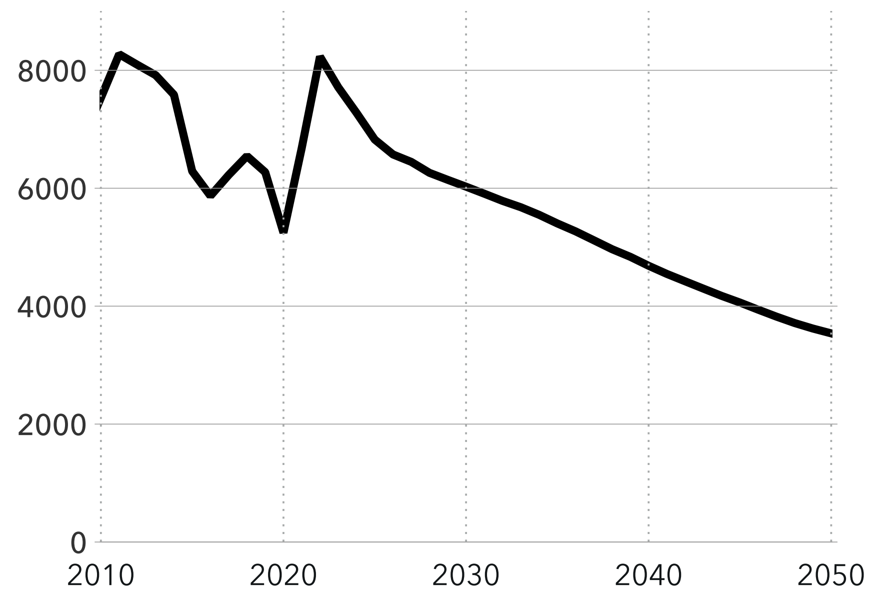
Higher penetration of more-efficient electric space heating, followed by continuous efficiency gains in household appliances, will start eating into the household energy bill. Similarly, the enormous capacity-side investments in renewable energy and grids will also start to translate into cheaper electricity for households in the 2040s. Over time, the energy transition will occur without any long-lasting increases in North American household energy bills; indeed, on the contrary, they will become smaller.

In addition to comparing household energy bills, we have also included a comparison of overall household energy expenditures, as shown in Figure 6.9.

FIGURE 6.9

North American household energy expenditure, including CAPEX

Units: USD/household/yr



Household energy expenditures include CAPEX for residential space heating and cooling, water heating (such as the cost of heat pumps), and cooking (such as the cost of electric stoves), and OPEX, which is the energy costs and energy taxes of running all the household equipment, along with passenger vehicles.

Rising interest rates along with associated inflationary pressures resulting in higher costs of energy-using equipment, more expensive fuel at the gas pump, greater household energy costs, and price rises for devices associated with supply-chain issues, have all combined to bring about a post-pandemic rise in average household energy expenditures in the US and Canada. Thus, in 2022, the average household energy expenditures in North America were higher than in the pre-COVID years. Prior to 2020, the five-year average of household energy expenditures in the region was USD 6,300 per household-year. The equivalent expenditures in 2021 and 2022 were, respectively, USD 6,700 and USD 8,200.

Stabilization of oil and natural gas prices and the resolution of supply-chain issues have contributed towards a decrease in expenditure levels. By 2025, average household energy expenditures are expected to reach 2021 levels and, by 2028, be as low as pre-pandemic levels. Furthermore, the size of this expenditure will continue to fall as cost-learning effects drive down the costs of heat pumps, while more renewables in the grid will reduce the cost of electricity. By 2050, we forecast that the average household energy expenditure will be around USD 3,600 per household-year, 57% less than the equivalent expenditure in 2022.

Thus, in addition to energy bills falling, household energy expenditures are also expected to decrease in the long term, as a result of the energy transition.

Energy equity

In the short-term, high household expenditures and the long lead time in returning of these to pre-pandemic levels is a burden that will disproportionately affect low-income households. Evidence shows that low-income households suffer from energy poverty in North America, with homeowners and renters unable to invest in energy services, and sometimes foregoing their health foregoing energy services, and sometimes sacrificing their health, due to high energy bills (DNV, 2023c).

In fact, high upfront costs of devices such as heat pumps, which are at the heart of the residential energy transition, will dissuade low-income households from investing in these. These households thus miss out on the reduction in their energy bill in the long run (or pay more for energy), which is a form of the phenomenon dubbed 'the poverty tax' in popular parlance. This contributes to perpetuating the poverty cycle.

This is not a new problem. It has not only been acknowledged within the energy industry, but state and provincial energy offices have also placed focus on equity to address this issue. For example, in the IRA there are specific equity provisions targeting low-to-moderate income communities or residents, historically underserved communities (Black, Indigenous and People of Color (BIPOC) etc.), and communities who have experienced disproportionately negative impacts from fossil-fuel industries. As an outcome, the IRA is projected to save the average US household USD 320 per year by 2030 in household energy costs.

While our ETO model does not have enough granularity to estimate household energy expenditures by household income, we have sufficient experience to be able to surmise that an income-based home energy rebate, as proposed by the Department of Energy of US (US DOE, 2023d), would, if implemented efficiently, help in ensuring that the financial burden placed by the transition on low-income households is decreased.

7 CARBON EMISSIONS

7.1 NORTH AMERICA EMISSIONS

North America's energy-related emissions fall from 5.2 $GtCO_2$ in 2022 to 1.3 $GtCO_2$ in 2050, a 75% reduction, or a 4.8% reduction year-on-year. Importantly, the policies enacted in IRA, IIJA and the Canadian federal budget provide an early runway for technology adoption critical to CO_2 removal, such as CCS and DAC. This will have the effect of shifting the emissions reduction curve to tackle currently-high emissions. Despite this front-loading of effort, however, overall emissions reduction falls very short of what is required for a net-zero energy system by 2050.

The energy sector is the main source of greenhouse gas emissions (GHG), both globally and in North America. CO_2 is the main contributor to these emissions and largely comes from the combustion of fossil fuels. In this chapter, we estimate energy-related CO_2 emissions until 2050 associated with the ETO forecast for North America. In addition, we calculate how much of these emissions are captured and stored, both from CO_2 generating processes as well as from the atmosphere.

FIGURE 7.1

Energy-related CO_2 emissions by fuel source

Units: $GtCO_2$/yr

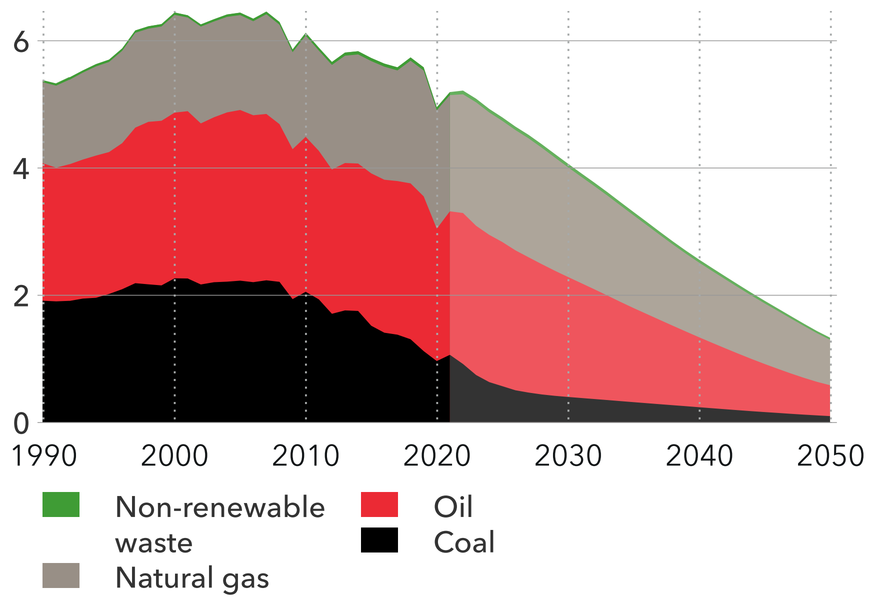
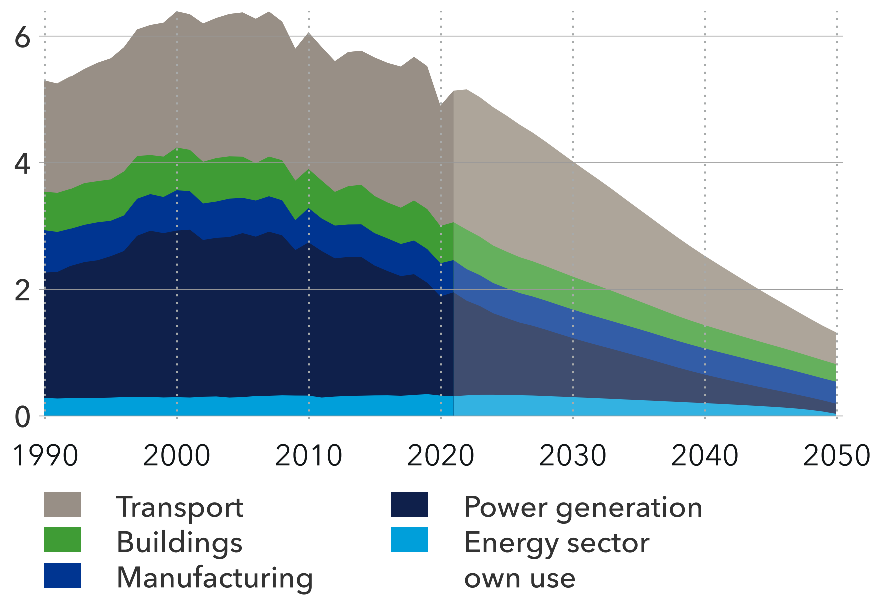


FIGURE 7.2

Energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Emissions by source

Energy-related CO_2 emissions in North America have declined continuously since early 2000s mainly due to gas replacing coal, and in more recent years the gathering pace of renewable installations. Figure 7.1 shows oil as today's main contributor (45%) of energy-related CO_2 emissions, followed by gas (36%) and coal (18%). CO_2 emissions from coal will see the strongest decline (89%), followed by oil (79%) and then gas (64%) between 2022 and 2050. Overall, the energy-related CO_2 emissions will decline by 75% from today's level which includes the capture of some fossil-based emissions.

Outside the energy sector, there are significant emissions from industrial processes that produce CO_2 through chemical reactions (e.g. cement making) or consume fossil fuels as raw material for feedstock (e.g. plastics and petrochemicals). These process-related emissions, net of carbon capture efforts, are included in our analysis as part of the manufacturing sector and in 2022, totaled almost 300 $MtCO_2$. Improvements in production efficiencies and emissions capture will gather pace such that these emissions will fall quickly from 2040 to more than half of today's levels by mid-century.

Sector emissions

The sectoral breakdown of energy-related CO_2 emissions is shown in Figure 7.2. Transport is currently the largest sectoral contributor to energy-related CO_2 emissions; 2.2 Gt in 2022, 43% of all energy-related CO_2 emissions. The power sector made up 29% (1.5 $GtCO_2$), while buildings, the third main energy demand sector, accounted for 12% (0.6 $GtCO_2$).

The power sectors emissions will decline with almost 90% representing only 12% in 2050, from 1.5 $GtCO_2$ in 2022. Yet, 160 $MtCO_2$ of emissions from power will remain in 2050 despite ambitions in both the US and Canada to achieve a decarbonized power grid by 2035.

In 2050, transport will remain the biggest emitter (43%), but with its annual emissions reduced to 0.5 $GtCO_2$. The manufacturing sector's emissions share will be 27% by then, while in absolute terms its emissions will reduce from 0.5 to 0.35 $GtCO_2$. Finally, the buildings sector's emissions decline almost 60% from 0.6 to 0.28 $GtCO_2$ and represent 22% of North American energy-related CO_2 emissions.

The dynamics behind these emission reductions are summarized as follows:

– Transport emissions fall 77% to 2050. The main reason is the electrification of road transport.. This is not just because EVs use energy more efficiently, but also because electricity production from renewable sources will increase, supplying ever-more emission-free electricity to the transport sector. However, the fall in emissions is somewhat arrested in the near term by increasing emissions within shipping and aviation. Both subsectors are hard to electrify and need to use decarbonized fuels such as hydrogen, biofuels, e-fuels or ammonia which only makes significant impact on emissions by late 2030s.

- **Manufacturing emissions** will decline slowly over the whole forecast period with electrification, fuel-switching and carbon capture and storage (CCS) combining to reduce emissions by almost 30%.

- **Buildings emissions** fall steadily to 56% of today's levels, despite significant growth in industrial/commercial and residential space. Continuous improvements in energy efficiency and switching to cleaner sources of fuel for heating (e.g. electric heat pumps) will be the main reasons for these reductions.

7.2 CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) and Direct Air Capture (DAC) both combined capture 15% of energy-related emissions in North America in 2050.

This is a meaningful contribution to emission reduction, aided both by the industry experience already present in US and Canada but also through the financial incentives for the capture technologies in IRA and the Federal budget of Canada. However, these capture levels fall far short of the level of carbon emissions needed for North America to achieve net zero emissions by 2050.

Both the US and Canada recognize carbon capture and storage (CCS) as a critical technology for achieving their net-zero targets by 2050. The interest in CCS stems from an already established experience with the technology in the two countries, albeit with relatively small-scale deployments. Furthermore, CCS is viewed as a good fit for achieving an equitable transition and addressing environmental concerns in the region with a fossil-dominated energy mix and abundant oil and gas reserves.

North America has been leading CCS deployment globally. The first small-scale projects capturing CO_2 from flue gases commenced as early as the 1980s, in Texas and New Mexico (Herzog, 2018). Much of the initial deployment was driven by the commercial opportunity for selling captured CO_2 for further utilization through enhanced oil recovery (EOR) operations. As a result, an extensive pipeline infrastructure for transporting CO_2 has been developed. In addition, substantial expertise has been accumulated in geologic storage and financing over the past three decades.

Some larger-scale commercial CCS projects in the industrial and power sectors were deployed in 2010s. Notable projects, with many technical firsts include Quest in Fort Saskatchewan in Alberta, Boundary Dam in Saskatchewan, and the Decatur Project/ADM Illinois Industrial in Illinois (Herzog, 2018). Over time, the commercial drivers for the larger-scale projects expanded beyond revenues from selling CO_2 for EOR to include monetary government support in the form of public investment contributions (i.e. government grants) and performance-based tax credits as per Internal Revenue Service section 45Q (commonly referred to as '45Q tax credits'). The 45Q tax credits in the US have been in effect since 2008 and have incentivized many of the currently operating projects capturing CO_2 for EOR, as well as for geologic storage without EOR.

Despite the incentives, the high cost, a big part of which comes from the energy penalty induced by the capture process, has been hindering the uptake of CCS. Today, only about 17 $MtCO_2$/yr is being captured in the North America region by capture technologies applied in several sectors. This constitutes about 61% of CO_2 emissions captured globally. About 85% of CO_2 emissions in North America is captured from natural gas processing, where the cost of capture from high-pressure streams is in the lower ranges. Ammonia production and hydrogen production each comprise about 5% of the captured emissions, followed by 4% of emissions captured from electricity production.

> US and Canada recognize carbon capture and storage (CCS) as a critical technology for achieving their net-zero targets by 2050.

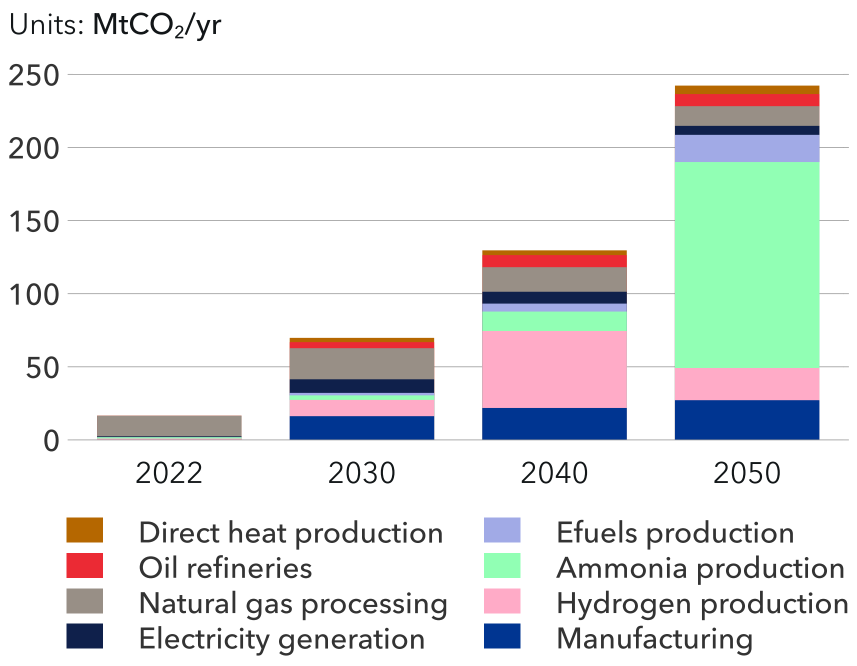
Going forward, we expect that operators of large point sources in the power and manufacturing sectors will increase the capture of carbon from their processes and waste streams. Additionally, we expect all carbon emissions from hydrogen production as an energy carrier to be captured in steam-methane reforming (SMR) process. We also foresee capture of an increasing share of emissions associated with hydrogen production for the process industry. Some capture is also expected when flaring occurs during natural gas processing.

The latest policy developments in the US and Canada substantially boosted the support for CCS. In the US, the Infrastructure Investment and Jobs Act provides over USD 12bn for various CCS and related activities, such as for carbon-storage validation and development of hydrogen hubs, including blue hydrogen.

The Inflation Reduction Act (IRA) enhances the 45Q tax credit up to USD 85/tCO_2 permanently stored and USD 60/tCO_2 used for EOR or where it is stored permanently. Furthermore, IRA extends the start of construction timing by another seven years (i.e. to the end of 2032) and reduces the capacity requirements for eligibility. Another significant change is the provision for direct pay and broad transferability of tax credits, which combined provides greater flexibility in the financial structures of projects and increase likelihood of a project reaching final investment decision. Some states in US have proposed further legislation pertaining to CO_2 storage support CCS (GCCSI, 2022).

FIGURE 7.3

CO_2 emissions captured

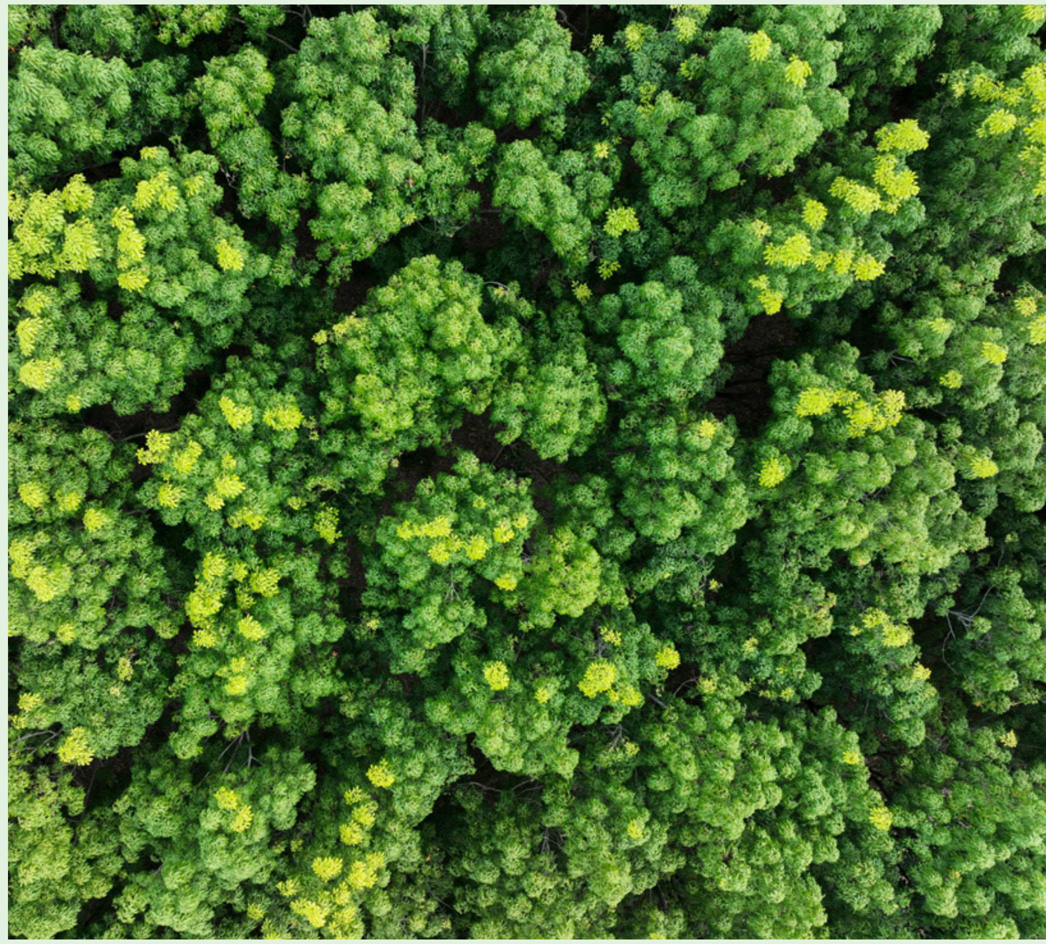


Canada, in its 2022 federal budget, provides strong support for CCS through an investment tax credit for capital costs, with the rates of 50% for carbon capture projects and 37.5% for transportation, storage, and use from 2022 through 2030; the tax credit rates are reduced to 30%, 25%, and 18.75%, respectively, from 2031 to 2040. The total pool of tax credits for CCS projects is set at CAD 2.6bn (GCCSI, 2022).

Based on the existing and announced policy developments, and on known facilities in the project development supply chain, we foresee an increase in CCS capacity in the near term leading to corresponding capture rates of 69 MtCO_2/yr in 2030. Although that is a 4-fold increase from the current levels, the uptake of CCS will still be rather limited in the near to medium term, and effectively too late and too little in the longer term. It is only in the 2040s that uptake accelerates and deployment at scale begins, when carbon prices in Canada and in those US states where carbon pricing mechanisms are in place will start to approach the cost of CCS.

By 2050, we find emissions captured by CCS to be close to 250 MtCO_2/yr, as portrayed in Figure 7.3. Ammonia production will become the leading source of CCS application, reaching almost half of all the emissions captured. About 60 MtCO_2/yr, or 60% of all the captured emissions, will be associated with 'blue' hydrogen production by 2040. Yet, as the production of 'green' hydrogen from renewables accelerates in the following decade, the emissions captured from 'blue' hydrogen production will drop by 2050 and account for only about a tenth of total captured emissions by mid-century. Around 7% of the emissions will be captured from e-fuels production. Those from natural gas processing and point-source capture in power will increase or remain around the same level relative to 2022, but will constitute only 5% and 2.5%, respectively, of total emissions captured.

Despite the increases in CCS capacity, the developments we are aware of today and have modelled are not happening at sufficient scale to make a significant contribution to the emissions reductions required to reach the region's climate ambitions. A further 1.5 GtCO_2/yr remains to be captured or removed by direct air capture of CO_2 (see highlight on carbon removal) to achieve net zero by 2050.



The rise of carbon removal

Carbon removal refers to a set of solutions to remove carbon dioxide directly or indirectly from the atmosphere. Afforestation (i.e. planting trees) is one example of natural carbon removal, but it needs huge areas to achieve significant carbon absorption. That is why artificial and industrial-scale solutions are increasingly viewed as essential to achieve the scale needed to compensate for the slow decarbonization in other sectors (e.g. aviation).

Several market opportunities coexist for the captured CO_2:

- The voluntary offset market, which is currently driving all the smaller-scale plants. This service has been chosen by some third-sector companies to compensate for their emissions. For instance, Microsoft is heavily investing in carbon removal (Microsoft, 2023) in its decarbonization portfolio to reach its ambitious targets.

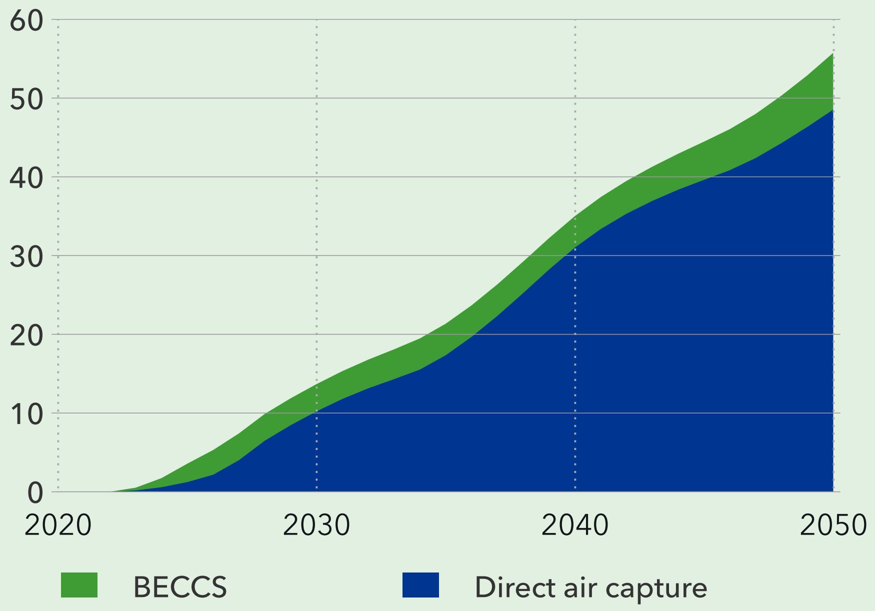
- Enhanced oil recovery (EOR), where CO_2 is injected into an existing oil well to 'push' the oil and recover a higher fraction of the oil in the reservoir. CO_2 is stored but leads to indirect emissions due to increased oil production. EOR will at first be the largest market for carbon-removal plants in North America, as the CO_2 infrastructure already exists.

- Carbon-neutral CO_2 can be reused to produce synthetic fuels like e-kerosene or as a replacement for traditional CO_2 use (e.g. in carbonated drinks).

FIGURE 7.4

CO_2 captured by carbon removal technologies

Units: $MtCO_2/yr$



The prohibitive cost of these technologies has long limited their full-scale deployment. But with the unprecedented support for carbon-removal solutions included in the recent US climate packages, North America will lead the way in technology development. Two technologies are expected to share the market – direct air capture (DAC), and bioenergy with carbon capture and storage (BECCS).

DAC projects have gained traction due to a significant increase of support in the IRA package, reaching up to 180 USD/tCO_2 if carbon dioxide is stored. The US Department of Energy also recently announced USD 1.2bn support for the development of the two first commercial-scale facilities (millions of tons of CO_2 per year) in Texas and Louisiana (US DOE, 2023). Canada also strongly supports DAC projects through investment tax credits for capital costs. The tax credit rate is 60%. As shown in Figure 7.4, we expect DAC plants to capture above 50 $MtCO_2/yr$ by 2050. BECCS uptake will be more limited, around 7 $MtCO_2/yr$ at the end of the forecasting period. As a result, we expect carbon-removal solutions to account for 55 $MtCO_2/yr$ by 2050, compensating for around 4% of North American CO_2 emissions by that time.

Pathway to Net Zero

Country pledges (2030) to the Paris Agreement have the US and Canada aiming for GHG emissions reductions of 50-52% and 40-45%, respectively, both compared to 2005 levels. Our forecast of energy-related emissions estimates a 37% CO_2 reduction (below 2005 levels), and 24% for CH_4 (below 2020 levels). Despite the enormous capital mobilized by the IRA, IIJA and a Canada's clean energy push, the region will not achieve net zero emissions in its energy sector, or in fact in any of its sectors.

The pathway to net zero (PNZ) for North America entails a war-footing effort starting from now and will very much require the kind of single-minded American focus that ushered in the atomic age, space age and which will likely find a cure for cancer.

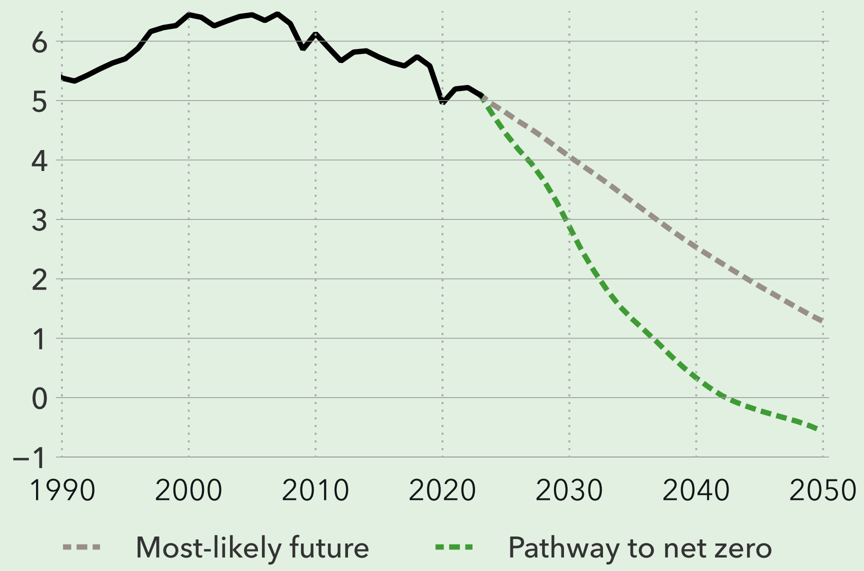
Photo by Werner Slocum, NREL

Figure 7.5 below shows the emission trajectories for our 'best estimate' of the most likely energy future (this ETO report) and for our PNZ (Pathway to Net Zero, 2023 forthcoming). The disparity between the two trajectories is stark: in the PNZ, North America reaches net zero thanks to a completely decarbonized power system by early 2040s. The PNZ also requires even more rapid scale-up of CCS, and 6 times as much DAC as in the ETO by mid-century.

FIGURE 7.5

Energy-related CO_2 emissions, after DAC

Units: $GtCO_2/yr$

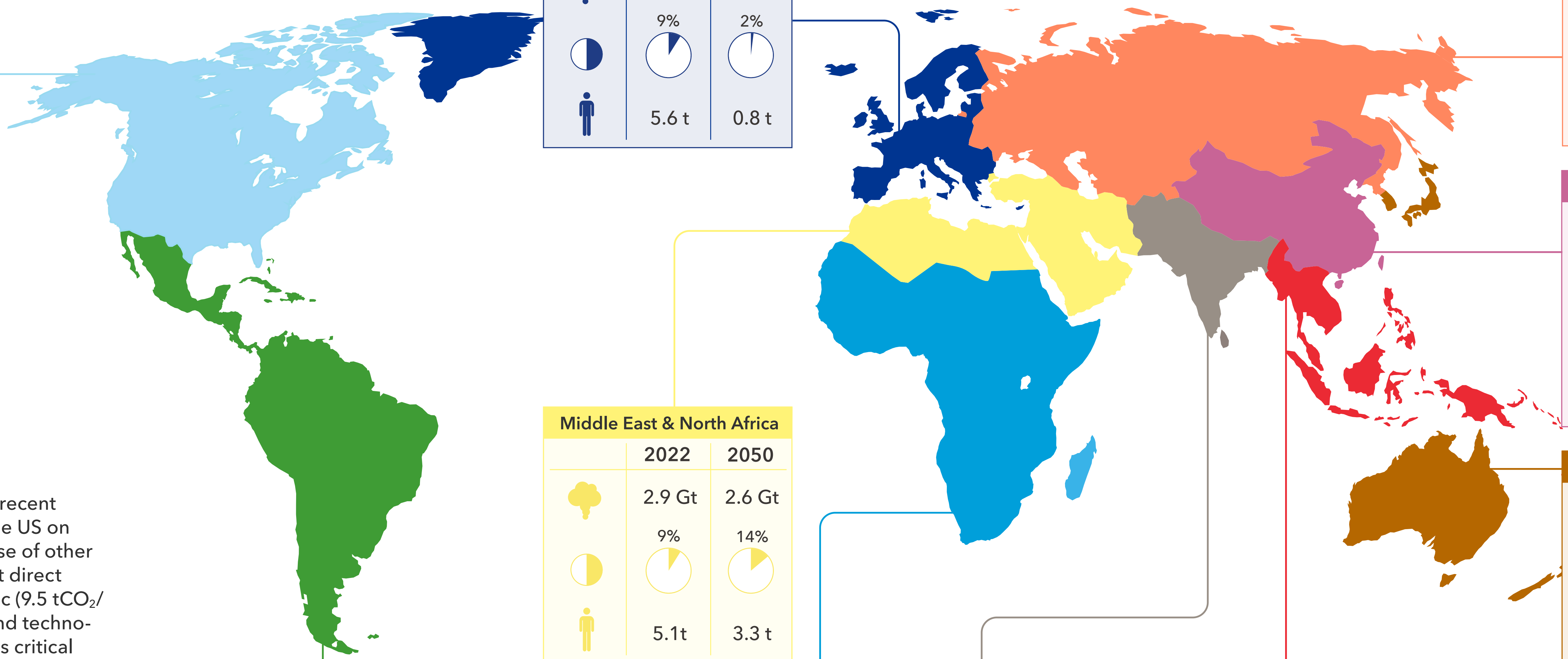


Energy-related regional emissions

Total energy-related CO_2 emissions

Share of world emissions

Energy-related per capita emissions



North America

	2022	2050
Total energy-related CO_2 emissions	5.2 Gt	1.3 Gt
Share of world emissions	16%	7%
Energy-related per capita emissions	13.8 t	3.0 t

Europe

	2022	2050
Total energy-related CO_2 emissions	3.1 Gt	0.4 Gt
Share of world emissions	9%	2%
Energy-related per capita emissions	5.6 t	0.8 t

North East Eurasia

	2022	2050
Total energy-related CO_2 emissions	2.4 Gt	1.7 Gt
Share of world emissions	7%	9%
Energy-related per capita emissions	7.6 t	5.0 t

Greater China

	2022	2050
Total energy-related CO_2 emissions	10.7 Gt	4.0 Gt
Share of world emissions	32%	22%
Energy-related per capita emissions	7.4 t	3.0 t

Middle East & North Africa

	2022	2050
Total energy-related CO_2 emissions	2.9 Gt	2.6 Gt
Share of world emissions	9%	14%
Energy-related per capita emissions	5.1t	3.3 t

OECD Pacific

	2022	2050
Total energy-related CO_2 emissions	2.0 Gt	0.4 Gt
Share of world emissions	6%	2%
Energy-related per capita emissions	9.5 t	2.0 t

Latin America

	2022	2050
Total energy-related CO_2 emissions	1.5 Gt	1.1 Gt
Share of world emissions	5%	6%
Energy-related per capita emissions	2.3 t	1.5 t

Sub-Saharan Africa

	2022	2050
Total energy-related CO_2 emissions	1.0 Gt	1.3 Gt
Share of world emissions	3%	7%
Energy-related per capita emissions	0.8 t	0.6 t

Indian Subcontinent

	2022	2050
Total energy-related CO_2 emissions	3.0 Gt	3.9 Gt
Share of world emissions	9%	22%
Energy-related per capita emissions	1.6 t	1.7 t

South East Asia

	2022	2050
Total energy-related CO_2 emissions	1.7 Gt	1.4 Gt
Share of world emissions	5%	8%
Energy-related per capita emissions	2.5 t	1.8 t

North America accounts for 16% of the world's energy-related emissions. A recent investigation by the Pew Research Center revealed little consensus within the US on how its efforts to combat the effects of climate change stack up against those of other large economies (Tyson et al., 2023). Per capita, North America is the largest direct emitter at 13.8 tCO_2/yr, almost 50% more than the next largest, OECD Pacific (9.5 tCO_2/yr), and twice the rate for Europe, which is comparable in living standards and technological prowess to North America. So, what North America does until 2050 is critical for the climate, regardless of the cost reductions in CCS and DAC technology it may transfer to the rest of the world.

Since last year's report, the 2050 forecast for energy emissions per capita in North America has reduced almost 20%, a direct result of recent climate-related legislation in both the USA and Canada. Despite these commendable provisions, we forecast that North America's energy sector will emit about 3 tCO_2 per capita in 2050, still more than most other regions and not yet a global leader in reducing total energy-related emissions with 1.3 $GtCO_2$ emitted.

In our Pathway to Net Zero report (2023, forthcoming), we detail how North America can go faster and deeper in its energy transition and emissions reduction to help the world achieve net-zero emissions by mid-century and secure the ambitions of the Paris Agreement.

REFERENCES

ACORE – American Council on Renewable Energy (2023) Expectations for Renewable Energy Finance in 2023-2026: *How companies are realizing the post-IRA opportunity while navigating headwinds*. Available at: https://acore.org/wp-content/uploads/2023/06/ACORE-Expectations-for-Renewable-Energy-Finance-in-2023-2026.pdf

Andersen, A. D. (2014) 'No transition without transmission: HVDC electricity infrastructure as an enabler for renewable energy?'. *Environmental Innovation and Societal Transitions*; Vol 13. https://doi.org/10.1016/j.eist.2014.09.004

BCG – Boston Consulting Group (2023) *Impact of IRA, IIJA, CHIPS, and Energy Act of 2020 on Clean Technologies - Deep Dive Geothermal.* April 2023. Available at: https://breakthroughenergy.org/wp-content/uploads/2023/05/Geothermal-Cleantech-Policy-Impact-Assessment.pdf

Bipartisan Policy Center (2021) *The Grid Wins Big in the IIJA*. By: Rachel Smith. Available at: https://bipartisanpolicy.org/blog/the-grid-wins-big-in-the-iija/

Bloomberg (2023a) *Billion-Dollar Power Lines Finally Inching Ahead to Help US Grids*. By: Eckhouse, B., Malik N. S., Merrill, D. Available at: https://www.bloomberg.com/news/articles/2023-03-06/billion-dollar-power-lines-finally-inching-ahead-to-help-us-grids

Bloomberg (2023b) *Energy Startup Says It Has Achieved Geothermal Tech Breakthrough*. By Michelle Ma. July 18. Available at: https://www.bloomberg.com/news/articles/2023-07-18/fervo-energy-says-it-has-achieved-geothermal-energy-tech-breakthrough

BloombergNEF (2023a) Sustainable Energy in America 2023 Factbook: Tracking Market & Policy Trends. Available at: https://bcse.org/images/2023%20Factbook/2023%20BCSE%20BNEF%20Sustainable%20Energy%20in%20America%20Factbook.pdf

BloombergNEF (2023b) *1H 2023 Corporate Energy Market Outlook.*

Brookings Institution (2022) *A Comprehensive Guide to the Infrastructure Law.* Brookings Institution. By A. Tomer, C. George, A. Bourne, and J.W. Kane. Available at https://www.brookings.edu/articles/introducing-the-brookings-federal-infrastructure-hub-a-comprehensive-guide-to-the-infrastructure-law/

California Energy Codes and Standards (2023) *2022 Code Cycle - Locally Adopted Energy Ordinances*. Accessed July 25. Available at: https://localenergycodes.com/content/adopted-ordinances

Canada.ca (2023) *Canada Greener Homes Grant.* Available at: https://natural-resources.canada.ca/energy-efficiency/homes/canada-greener-homes-initiative/canada-greener-homes-grant/24833

Canadian Climate Institute (2023) *The Case for Adapting to Extreme Heat – Costs of the 2021 B.C. heat wave*. Available at: https://climateinstitute.ca/wp-content/uploads/2023/06/The-case-for-adapting-to-extreme-heat-costs-of-the-BC-heat-wave.pdf

Canada Energy Regulator (2023) *Market Snapshot: Household energy expenditures vary significantly by province and territory*. Available at: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2020/market-snapshot-household-energy-expenditures-vary-significantly-province-territory.html

Canadian Press (2023) *Canada to take 'hard' look at UN call to hit emissions targets 10 years sooner: minister*. By: Mia Rabson. March 20 Available at: https://globalnews.ca/news/9565677/climate-change-emissions-un-canada/

Canadian Renewable Energy Association (2023) *News release: 2023 Federal Budget ushers in new era for Canadian renewables*. March 28. Available at: https://renewablesassociation.ca/news-release-2023-federal-budget-ushers-in-new-era-for-canadian-renewables/

Canary Media (2023) *White House proposes new rule to speed up clean energy permitting*. By: Akielly Hu. August 2. Available at: https://www.canarymedia.com/articles/clean-energy/white-house-proposes-new-rule-to-speed-up-clean-energy-permitting

CEQ – Council on Environmental Quality (2023) *Biden-Harris Administration Proposes Reforms to Modernize Environmental Reviews, Accelerate America's Clean Energy Future*, and *Strengthen Public Input*. July 28. Available at https://www.whitehouse.gov/ceq/news-updates

CIAT – Inter-American Center of Tax Administrations (2022) *Review of some climate-related tax changes announced for 2023* - Part 1. By: Andre Dumoulin, December 29. Available at: https://www.ciat.org/ciatblog-review-of-some-climate-related-tax-changes-announced-for-2023-part-1/?lang=en

CleanTechnica (2023) *Full Steam Ahead: Unearthing The Power Of Geothermal*. Available at: https://cleantechnica.com/2023/03/08/full-steam-ahead-unearthing-the-power-of-geothermal/

Climate Power (2023) *One Year of Our Clean Energy Boom*. July 23. Available at https://climatepower.us/wp-content/uploads/sites/23/2023/07/Clean-Energy-Boom-Anniversary-Report-1.pdf

CNN (2023) *Half of the biggest global companies plan to cut office space. US cities will suffer most*. By: Hanna Ziady. Available at: https://edition.cnn.com/2023/06/06/business/global-companies-office-space-cuts/index.html

Credit Suisse (2022), *Treeprint: US Inflation Reduction Act – A tipping point in climate action*. Available at: https://www.credit-suisse.com/treeprintusinflationreductionact

CSIS – Center for Strategic & International Studies (2023) *Permitting reform in the Debt Ceiling Bill: A first step, with more to come*. By: Michael Catanzaro. June 7. Available at: https://www.csis.org/analysis/permitting-reform-debt-ceiling-bill-first-step-more-come

CSG – Council of State Governments (2022) *Transmission, NIMBY, and the quest to decarbonize the grid*. By: Rona Cohen. January 28. Available at: https://csg-erc.org/transmission-nimby-and-the-quest-to-decarbonize-the-grid/

Delphi Group (2022) *Towards Net Zero: Developing a Rail Decarbonization Roadmap for Canada*. Available at: https://www.railcan.ca/wp-content/uploads/2022/12/Rail-Pathways-Decarbonization-Roadmap.pdf

Department of Finance, Canada (2023) *Budget 2023 – A Made-in-Canada Plan*. Available at: https://www.budget.canada.ca/2023/pdf/budget-2023-en.pdf; https://www.canada.ca/en/department-finance/news/2023/03/government-of-canada-releases-budget-2023.html

DNV (2023a) *Energy Transition Outlook – A global and regional forecast to 2050*. Forthcoming October. Available at: https://www.dnv.com/energy-transition-outlook/index.html

DNV (2023b) *Pathway to Net Zero Emissions*. Forthcoming October. Available at: https://www.dnv.com/energy-transition-outlook/index.html

DNV (2023c) *Final report - Essential Use of Electricity Study*. Prepared for Southern California Edison, Pacific Gas and Electric Company, and San Diego Gas & Electric Company

DNV (2023d) *Use of biofuels in shipping*. Available at: https://www.dnv.com/news/use-of-biofuels-in-shipping-240298

DNV (2022a) *Energy Transition Outlook – A global and regional forecast to 2050*. Available at: https://www.dnv.com/energy-transition-outlook/index.html

DNV (2022b) *The future of floating solar: drivers and barriers to growth*. Available at: https://www.dnv.com/Publications/the-future-of-floating-solar-224530

DNV (2022c) *Spatial Competition Forecast – Ocean's Future to 2050*.

DNV (2022d) *Hydrogen Forecast to 2050*.

EIA – US Energy Information Administration (2023a) *Oil and petroleum products explained – Oil imports and exports.* Accessed June 2023: https://www.eia.gov/energyexplained/oil-and-petroleum-products/imports-and-exports.php

EIA – US Energy Information Administration (2023b) *U.S. Natural Gas Exports and Re-Exports by Country* Accessed June 2023: https://www.eia.gov/dnav/ng/ng_move_expc_s1_a.htm

EIA – US Energy Information Administration (2023c) *Residential energy consumption survey (recs) – 2020 recs survey data*. Accessed July 2023. Available at: https://www.eia.gov/consumption/residential/data/2020/index.php?view=consumption

Eisenson, M (2023) *Opposition to Renewable Energy Facilities in the United States: May 2023 Edition*. From: Sabine Center for Climate Change Law. Available at: https://smith.faculty.polsci.ucsb.edu/wind.pdf

Electricity Canada (2023) *Build Things Faster*. Available at: https://issuu.com/canadianelectricityassociation/docs/ec_sel_frame_-_2023_21_b1a2024679b3b0

Electric Power Research Institute (2021) *Powering Decarbonization: Strategies for Net-Zero CO_2 Emissions*. Available at: https://www.epri.com/research/programs/109396/results/3002020700

REFERENCES

Energy Innovation Policy & Technology LLC (2022) *State Policy Key to Unlocking Inflation Reduction Act Electricity Sector Benefits*. Available at: https://energyinnovation.org/wp-content/uploads/2022/11/Inflation-Reduction-Act-Electricity-State-Policy-Roadmap-One-Pager.pdf

Energy Institute at Haas (2023) *Can Targeted Tax Credits Bring Clean Energy to Coal Country?* By: Meredith Fowlie. May 22. Available at: https://energyathaas.wordpress.com/2023/05/22/can-targeted-tax-credits-bring-clean-energy-to-coal-country/

Energy Monitor (2022) 'How developers can overcome local opposition to onshore wind projects' Written by: van Halm, I. Available at: www.energymonitor.ai/finance/corporate-strategy/how-developers-can-overcome-local-opposition-to-onshore-wind-projects/

European Commission (2023) *State aid: Commission adopts Temporary Crisis and Transition Framework to further support transition towards net-zero economy*. March 9. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1563

Executive Office of the President (2021a) *Tackling the Climate Crisis at Home and Abroad*. E.O. 14008 of Jan 27, Available at: https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

Executive Office of the President (2021b) *Improving the Nation's Cybersecurity. Executive Order 14028 of 12 May 2021*. 86 Federal Register 26633. https://www.federalregister.gov/documents/2021/05/17/2021-10460/improving-the-nations-cybersecurity

Federal Register (2023) *Building a Better Grid Initiative To Upgrade and Expand the Nation's Electric Transmission Grid To Support Resilience, Reliability, and Decarbonization*. Available at: https://www.federalregister.gov/documents/2022/01/19/2022-00883/building-a-better-grid-initiative-to-upgrade-and-expand-the-nations-electric-transmission-grid-to

FERC - US Federal Energy Regulatory Commission (2023a) *Improvements to Generator Interconnection Procedures and Agreements.* RM22-14-000; Order No. 2023. Issued July 28. Available at: https://www.ferc.gov/media/e-1-order-2023-rm22-14-000

FERC – US Federal Energy Regulatory Commission (2023b) *FERC Transmission Reform Paves Way for Adding New Energy Resources to Grid*. July 27. Available at https://www.ferc.gov/news-events/news/

Financial Post (2023) *One year on, how America's Inflation Reduction Act has changed Canada*. By: Naimul Karim. August 15. Available at: https://financialpost.com/commodities/mining/how-inflation-reduction-act-changed-canada

FT – Financial Times (2023a) *Gridlock: how a lack of power lines will delay the age of renewables*. By: Attracta Mooney. June 11. Available at: https://www.ft.com/content/a3be0c1a-15df-4970-810a-8b958608ca0f

FT – Financial Times (2023b) *India's power minister accuses west of hypocrisy over energy transition*. Written by: Benjamin Parkin in New Delhi, June 18. Available at: https://www.ft.com/content/d27c3b26-275e-45c0-95fd-af64169e500d

FRED - Federal Reserve Economic Data (2023) *All Employees, Coal Mining*. Accessed June 2023, Available at: https://fred.stlouisfed.org/series/CES1021210001

Government of Alberta (2023) *Creating certainty for renewable projects.* Dated 3 August 2023. Available at: https://www.alberta.ca/release.cfm?xID=887605547987E-EABF-5E23-DFF2C9F72DB845E6

Government of Canada (2023a) *Budget 2023, A Made-in-Canada Plan: Strong Middle Class, Affordable Economy, Healthy Future*. Department of Finance. Available at: https://www.budget.canada.ca/2023/home-accueil-en.html

Government of Canada (2023b) *Coal Facts, 2023*. Accessed June 2023. Available at: https://natural-resources.canada.ca/our-natural-resources/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/coal-facts/20071

Government of Canada (2022a) *2030 Emissions Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy*. Available at: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html

Government of Canada (2022b) *Canada's Aviation Climate Action Plan 2022-2030.* Available at: www.tc.gc.ca/aviation-emissions/

Government of Canada (2021) *Canadian Net-Zero Emissions Accountability Act*. https://www.laws-lois.justice.gc.ca/PDF/C-19.3.pdf

Graham, N., Caroll, W.K., Chen, D. (2019) *Big oil's political reach: Mapping fossil fuel lobbying from Harper to Trudeau*. Report part of the Corporate Mapping Project jointly led by the University of Victoria, Canadian Centre for Policy Alternatives, and the Parkland Institute. Available at: https://policyalternatives.ca/sites/default/files/uploads/publications/BC%20Office%2C%20Saskatchewan%20Office/2019/11/ccpa-bc_cmp_BigOil_web.pdf

HeatMap (2023) *What Is Permitting Reform? Here's a Cheat Sheet*. By: Robinson Meyer. Available at: https://heatmap.news/politics/permitting-reform-transmission-nepa-geothermal

Hydrogen Central (2022) *Stadler and San Bernardino County Transit Authority (SBCTA) are presenting Stadler's First Hydrogen FLIRT Train at InnoTrans – US*. September 22. Available at: https://hydrogen-central.com/stadler-san-bernardino-county-transit-authority-sbcta-presenting-stadlers-fist-hydrogen-flirt-train-innotrans-us/

IAEA – International Atomic Energy Agency (2023) *The Database on Nuclear Power Reactors*. Available at: https://pris.iaea.org/PRIS/home.aspx

IEA – International Energy Agency (2022a) *Unlocking the potential of distributed energy resources – Power systems opportunities and best practices.* ®International Energy Agency. www.iea.org

IEA – International Energy Agency (2022b) *Canada 2022 Energy Policy Review*. ®International Energy Agency. www.iea.org

IEEFA – Institute for Energy Economics and Financial Analysis (2023) *Eye-popping new cost estimates released for NuScale small modular reactor*. Available at: https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor

IRENA (2019) *Innovation landscape brief: Flexibility in conventional power plants*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Flexibility_in_CPPs_2019.pdf

IRS – Internal Revenue Service (2023a) *Energy Efficient Home Improvement Credit*. Accessed July 2023. Available at: https://www.irs.gov/credits-deductions/energy-efficient-home-improvement-credit

IRS – Internal Revenue Service (2023b) *Energy Efficient Commercial Building Deduction*. Accessed July 2023. Available at: https://www.irs.gov/credits-deductions/energy-efficient-commercial-building-deduction

IREC – Interstate Renewable Energy Council (2023) *Key Recommendations: Cultivating a Diverse and Skilled Talent Pipeline for the Equitable Transition*. February. Available at: https://irecusa.org/resources/key-recommendations-cultivating-a-diverse-and-skilled-talent-pipeline-for-the-equitable-transition/

IREC - Interstate Renewable Energy Council (2022) *National Solar Jobs Census 2021* (July 2022). Available at: http://www.SolarJobsCensus.org

JD Power (2023) *Public Charging Issues May Short-Circuit EV Growth, J.D. Power Finds*. Available at: https://www.jdpower.com/business/press-releases/2023-us-electric-vehicle-experience-evx-public-charging-study

Jenkins, J.D., Mayfield, E.N., Farbes, J., Jones, R., Patankar, N., Xu, Q., Schivley, G. (2022) *Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022*. REPEAT Project, Princeton, NJ, August 2022. DOI: 10.5281/zenodo.7106218. This version updated September 21, 2022.

Jenks, C., Dobie, H.O., Dewey, S., Perls, H. (2023) *EPA's proposed greenhouse gas emission standards for powr plants are consistent with statutory factors and market trends*. Harvard Law School, Environmental & Energy Law Program. Available at: https://eelp.law.harvard.edu/2023/05/epas-proposed-greenhouse-gas-emission-standards-for-power-plants-are-consistent-with-statutory-factors-and-market-trends/

Lazard (2023) 2023 *Levelized Cost of Energy + Report*. Available at: https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

LBNL – Lawrence Berkeley National Laboratory (2023a) *Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2022*. April. https://emp.lbl.gov/sites/default/files/queued_up_2022_04-06-2023.pdf

REFERENCES

LBNL – Lawrence Berkeley National Laboratory Electricity Markets & Policy (2023b) *Generator Interconnection Costs to the Transmission System – Summary Briefing*. Available at: https://emp.lbl.gov/publications/generator-interconnection-costs

Lebel, E. D, Finnegan, C. J et al. (2022) *Methane and NOx emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes. Environmental Science & Technology* 56 (4), 2529-2539 DOI: 10.1021/acs.est.1c04707

Lovins, A. (2023) *Quintupling global energy efficiency by 2060*. Speech at: Sustainability Accelerator Workshop. Stanford, California, USA, 24 May 2023.

McKinsey Sustainability (2023) *Toward a more orderly US energy transition: Six key action areas*. Available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/toward-a-more-orderly-us-energy-transition-six-key-action-areas

Microsoft (2023) *Carbon Removal Program*. Available at : https://www.microsoft.com/en-us/corporate-responsibility/sustainability/carbon-removal-program

Ministry of Natural Resources, Canada (2023) *Hydrogen Strategy for Canada*. Available at : https://natural-resources.canada.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen%20Strategy%20for%20Canada%20Dec%2015%202200%20clean_low_accessible.pdf

Müller N, Kouro S, Zanchetta P, Wheeler P, Bittner G, and Girardi F. (2019) 'Energy Storage Sizing Strategy for Grid-Tied PV Plants under Power Clipping Limitations'. *Energies* 12, no. 9: 1812. https://doi.org/10.3390/en12091812

Nat.Clim.Chang. – Nature Climate Change (2019) *Lobbying for and against climate solutions*. 9, 427. May 28. https://doi.org/10.1038/s41558-019-0499-4

NJ (2023) *Offshore wind isn't killing whales. Big oil and gas want you to think it is*. Written by: Freeman, M. Available at: https://www.nj.com/opinion/2023/07/offshore-wind-isnt-killing-whales-big-oil-and-gas-just-want-you-to-think-it-is-opinion.html

Norman, Will (2023) *IRS releases guidance on domestic content requirements for renewables under the IRA'*. May 16. Available at: https://www.pv-tech.org/irs-releases-guidance-on-domestic-content-requirements-for-renewables-under-the-ira/

NPR – National Public Radio (2011) *Solar-Powered Marines See Gains In Afghanistan*. By: Bill Chappell. January 17. Available at: https://www.npr.org/sections/alltechconsidered/2011/01/17/133006575/solar-powered-marines-see-gains-in-afghanistan

NYT – New York Times (2023) *The U.S. Weather by the Numbers*. By: Colbi Edmonds, Camille Baker. July 24. Available at: https://www.nytimes.com/article/us-heat-wave-temperatures.html

PNNL – Pacific Northwest National Laboratory (2021a) *Impacts of Model Building Energy Codes – Interim Update*. July. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-31437.pdf

PNNL – Pacific Northwest National Laboratory (2021b) *Keeping an Eye on the World's Largest Machine: How Measurements are Modernizing the Electric Grid*. Presented by: Jim Follum. November 9. Available at: https://www.pnnl.gov/events/keeping-eye-worlds-largest-machine-how-measurements-are-modernizing-electric-grid

Politico (2023a) *Why Canada could be the answer to China's clean tech dominance*. By: Doug Palmer, Zi-ann Lum and Kelsey Tamborrino. March 24. Available at: https://www.politico.com/news/2023/03/24/united-states-and-canada-break-china-tech-dominance-00088598

Politico (2023b) *Utilities to Biden's carbon capture money: Meh*. By: Arianna Skibell. July 7. Available at: https://www.politico.com/newsletters/power-switch/2023/07/11/utilities-to-bidens-carbon-capture-money-meh-00105650

Princeton University (2020) *Net-Zero America: Potential pathways, infrastructure, and impacts*. Available at: https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

Quartz (2023) *The US is laying new power lines too slowly for its renewables transition*. By: Aurora Almendral. April 13. Available at: https://qz.com/the-us-is-laying-new-power-lines-too-slowly-for-its-ren-1850326951

RBC – Royal Bank of Canada (2022) *Green Collar Jobs: The skills revolution Canada needs to reach Net Zero*. Available at: https://thoughtleadership.rbc.com/green-collar-jobs-the-skills-revolution-canada-needs-to-reach-net-zero/

Rhodium Group (2022) *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*. Written by: John Larsen, Ben King, Hannah Kolus, Naveen Dasari, Galen Hiltbrand, and Whitney Herndon. August 12. Available at: https://rhg.com/research/climate-clean-energy-inflation-reduction-act/

Rosen, J. A., and Gribbin, D.J. (2021) 'The most important part of the infrastructure bill is little noticed'. *The Hill*, 29. September. https://thehill.com/opinion/finance/574370-the-most-important-part-of-the-infrastructure-bill-is-little-noticed/

RMI – Rocky Mountain Institute (2022) *RMI comments to SEC on proposed climate-related disclosure rule*. By: RMI's Center for Climate-Aligned Finance. June 27. Available at: https://climatealignment.org/wp-content/uploads/2022/06/rmi_comments_to_sec_on_proposed_climate_related_disclosure_rule_june_2022.pdf

S&P Global (2022) *Battery storage arbitrage potential charged by renewables growth*. Available at: https://www.spglobal.com/marketintelligence/en/news-insights/research/battery-storage-arbitrage-potential-charged-by-renewables-growth

SEIA – Solar Energy Industries Association & Wood Mackenzie Power & Renewables (2023) *Solar Market Insight Report Q1 2023*.

Smart Energy USA (2023) *The Rise of Automation in Solar Farm Construction*. May 18. Available at: https://smartenergyusa.com/news/the-rise-of-automation-in-solar-farm-construction/

Smith, E. R. A. N, and Klick, H. (2007) *Explaining NIMBY Opposition to Wind Power*. Available at: https://smith.faculty.polsci.ucsb.edu/wind.pdf

Statistic Canada (2023a) *Coal, monthly production and exports*. Accessed June 2023. Available at: https://www150.statcan.gc.ca/n1/en/catalogue/25100046

Statistic Canada (2023b) *Supply and disposition of crude oil and equivalent*. Accessed June 2023: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510006301

Statistic Canada (2023c) *Supply and disposition of natural gas, monthly*. Accessed June 2023: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510005501

Stringer, T., Joanis, M. (2022) 'Assessing energy transition costs: Sub-national challenges in Canada'. *Energy Policy* 164, 112879, Elsevier.

Sustainable Finance Action Council (2022) *Taxonomy Roadmap Report: Mobilizing Finance for Sustainable Growth by Defining Green and Transition Investments*. Available at: https://www.canada.ca/en/department-finance/programs/financial-sector-policy/sustainable-finance/sustainable-finance-action-council/taxonomy-roadmap-report.html

TD Economics (2021) *Don't Let History Repeat: Canada's Energy Sector Transition and the Potential Impact on Workers*. Available at: https://economics.td.com/esg-energy-sector

The Geography of Transport Systems (2020) *World Main Highway and Primary Road Network*. Written by: Jean-Paul Rodrigue. Available at: https://transportgeography.org/contents/chapter5/road-transportation/world-road-network/

Tyson, A., Funk, C., Kennedy, B. (2023) *What the data says about Americans' views of climate change,* Pew Research Center. Available at: https://www.pewresearch.org/short-reads/2023/08/09/what-the-data-says-about-americans-views-of-climate-change/

US DOE – Department of Energy (2023a) *Energy earthshots: Industrial Heat Shot™*. https://www.energy.gov/eere/industrial-heat-shot

US DOE – Department of Energy (2023b) *Weatherization Assistance Program*. Available at: https://www.energy.gov/scep/wap/weatherization-assistance-program

US DOE – Department of Energy (2023c) *Biden-Harris Administration Announces Up To $1.2 Billion For Nation's First Direct Air Capture Demonstrations in Texas and Louisiana*. Available at: https://www.energy.gov/articles/biden-harris-administration-announces-12-billion-nations-first-direct-air-capture

REFERENCES

US DOE – Department of Energy (2023d) *State and Community Energy Programs (SCEP) Inflation Reduction Act of 2022 Home Energy Rebates: Home Efficiency Rebates & Home Electrification and Appliance Rebates*. Available at: https://www.energy.gov/sites/default/files/2023-07/Home_Energy_Rebates_ALRD.pdf

US DOE – Department of Energy (2023e) *Federal Solar Tax Credits for Businesses.* Available at: https://www.energy.gov/eere/solar/federal-solar-tax-credits-businesses

US DOE – Department of Energy (2023f) *DOE Hydrogen Program Request for Information # DE-FOA-0002529*. Available at: https://www.energy.gov/eere/fuelcells/articles/doe-hydrogen-program-request-information-de-foa-0002529

US DOE – Department of Energy (2022a) *Carbon Negative Shot™*. https://www.energy.gov/fecm/carbon-negative-shot

US DOE – Department of Energy (2022b) *Biden-Harris Administration Announces Steps to Electrify and Cut Emissions from Federal Buildings. December 7*. https://www.energy.gov/articles/biden-harris-administration-announces-steps-electrify-and-cut-emissions-federal-buildings

US DOE – Department of Energy (2022c) *Land-Based Wind Market Report: 2022 Edition*. Available at: https://www.energy.gov/sites/default/files/2022-08/land_based_wind_market_report_2202.pdf

US DOE – Department of Energy (2022d) *Building a Better Grid initiative*. Available at: https://www.energy.gov/gdo/building-better-grid-initiative

US DOE - Department of Energy (2021) *Civil nuclear credit program.* Available at: https://www.energy.gov/gdo/civil-nuclear-credit-program

USDS – United States Department of State and the United States Executive Office of the President (2021) *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. Washington DC. November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

US Department of the Treasury (2023) *Remarks by Secretary of the Treasury Janet L Yellen on the Economy Ahead of Inflation Reduction Act Anniversary in Las Vegas,* Nevada. August 14. Available at: https://home.treasury.gov/news/press-releases/jy1693

US Public Law (2023) H.R.3746 - *Fiscal Responsibility Act of 2023*. Public Law No: 118-5. 06/03/2023. https://www.congress.gov/bill/118th-congress/house-bill/3746

Utility Dive (2022) *Utilities sound alarm over distribution transformer shortage as procurement times surpass 1 year and costs triple.* By: Robert Walton. Available at: https://www.utilitydive.com/news/distribution-transformer-shortage-appa-casten/639059

Visual Capitalist (2023) *Breaking down Clean Energy Funding in the Inflation Reduction Act*. Available at: https://decarbonization.visualcapitalist.com/breaking-down-clean-energy-funding-in-the-inflation-reduction-act/

Washington Post (2023) *They opposed the infrastructure law. Now, some in the GOP court its cash*. July 9. Available at https://www.washingtonpost.com/business/2023/07/09/gop-spending-infrastructure-ira-biden/

White House (2023) *Building A Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action*. January, 2023, Version 2. Available at: https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

White House et al. (2023) *U.S. National Clean Hydrogen Strategy and Roadmap*. Available at: https://www.powermag.com/wp-content/uploads/2023/06/us-national-clean-hydrogen-strategy-roadmap.pdf

White House (2023-08-16) *Fact Sheet: One Year In, President Biden's Inflation Reduction Act is Driving Historic Climate Action and Investing in America to Create Good Paying Jobs and Reduce Costs*. Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2023/08/16/

White House (2023-07-28) *Biden-Harris Administration Proposes Reforms to Modernize Environmental Reviews, Accelerate America's Clean Energy Future, and Strengthen Public Input*. Available at: https://www.whitehouse.gov/ceq/news-updates/2023/07/28/biden-harris-administration-proposes-reforms-to-modernize-environmental-reviews-accelerate-americas-clean-energy-future-and-strengthen-public-input

White House (2023-05-20) *G7 Clean Energy Economy Action Plan.* https://www.whitehouse.gov/briefing-room/statements-releases/2023/05/20/

White House (2022a) *Delivering on the U.S. Methane Emissions Reduction Action Plan*. November. https://www.whitehouse.gov/wp-content/uploads/2022/11/US-Methane-Emissions-Reduction-Action-Plan-Update.pdf

White House (2022b) *Building a better America: A guidebook to the Bipartisan Infrastructure Law for state, local, tribal, and territorial governments, and other partners*. 2nd edition. Available at: https://www.whitehouse.gov/wp-content/uploads/2022/05/BUILDING-A-BETTER-AMERICA-V2.pdf

White House (2022-12-07) *US-UK Energy Security and Affordability Partnership*. https://www.whitehouse.gov/briefing-room/statements-releases/2022/12/07/

White House (2022-11-07) *Joint Readout of U.S.-EU Task Force Meeting on Energy Security*. https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/07/

White House (2022-10-19) *Remarks by President Biden on Actions to Strengthen Energy Security and Lower Costs.* https://www.whitehouse.gov/briefing-room/speeches-remarks/2022/10/19/

White House (2022-08-09) *Fact Sheet: CHIPS and Science Act.* https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

White House (2021) *Fact Sheet: President Biden Tackles Methane Emissions, Spurs Innovations, and Supports Sustainable Agriculture to Build a Clean Energy Economy and Create Jobs*. November 2. Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/02/

Wood, Kimberly (2023) *Cybersecurity Policy Responses to the Colonial Pipeline Ransomware Attack.* Georgetown Environmental Law Review. May 7. https://www.law.georgetown.edu/environmental-law-review/blog/cybersecurity-policy-responses-to-the-colonial-pipeline-ransomware-attack/

WRI – World Resources Institute (2023) *US Clean Energy Goals Hinge on Faster Permitting.* By: Lori Bird and Katrina McLaughlin. February 9. https://www.wri.org/insights/clean-energy-permitting-reform-us

Historical data

This work is partly based on the World Energy Balances database developed by the International Energy Agency© OECD/IEA 2023, but the resulting work has been prepared by DNV and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2022) numerical data is mainly based on IEA data from World Energy Balances© OECD/IEA 2023, www.iea.org/statistics, License: www.iea.org/t&c; as modified by DNV.

THE PROJECT TEAM

Core contributors

Steering committee: Remi Eriksen, Ditlev Engel, Ulrike Haugen, Trond Hodne, Liv Hovem, Jin James Huang.

Regional leadership: Richard Barnes, Antony DSouza

Project director: Sverre Alvik

Project manager: Sujeetha Selvakkumaran (sujeetha.selvakkumaran@dnv.com)

Editor: Mark Irvine (mark.irvine@dnv.com)

Modelling responsible: Onur Özgun

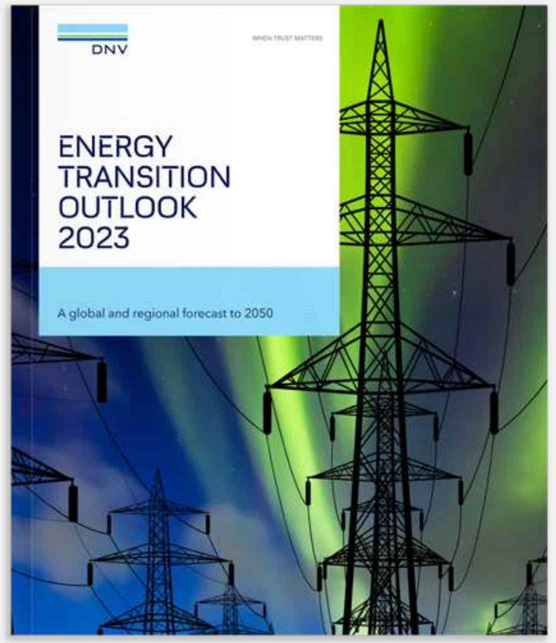
Core research team and authors: Jan Hagen Andersen, Michelle Bruchs, Kaveh Dianati, Mahnaz Hadizadeh, Thomas Horschig, Anne Louise Koefoed, Margaret Konsella, Matt Lockwood, Mats Rinaldo, Eduard Romanenko, Steven Sawhill, Adrien Zambon.

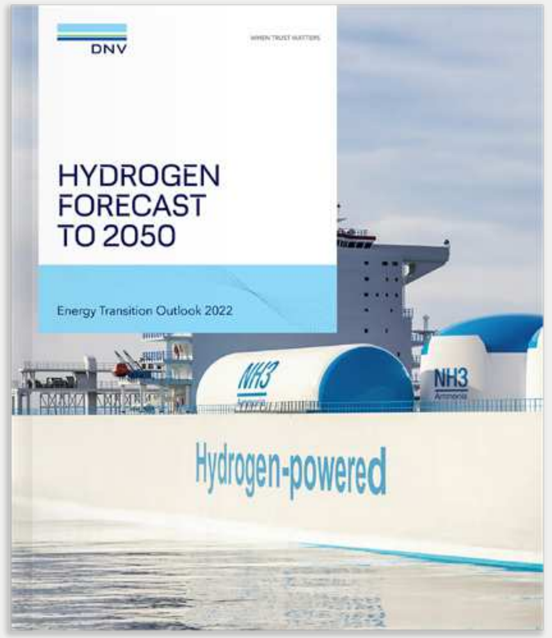
Energy systems: Adam Abatzis, Amanda Raddatz Bopp, Andre Boulet, Philippe Brodeur, Timothy Burke, Kora Dreffs, Pedram Fanailoo, Jake Frye, Miriam Goldberg, Jason Goodhand, Amit Goyal, Marion Hill, Elizabeth Kangu Kaiga, Amit Kanungo, James Killigrew, John Landry, Brady McNall, Jennifer McWilliams, Satyen Moray, John Negus, Dana Olson, Vineet Parkhe, Graeme Pirie, Doug Price, Morgan Putnam, Jose Quevedo, Mitchell Rosenberg, Gomathi Sadhasivan, Mark Sayer, Cynthia Spitzenberger, Susan Stefanovich, Carrie Webber, Wesley Whited, Roel Jouke Zwart.

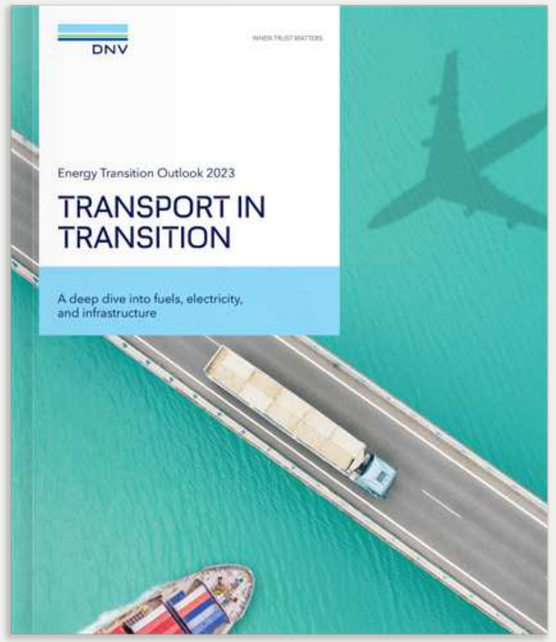
Maritime: Richard Kennedy

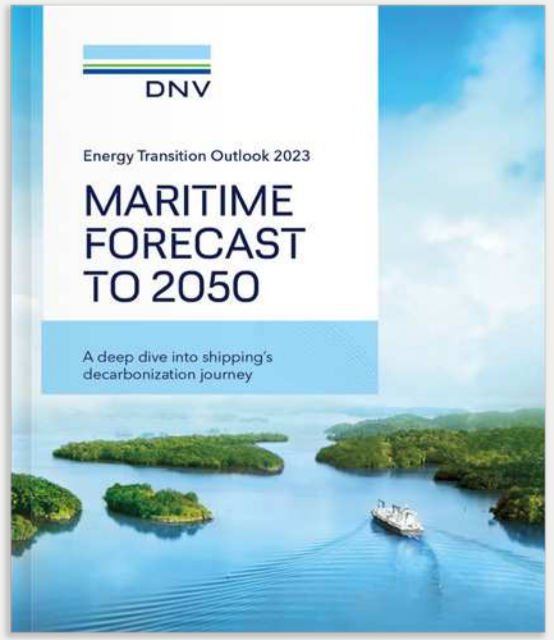
Communications: Bethany Genier, Kayla Leary

Published by DNV AS.
Design: Minnesota Agency/Fasett.
Images: P. 92, Getty Images. P. 1, 6, 9, 11, 17, 20, 22, 31, 32, 36, 58, 60, 64, 66, 74, 76, 79, 90, 91, 94, 95, 96, Shutterstock. P. 5, 8, 19, 24, 25, 28, 29, 39, 57, 61, 72, 78, 80, 82, 84, 88, Unsplash. P. 37, 56, Adobe Stock. P. 13, 18, 42, 44, 47, 53, 70, 86, NREL. P. 2, 67, DNV.









Don't miss our upcoming reports:

Energy Transition Outlook 2050 (main report) and our Pathway to Net Zero Emissions (October 11, 2023).

Subscribe to the latest Energy Transition insights from DNV
dnv.com/energy-transition/subscribe.html

For our Maritime Forecast (2050)
dnv.com/maritime-forecast

DNV

WHEN TRUST MATTERS

About DNV

DNV is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable organizations to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries.

Combining technical, digital and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide customers and society with operational and technological foresight. With 125 years of experience in North America, our experts are dedicated to helping customers make the world safer, smarter and greener.

www.dnv.com

Headquarters
DNV AS
NO-1322 Høvik, Norway
Tel: +47 67 57 99 00

United States
1400 Ravello Drive
Katy, Texas 77449
Tel: +1 281 396 1000

Canada
1771 Robson St
V6G 1C9 Vancouver
Tel: +1 604 689 7425