DEEP DECARBONIZATION FROM A GLOBAL PERSPECTIVE:

FINDING CANADA'S FUTURE IN A NET-ZERO WORLD

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Accelerating industrial change to drive decarbonization and sustainable economic development.

The *Clean Competitiveness Roadmaps* project seeks to create the foundations for a Canadian green industrial strategy. The goal is to build collaboration between governments, businesses, First Nations, civil society, and finance in high priority action areas.

This is the first of two reports that lay the groundwork for co-designing and co-deploying transition pathways in specific sectors. This report provides a vision of the 2050 global energy system and begins the work of placing Canada within it. The second report assesses Canada's prospects for building competitive green industries across sectors, identifies the top opportunities for concerted action, and lays out the principles for successful green industrial strategy.

These analyses inform our engagement work in the priority sectors. This work focuses on co-designing transition pathways or roadmaps for technological, economic, and social change with partners in the sectors.

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Executive Summary

Canada needs a strategic, mission-driven approach to building the industries that will create value in the Canadian economy throughout the energy transition and beyond. We must identify ways to catalyze the development of Canadian industries in areas that will facilitate rapid decarbonization while creating the conditions for long-term prosperity.

The analytical challenge for such a project is to assess economic opportunity in the absence of knowledge about what technologies will be thermodynamically and socially viable over long timelines. The first step is to establish a vision of the global energy system in 2050 and to think about how a small, open economy like Canada might position itself economically in that world.

To begin this work, the Pacific Institute for Climate Solutions, the Smart Prosperity Institute, and Transition Accelerator conducted a study that synthesizes the existing literature on the future of decarbonization technology and policy strategies. This is the first of two reports that lay the groundwork for our project. The companion report places Canada within the net-zero world outlined here and assesses Canada's prospects for building competitive green industries across sectors.

This report reviews the major findings from several of the leading model-based studies of deep decarbonization. We focus on global models, for the most part, and models that attempt to simulate the behavior of the entire economy. As such, their results are highly sensitive to a large number of assumptions and simplifications that are necessary to make such modeling activities tractable. Thus, these results must be treated as not the final word but a starting point for analysis.

This report outlines what is likely, probable, and unknown in the development of global energy systems between now and 2050. First, nearly all studies agree that deep decarbonization involves profound **electrification**, with the share of final energy delivered in the form of electricity doubling or tripling over the coming few decades. The extent of electrification depends heavily on progress with end use electrification technologies such as heat pumps and high-power density batteries that can be used for heavy duty vehicles. If progress with these technologies is unexpectedly rapid then the degree of electrification could be even more extensive.

Electrification is emblematic of one of the most important implications of deep decarbonization for investment and for industrial policy: **deep decarbonization means electrification and capitalization**. Deep decarbonization is highly likely to involve a reduction in spending on operating costs, such as fuels, and a big increase in long-duration capital expenditures. It will be extremely important for policymakers to identify and implement strategies that invest capital wisely and keep the costs of capital for the private sector low. Governments and firms that succeed in this domain could be big winners in the effort to decarbonize.

Over time, nearly all these models have envisioned decarbonization of the power sector involving a greater and greater share of renewables. That suggests that it will be important to pay attention to the integration of renewable power into grids while keeping costs and reliability tolerable. A suite of technologies that provide **firm, clean power** will be important. That might include large storage systems, natural gas with carbon capture and storage (CCS), power plants that consume hydrogen, small modular nuclear reactors, or something else. This is an area the modeling points to a clear need but the solutions are, as of yet, hard to pin down.

Electrification presents a number of economic opportunities. The supply chains for core renewable technologies are already formed and dominated by big global players. So it is unlikely that a small economy like Canada will capture significant market share there. But adding renewables to its already clean grid will create jobs and could generate exportable power. Moreover, electric vehicle supply chains, battery technologies, cleantech for buildings, and geothermal options are still emerging and Canada could make a play in these areas to benefit from widespread electrification.

Second, there are many sectors and systems where the technological solutions for deep decarbonization are still at an early stage. In these areas strategic policymaking must grapple with deep uncertainty. **Hydrogen**, for example, could become a very important energy carrier and there is already extremely rapid expansion of investment in electrolyzers for producing hydrogen around the world, especially in Europe where investors enjoy strong policy support. It is probable that there will be economic opportunities for countries with relevant expertise in hydrogen supply chains, but the size of the ultimate global market for hydrogen is uncertain.

Agriculture and forestry play a substantial role in the overall emissions picture. In the future they could be areas of massive mitigation opportunity. However, most of the global models were not designed for studying agriculture and land use—they are stronger in their representation of industry, especially energy—and thus the opportunities they suggest must be tempered with the reality that policies that alter land use are difficult to design and implement.

Protecting and expanding existing forests, including in the temperate and boreal zone, could offer substantial opportunities to expand carbon sinks that are already growing. Perhaps most intriguing is the possibility of new specialized crops that sequester carbon in soils, along with expansion of specialized bioenergy crops. The models identify these opportunities and suggest that, with the right technologies, bioenergy and biosequestration could be major industries.

In general, the large industrial system models are not tuned to focus on what happens to the **incumbents**. Politically, however, the implications for the incumbents and their behavior is likely to have a big impact on the policies and the shift in capital that results. Essentially all the models suggest that incumbent high carbon industries, notably coal but also oil and perhaps natural gas, will suffer substantially. Countries that depend on these industries will face significant challenges. But there are uncertainties here too. The rate of implosion for the oil industry depends a lot on the viability of alternatives, including biofuels.

One of the biggest wildcards for the future concerns natural gas. Until very recently most studies showed an expansion and natural gas utilization, but deep decarbonization might bring about a contraction of natural gas. One of the most critical questions concerns the availability of CCS, which would allow continued use of natural gas in many applications. Another possibility is that hydrogen and biomethane could be blended with conventional natural gas to allow the ongoing use of the costly natural gas infrastructure. Many countries are investing in CCS, but its cost structures and therefore tenability as a strategy remains uncertain.

Studies like this tend to focus on the knowns and the probable outcomes, rather than recognize the full scope of uncertainty. The fact is we can’t establish a concrete vision of the 2050 global economy and its specific technological components. But governments have to find ways to act strategically despite the profound uncertainties that cloud the energy transition. Strategic government action is needed to focus action, absorb risk, and represent the interests of society as a whole. Our review suggests that governments should pay close attention to a handful of **design principles** for policy that can help balance these aims:

- Deep decarbonization means industrial scale innovation and commercialization. The best bet for doing it fast is to use nimble, collaborative forms of green industrial policy.
- A green industrial strategy must distinguish between areas where the outcomes are broadly understood, such electrification, and the many more areas where the pathways are unknown.
- In the unknown areas, adopt experimentalist orientation to policy where government and business work together to explore the options and learn what's feasible. In better understood areas, more directed forms of industrial policy are possible.
- To manage uncertainty, build a balanced portfolio of societal investments, making some in well understood areas, and some in unknown areas.
- Invest in knowledge and experience through clean energy research development and demonstration. This knowledge can be applied throughout the transition.

Policy experiments need to start now and must be integrated into long-term strategies if **small open, economies like Canada** are to seize the considerable economic opportunities that the energy transition presents.

Introduction

The global economy is in the early stages of a pervasive deep decarbonization that will reconfigure patterns of production, trade, and power. Canada needs to position itself in the 21st century global green economy that will emerge from the transition. Doing that requires thinking about two big strategic questions:

- What will the global, decarbonized economy in 2050 look like?
- How should a small, open economy like Canada position itself in that economy?

Looking to 2050, Canada's strategic position contains both opportunities and risks. Deep decarbonization demands the transformation of all the core industries in the global economy. Energy production, automobiles, aviation, shipping, steel, cement, and more must be reinvented. The resulting shifts in production and trade present opportunities for countries and firms that act early and decisively. Moreover, there is a real possibility that the transition will create abundant cheap energy that enhances the competitiveness and productivity of some economies.[1]

But there are also downside risks, especially for countries like Canada that are heavily invested in the oil & gas sector. [2] If Canada transitions the oil & gas sector while building up clean industry, it has the potential to become a global leader in the technologies and services that the 2050 global economy needs. This would add value to the Canadian economy and secure its long-term prosperity.

If it lags, Canada could experience financial instability and economic stagnation as the oil & gas sector declines under competition from alternative energy sources and global capital flees due to high transition risks.[3] Most of the modeling on this question suggests that oil & gas markets will transition smoothly, but the real risk is of a "climate Minsky moment"—a sudden collapse in asset prices.[4] This would have systemic effects on investors throughout the economy, especially in Canada where institutional investors hold oil & gas assets.

There are also political risks that could be compounded by Canada's strong carbon pricing plan. Without investments in technological and behavioral alternatives, carbon prices could increase firm and consumer costs without inducing the transformation needed in the industrial system.[5] This could generate a political backlash that will set Canadian progress on climate policy back.[6]

Building clean industries can make the politics of decarbonization easier.[7] It creates and strengthens actors that are invested in the transition and makes the economy less dependent on the incumbent fossil-fuel economy. This increases the government's ability to politically manage intransigent incumbents and foster a just transition.

Canada needs a strategic approach to rapidly reposition its economy in the emerging global green economy. It must intentionally build clean industries that provide essential technologies and services for the decarbonized global economy.

Any strategic approach to building competitive clean industries in the global economy faces three interlocking challenges. First, energy technologies and industries are parts of larger systems with many interdependent parts. To make EVs commercially and politically viable, there is a need for cheap batteries and their associated supply chains along with networks of charging stations and viable business models for sales and charging. Failure in any element of these interlocking actions and markets slows progress in all the others; each element in the overall system is co-determined with the others. Building these interconnections requires strategic coordination among governments, industry, and researchers across sectors.

Second, as a smaller economy open to international trade and investment, Canada's prospects depend critically on the global context. Indeed, the supply chains for the prospective technologies and industries are globalized. They must be forged in collaboration with other countries. For example, in solar and wind supply chains, China dominates final production but German firms capture significant value as an intermediary producer and some US firms receive benefits from IP licensing.[8] (Variation in tax and employment regimes affect, in turn, how widely those firm-focused benefits accrue to the broader society.) Across nearly every major area of rapid progress in deep decarbonization—from renewables to batteries to EVs—globalization of supply chains has been a major determinant of success. Canada must assess its ability to contribute to globalized production for key technologies while also operating strategically in a world where there are pressures for de-globalization, including within Canada's largest trading partner the US.

Third, all of this must be done under the conditions of profound uncertainty. Canada must find its competitive advantage inside global value chains without knowing the technological landscape of 2050. Government and industry must invest in infrastructures without knowing which investments will be most rewarding and how the variation in returns will shape the overall direction of the system. It must engage with and shape political processes—including confronting political winds against globalization that has been a backbone of an open economy—not knowing which political forces will prove easy or impossible to manage. The task of identifying and backing the technologies that will play a key role in 2050 is daunting. It necessitates an experimentalist orientation that allows the country to make investments and update those bets as we collectively learn which initiatives fit within the existing sociopolitical landscapes, energy systems, and global value chains.[9]

Deep Decarbonization from a Global Perspective

This report seeks to address these challenges by synthesizing the massive and rapidly growing literature on how to achieve global deep decarbonization. It presents a vision of a 2050 global energy system that recognizes that it is impossible to chart a detailed path from today to net zero. In some senses, the powerful images of a clean decarbonized economy get in the way of serious policy planning because those images suggest knowns where, in fact, the future is mostly a parade of unknowns.[10] Thus, we offer less an exhaustive and detailed assessment of technological options—other studies offer that—and more the strategic insights that emerge from the literature.

We focus on three central questions.

1. **Where are the patterns of deep decarbonization known with high confidence, and where are the unknowns more profound?**
2. **What are the attributes of the industries will have the most value in a decarbonized global economy, and which kinds of industries will likely face decline?**
3. **As Canada grapples with its opportunities in this global effort, what has been learned about design criteria and investment principles for effective action under the conditions of profound uncertainty?**

To answer these questions we will distill key insights from highly credible global decarbonization studies. We, in particular, draw heavily from three sources:

- The IPCC's most recent assessment reports, including Assessment Report #5 (AR5) published in 2014 (AR6 is not yet complete at this writing).[11]
- The IPCC Special Report on 1.5 degrees (SR1.5).[12]
- The annual International Energy Agency World Energy Outlook (WEO), in particular the Sustainable Development Scenario (SDS) and Net zero by 2050 scenarios publishes as part of the 2020 report.[13]

Along the way, we complement these studies with input from particular integrated assessment model (IAM) research groups that are highly reliable and credible.

Global studies are, by design, very broad. We thus also look at two different kinds of focused studies. Some studies have concentrated on particular sectors, in the special roles of the electric power sector[14] and also at the so-called "hard to abate" sectors, such as steel and aviation, where known solutions are still in the very early stages of technological development.[15] We also looked at regional studies, with a special emphasis on Canadian and US modelling.[16]

In relying on studies that, in turn, depend on IAMs we are mindful of the strengths and weaknesses of these modeling frameworks. The strengths include the ability to look at deep decarbonization in an integrated economic context, at full or partial equilibrium, which offers insights into how the economic system as a whole evolves. Among the many limitations, of course, is the heavy dependence on assumptions—including around technological change, which plays a central role in projecting future costs and actions—and the difficulty of representing important social and political processes in these models.

In distilling insights from these models we focus on three core premises. First, the energy transition is underway and while there is wide uncertainty about the rate and extent of the transformation, the biophysical and economic advantages of emerging technologies will be disruptive. And while uncertainty about public policy targets and private investment commitments further clouds the picture, they have already seeded broad change.

Second, deep decarbonization is technological challenge but technology co-evolves with politics, industrial organization, and socio-cultural elements.[17] Technological and industrial frontiers are shaped by governments' industrial and military strategies as well as corporate spending. Those patterns of investment in turn depend on how the interests of states and firms have been structured by geopolitics, history, and markets. But technology is also not reducible to R&D. What works depends on landscapes of sociocultural norms and institutions as well as the interests of political and market incumbents. Technological uncertainty is compounded by political and social uncertainty.

Third, in the realm of geopolitics, we assume that patterns of production and trade will continue to be globalized. Efforts to onshore manufacturing and supply chains will alter economic patterns but not fundamentally transform them. That said, competition for market share among advanced economies will intensify as countries pursue industrial strategies to build industries for net-zero economies and seek to use investment and trade policy to advance those goals—only to find other countries making countervailing moves. For smaller open economies these patterns create risks (that economies will be sidelined or markets for innovative products will be smaller than expected) and opportunities (that reliable open economies can occupy market shares at the expense of geopolitical giants such as China).

The rest of this paper looks at the future of global energy systems from six perspectives. First, we examine the state of new energy technologies, focusing on 10 emitting sectors in particular. Second, we identify industrial changes that are virtually certain to be required in a world of deep decarbonization. Third, we look at probable—but far from certain—areas of industrial growth in a decarbonizing economy. Fourth, we look at unknowns: places where transformative technological and industrial changes could occur but are, at present, deeply uncertain. Fifth, we examine the mostly dark futures for the incumbents—high emitting fuels and industries. Sixth, and finally, we identify design principles that can govern policy and investment in deep decarbonization—principles anchored in the observations made across the rest of the paper about the state of the technology, the places where the right actions are known, and management of the many unknowns in deep decarbonization strategy.

The Uncertain Futures of Global Energy Systems

Given the central role for efficiency and decoupling of industrial services from carbon emissions, success with decarbonization will hinge on the creation, deployment and diffusion of new technologies throughout societies. Before looking at scenarios for the future of the global energy system, it is worth taking stock of where we are at present and what kind of emissions cuts are needed.

As a general matter, nearly all the variation in future emissions comes from changes in efficiency and in decarbonization of the energy system. The deeper the projected cuts in emissions the more important these efficiency and decarbonization factors. This is seen in Figure 1, reprinted from AR5, which looks across baseline assumptions for scenarios published at the time; the orange and grey shading shows the credible ranges in the assessments.

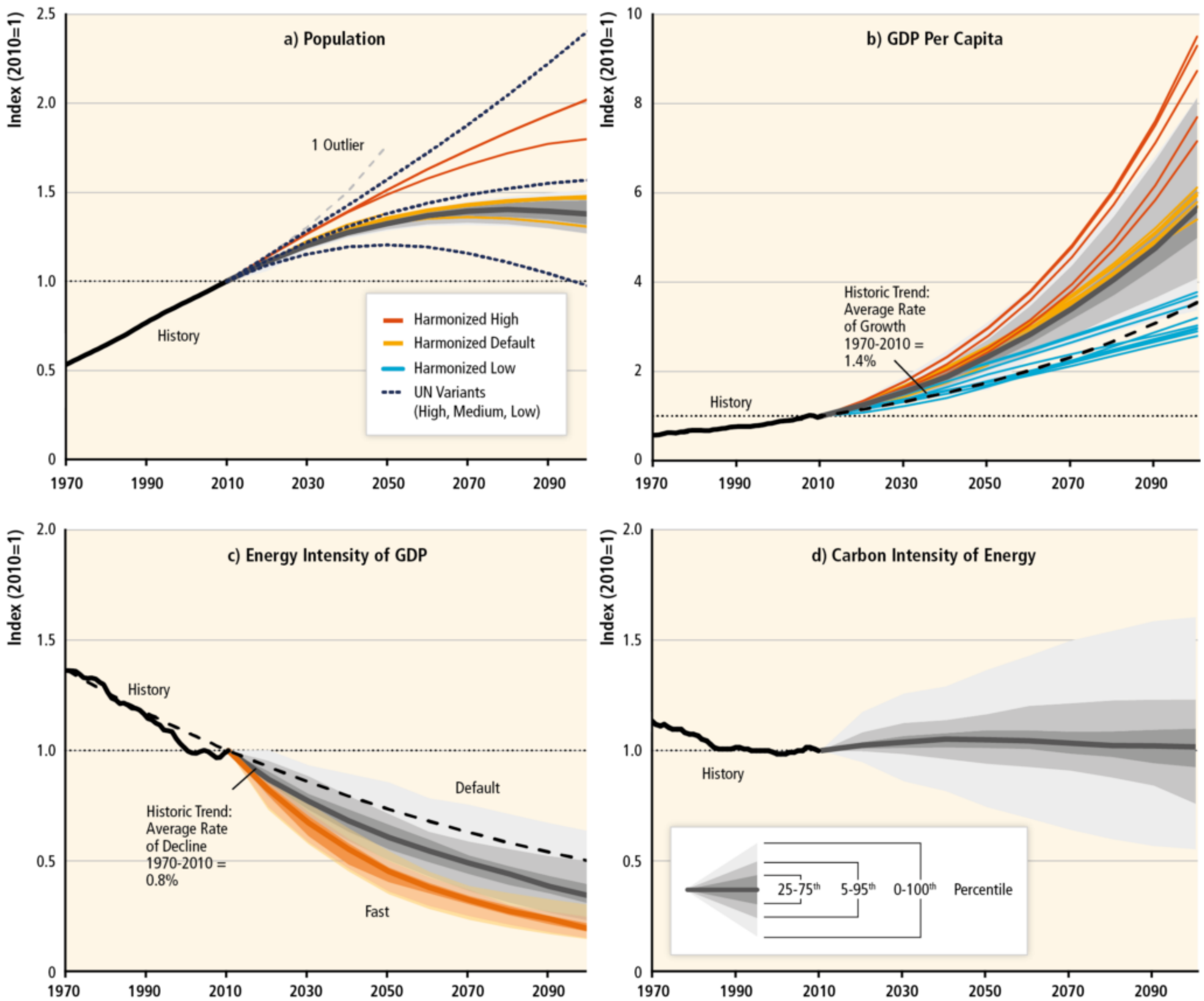

Figure 1: IPCC's evaluation of baseline assumptions. Source: IPCC AR5 SPM.

Put differently, the practical opportunities for deep decarbonization do not lie with population, the size of the economy and the demand for energy services. Those are a function of exogenous forces. Nearly all the leverage for achieving deep cuts in emissions comes from efficiency and carbon intensity—and that means technology and industrial transformation, not shrinking the population or the economy.

According to the IEA, 35% of the cumulative emission reductions between now and 2070 will come from technologies that today are in the early (demonstration or earlier) phases of development. If emission reductions are accelerated to net zero by the year 2050 then the emission cuts needed from these early stage technologies would nearly double.[18] These technologies won't advance without substantial additional investment in innovation.

There is no single "state" of technology. Instead, it is important to look at clusters of technologies fit for addressing particular high emission industrial and agricultural applications. Figure 2 offers one assessment of where the world is for 10 key emitting sectors.[19] In electric power, which nearly every study finds is crucial to deep decarbonization (more below), the world is furthest along. In many industrial sectors, by contrast, the needed changes are still at their infancy. A key message of Figure 2 is that the opportunity structure of different industries depends on their state. Electric power, cars, and buildings all present opportunities for those that can scale the technology or benefit from iterations that drive down costs. In plastics, heavy industry, long-distance transport, and agriculture there are opportunities to develop strong intellectual property positions and build innovative firms.

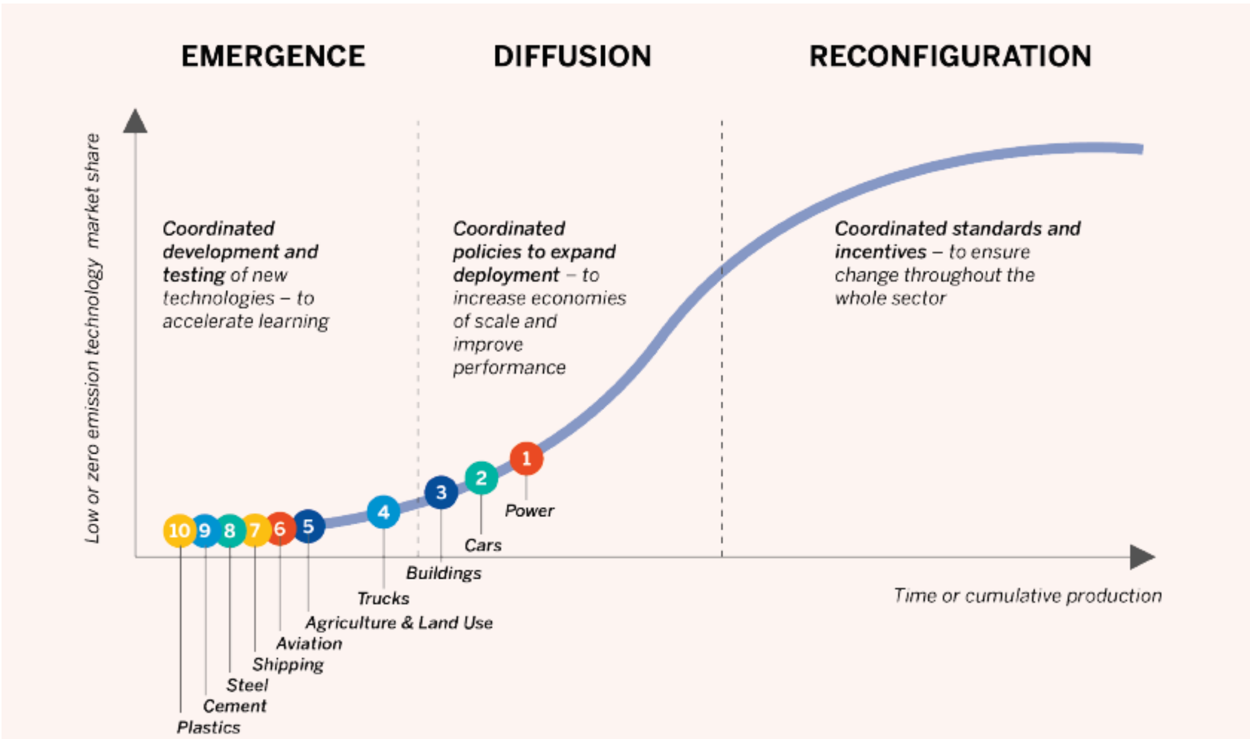

Figure 2: ETC analysis of the state of decarbonization technologies for each of 10 major emitting sectors. The figure aligns that assessment, which is anchored in more details sector-based studies, along the iconic S-shaped curve for emergence, diffusion and reconfiguration of markets that is familiar throughout the history of technological change. Source: Victor, Geels, and Sharpe 2019 [note 19].

At the opposite extreme are a number of studies that have imagineered the future—offered visions for what a decarbonized industrial system might look like. For example, Figure 3 envisions a future for a fully decarbonized energy system anchored around three interconnected infrastructures: electric power, fuels (hydrogen, ammonia, and decarbonized hydrocarbons), and CO_2.[20] The first two of these infrastructures are "energy carriers"—that is, they convey useful energy (in decarbonized form) to ultimate users. The third, CO_2, is a disposal infrastructure—a means of taking and CO_2 generated from these infrastructures and putting it safely underground (or through weathering of rocks) as carbon capture and storage (CCS), which allows for zero or even negative emission energy carriers. In the future, yet other energy carriers might become viable.

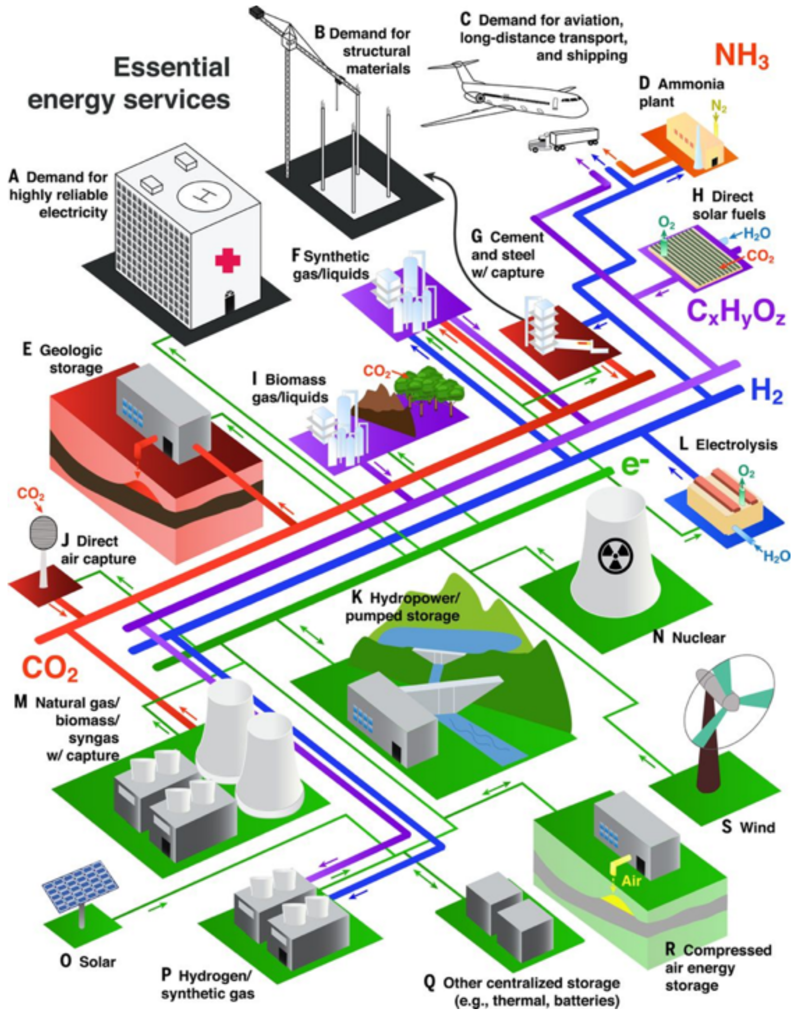

Figure 3: A vision for a decarbonized future energy system anchored around climate-friendly infrastructures. Source: Davis et al 2018 [note 20].

The key message of Figure 3 is that a decarbonized energy system is actually a system of systems—each highly interdependent. We can start action at the technological or sectoral level, but ultimately, efficiencies and economies of scale will be achieved at the level of systems flows between electric power, decarbonized fuels, and CO_2 management. To achieve these systemic outcomes, many of these pieces have to be created and commercialized together. Building these systems quickly will require industrial scale innovation and collaboration, for to varying degrees each system is co-dependent with the others.[21]

In some industries, such as electric power, the processes for innovation are shifting—to a greater role for innovations from outside the sector to "spill in" from external industries and thus provide innovation, to some degree, for "free." Innovations in solar cell manufacturing (rooted in semiconductor fabrication), in advanced batteries (rooted in advances in consumer electronics and then electric vehicles), and decentralized control systems (from theory of complex systems) are all examples of this.[22]

These new realities are a reminder that it is often hard to put firm boundaries around a "system of innovation" (and with globalization, even hard to do that on a territorial basis) and that some innovations arrive within a sector more easily than others. Yet policy will need to grapple with those difficulties because one of the central implications of Figures 2 and 3 is that a deeply decarbonized future hinges on devices and systems that often do not exist. No credible study sees a future of deep decarbonization without a future of massive increased investment in basic research along with applied development and demonstration. There is, at present, no authoritative estimate of under-investment in clean energy innovation, but a number of studies looking at particular systems, notably the US, suggest that innovation spending should increase by a factor of 2x to 4x.[23] The US already spends 3% of GDP compared to Canada's 1.5%.[24] To be competitive Canada will need to increase and target its investment in learning.

New Services that are virtually certain to be required

Nearly all studies of deep decarbonization agree that three things are all but certain if the world is to follow credible paths to much lower emissions.

First, and most striking, is electrification. Indeed, among the few maxims that all energy system models agree is true is that economies that decarbonize are economies that electrify. This agreement also helps explain the relatively modest levels of uncertainty around the degree of electrification likely, at least out to the year 2050. As shown in Figure 4, from the IPCC AR5 Assessment, even under baseline conditions the world economy is expected to continue electrification at a pace that would raise the share of final energy as electricity by about half. With substantial mitigation, electrification roughly doubles over that same period.[25]

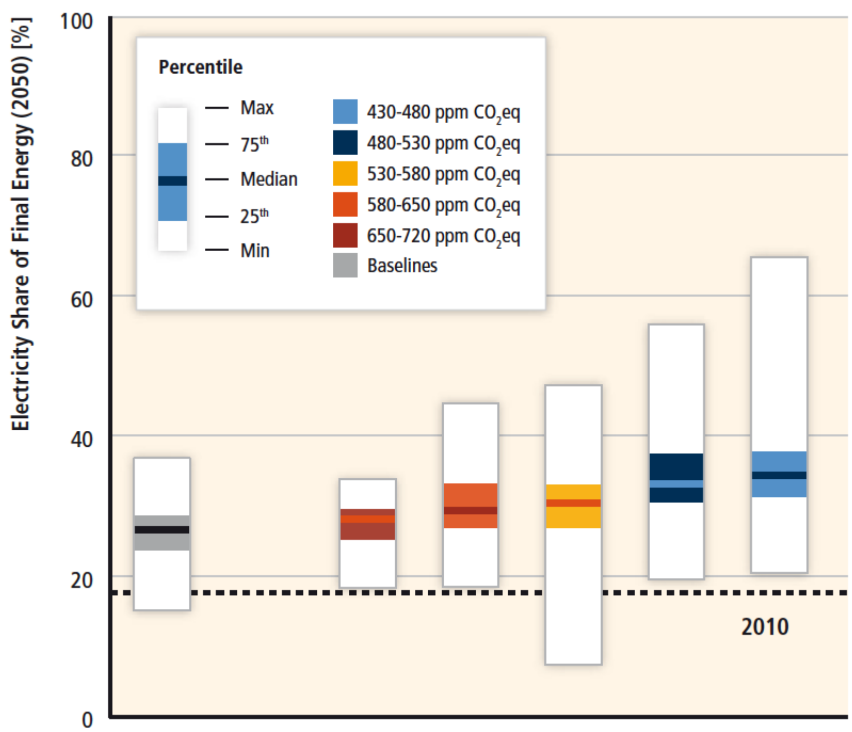

Figure 4: Electrification of final energy, currently at about 18%, rises under baseline conditions and doubles by the year 2050 for the most aggressive mitigation scenarios. Source: IPCC AR5 figure 7.13.

The logic behind electrification is rooted in a blend of technological happenstance and, in some places in the world, policy. It is proving less costly (and also easier from the perspective of industrial reorganization) to decarbonize electricity as an energy carrier and then electrify as many loads as practical. The question of how far electrification of loads can proceed is still hard to pin down. For light duty vehicles and many buildings electrification is straightforward and the models show that will accelerate. The role of biofuels in transportation services remains an important wildcard, but today both the models and reality envision electrification as the main route to decarbonization for light and medium duty vehicles.

In practice, electrification of end uses will vary enormously by the use—and the models that offer the most insight into that point are those focused in particular regions and on particular uses. For example, Figure 5 shows results from the US-focused Zero Carbon Action Plan (ZCAP) study and charts the possible replacement of fossil fuels in incumbent applications (space heating, water heating, light duty vehicles, and trucks) with non-fossil alternatives, mainly electric. These visions hinge on a few pivotal clusters of technologies—notably heat pumps, electric drivetrains & storage, and fuel cells.

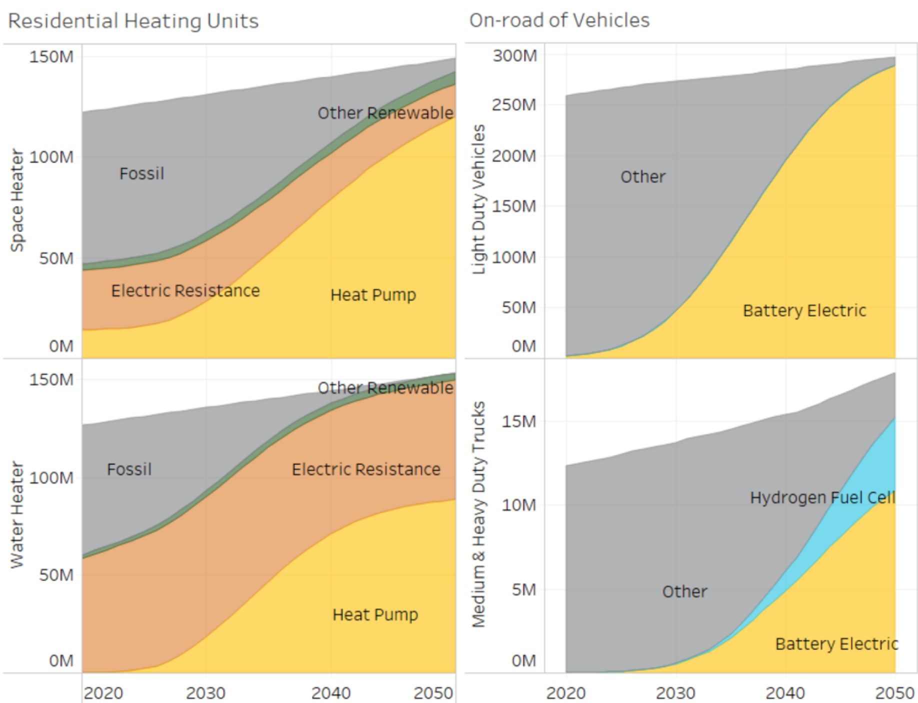

Figure 5: End use electrification in four applications. Source: ZCAP figure 2.6.

Second, it is also virtually certain that with electrification will also come renewabilization of the electric power system. On this front, the large energy system models often find it difficult to keep pace with the blistering improvements in renewable technology. Among the most recent scenarios are those from the IEA WEO, which has recently had a major update in technology assumptions, and envisions rapid growth of wind and especially solar as shown in Figure 6. These models typically make generous assumptions about the viability and investment in CCS and nuclear power; other studies that are more pessimistic tend to fill in the difference with still more renewables.

To varying degrees, these large energy system models also approximate the kinds of deployments that will be needed to integrate these renewables, although the full calculation of those factors requires complex power flow models tailored to particular grids and configurations. Many studies suggest that lots of renewables mean, as well, lots of batteries. However, that shorthand is often hard to square with the real world where, at present, the dominant electricity storage technology is pumped hydro.[26] (Batteries may supplant that, in time, with ongoing innovation and deployment.)

Moreover, careful power flow modeling studies applied to grids that are actually in the midst of deploying renewables find that while storage has a role to play a much more critical resource for integration of large volumes of renewable power is clean, firm power—for example, gas with CCS, nuclear, hydro, geothermal or other resources that can ramp up and down as needed and sit ready for use during periodic prolonged periods when the wind is not blowing or weather is not reliably sunny.[27]

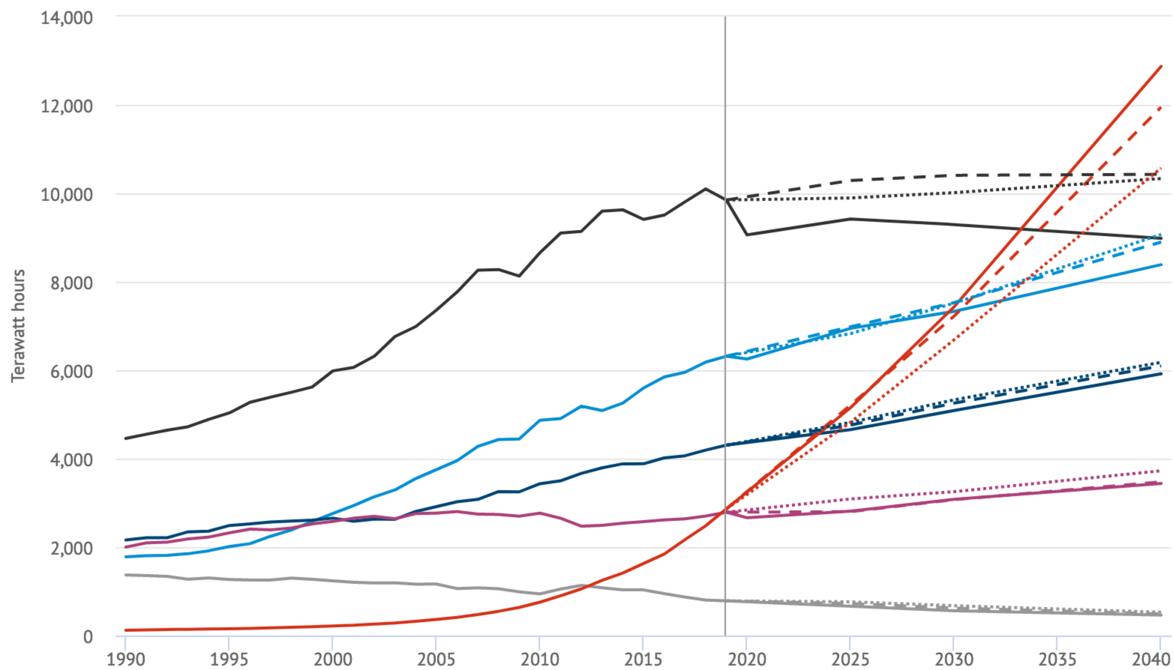

Figure 6: the rise of renewable electricity output, as reported in the IEA WEO (2021). Scenarios are the continuation of current policies, sustainable development, and net zero by 2050. Source: IEA SDS AND NZERO scenarios, via CDP.

Third, it is virtually certain that cost effective deep decarbonization will involve large net reductions in forestry-related emissions. Protection of forests in the tropics is already one of the least costly (often negative cost) options for avoiding emissions, albeit one that involves political challenges such as assertion of government authority and reduction in corruption—factors that don't neatly translate into assumed cost factors that are the key drivers of large energy and climate models. The IPCC AR5 assessment found that the effort needed to control emissions was consistent with a rising global carbon price—at levels centered on about \$100/tonne CO2 around 2030 and rising.[28] (These models usually compute carbon prices associated with effort because that is easiest; in the real world "effort" will likely, in most cases, take the form of a mix of regulatory and market measures.) At that level of society-wide effort, massive afforestation and improved forest management should be highly cost effective—although with similar caveats around practicality under real world conditions.

A special report from IPCC on the relationships between climate change and land use looked at the potential allocation of land area over the coming century under a range of different scenarios known as "shared socioeconomic pathways (SSPs)," which are internally consistent yet differing views of how the future may unfold.[29] In all these SSPs it is possible to cut emissions and stop warming; it is the means by which those environmental goals are achieved that vary.[30] Figure 7 shows these different visions for land use—with all implicating a big rise in forest cover (and most seeing other uses for land, such as for crops and pasture, in decline—extending patterns already evident today). While the future for forests (bigger) is highly consistent across the SSPs, one of the biggest unknowns is the future for bioenergy crops.

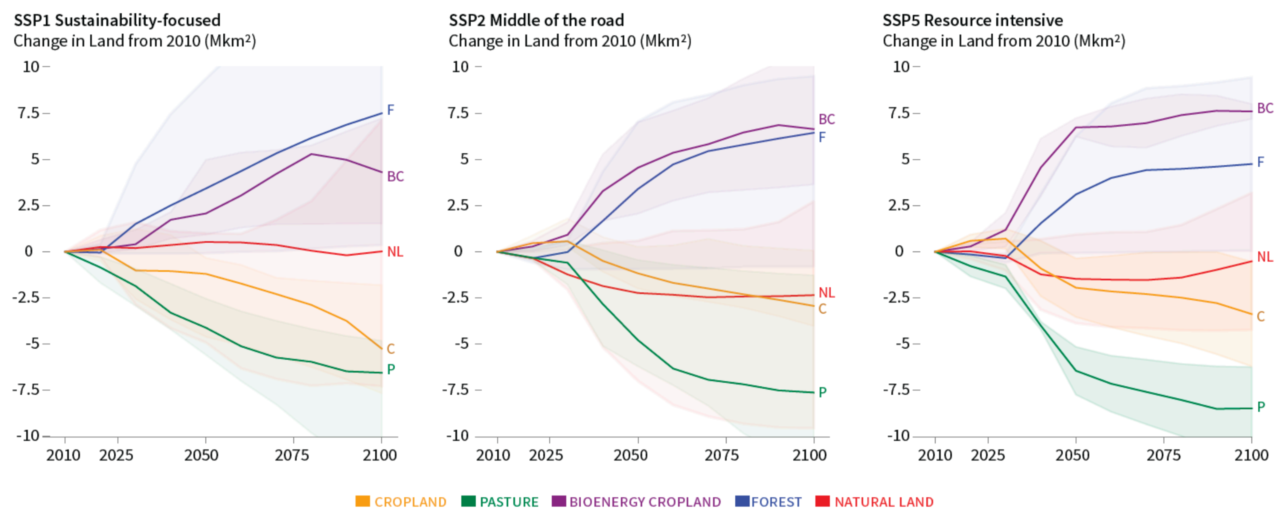

Figure 7: the outlook for land. Source: IPCC Special Report on Climate change and Land (2019), figure SPM.A.

Finally, it is highly likely that in the real-world cost-effective mitigation will include a big role for limits on short-lived climate pollutants (SLCPs) such as soot, industrial gases and methane. In general, the integrated assessment models that are used to craft a global mitigation perspective are industrial energy models to which some insights into industry, agriculture and land use have been added. As such, these models tend to focus a lot on one pollutant—CO_2—and have much less detail around N2O and CH4. In general, they are silent about the rest of the radiatively active species, such as soot and industrial gases. This reflects the need for focus and for tractability, but it also means that when looking to the models for guidance about likely emission control strategies that other elements of a global strategy will be less apparent in the model results. A big program to control potent industrial gases (e.g., as per the Kigali Amendments) and black carbon, along with methane, are highly likely to be part of any serious global strategy.

New Services that are likely to be highly valuable

Having looked at the "virtually certain" elements of cost-effective deep decarbonization we now turn to areas that are likely to be highly valuable—if key technological or political barriers can be resolved. Even for options likely to play some role, the magnitude of their contribution is hard to estimate.

First is low carbon transportation fuels. While electricity seems the likely winner for light duty vehicles (and rail, where densities allow), the best options elsewhere in transportation system are unknown. A variety of liquid fuels—some "drop in" replacements for current fuels (e.g., biodiesel or sustainable aviation fuel), and others requiring new infrastructures (e.g., ammonia for long distance ships)—will vie for market share. Some attract a lot of attention by analysts yet seem, upon reflection, somewhat crazy to be considering as options—ammonia may be in that category, for it is highly toxic. Ammonia powered ships and heavy trucks are easy dreams for the mind of an engineer or energy system analyst. In the real world where ships run aground, trucks crash, and fuel tanks leak it is bit harder to see how the world becomes comfortable with ammonia. Thus, as a practical matter, we will focus on the most probably transportation fuels: biofuels and synthetic liquids.

Judging by the models, the most likely of these options will be biofuels. For many, this reliance upon nature to grow energy crops portends an ecological horror show that, for many crops, won't have much net benefit for carbon.[31] That said, there have been many technological advances that, when combined with political forces, raise the odds that bioenergy will be a big part of a low carbon future.

A recent IEA analysis, seen in Figure 8, shows a substantial increase in liquid biofuels—a rise even more profound than the shift to solid bioenergy crops for use in negative emission power plants. (it also sees a big shift to hydrogen, a topic to which we return below.). At present, drop-in replacements for liquid fuels are a tiny share of the market—about 4%, dominated by ethanol.[32]

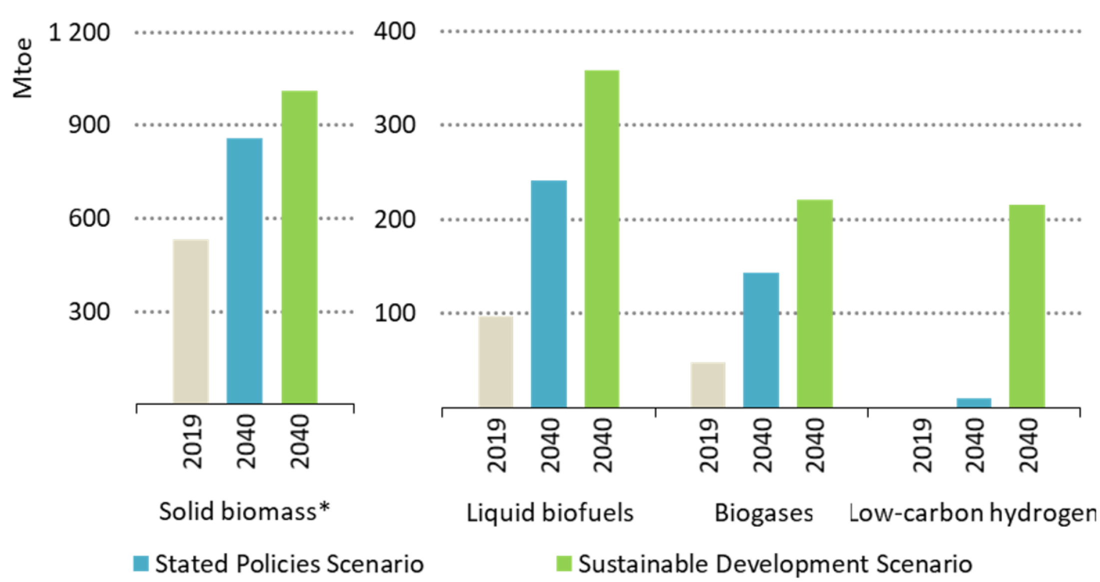

Figure 8: IEA assessment of the future energy supply (in million tonnes oil equivalent, mtoe) for different types of combustible solid biomass (for power plants, left) and replacements for liquid and gaseous fuels (for mobility and direct combustion, right). In energy terms, liquid biofuels dominate, but the rise of gaseous hydrogen is most striking. Source: IEA WEO (2020), figure 7.19.

Second is agriculture. A standard view is that most of the reduction in emissions will come from energy services and industrial facilities. That view is derived, however, from a host of assumptions built into models that, by design, focus on energy and industrial activities. Yet, in the real world, there are many advances occurring in crop management—from the use of biochar to enhance soils (and sequester carbon) to no till agriculture to crop engineering for the purpose of actively sequestering carbon in root stock.

Third, one of the most striking disconnects between energy modeling studies that focus on the cost-effective routes to deep decarbonization and the real-world concerns CCS. Nearly all the quantitative studies show a big role for CCS—because it is assumed (with some substantive support) that continued use of fossil fuels coupled to cleanup at end of pipe (ie, CCS) is more cost effective than ridding the planet completely of conventional fossil fuels. This is seen, for example, in the last IPCC report that compared cost-effective emission controls with and without CCS as an option, shown below in figure 9.

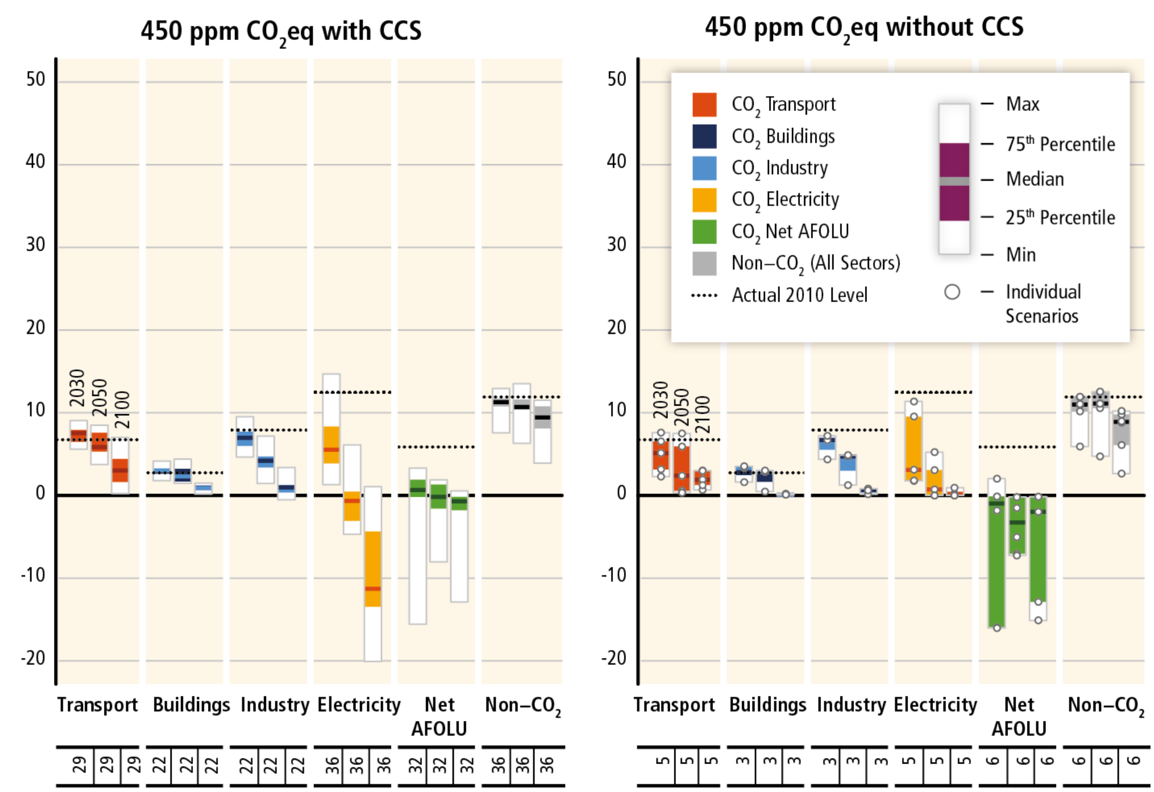

Figure 9: IPCC estimates for emissions, by sector, from models that estimate the most cost-effective pathways for 450ppm CO2-equivalent concentrations: scenarios that include all technologies as well as CCS (left) and those without CCS (right). Source: IPCC AR5 SPM 1.7.

While the value, in theory, for CCS is high the real world has shown a high death rate for CCS projects that are proposed—with the highest death rate (95%) for the most important and transformative CCS projects: those that capture pollution from power plants (figure 10). Studies that have looked closely at the disconnect—the high value in theory for CCS, and the high death rate in reality for CCS projects—show a host of factors at work.[33] Some are familiar in the energy modeling community, such as the tendency for costs often to rise higher than expectations for first of a kind (FOAK) deployments. Some are familiar to financiers and project developers, notably erratic policy signals—leading to low institutional credibility and undermining the need to think of FOAK deployments are one in a long stream of investment that will bring costs down and help seed a new industry.[34]

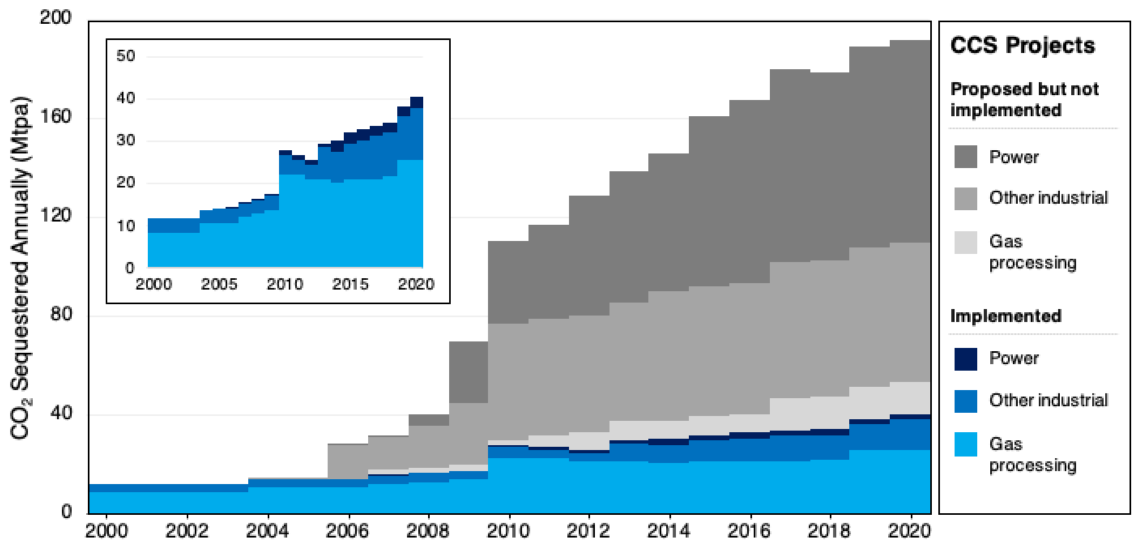

Figure 10: Death rate for proposed CCS projects over time and by type. Source: Abdulla et al (2021) [note 33].

A fourth major area of potential action concerns hydrogen—an energy carrier that, like electricity, has the potential to move zero carbon primary energy to users. Unlike electricity, however, hydrogen has some special properties—as a gas it is easy to store, as a liquid (cryogenic) it has a power density comparable with jet or diesel fuel, and in chemical applications such as making steel the reactive properties of H2 are attractive. Thus, hydrogen has some big advantages for many applications from aircraft to steelmaking to conveyance of clean energy via gas pipeline. This bright future for hydrogen is illustrated in Figure 11, which shows (top panel) a shift in low carbon gases away from technological proximate solutions (biogas and biomethane) toward more innovative solutions (hydrogen) as limits on emissions are tightened. And for the IEA's two major scenarios (bottom panel) the shift over time toward diverse new uses for hydrogen is striking—with the biggest uses in so-called "hard to abate" sectors such as heavy vehicles and ships (mobility) and chemicals and steel.

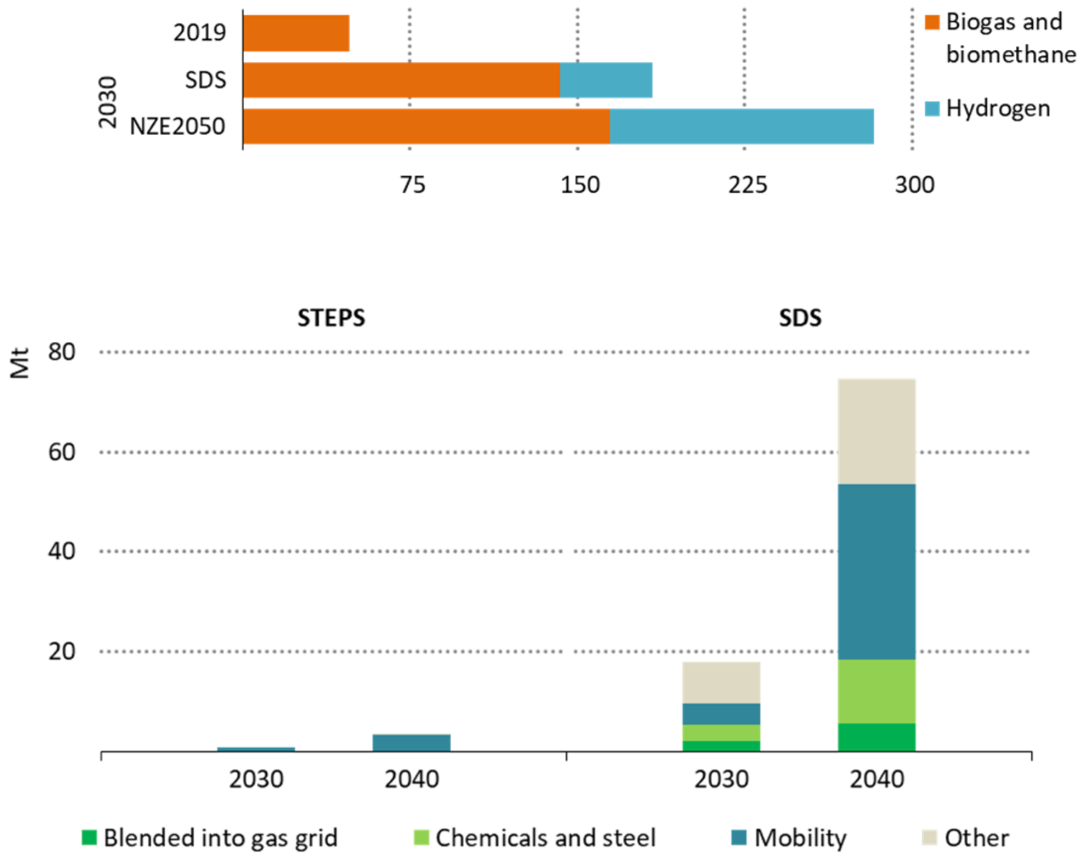

Figure 11: Futures for low carbon gases. The top image shows a big near term (2030) rise in the use of low carbon replacements for natural gas. In the SDS that shift is dominated by biomethane, which is the easiest to integrate into the existing pipeline network. But in the Net Zero by 2050 scenario, which sees much more aggressive control of emissions, there is a big shift to hydrogen. The bottom image focuses just on the role of hydrogen and looks across all potential applications, revealing that the single largest use will be in mobility—heavy duty trucks and some shipping. (By 2040, some hydrogen may be used in aircraft, though it is hard to see that use scaling so quickly.) There is also a big role for hydrogen in chemicals and steel production—among the so-called "hard to abate" sectors. Source: IEA WEO (2020)

New Services whose future is unknown yet theoretically valuable

So far we have looked to the integrated assessment models' insights about cost effective deep decarbonization from two angles. One was the highly likely routes to deep decarbonization, such as electrification. A second was probable elements of deep decarbonization—pending further technological and political advances that are, to varying degrees, unknown. Now we look at that literature from a last, third angle: the deep unknown. Here, uncertainties are particularly large because of a combination of technological, social and political factors that interact in ways that are hard to predict. At best, one can be Bayesian in looking to the future: set expectations based on today's knowledge and update often in light of experience. Because these potential elements of deep decarbonization are unknown does not mean they will not happen, but just that they will be the source of many surprises—and with those surprises, potentially large opportunities for creating new industries and for deep decarbonization.

The first of these is the cluster of "hard to abate" industries—a hodgepodge of challenges unified only in the fact that they are difficult.[35] These include decarbonizing steel, plastics, aviation, cement and others.

Sector	Today's Emissions	% of Today's Global Emissions	Total Emissions 2050 BAU
Plastics	1.5 GtCO2	5%	4.2 GtCO2
Steel	2.3 GtCO2	7%	3.3 GtCO2
Cement	2.2 GtCO2	7%	2.2 GtCO2
Aviation	1 GtCO2	1%	1.8 GtCO2

Table 1. Source: Mission Possible Reaching Net Zero Carbon Emissions From Harder-To-Abate Sectors by Mid-Century, 2018

In some of these cases the solutions might involve switching to alternative modes of providing the same service—instead of steel, for example, other building materials might be invented or applied. (Existing alternatives, such as bamboo, might prove difficult to use structurally for a future Burg Khalifa, for example.). In these domains, some of the solutions seem to rest with advanced chemical engineering and advanced methods for obtaining high temperatures for process heat—those twin needs are the root of much of the enthusiasm for the use of hydrogen in some "hard to abate" sectors, notably steel and petrochemicals. Other solutions may rest with intelligent control systems (e.g., building controls). Still others hinge on improvements in the end uses of electricity, including possibly direct reduction of iron with electricity to make steel—these electrification routes, where they prove feasible, feed the vision of deep decarbonization through electrification.

It is difficult to predict the rate at which technological advance may occur in these sectors. For many years the needed technology, it was assumed, was not far advanced. There is some evidence that is changing—in part in reality and in part in imagination. The Energy Transitions Commission recently offered their update on Figure 2 that repositions (by eraser and pencil, if not reality) many of the sector frontiers a bit further along the diffusion curve—offering an alternative and more optimistic view of technological state, shown in Figure 12.[36] We remain more skeptical, noting that options the ETC finds on the cusp of widespread diffusion account, today, for very small markets—replacements for jet fuel, for example, still account for less than 1% of the global jet fuel market, hydrogen electrolysis remains fantastically expensive (but improving rapidly—possibly the new big story in energy technology) and hydrogen trucks are not plying the roads in big numbers anywhere. Skepticism and dreaming co-mingle; the futures for these sectors are hard to parse.

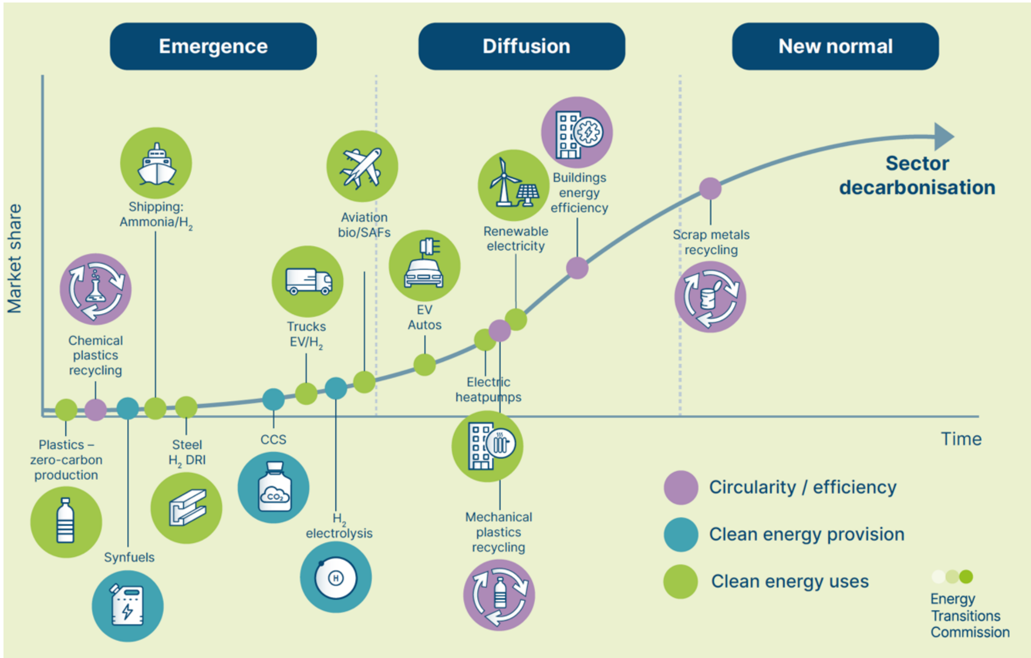

Figure 12: An updated view of possible technological progress in hard to abate sectors. Source: ETC 2020 "Making Mission Possible".

The second of these unknown clusters concerns a technology that is already ubiquitous: nuclear power. Most energy models that are allowed to select freely among many choices select substantial amounts of new nuclear—even as most new electric power comes from solar and wind, power systems benefit from diversity and, especially, from clean firm sources of energy. The IPCC's AR5 assessment of the implications of deep decarbonization for investment patterns noted that most IAMs at the time, in fact, did not allow for a detailed assessment of shifts in investment, which is striking since redirection of investment is one of the (if not the most) important policy implications from deep decarbonization research. The IPCC review showed a modest uptick in nuclear investments in the western nations (OECD) and especially the rest of the world (non-OECD).[37] In the real western world, however, at best nuclear is treading water—retirement of plants is being offset by continuous improvement in operations (and some power uprates) such that nuclear's fraction of power generation has been roughly steady. In the non-OECD countries—at least some such as China and possibly India and potentially some frontier new commercial nuclear powers such as the UAE which has brought online its first of four reactors in 2020—the nuclear share is rising. Overall, however, the real-world picture for nuclear does not align with the visions of the IAMs assessed by IPCC, in no small part because the world effort motivated by deep decarbonization does not align with the rapid policy action scenarios that commanded much of the IPCC's focus. Since real world of emissions abatement does not (yet) align so perhaps a nuclear renaissance is imminent, or perhaps the renaissance will be passed over for other technologies such as renewables. For many observers of the nuclear industry the next interesting wave is with small modular reactors and other novel designs that are more flexible, intrinsically safe, more resistant to proliferation, and possibly cheaper with mass production.[38] A boy can dream.

Third is the domain of negative emission technologies. As the constraints on emissions grow tighter, all the major energy models assume (by fiat more or less) that there will be growing investment in negative emission technologies (NETs), such as bioenergy carbon capture and storage (BECCS) and direct air capture (DAC). If nations do, indeed, hold firm on binding goals like "net zero" then, mathematically, NETs must play a big role. One wildcard in this vision is the role of conventional offsets—for example, credits issued in exchange for supposedly additional activities such as protecting a forest from clear-cutting or altering an agricultural practice. The cost of those offsets is low, and there is substantial and growing evidence that the quality if also low.[39] More quality control in the offsets market will give rise to the need for higher quality NETs—opening the space for BECCS (controversial because of its implications for land use to grow solid biomass, as discussed above) or DAC (elegant yet exceptionally expensive).[40]

What Happens to the Incumbents?

While most of the modeling studies focus on what's new, the creation of "new" also implicates the "old." Many elements of decarbonization involve creating wholly new industries—areas where existing high emission incumbents may have few if any relevant skills. What happens to these incumbents is important politically and morally. Politically, incumbents are the kernels of opposition to change; if they can see advantage in change, or be made less capable as political blockers, then the deep decarbonization transformation will accelerate. That "dynamic" view of technology and politics is central to many studies by political scientists who have been keen to identify mechanisms for a politically self-sustaining and accelerating transformation.[41] The global energy models reviewed in this study don't have much to say about the politics, but they do help identify the scale of the challenge and the potential speed of the shifts away from incumbents.

One measure of the overall shift is investment. Figure 13 shows IEA's projections for the shift in annual capital investment. Two things emerge from this study, both typical of most research in this area.

A first insight is that total investments in the energy sector go up modestly—in the IEA's assessment, about 10%. (That rise is computed as the increase from baseline to the IEA SDS scenario; a faster shift to net zero emissions by 2050 leads to an even larger rise.)[42] The key point is that, as nearly all the models find, a global economy that decarbonizes is an economy that also capitalizes.[43] High emission economies tend to have relatively high operating costs for energy systems—notably the cost of buying fuels such as coal, refined petroleum products and natural gas. Many studies suggest that the total cost of energy services can be kept roughly flat as these higher investment costs are offset, in time, with savings from lower fuel costs.[44]

But that hope—which, if it holds, will help make the political challenges of deep decarbonization more tolerable—is extremely sensitive to whether investors focus on the "right" technologies and also highly sensitive to the cost of capital. Variations in the cost of capital by just tens of basis points could be decisive, although very little of the literature has examined this topic—a matter of extreme importance for policy makers since capital costs reflect, in part, policy risks. Indeed, studies using large energy system models have found that aligning model assumptions about the cost of capital with real world conditions leads to projections that see a big shift in decarbonization investment toward countries with good economic and political institutions where the costs of capital are relatively low.[45] Put differently, a world that decarbonizes is a world that benefits, relatively speaking, places that are good at attracting capital. Insofar as today's concerns about income inequality are rooted, in part, in the unequal returns within the society that arise from control over capital then deep decarbonization could exacerbate those challenges.

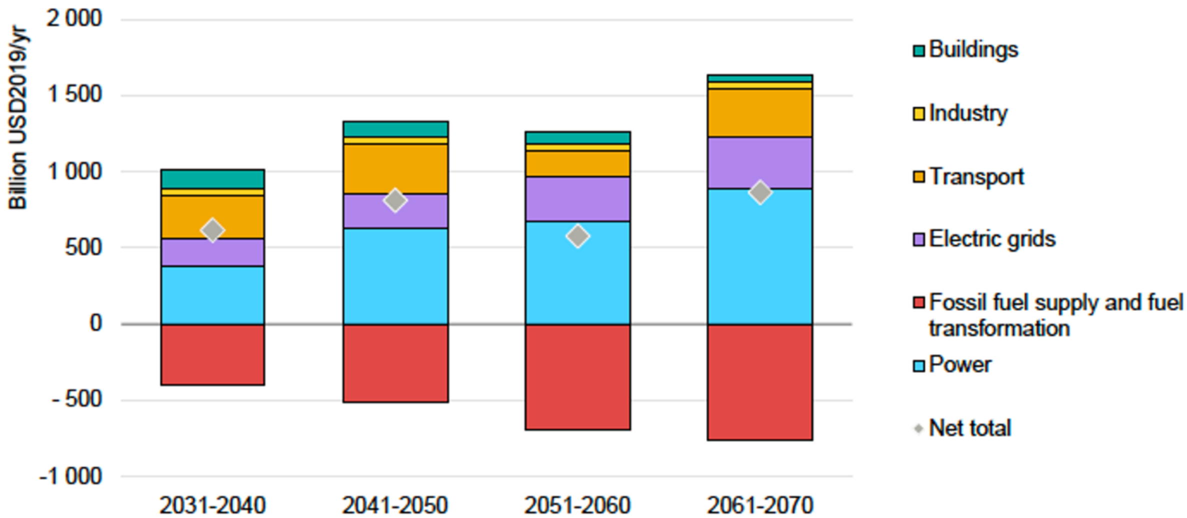

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Figure 13: Annual shift in investment (by decade) under the IEA SDS scenario, compared with the baseline Stated Policies scenario. Source: IEA ETP (2020), figure 3.21.

A second insight, hardly news, is that fossil fuel supply and transformation see substantial declines in investment. For conventional coal, the implosion is particularly striking—as shown in Figure 14. Indeed, in the west that implosion is well under way—accelerated by factors such as the emergence of cheap natural gas. This has already given rise to highly disruptive changes in communities that depend on coal, and the problem of coal has been central to many studies that have looked at worker retraining and community support under the concept of a "just transition."[46] Under some technology assumptions, notably around inexpensive CCS, coal hangs on longer—but those scenarios are diminishing in credibility and frequency. The question of whether the planet, as a whole, speedily moves to net zero emissions depends centrally on how quickly conventional coal leaves the energy system.

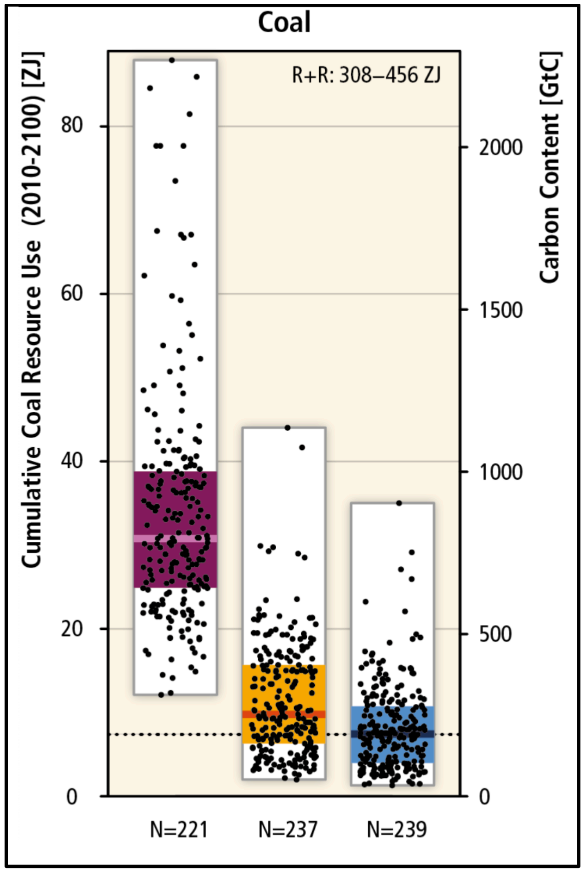

Figure 14: All published IPCC AR5 scenarios reporting on futures for coal. On left are baseline scenarios. In the middle are modest mitigation scenarios (530-650ppm of CO2) and on the right are more aggressive mitigation scenarios (430-530 ppm of CO2). Source: figure 6.15 IPCC AR5.

For the other fossil fuels the futures are murkier. For oil, until recently, most studies envisioned a continued rise (even at a slower pace) because oil provides such vital functions in the global energy systems (e.g., transportation fuels) and industry (e.g., petrochemicals). As shown in Figure 15 that confidence is now fraying. Until about 2005 every scenario published by the IEA saw oil demand rising—albeit at varying rates. Since then, principally due to concerns about climate change, downside projections have grown more numerous and the downside deeper. BP and Shell, among others, now make projections that see demand for oil dropping by one-quarter or more in the coming few decades. Here we have focused on industry projections because they, in many senses, are even more revealing than energy system studies made by researchers who are a step or more removed.

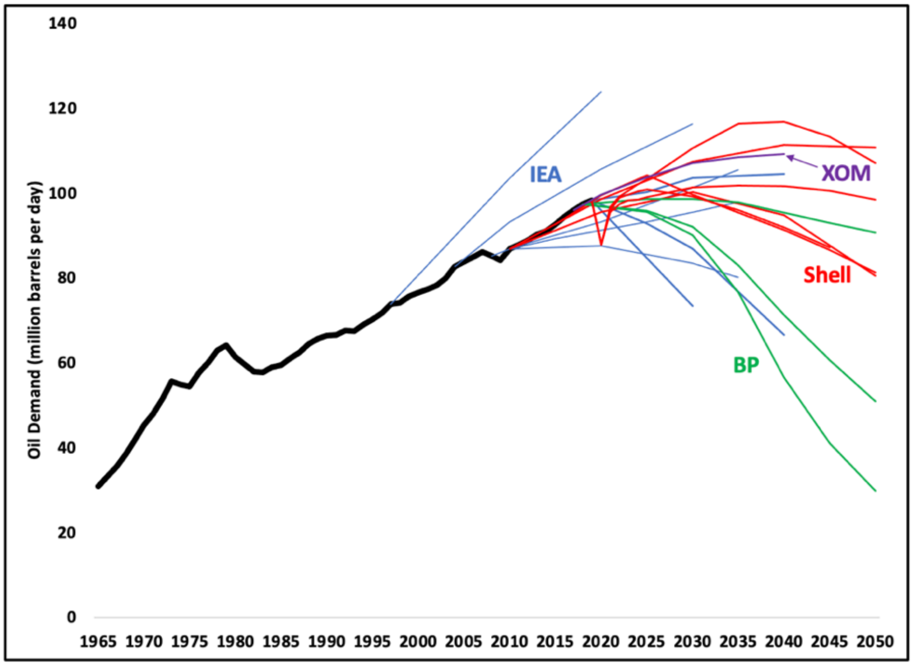

Figure 15: Many outlooks for oil demand: recent scenarios published by BP, Shell, Exxon (XOM) and IEA. See Victor and Engine No.1 (2021).[47]

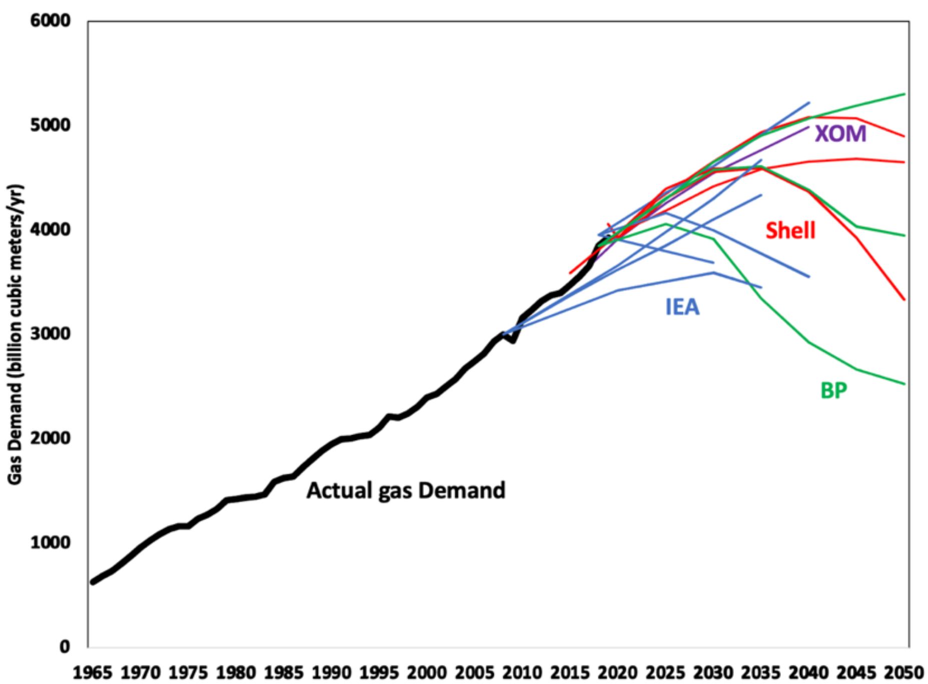

Figure 16: Many outlooks for gas demand: recent scenarios published by BP, Shell, Exxon (XOM) and IEA. See Victor and Engine No.1 (2021).

A similar story is now unfolding for natural gas, which is probably the biggest single wildcard about the future of today's energy system. For decades the gas industry—which, for producers, has become synonymous with the oil industry—assumed it was indispensable to the future. Gas was a lot cleaner burning than other fossil fuels—in modern electricity generating stations plants that burn gas emit less than half the CO2 per unit electricity compared with coal—and a lot more flexible.

That consensus is also fraying, although less quickly than for oil. A caveat is in order: the track record of expert forecasting around natural gas is particularly atrocious. On the one hand, forecasters see robust demand for gas due to its cleanliness and due to cost reductions such as fracking and in LNG-based shipping. On the other hand, gas is still a fossil fuel and causes emissions (even more so when fugitive methane, a potent warming gas, is included in the calculation). In a world that engages in shallow decarbonization the role for gas is strong. Deep decarbonization creates a more uncertain future, especially when political and financial pressures against fossil fuels are considered. Over time, as shown in Figure 16, uncertainty in projecting demand for gas has gone up, mainly due to rising awareness of possible downside risks. Until 2020, every IEA projection for gas showed rising global demand—the only uncertainty portrayed was the rate of growth.

For years there has been a blind spot among oil and gas analysts about the potential roles for these fossil fuels in a decarbonizing economy. Oil, it was assumed, would always be valuable because it was a liquid with high power density. Gas, it was assumed, would be valuable—especially if production costs could be kept low—because of its flexibility for high heat and power generation and its intrinsic cleanliness compared with other fossil fuels. As the markets arrive at a new realization there could be not just financial instability for countries (e.g., Canada) that depend heavily on these fuels but also the existential and social instabilities in the communities at the epicenter of this dependence.

Design Principles for Investing in Decarbonization

Thus the future of deep decarbonization involves a mix of things that are highly likely to happen (e.g., electrification, efficiency) and a large number of other outcomes with varied degrees of unknown. That uncertain landscape presents both opportunities and pitfalls. This suggests a need for policy strategies that are nimble and adaptive to rapidly changing context and technological frontiers—policies that redefine those frontiers and yet recognize that it is impossible to chart a detailed path from today to net zero.[48] Managing those unknowns must proceed in a way that still offers confidence to investors, lest the risks and cost of capital for projects rise to a level that makes overall costs intolerable. Managing these two contrasting tensions—between the need for learning and adaption and change, on the one hand, and the need for strategy and stability on the other—are poised to become central to every country's effort at deep decarbonization. The existing modeling literature is largely silent on how to manage those tensions, but from the patterns in that literature we have already discussed a number of design principles can be identified. We conclude this section by providing a framework for open economy investment strategies that incorporate these principles.

First is investing in knowledge and experience. Given the deep uncertainties, we need to increase society's capacity to innovate over time. In addition, we have to invest in learning through RD&D to see what works and what does not. It is very hard to take the pulse of the global level of investment in new knowledge. Nonetheless, in Figure 17 we show IEA data by sector through the year 2019, revealing that public spending on energy-related RD&D is about $20b and barely rising since the one-time blip in 2009 associated with the US economic recovery package. Spending today is more diverse in its sectoral coverage—notably due to the decline in public sector spending on nuclear power—but has barely reached the levels of the late 1980s.

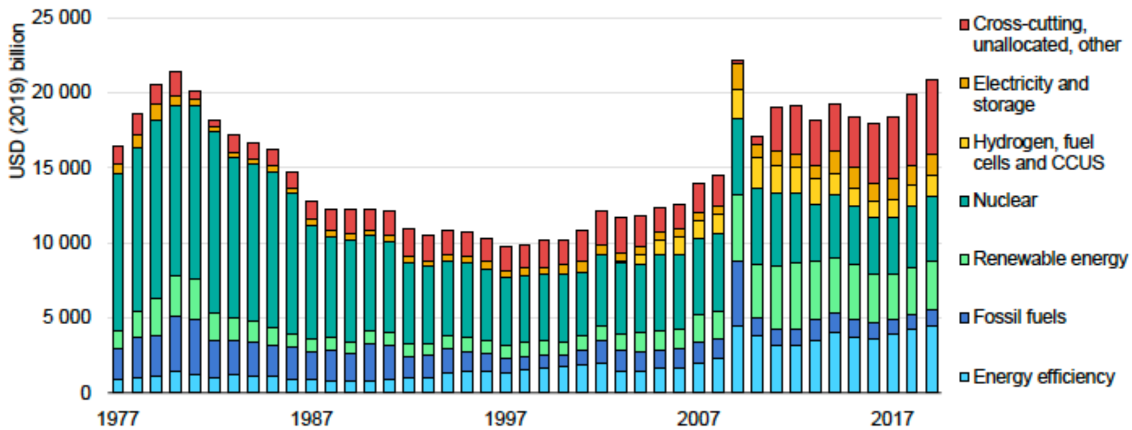

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Figure 17: Public energy-related spending on RD&D by IEA members, 1977-2019. Source: IEA Energy Technology Perspectives (2020), figure 6.2

Total spending, by itself, does not guarantee profound technological change. Both supply-push and demand-pull spending is needed.[49] Government regulations and procurement strategies are essential to the latter. In effect, a much bigger public sector role in clean energy technology is calling upon the "Entrepreneurial State" to learn how to intervene effectively.[50] In many countries it has, and a playbook has emerged that emphasizes the need for government agencies to move personnel back and forth with industry, to pursue a portfolio of approaches rather than picking winners, and other institutional features that improve the economic efficiency of government intervention and raise the odds that such interventions contribute to technological transformations.[51]

Second is thinking about the design of institutions to enact industrial strategy. The interdependent and global nature of energy technologies means that concerted action is needed. Other national experiences with industrial strategy provide important lessons that can be applied in context. Successful industrial projects involve fostering communication and cooperation between the government and the private sector without either side capturing the decision-making process.[52]

However, there is an added challenge in the context of the energy transition. Previous industrial strategies have had a clear sense of the technological goal. Japan sought to copy the US's electronic industry, Korea aimed to build auto manufacturing and chemicals on others' models, and so on. The challenge today is mission-oriented action under uncertainty. We need institutions that foster public-private collaborations to learn from the experiments and use the results to yield shifts in investment and politics that make industrial revolutions more viable and self-sustaining.

Doing this well means taking risk and managing exposure to that risk in a balanced portfolio of societal investments. A key message of this report is that investments should be spread across likely, probably, and unknown elements of the future energy system. Two further elements to balance are time horizon and level of risk. Both of these can be managed with a portfolio of sectoral investments that balance short and long-term priorities as well as lower risk and higher risk economic opportunities.

Third is designing policy to explore, narrow and adjust around the unknowns. In effect this requires what is increasingly called "experimentalist governance"—that is, active experimentation by business and government together (for neither, by itself, has the breadth to run the experiments themselves).[53] There are not universal answers here since what works depends on complex social, political economic, and technological landscapes that are country-specific. This approach requires exploring the wide range of possible outcomes, learning quickly which approaches are viable, and swiftly designing the next waves of experiment. This means investing actively and experimentally to reduce uncertainty and continually update the societal bets. But investing in learning is an upstream investment that can continually generate returns across sectors and over time.

Fourth is to learn how to ease the incumbents out of the way. Deep decarbonization requires expanding the zone of engineering, investment and political action around low carbon energy, industrial and agricultural systems. The size of that zone—and the extent to which is tolerates or invites change—depends heavily on the incumbents. Part of the strategy here involves sequencing policies to build a coalition of green interest groups that can provide the support necessary to confront incumbents.[54] That in turn means finding just transition pathways for fossil fuel workers and other marginalized groups.

Those experiments need to start now and must be integrated into long-term strategies if small open, economies are to seize the considerable economic opportunities that the energy transition presents.

Toward an Open Economy Investment Strategy

Another key lesson is that due to the globalized nature of technology production, small open economies like Canada will have to act strategically if they hope to break into rapidly forming and highly competitive value chains. With scarce capital, they cannot afford to overspend on deep decarbonization and they have an imperative to develop export markets. This means they should invest in deep decarbonization where there is an opportunity to build globally competitive industries.

How can small open economies effectively deploy capital to position their economies in a net-zero world? There are three pieces to this question: how to build industry, how to add value, and how to create globally competitive industries.

The literature is clear that governments can build green industry with a mix of technology-push and demand-pull policies.[55] Public support for R&D and demonstration projects can drive innovation while subsidies, pricing, standards, regulations, and procurement can drive deployment. Done in the right way, this policy mix can drive big cost reductions and make new energy technologies competitive with established fossil fuel options.

But will these policies create established, globally competitive industries, or simply rely on imports? If the latter, countries can still reap the benefits of deployment but this will only add value to the local economy at the margins. To build competitive industries, small open economies need to identify big market opportunities and then specialize, playing to their strengths. This report has begun to identify the market opportunities. The next step is to identify areas where the country is already highly competitive globally, or where global competition is likely to be restrained, creating a pocket for domestic industry.

Consider two variables: potential for major cost reductions and the maturity of the technology. The potential for major cost reductions is a function of whether the technology is amenable to mass production, or whether its design and installation is highly contextual and therefore requiring localization and customization. The potential for major cost reductions is a good proxy for how intense global competition is likely to be. The maturity of the technology is its technology readiness level.

Technologies that are amenable to mass global production may seem like good investments.[56] These technologies will have large markets and see cost reductions as they go to scale. However, if these technologies are already mature, they are unlikely to be good investments for small open economies. Cost reductions are likely to benefit late entrants, undermining long-term value-added to the economy. The highly competitive environment around these technologies presents a big investment risk.

	Mass global production	Contextual application
Emerging	**Invest if** you have relevant expertise or cost advantages.	**Invest in upstream** skills and technologies
Mature	**Import** and deploy.	**Invest in established**, competitive firms.

Table 2. What technology areas should small open economies invest in?

Wind and solar are good examples of mature mass-produced technologies. The global value chains for these technologies were built in the 2000s as companies from China, Germany, and the United States found their niches within a complex system of global production.[57] It would be difficult for a small open economy to position itself in this value chain at this point.

Small open economies could invest in emerging mass production technologies, provided they have relevant domestic expertise or comparative advantage. For example, Canada has relevant strengths in chemistry that could support a world-class industry in biofuels.[58] But the final decision there would need to rest on a complete analysis of the cost structures for the final products including clean energy and transport costs.

Technologies with contextual applications are on balance better choices for small open economies, because the need for adaptation could support domestic industries over the long-run. Good examples here include CCS installations, which are usually site specific, and EV batteries, which are tailor made for specific vehicles. The challenge is to identify contextual technologies that will have global markets. The key in these areas is to identify opportunities to invest in upstream technologies and skills. Upstream technologies and skills are those that make other technologies possible. An example would be the power electronics and control systems with applications across the energy system.

Such investments are better located in emerging rather than mature areas, unless the small open economy already has a cluster of established firms with the expertise to support industries in these areas. This raises one concluding question: how can we identify the existence of domestic expertise which predicts global competitiveness? This question is the focus of this project's companion report, *Canada's Future in a Net-Zero World: Securing Canada's Position in the Global Green Economy*.

Conclusions

The next report will pick up where this one leaves off—with implications for Canadian economic opportunities. But as we turn to those implications we close with two sets of observations.

First, the global modeling offers a large number of insights into the kinds of changes that might be expected in the future and, by implication, the shifts in policy, social engagement and other changes that might be needed to achieve those goals. Nonetheless, it remains striking that the modeling outputs are somewhat removed from the kinds of variables and insights that real societies—real political leaders, activists, corporate leaders and the like—need to know to achieve those outcomes. Policy levers are, for the most part, modeled as idealized carbon taxes rather than the targeted policy instruments that, so far, have achieved most emission reductions in the real world. Model outputs are often quite coarse and focused on variables such as total energy volumes and emissions rather than indicators that are much more proximate measures of industrial change, such as shifts in investment.

Second, despite the coarseness of the global view, the attributes of the technologies and industries of the decarbonized future is already readily apparent:

- While there are large unknowns, it is almost certain that a deeply decarbonized global economy will be much more highly electrified. And decarbonization of the electric system is highly likely to occur principally through larger deployment of renewables.
- Energy efficiency is likely to be much higher in the future—to the point where many scenarios envision an overall reduction in primary energy consumption despite much higher levels of economic prosperity and larger populations.
- Efficient systems are likely to be based on extensive dematerialization because reductions in material intensity go along with reductions in the energy needed (and emissions) associated with production of materials.
- Investments in non-electric energy systems need to be assessed by whether or not they are likely to compete directly with highly efficient electric options. This is what drives the uncertainty in the probable and unknown opportunity areas.
- Because of the greater needs for energy efficiency and much greater use of renewables, energy systems of the future will need to be much more adaptive and "smart"—whether through greater use of real time markets or greater automation of control systems or both.
- While the overall cost of deep decarbonization remains somewhat uncertain, many studies are pointing to modest long-term costs because they assume that the energy system will replace relatively high operating costs (mainly, the cost of carbon rich fuels like coal and oil) with capital intensive energy systems (e.g., electric and hydrogen grids). That will create a huge premium for policy and investments systems that can identify and back the right systems while keeping the capital costs for those systems low. In a world where the local costs of capital—and associated risks, including from policy—vary enormously that puts a premium on countries that can combine deep decarbonization with inviting capitalization.

Put simply, economies that decarbonize are economies that electrify and renewabilize. They are economies that become a lot more efficient and intelligent. And perhaps above all, they are economies that will reward the strategic deployment of capital.

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