

# Global Energy System Transitions

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## Preface

This article is the first in a series that explores the role of energy in global climate change. Our focus is the energy system as a whole and the interactions of the system's components. At present, the energy system is in transition because of efforts to meet the Paris Agreement's goal of limiting climate change to well below 2°C. This article complements other symposium papers that dive deeper into specific sectors and technologies. We outline the current understanding of global energy transition pathways and then identify knowledge gaps and frontier issues.

## Introduction

The global energy system powers the global economy. Climate change is intimately linked with the energy system, which in its current form is responsible for the majority of CO<sub>2</sub> emissions and emissions of other important greenhouse gases (GHGs). Roughly three-quarters of the Earth's anthropogenic emissions are associated with energy production, processing, transport, and use. The most important drivers of GHG emissions are the level of economic activity, the technology employed in economic activities, resource availability, consumer preferences, and government policies.

Fossil fuel CO<sub>2</sub> emissions have been growing since the beginning of the industrial age. Prior to 1950, fossil fuel CO<sub>2</sub> emissions were dominated by coal use in currently developed economies. After 1950, oil and gas emissions became increasingly important, though the absolute growth in coal emissions continued. Although developed economies' emissions appear to have peaked around 2000, rapid economic expansion in developing economies has pushed global emissions upward in the twenty-first century.

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Two complementary strategies are needed to reduce net CO<sub>2</sub> emissions to zero. One involves replacing energy-producing technologies that are based on fossil fuels with technologies that do not emit CO<sub>2</sub> at all or have net negative emissions. The other is to substitute electric power for fossil fuels in end-use applications where feasible. An example that combines the two approaches is to generate electricity through solar power and then charge electric cars as the end use.

The first part of this article will address energy-producing technologies, followed by end use, and then will turn to the possibilities of capturing carbon emissions. The second part of this article will discuss transition pathways.

## The Energy Picture

Electric power generation using fossil fuels accounts for a quarter of all CO<sub>2</sub> emissions. CO<sub>2</sub> emissions vary across fossil fuels. They can be measured in kilograms of carbon emitted per energy produced. Average emissions factors are 20 kg of carbon per gigajoule of energy for crude oil, 15.3 kg per gigajoule for natural gas, and 26.2 kg per exajoule for bituminous coal (IPCC 2006). Specific values vary depending on the specific source, but relative emissions intensities are relatively stable.

Bioenergy includes biomass (such as wood) and biofuels (plant matter that provides feedstock from which fuel is derived). Bioenergy typically has a carbon-to-energy ratio greater than that of coal. However, the carbon in such bioenergy sources was derived from the atmosphere; hence, its emission is simply a return to the atmosphere with no net change over the bioenergy life cycle. Care must be taken to ensure that carbon accounts are kept accurately. Harvesting old forests for bioenergy is not the same as using sustainable, purposefully grown wood. Old forests drew down carbon long ago so that cutting and burning these trees release carbon that is “new” in terms of the current atmospheric concentration. By contrast, sustainably managed forests draw down and release carbon in a relatively balanced manner over a short period of time. The same is true for biofuels, which are derived both from crops grown specifically for energy and from the residue of crops grown for other purposes. The well-managed cultivation, harvest, and transformation of biological resources to usable energy do not entail net CO<sub>2</sub> emission. Thus, there are no net direct emissions from a biologically derived fuel over its life cycle. However, there are indirect net emissions from cultivating, harvesting, and processing trees and biofuel feedstock.

Renewable energy resources such as solar, wind, and hydroelectric power are treated as having no direct net carbon release to the atmosphere. The same is true for nuclear power. However, renewables and nuclear power have indirect emissions associated with their installation and operation. And hydroelectric power has emissions associated with the creation of the reservoir.

Net emissions from hydrogen production are complicated. Hydrogen can be derived chemically by harvesting hydrogen atoms from water, fossil fuels, or biological sources. Fossil fuel-derived hydrogen feedstocks produce carbon and other by-product residues, which are emissions unless they are captured and disposed of. Because the carbon in bioenergy was derived from the atmosphere, hydrogen produced from these sources would be considered to have no net direct emissions. Electrolysis—the use of electricity to separate water into hydrogen and oxygen—would be considered to have no net direct CO<sub>2</sub> emissions if the electricity is generated by renewable energy sources. The same is true for electrolysis or thermal separation of water using nuclear power.

We now turn to final energy use. Final energy use is conventionally divided into four categories: buildings (residential and commercial), industry (a wide range of manufacturing, mining, agriculture, and construction activities), transport (freight and passenger), and power generation. Once electricity has been generated, no further direct CO<sub>2</sub> emissions are associated with final electricity use (e.g., driving an electric car). However, as in the examples above, indirect emissions (such as building charging stations) can be substantial.

Hydrogen and biofuels could play the same role as electricity. However, not all final energy uses can be electrified. Hard-to-decarbonize activities will need to be addressed individually. Biofuels, hydrogen, and carbon dioxide removal (CDR) offsets all potentially have roles.

CO<sub>2</sub> emissions can be captured from large fossil fuel facilities. CO<sub>2</sub> scrubbers can be appended to or incorporated into existing and new facilities with a variety of technologies available. To ensure that the captured CO<sub>2</sub> does not enter the atmosphere, it must be transported to and stored in a repository isolated from the atmosphere. Storage reservoirs include, for example, depleted oil and gas wells, deep saline aquifers onshore and offshore, coal seams, and basalt formations. Although not available everywhere, CO<sub>2</sub> storage reservoir capacity is large and distributed globally.

Current CO<sub>2</sub> capture facilities have widely varying net costs. Some opportunities exist for chemical processes, in which relatively pure by-product CO<sub>2</sub> streams would be retained; they would then either be stored in a nearby repository or be sold for enhanced oil and gas recovery.

However, adding CO<sub>2</sub> capture to new or existing coal plants is prohibitively expensive in the absence of either a regulatory requirement or a carbon price or subsidy high enough to change the economic calculation. In emissions mitigation studies, carbon prices generally rise to levels that would make large-scale deployment of carbon capture and storage (CCS) potentially attractive. However, issues of liability and institutional barriers, such as local opposition to facility siting or lack of enabling permitting processes, could inhibit CCS deployment.

CDR technologies are anthropogenic activities removing CO<sub>2</sub> from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs or in long-lived products. Combining CCS with bioenergy (BECCS) in a range of applications, such as power generation, biofuel production, or hydrogen production, could deliver net negative emissions. BECCS is only one of many potential CDR technology options that could be deployed to meet the challenge of delivering global net negative CO<sub>2</sub> emissions (Fuhrman et al. 2021).

## Transition Pathways

The Paris Agreement of 2015 (United Nations 2016), negotiated under the UN Framework Convention on Climate Change (United Nations 1992), established as one of its goals “holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (3).

Implementing Paris goals implies a revolutionary transformation of the global energy system. Transition pathways consistent with “well below 2°C” require limits on cumulative CO<sub>2</sub> emissions and global CO<sub>2</sub> emissions pathways that decline rapidly to zero and then turn negative. The need for net negative global emissions can be avoided only if emissions decline sufficiently rapidly in the near term (IPCC 2021). Despite the high ambition articulated in the Paris Agreement, global emissions of GHGs have continued to rise, though recently at a slower rate (Dhakal et al. 2022).

## Tools and Models: Integrated Assessment Models

The long-term emissions scenarios of integrated assessment models (IAMs) have served as the primary basis for assessing future climate change and response strategies (Moss et al. 2016; IPCC 2021) and informing policy responses and designs (IPCC 2014b, 2018, 2022; Aldy et al. 2016; van Beek et al. 2020; Horowitz et al. 2022) to reach Paris Agreement goals. They provide insights into key emission drivers, including population, economic growth, technology, resources, policy, and the corresponding emissions and energy production outputs.

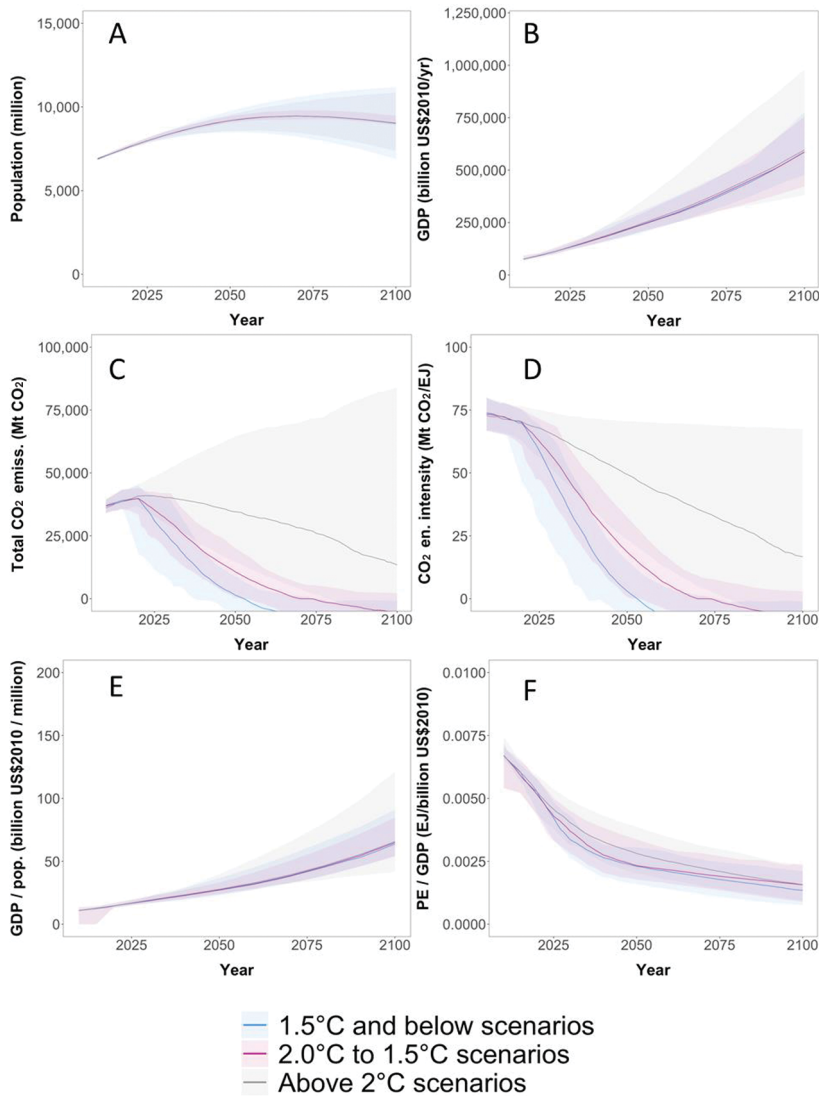
## Inputs and Outputs

Models that produce energy and emissions pathways have four fundamental components: drivers, model structure, parameters, and outputs. Drivers are critical input assumptions that come from outside the model. The model structure is the basic set of relationships between drivers and model outputs. In quantitative models, the equations form the model structure. Model parameters are the data that transform the general relationships described by the model's equations into specific relationships. The model's outputs are the variables, whose values the model produces—for example, domestic and international quantities, prices, and trade of energy, energy mix, land use, and water (Riahi et al. 2017). In addition to the energy system, IAMs also include representations of agriculture, land use, water, atmosphere, oceans, and climate.

## Energy System Pathways

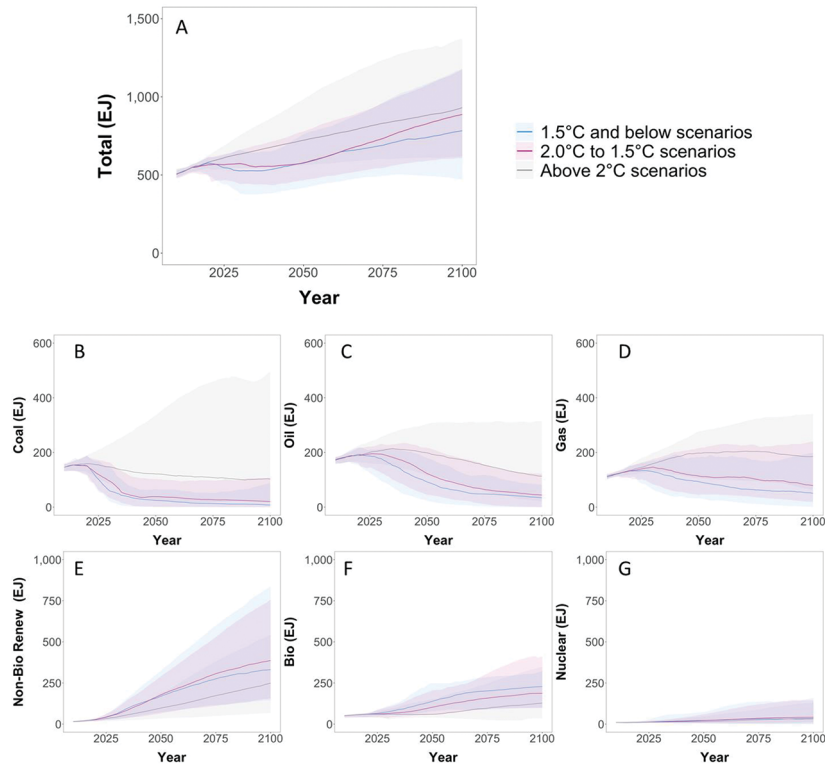
One of the most important global energy system drivers, particularly for deep decarbonization scenarios, is the policy environment. The studies in the Intergovernmental Panel on Climate Change (IPCC) scenarios database (Byers et al. 2022) either explicitly or implicitly use a single policy instrument, the carbon price, to achieve deep decarbonization outcomes. A price can be placed on carbon emissions either as a tax or through a “cap-and-trade” system, which distributes permits to emit carbon and allows permit holders to sell them. As discussed later, relying on a carbon price is an important limitation of current models. Two other important global energy system drivers are population and GDP per capita. Scenarios typically assume continued albeit slowing population growth throughout the twenty-first century. (Population is generally thought to peak sometime during the twenty-first century.) GDP grows in all scenarios in figure 1. A set of five “shared socioeconomic pathways” (SSPs) were created to provide a set of common reference scenario drivers (O'Neill et al. 2014; Riahi et al. 2017). SSP2, called “Middle of the Road,” is the most common set of reference scenario assumptions employed by modelers. The passage of time has led most modeling teams to utilize an updated set of SSP2 population and GDP growth assumptions. National energy system analyses generally use assumptions derived locally. Another major driver, technology, has changed dramatically in recent years. Renewable energy and energy efficiency technologies have improved relative to their fossil fuel competitors (IPCC 2022, figure TS.7). This trend is assumed to continue in long-term global energy scenarios.

Global energy system pathways contained in the IPCC AR6 database are shown in figure 2, primary energy use; figure 3, sources of power production; figure 4, global end-use energy consumption by fuel and sector; and figure 5, global CO<sub>2</sub> offsets. Scenario pathways are divided into three groups:



**Figure 1** Six key variables are shown. Global population (A) and GDP drivers to 2100 (B), with associated per capita income (E) and energy intensity (F), where energy is measured as primary energy (PE) measured in exajoules (EJ), total CO<sub>2</sub> emissions (C) and CO<sub>2</sub> per unit energy (D). Lines correspond to the median value within a scenario group, with lower- and upper-shaded boundaries corresponding to the 5th and 95th percentiles, respectively. GDP-related metrics utilize purchasing power parity (PPP) values for GDP. Carbon intensity is calculated using total CO<sub>2</sub> emissions. Data are from the IPCC AR6 database (version 1.1).

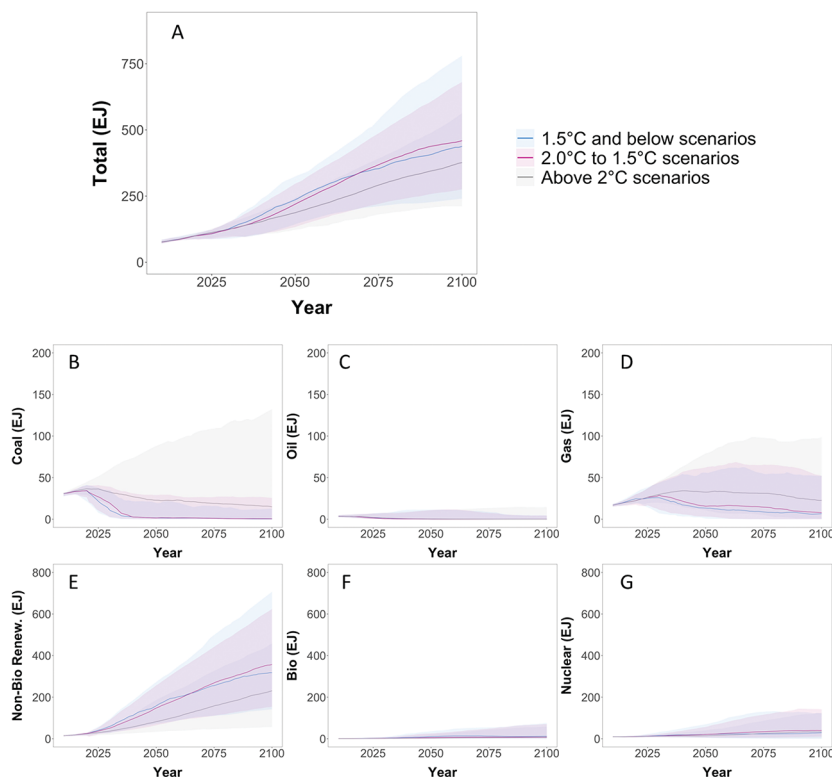
- 1.5°C and below: Scenarios that achieve or exceed the Paris goal of limiting 2100 average Earth surface temperature change to 1.5°C or better ( $0^{\circ}\text{C} \leq 2100 \Delta T \leq 1.5^{\circ}\text{C}$ );
- 2°C–1.5°C: Scenarios that are Paris compliant, limiting 2100 average Earth surface temperature change to between 1.5°C and 2°C ( $1.5^{\circ}\text{C} \leq 2100 \Delta T \leq 2.0^{\circ}\text{C}$ );
- Above 2°C: Scenarios that fail to achieve Paris goals in 2100 ( $2^{\circ}\text{C} < 2100 \Delta T$ ).



**Figure 2** Global primary energy consumption, total (A) and by fuels: coal (B), oil (C), gas (D), nonbiomass renewables (E), biomass energy (F), and nuclear power (G). Lines correspond to the median value within a scenario group, with lower- and upper-shaded boundaries corresponding to the 5th and 95th percentiles, respectively. GDP-related metrics utilize GDP-PPP. Carbon intensity is calculated using total CO<sub>2</sub> emissions. Data are from IPCC AR6 database (version 1.1).

Although space limitations prevent us from delving too deeply, the temperature time path is an important characteristic of 1.5°C and even some 2°C scenarios. Higher near-term emissions have higher near-term temperatures, even when cumulative emissions and year 2100 temperatures are identical. The IPCC AR6 distinguishes between scenarios with “no to limited overshoot” and those with “high overshoot.” The former is associated with lower overall impacts compared with the latter.

In general, these figures speak for themselves. A few highlights include the observation that the energy system grows in all scenarios that fail to achieve Paris goals (figure 2). That growth is tempered and (in some sectors and policy regimes) eliminated in stringent emissions mitigation scenarios. Coal use is all but extinguished by 2050 in Paris-compliant scenarios, owing largely to its high carbon-to-energy ratio (figure 4). Natural gas has a more complex trajectory, owing to its lower carbon-to-energy ratio. Some natural gas use continues throughout the century (figure 2). And even in scenarios that fail to achieve Paris goals, natural gas growth ceases before the end of the century. Oil use remains a fixture in the transport sector, even in Paris-compliant scenarios, though its use is diminished. The degree to which it is phased out depends on the success of electricity in replacing it as a prime mover of surface transport.

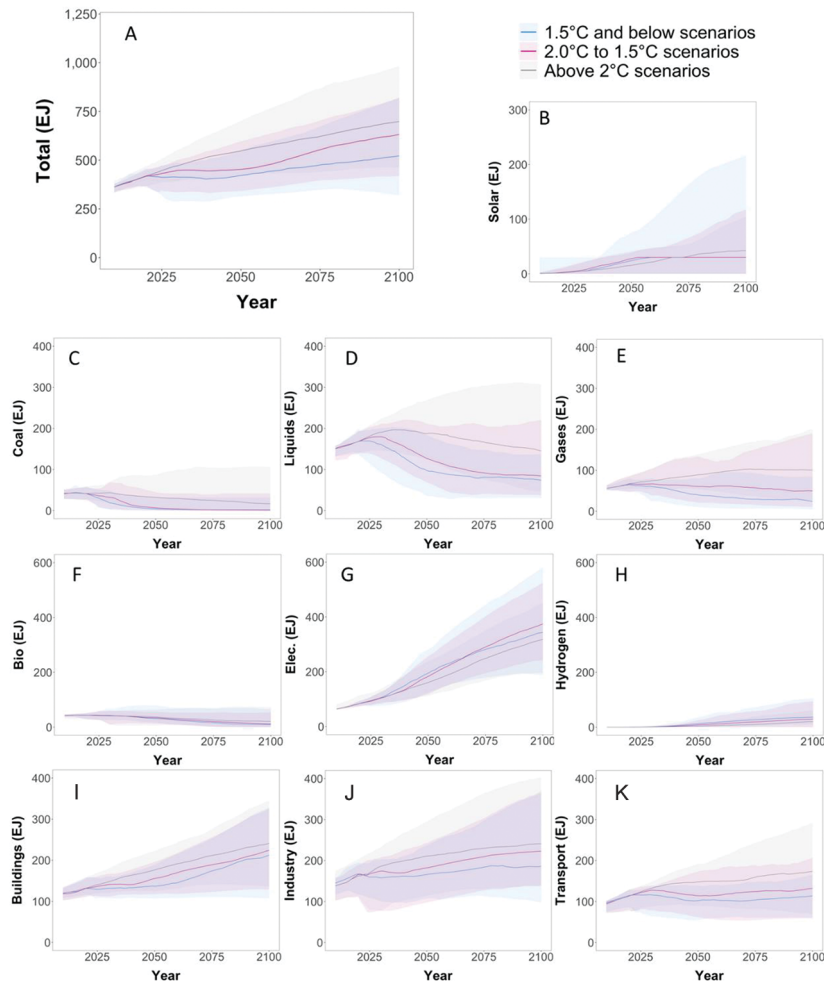


**Figure 3** Global electric power production, total (A) and by fuels: coal (B), oil (C), gas (D), nonbiomass renewables (E), biomass energy (F), and nuclear power (G). Lines correspond to the median value within a scenario group, with lower- and upper-shaded boundaries corresponding to the 5th and 95th percentiles, respectively. Data are from IPCC AR6 database (version 1.1).

Renewable energy use grows in both current-policy and Paris-compliant scenarios, but its deployment is greatly accelerated in Paris-compliant scenarios. In Paris-compliant scenarios, wind, solar, bioenergy, and other renewable energy forms come to dominate the global energy system.

There is a long-term trend toward greater use of electricity in end-use applications. That trend is accelerated in the face of deep decarbonization. Renewable energy use is a central feature in all energy system pathways. Its use in the power sector grows more quickly in Paris-compliant scenarios, though the range across Paris-compliant scenarios is large and does not necessarily increase with the stringency of the emissions mitigation. This is because electricity, which is used in end-use applications, must compete with energy efficiency; if the need for electricity is reduced through energy efficiency, then it is not necessary to build as much renewable electricity.

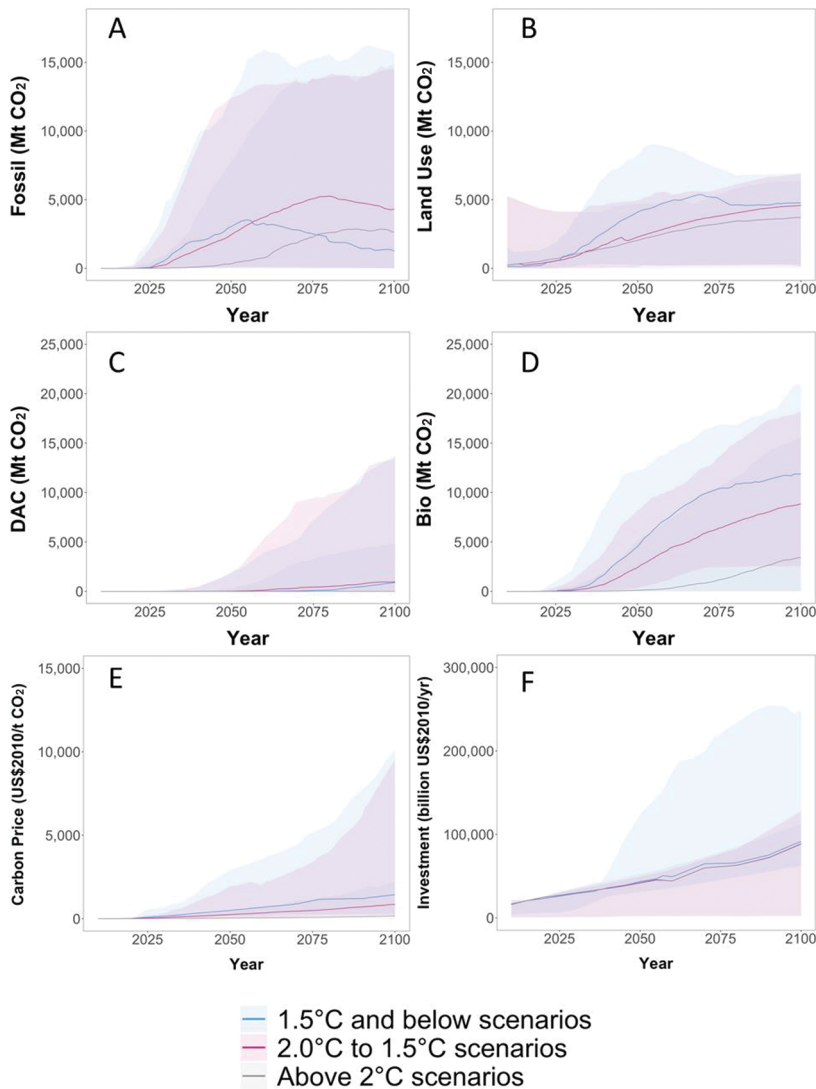
CCS is indispensable to achieve net-zero CO<sub>2</sub> emissions by midcentury (IPCC 2022). It is described in scenarios (Riahi et al. 2017; IPCC 2018; Gidden et al. 2019), international treaties (United Nations 2016), and national policies (Horowitz et al. 2022). Many scenarios in the IPCC AR6 database offset remaining positive emissions with either BECCS and/or other CDR technologies, for example, direct air capture (DAC) or terrestrial system carbon accumulation (figure 5). The use of CO<sub>2</sub> capture in conjunction with continued fossil fuel use varies greatly across scenarios. Although total use can be large in some scenarios, capture from fossil



**Figure 4** Global end-use energy consumption, total (A) and by fuels: solar (B), coal (C), liquids (D), gasses (E), biomass energy (F), electricity (G), and hydrogen (H) and by sector: buildings (I), industry (J), and transport (K). Lines correspond to the median value within a scenario group, with lower- and upper-shaded boundaries corresponding to the 5th and 95th percentiles, respectively. GDP-related metrics utilize GDP-PPP. Carbon intensity is calculated using total CO<sub>2</sub> emissions. Data are from IPCC AR6 database (version 1.1).

fuel use tends to peak and decline because CCS captures less than 100 percent of emissions and eventually becomes inconsistent with driving CO<sub>2</sub> emissions to net zero. On the other hand, the use of BECCS rises over time, and it does so more rapidly with more stringent emissions mitigation. Average annual BECCS CDR in Paris-compliant scenarios exceeds 5 gigatonnes of CO<sub>2</sub> (GtCO<sub>2</sub>) by 2050. Relatively few scenarios include DAC. Terrestrial systems—for example, afforestation—remove on average 5 GtCO<sub>2</sub> per year even in 2100.

The use of CDR technologies is generally thought to be less attractive than using renewable energy, for a variety of reasons, including concerns about double counting and moral hazard (Rogelj et al. 2021), forest fires (Costa et al. 2020; Brack and King 2021), and social challenges for indigenous and local communities (Ramos-Castillo, Castellanos, and McLean 2017; Sen and Dabi 2021).



**Figure 5** Global CO<sub>2</sub> offsets. Lines correspond to the median value within a scenario group, with lower- and upper-shaded boundaries corresponding to the 5th and 95th percentiles, respectively. GDP-related metrics utilize GDP-PPP. Carbon intensity is calculated using total CO<sub>2</sub> emissions. Data are from IPCC AR6 database (version 1.1).

Countries do not need to reach zero at the same time (van Soest et al. 2021b). Van Soest et al. (2021b) found that, based on economic efficiency alone, domestic net-zero GHG and CO<sub>2</sub> emissions in Brazil and the United States are reached a decade earlier than the global average and in India and Indonesia later than the global average. They explored the factors that drive countries to reach net zero at different years, including the potential for emissions mitigation through land-use changes, rate of economic growth, degree of international cooperation, and how the burden of mitigation is shared across societies.

## Frontier Issues

Tools and methods for producing and understanding emissions pathways continue to evolve and improve. Still, better data, methods, and tools are needed. Models need to be improved in ways that both enhance the level of detail for topics that are already included in the models and expand the scope of the models. Many of the frontier research areas do not fit neatly into just one category but spill over.

### Enhanced Resolution

Active research foci that build on existing foundations within the energy and integrated assessment modeling paradigms include technology characterizations, for example, electrification, CDR, and energy end use; representation of more realistic policies and measures; and climate finance.

### Technology

Technologies that deliver power without GHG emissions are core to net-zero emissions strategies. Solar and wind power expand dramatically in future climate mitigation scenarios. Their major challenges are cost and spatial and temporal variability in natural resource endowments. Dhakal et al. (2022) document substantial cost drops in wind and solar technologies over the last decade. The competition between energy resources will depend on technology developments—for example, ability to manage variability in solar and wind (Ueckerdt, Brecha, and Luderer 2015). Technologies to manage resource variability are under development, including batteries (where the cost of lithium-ion batteries has dramatically declined; Dhakal et al. 2022), pumped hydropower, hydrogen, and demand-side management, such as heat-pump appliances and electric vehicles.

The second part of the decarbonization strategy is to replace fossil fuel use with electricity and/or bioenergy. Electrification is the most cost-effective technological option to decarbonize many end-use energy services (Edmonds et al. 2006; Sugiyama 2012; McCollum et al. 2013; Zhang and Fujimori 2020; Sakamoto et al. 2021). However, electrification will not facilitate decarbonization in all applications; the so-called hard-to-abate sectors will need other technological solutions or offsets. The transport sector, especially trucks, ships, and airplanes, has been recognized as hard-to-abate energy services. Some industries that need high-temperature heat (e.g., furnaces) would also be classified “hard to abate” (Luderer et al. 2018).

There are multiple options other than electrification to decarbonize hard-to-abate energy services. Bioenergy is another nonemitting energy carrier but would need attention to adverse side effects of large-scale usage, as discussed below. Hydrogen is another non- or low-emitting energy carrier (Edmonds et al. 2004; van Ruijven, van Vuuren, and De Vries 2007). Hydrogen could potentially be used by multiple end-use technological devices and energy services (e.g., hydrogen furnaces and hydrogen vehicles). However, cost is still an issue in both hydrogen generation and hydrogen energy consumption devices (Oshiro and Fujimori 2022). Hydrogen can be used to produce ammonia (which is a higher-energy-density fuel than hydrogen) that could be used in transport. However, Wolfram et al. (2022) raise serious concerns that the use of ammonia as a shipping fuel could disturb the nitrogen cycle and result in increased NO<sub>x</sub> and N<sub>2</sub>O emissions, creating an air pollution problem and canceling out the climate benefits of reducing CO<sub>2</sub> emissions.

The IPCC has concluded that, in addition to decarbonizing the global energy system, CDR technologies will also be needed to meet Paris goals (IPCC 2022). BECCS, afforestation (including reforestation), and DAC are the main CDR options in IAMs. Models are just beginning to include technology options other than BECCS and afforestation. BECCS has been researched intensively over the last decade (Rose et al. 2022), and several considerations will likely limit its deployment, including food security concerns (Hasegawa et al. 2015, 2020), ecosystem impacts (Ohashi et al. 2019), and land and water use impacts of bioenergy (Calvin et al. 2014; Hejazi et al. 2014). The cost of DAC has decreased recently (e.g., <200\$/tCO<sub>2</sub>). Widely available CO<sub>2</sub> from DAC facilities opens the door to carbon-free synthetic fuels. In theory, at least, carbon-neutral fuels could be available for all hard-to-abate sectors (Akimoto et al. 2021). Cost is still the major obstacle to large-scale penetration of such fuels.

The prospect of large-scale deployment of CDR technologies raises many social and environmental concerns. Numerous studies have pointed to issues raised by the prospect of large-scale deployment of BECCS (Hasegawa et al. 2018; Ohashi et al. 2019), such as trade-offs between growing food crops and biofuel crops. In contrast, afforestation is thought to raise fewer concerns than BECCS. But the carbon sequestration potential of afforestation is limited compared with BECCS because of relatively low productivity and the fact that forests grow to maturity and become a carbon stock, with no additional net removal of carbon from the atmosphere. The mature forest also becomes a carbon stock that must be defended against future deforestation and carbon rerelease. Further, afforestation could induce food security concerns if it replaces cropland (Doelman et al. 2020; Fujimori et al. 2022).

### Real policies

Most analyses of transition scenarios that explore policies beyond those currently in place assume a carbon price that is common across all sectors and all regions at any point in time. This produces a cost-effective allocation of resources across regions and technologies, though not necessarily across time. In reality, policies and measures that are contemplated and enacted by governments are often complex and rarely rely on a single common global carbon price applied across sectors and regions. A few studies have pioneered the examination of heterogeneous policies and measures, for example, Calvin et al. (2014), Hultman et al. (2020), Peng et al. (2021a), van Soest et al. (2021a, 2021b), Baptista et al. (2022). If analysis is to better inform decision makers, more analyses that explore pathways with heterogeneous policies and measures are essential.

### Climate finance

“Climate finance” is a term that covers a multitude of issues, including analysis of investment resources needed to meet Paris goals, stranded assets (capital that is forced out of operation by the climate policy before its useful life is over), scenarios for private sector strategic planning, scenarios for development bank planning, scenarios to realign financial institution portfolios, and scenarios for central bank stress testing. Transforming the energy system toward the Paris Agreement goals requires a significant ramp-up in clean energy investment and a change in the composition of energy investment, shifting from fossil fuels to low-carbon energy. McCollum et al. (2018b) estimated that an extra \$130 billion per year needs to be invested in energy efficiency and clean energy in the next decade to achieve the nationally determined contributions

(NDCs), representing individual countries' commitments to reduce emissions. This need increases to \$460 billion per year to limit global temperature rise to 1.5°C. Significant upscaling in public and private finance is needed to close the investment gap and accelerate the energy system transition (Susantono et al. 2021; Meckling et al. 2022).

At the same time, fossil fuel markets would be negatively affected. Transitioning to a low-carbon economy could result in the devaluation or retirement of carbon-intensive assets before the end of their lifetime, including fossil fuel reserves and fossil fuel–using assets (Binsted et al. 2020; Semieniuk et al. 2022).

A growing literature has also started to explore policy interventions that can be taken to avoid or reduce stranded assets, especially the impact of early mitigation actions on reducing stranded assets (Bertram et al. 2015; Iyer et al. 2015b; Johnson et al. 2015; IRENA 2017; Mercure et al. 2018; Binsted et al. 2020; Caldecott 2020; Fisch-Romito et al. 2021).

Accelerating the energy system transformation also has strong implications for the global and national financial systems. A broad range of scenarios and analytical tools will be needed to facilitate that transition; these include scenarios for central banks and financial supervisors, analytical tools for development banks, analytical tools for investment banks, and analytical tools for private sector decision makers. A growing number of banks and investors are committed to aligning their portfolios with the net-zero transition (Robins, Dikau, and Volz 2021). Central banks and financial supervisors also have started to deepen their work to include climate risks in the financial analysis. The Network for Greening the Financial System, a network of central banks, has been using IAMs, climate models, and fiscal-monetary models to understand physical and transition risks under different climate scenarios and how the energy system transition interacts with employment, inflation, and real economic growth (Bertram et al. 2021; NGFS 2021, 2022).

## Expanding the Scope of Models

Decision makers need information that goes well beyond the domain of the current generation of models and analytical tools. Issues that have emerged as critical to defining energy transformation pathways include information about well-being in general, including sustainability, equity, justice, jobs, lifestyle and lifestyle change, the role of institutions, and uncertainty.

### Well-being

Well-being is a broad concept that extends well beyond human material needs. We use it here to cover the need to inform decision makers about the consequences of alternative decisions in multiple dimensions, including the fact that humans cohabit the Earth with other living and physical systems.

### Sustainability

The United Nations (2018) established 17 sustainable development goals (SDGs), all of which are intertwined and only about half of which are easily amenable to quantification (van Soest et al. 2019). Actions to pursue any individual goal have consequences that make achieving the other goals either easier or more difficult (van Vuuren et al. 2015; von Stechow et al. 2016; McCollum et al. 2018a). For example, bioenergy use carries implications for food production, food prices, dietary composition, competition for water, and biodiversity (Smith et al.

2016; Hanssen et al. 2022). Carbon mitigation strategies can also create synergies, such as the alignment with air pollution and energy security goals (Cherp et al. 2016; Markandya et al. 2018; Reis, Drouet, and Tavoni 2022).

A smaller set of studies explores simultaneously achieving multiple SDGs (van Vuuren et al. 2015; Soergel et al. 2021). A relatively larger body of research explores the nexus of water-energy-land-climate interactions (Kraucunas et al. 2015; Liu et al. 2015; van Vuuren et al. 2019; Vinca et al. 2020). Other research looking at SDG interactions includes examination of food and biodiversity interactions (Leclère et al. 2020).

### Lifestyle

Lifestyle can play a critical role in determining energy-related emissions through, for example, travel behavior, diet, and residential energy use (Fujimori et al. 2014; Grubler et al. 2018; van Vuuren et al. 2018). Too little is known about how lifestyle is determined and about the distribution of lifestyles across society.

### Environmental justice

The manner of carrying out the energy transition to reach the Paris goals will inevitably benefit some and disadvantage others. Choosing a just transition path requires a much broader set of information about transition pathways, including information at a wide range of scales, such as international, intranational, and intergenerational.

The examination of international equity has a long history, often under the banner of burden sharing (Rose et al. 1998; Clarke et al. 2014; Van den Berg et al. 2020). Countries' NDCs reflect a wide range of interest in reducing emissions, reflected in large differences in the marginal abatement cost—the cost of reducing an additional unit of emissions—that will be associated with successful implementation of NDC goals (Fujimori et al. 2016; Hof et al. 2017; Akimoto, Sano, and Tomoda 2018; Edmonds et al. 2021).

Within a country, carbon pricing policies tend to be regressive—they place a higher burden on lower-income residents (Bataille et al. 2018; Klenert et al. 2018). Tax revenue recycling—for instance, distributing the proceeds of a carbon tax to lower-income citizens—could potentially offset some adverse distributional effects (Kerkhof et al. 2008; Callan et al. 2009; Hussein, Hertel, and Golub 2013; Dissou and Siddiqui 2014; Dorband et al. 2019; Fujimori, Hasegawa, and Oshiro 2020; World Bank 2020; Soergel et al. 2021).

Climate change is an intergenerational issue that raises intergenerational justice and equity issues. To achieve a given long-term climate goal, the more CO<sub>2</sub> that is emitted before 2030, the less CO<sub>2</sub> can be emitted after that date (Riahi et al. 2015). Many studies have looked at the implications of emissions mitigation timing for intergenerational equity (Liu, Fujimori, and Masui 2016; Vrontisi et al. 2018; Aldy and Armitage 2022). There is also a rich literature on intergenerational optimality—the most efficient distribution of mitigation efforts over time—starting with Nordhaus (1975).

### Jobs

Jobs are a central question of political discourse as well as human well-being. Better tools and analysis are needed for the questions of where, when, what type of jobs, and for whom. Jobs are intimately tied up with other issues such as finance, technology, and policy choice. Several

studies have found that clean energy industries provide more jobs than fossil fuel industries and that transitioning toward a low-carbon future would increase energy sector jobs globally (Cameron and Van Der Zwaan 2015; E2 2019; Ram, Aghahosseini, and Breyer 2020; Pai et al. 2021). Secondary job implications have also been estimated. IEA (2021) estimated that 14 million new jobs would be created in energy supply sectors by 2030 in a net-zero transition scenario, outweighing the loss of 5 million jobs in fossil fuel industries over the same period—a net gain of 9 million jobs in energy supply sectors. Shifting job markets mean that those in declining sectors will find wages falling and jobs disappearing and will need to retrain for and move to the emerging jobs (Carley and Konisky 2020). Coal currently employs roughly 8 million people (Jakob et al. 2020). Coal-mining jobs have high spillovers in other economic sectors because of increased economic activity along the coal supply chain and through indirect demand for local goods and services (Lobao et al. 2016; Della Bosca and Gillespie 2018; Ruppert Bulmer et al. 2021). Burke, Best, and Jotzo (2019) found that closing coal mines or coal-fired power plants produced a significant loss of retail and commercial employment in local communities.

### Institutions

The future energy transition will take place within the context of institutions, organizations, and society more broadly (Victor, Geels, and Sharpe 2019). The transition to a net-zero future requires a shift in technology and facilitating changes in the underlying institutional environment, broadly comprised of the political and legal systems that protect property rights and facilitate information sharing and coordination across actors.

New institutions will be needed to facilitate deployment of low-carbon technologies at the needed scale and speed to achieve the Paris goals. These include regulatory frameworks to manage a more interconnected grid with unprecedented levels of intermittent renewable energy sources; trade regimes and networks to manage the demand for critical minerals required to manufacture low-carbon technologies (e.g., lithium, cobalt, rare-earth elements, etc.); regulations that adequately govern the transport and storage of CO<sub>2</sub>; and financial frameworks to ensure the availability of capital and incentives for risk-taking.

Yet coordination across various stakeholders, including governments, industry, and society, is lacking. Although business leadership coalitions that aim to coordinate action to accelerate transitions do exist, they lack the serious engagement of governments that could achieve change with the necessary scale and pace. Moreover, many such coalitions are dominated by actors from industrialized countries and lack participation from emerging economies whose growing industrial capability and market will be crucial to shaping future transitions.

Traditionally, IAMs have assumed rational decision makers at scales ranging from individual sectors to whole nations or aggregations of nations. Adjustments in prices—for example, the introduction of a price on carbon—or constraints on the choice of technologies can alter these agents' behavior. By contrast, real-world policy and industrial choices are made by a myriad of actors that vary in their incentives, organization, and power over outcomes. Some IAM studies have begun to account for such considerations. These include how political disagreements can delay policy action and hence increase the mitigation cost (Bosetti et al. 2009; Jakob et al. 2012; Luderer et al. 2013), how variations in the quality of governance affect those choices (Iyer et al. 2015a), and how perceptions of risk and the time horizons might influence investment planning (Bosetti and Victor 2011). These studies signal an important beginning.

However, a more coordinated community-wide effort to better account for institutions and institutional change, as well as how these affect energy system transitions in IAMs, will be important to facilitate a clearer understanding of the costs and characteristics of energy system transitions and consequently make IAMs more useful decision-making tools (Peng et al. 2021b).

## Uncertainty

IAMs typically provide conditional forecasts. Both model structures and assumptions contribute to uncertainty in model forecasts. The former is referred to as “structural uncertainty” and the latter as “parametric uncertainty.” One established way to address structural uncertainty is to conduct experiments with multiple IAMs that are based on different structures but with a loosely coordinated set of parametric assumptions driving them. Parametric uncertainty is typically addressed using scenarios (van Vuuren et al. 2013). Scenarios refer to alternative plausible descriptions (quantitative or qualitative or both) of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces. Many studies use community scenarios such as the SSPs that are based on qualitative descriptions (or storylines) “that highlight the scenario’s main characteristics, relationships between key driving forces, and the dynamics of the scenarios” (IPCC 2014b; O’Neill et al. 2015). Many individual studies also construct scenarios that are based on an a priori expert judgment about the most important drivers or combination of drivers that might affect the outcomes of interest.

Although scenarios are tremendously helpful in providing bounds on the uncertainty, they are limited in their scope of exploring the full space of relevant futures. Newer and more quantitative approaches include scenario discovery. Scenario discovery shifts the role of expert judgments that inform scenario selection from merely an a priori effort to a discovery process that occurs after important combinations are quantitatively identified. The scenario discovery approach uses exploratory model simulations to evaluate the uncertainty space defined by the combinations of key drivers and to test the implications of different combinations for outcome measurements of interest (Guivarch, Rozenberg, and Schweizer 2016; Lamontagne et al. 2018; Dolan et al. 2021). By systematically testing across a large ensemble of model simulations and applying statistical techniques, insights about which combinations of drivers are most critical to achieving or avoiding certain outcomes can be derived. These insights can then be used to identify a limited number of the most important driver combinations. The scenario discovery approach is particularly relevant for multisector applications because deep uncertainties (Walker et al. 2003) concerning the complex dynamics of natural and human systems could make a priori selection of meaningful driver combinations extremely difficult (Greeven et al. 2016).

Conducting a large ensemble of model simulations using IAMs will require strengthening computational expertise within modeling teams and maintaining modern model codes that can be run on parallel high-performance computing platforms (Scott et al. 2016; Lamontagne et al. 2018). The computational requirements for conducting such exercises could be substantial but less onerous than for climate models (Kay et al. 2015).

## Concluding Thoughts

This cursory review of the current state of understanding of global energy system transitions hardly does justice to the field. Even nominally comprehensive assessments such as IPCC

(2022) are merely places to start. Our guidance and recommendations come out of our unique perspectives. We offer a few final thoughts to help guide future work.

Foremost, modeling and analyses depend on the audience. Although some information is broadly useful, individual users will often have specific needs. Good modeling, data development, and analysis will incorporate those needs. For example, national policy analysis may value wide-ranging sensitivity analysis to explore policy robustness. Corporate planners may value sectoral and technological detail. Central bankers may want extreme scenarios for stress testing purposes.

In that same vein, energy transition problems are highly disrespectful of academic disciplinary boundaries. Following the problem will mean establishing new collaborations. For example, coupling to finer spatial and temporal scale modeling could facilitate research into the local and near-term implications of system-wide, global, and long-term transitions. See, for example, Vernon et al. (2023).

Collaborations between energy system transition modelers and social scientists could enable a better understanding and representation of the societal and institutional context within which transitions occur (Peng et al. 2021b). The success of such collaborations will hinge on multidisciplinary communication. In the longer term, interdisciplinary education to train the next generation of scientists could improve the likelihood of success.

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