Projecting Energy and Climate for the 21st Century

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ABSTRACT

The growing evidence of severe climate change impacts on human life and the global economy has created the increasing need for an assessment of low-carbon pathways. While the ultimate goal of zero- or near-zero global emissions is clear, the timing and trajectory to achieve low-carbon economic system is not. Projecting energy and climate is getting more challenging because the current energy and emission policies diverge further and further from the stated long-term policy goals. We provide a discussion of descriptive and prescriptive approaches to energy and climate forecasts. While the fundamental uncertainties are unavoidable, a group of scenarios that project the entire range of plausible developments provides better guidance for decision-making than any (or several) individual scenario(s). We offer an example of an integrated approach from the MIT Joint Program Outlook that can be used for a quantitative analysis of decision-making risks associated with different energy pathways. Despite the broad variety of scenarios, the article finds some robust findings for the energy system.

Keywords: Energy transition, Scenarios, Climate policy, Energy system, Emission mitigation

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1. INTRODUCTION

Energy scenarios have an important role to play in assessing the energy system transition required to mitigate climate challenges. Energy and industrial companies, governments, civil society and other stakeholders need to align their strategies with the science-based targets while continuing economic growth and development including providing reliable and affordable energy. Numerous expert groups and individual researchers produce energy scenarios and analyze their implications for climate. The Intergovernmental Panel on Climate Change (IPCC) produces periodic reports that assess the literature relevant to understanding the impacts of climate change. These reports cover the scenarios of the future energy system development, with some scenarios developed by the members of the Integrated Assessment Model Consortium (IAMC). Other well-known scenario producers include the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the U.S. Energy Information Administration (EIA), and energy companies, such as Shell, BP, and ExxonMobil.

The goal of this paper is to explore the major dimensions of the long-term energy and climate forecasts and to compare their similarities and reasons for their diversity. Any scenario starts with initial conditions and then models the evolution of the system (Ansari, Holz,

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and al-Kuhlani 2020). Projecting energy and climate is getting more challenging because the global society through the Paris Agreement process (UN 2015) decided to change the current energy system and move to low-carbon economy. While the ultimate goal of zero- or near-zero global emissions is clear, the timing and trajectory to achieve low-carbon economic system are subject to substantial uncertainty driven by policy structures, technological progress, and societal pressures. As a result, most of the scenarios that do not force a particular outcome (like net-zero emissions or certain percentage of renewable energy) diverge substantially from the scenarios that define a set of particular desired outcomes and explore the ways to achieve those outcomes.

For the Paris Agreement process, countries have submitted their plans to reduce greenhouse gas (GHG) emissions. Numerous studies (e.g., IEA 2019; MIT Joint Program 2018; UNEP 2018) have shown that the current pledges, formulated as Nationally Determined Contributions (NDC), are inadequate to bridge the gap between the resulting emissions in the next decade and the least-cost pathways to stay below 1.5°C or 2°C. The current emission pathways imply the global warming by around 3°C by 2100 with a continuing increase in temperature afterwards. Despite the numerous efforts to accelerate the energy transition, the progress has been rather slow. A discrepancy between the stated ultimate goals that require zero global emissions and the current actions create a particular challenge to the "best guess" scenarios that are designed to project the most likely outcomes without assigning any value judgements to them.

The paper is organized in the following way. Section 2 provides an overview of the historic trends in global energy and energy-related emissions. In Section 3 we discuss the main forecasts of the current energy trends for the next two decades and compare them to prescriptive scenarios that are formulated to achieve particular goals. In Section 4 we offer an illustrative example of an integrated approach that is used to analyze different pathways for the 21st century. Section 5 offers some concluding remarks.

2. HISTORIC TRENDS IN ENERGY AND EMISSIONS

Fossil fuels have played a decisive role in human development. For many years, economic development has been primarily supported by obtaining energy from oil, coal, and natural gas (BP 2019a). Figure 1 represents the contributions to the global primary energy use in 2018 (IEA 2019), which shows that fossil fuels provide 81% of global primary energy. During the last several decades, this global share of fossil fuels has been almost the same, while the global primary energy use has increased by about 60% from 1990 to 2017 (ExxonMobil 2019). In terms of individual fuel contributions, in 2018 oil had the largest share of 31%, coal's share was 27%, and natural gas contributed 23% to the total global energy use. Bioenergy (combining both traditional (i.e., non-marketed) and commercial use) had a share of 9%. Nuclear had 5% share. Hydropower's share was 3%. Other renewables (including solar and wind) contributed 2% to the global primary energy in 2018.

From 1990s, the global community recognized the dangers of uncontrolled increases in GHG emissions, which are mostly driven by the combustion of fossil fuels. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted with a goal to stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UN 1992). In 1997, the Kyoto Protocol was adopted that set the emission reduction targets for developed countries for 2008-2020. In 2015 the Paris Agreement was signed to limit the global warming to less than 2°C and pursue efforts to limit the rise to 1.5°C (UN 2015).

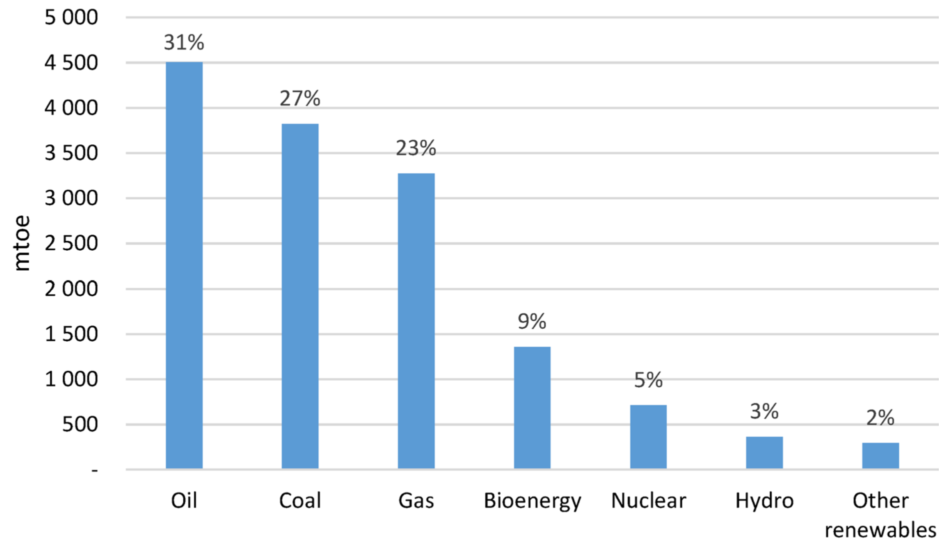


FIGURE 1

Global primary energy use in 2018 in million tonnes of oil equivalent (mtoe) and shares (%).

Data source: IEA (2019).

Despite the global efforts, GHG emissions continue to rise. Figure 2 shows the data for 1965-2018 for global carbon dioxide emissions from fossil fuel combustion. Emissions in 1965 were 11.2 gigatonnes (Gt). By 2018 they have grown to about 34 Gt CO_2. In the last ten years (after the entrance of the Kyoto Protocol), global emissions has grown by 12%. Even after the adoption of the Paris Agreement, global emissions continue to rise, and in 2018 they were at the highest level ever. As shown in Figure 2, about 60% of global emissions in 2018 came from four regions: China (with 28% of global emissions), USA (15%), European Union (EU) (10%), and India (7%). These regions exhibited different dynamics in terms of a change in their emissions in 2018 relative to 2017. While the EU emissions are decreased by 2%, China's emissions are higher by 2.2%, the U.S. emissions are higher by 2.6%, and India's emissions have grown by 7% in 2018. The emissions in the rest of the world have increased by 1.7%. The overall global increase in emissions by 2% is at odds with the stated goals of emission reductions.

3. ENERGY-CLIMATE SCENARIOS

Energy-climate scenarios include a description of how socio-economic factors, policy designs, and energy technologies will develop and interact to produce particular energy mixes and emissions profiles, which over time lead to changes in global climate conditions. Paltsev (2017) provides an overview of the value and limits of energy scenario analysis and distinguishes between the descriptive or "the best guess" scenarios and prescriptive scenarios. Descriptive scenarios are constructed to provide the "most likely" outcomes under current policies. Prescriptive scenarios are constructed to explore the required energy trajectories to reach a particular target (e.g., achieving a certain percentage of renewables, the 2°C target, or net-zero emissions by a certain date).

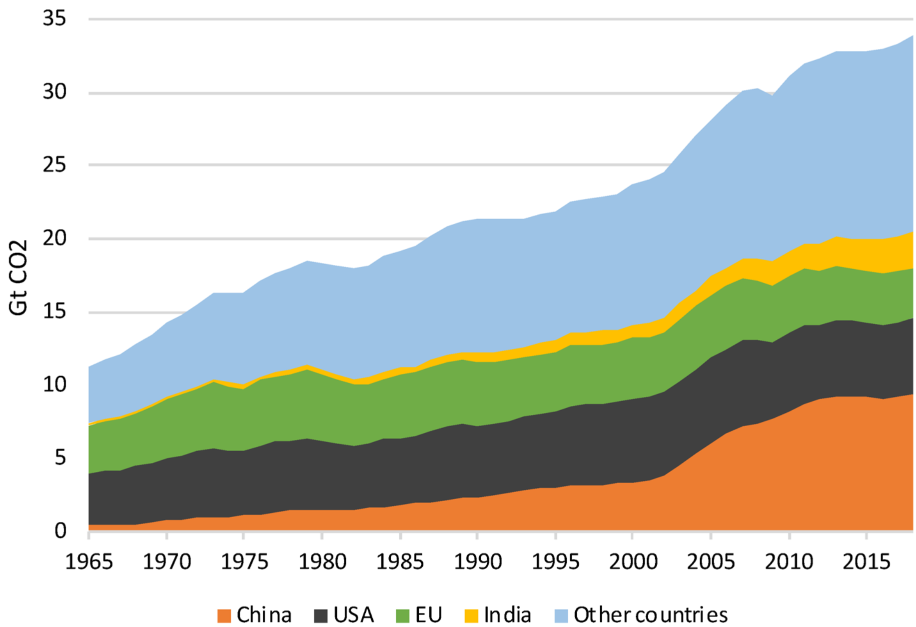


FIGURE 2

Historic carbon dioxide emissions from fossil-fuel combustion.

Data source: BP (2019a).

The scenarios provide a description of a plausible future and they explore "what if" conditions. Typically, the more plausible a scenario is, the more useful it is likely to be. However, the plausibility of any particular scenario is challenging to assess. It is easier to quantify rates of technological improvement, cost curves, economic growth, technology availability, and their uncertainties, for example, than it is to do so for rates of societal adoption, cultural attitudes, and lifestyle shifts. Below we start with the main projections of global primary energy use.

3.1 Descriptive Scenarios

Although not formally approved by any regulatory body, the IEA scenarios included in its World Energy Outlooks represent the current de facto standard for global energy transition scenarios. Despite some critical assessments of certain aspects of IEA projections, especially regarding the deployment of renewable energy (Paltsev 2017; Mohn, (2020)), IEA's annual energy outlooks constitute the most reputable source among energy experts. The three most commonly referenced scenarios from the IEA include the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) (previously known as the New Policies Scenario), and the Sustainable Development Scenario (SDS). CPS and STEPS are in a category of descriptive scenarios. The IEA scenarios run up to 2040 and CPS represents current policies, while STEPS includes an assessment of the likely effects of announced policies as expressed in official targets and plans (however, the full implementation of some stated goals is not taken for granted). The SDS is a prescriptive scenario that well be discussed in the next sub-section.

Figure 3 shows a projection of the global primary energy use in the Stated Policies Scenario that includes NDC targets submitted to the Paris Agreement Process. "Other renewables" category (that does not include hydro and bioenergy) is the fastest growing energy source. It increases 4.5 times between 2018 and 2040 and its share in the total energy grows from 2%

in 2018 to 7% in 2040. Fossil fuels in this scenario reduce their share from 81% in 2018 to 74% in 2040, but they still provide a major contribution to the world's energy needs. Coal use is virtually flat, oil use grows slightly (at an average annual growth rate of about 0.4%), and natural gas growth is faster (at an average annual growth rate of about 1.4%). The global energy use grows by about 24% from 2018 to 2040 to about 17,700 mtoe.

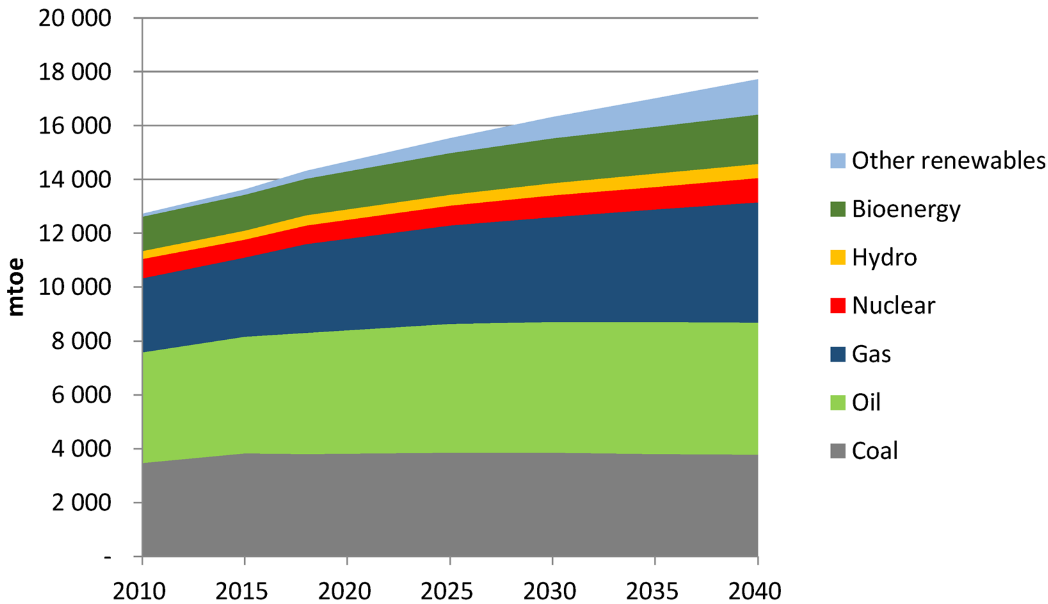


FIGURE 3

Global primary energy projection in the Stated Policies Scenario of the 2019 IEA World Energy Outlook.

Data source: IEA (2019).

ExxonMobil (2019) also projects up to 2040 (Figure 4). Its Energy Outlook uses 2017 as a base year for future projections. In the ExxonMobil Outlook, the "Other renewables" category includes biofuels (but not biomass energy and waste) in addition to wind, solar, and geothermal. As a result, its 2017 value is slightly larger than the 2018 value from the IEA's "Other renewables" category (about 331 mtoe in the ExxonMobil Outlook vs 293 mtoe in the IEA Outlook). This category also is the fastest growing source of energy, with a factor of 3.1 increase from 2017 to 2040. Its share in the total energy grows from 2% in 2017 to 6% in 2040. Fossil fuels reduce their share from 81% in 2017 to 76% in 2040. Coal use in the ExxonMobil Outlook is reduced by 10% between 2017 and 2040. Oil use grows at an average annual growth rate of about 0.56%, and natural gas grows at about 1.35%. The global energy use grows by about 20% from 2017 to 2040 to about 17,000 mtoe. Overall, ExxonMobil projections are quite similar to the IEA's Stated Policies Scenario.

BP (2019b) projections to 2040 also use 2017 as a base year. BP Outlook tracks only commercially-traded fuels, so traditional biomass is not included. Figure 5 presents the projections for the Evolving Transition Scenario. For reporting, we have adjusted BP values for hydro (BP reports it at fossil fuel equivalence) and nuclear (BP uses different conversion efficiency in comparison to IEA). BP's "Renewables" category includes solar, wind, geothermal and commercial biofuels. BP also reports wind energy and solar energy separately. Based on that reporting, we

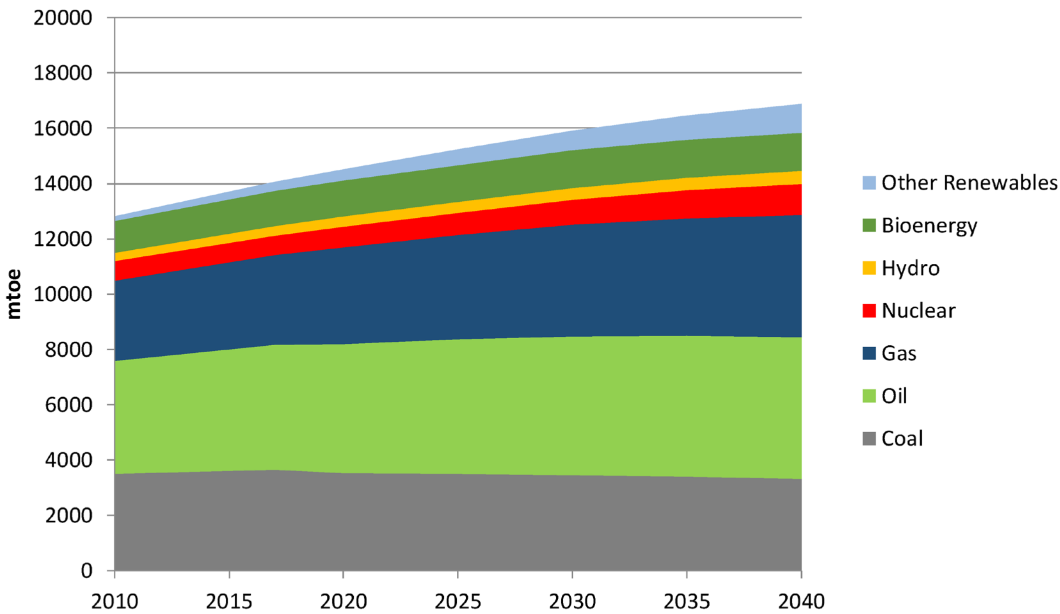


FIGURE 4

Global primary energy projection in the 2019 ExxonMobil Outlook.

Data source: ExxonMobil (2019).

have labelled their combination as "Other renewables" in Figure 5. In the BP's Evolving Transition Scenario, the "Other renewables" is the fastest growing source of energy, with an increase of 6.5 times from 2017 to 2040. Its share in the total energy grows from 3% in 2017 to 13% in 2040. Fossil fuels reduce their share from 88% in 2017 to 76% in 2040. Coal use in the BP Outlook is reduced by 3% between 2017 and 2040. Oil use grows at an average annual growth rate of about 0.3%, and natural gas grows at about 1.67%. The global energy use grows by about 32% from 2017 to 2040 to about 17,200 mtoe. Overall, BP projections are also quite similar to the results from the IEA's Stated Policies Scenario.

The MIT Joint Program Outlook (MIT Joint Program 2018) reports the detailed results for their projections to 2050. It also reports GHG emission and climate projections up to 2100. It uses 2015 as a base year. The MIT Outlook also tracks only commercially-traded fuels, so traditional biomass is not included in the energy reporting, but it is captured in the emission accounting, so we have added it for reporting purposes here. Figure 6 presents the projections from the MIT Outlook. For reporting, we also have adjusted the values for hydro (MIT reports it at fossil fuel equivalence) and nuclear (MIT uses different conversion efficiency in comparison to IEA). MIT's "Other Renewables" category includes solar, wind, geothermal and commercial biofuels. In 2015 its value is reported at 594 mtoe. According to MIT, the "Other Renewables" is the fastest growing source of energy, with 3.5 increase from 2015 to 2040. Its share in total energy grows from 4% in 2015 to 12% in 2040. Fossil fuels reduce their share from 79% in 2015 to 73% in 2040. Coal use in the MIT Outlook is reduced by 3.5% between 2015 and 2040. Oil use grows at an average annual growth rate of about 0.7%, and natural gas grows at about 1%. The global energy use grows by about 23% from 2015 to 2040 to about 17,400 mtoe. Overall, the MIT projections are also quite similar to the results from the IEA's Stated Policies Scenario.

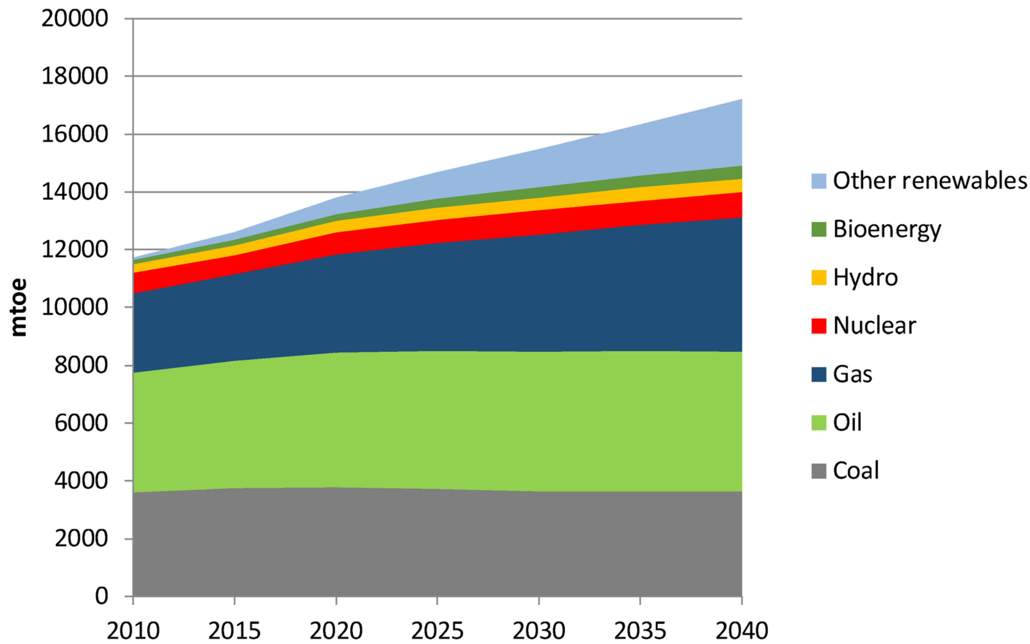


FIGURE 5

Global primary energy projection in the Evolving Transition Scenario of the 2019 BP Outlook.

Data source: BP (2019b).

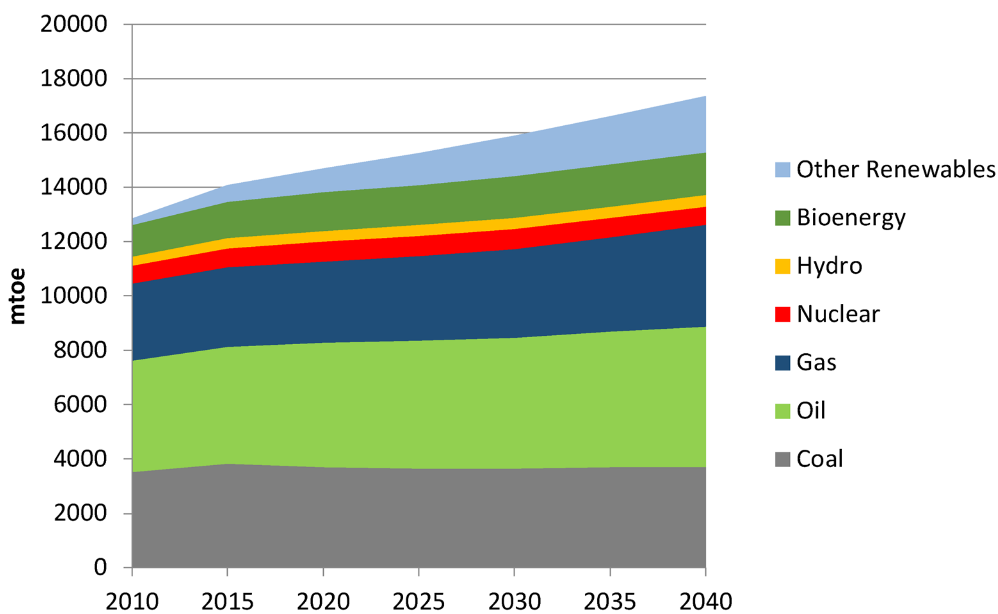


FIGURE 6

Global primary energy projection in the Current Outlook Scenario of the 2018 MIT Joint Program Outlook.

Data source: MIT Joint Program (2018).

The above-described outlooks are produced by using very different approaches: a simulation model with exogenous fuel prices in the case of IEA, a set of simulation models with exogenous fuel prices in the cases of ExxonMobil and BP, an optimization model with endogenous fuel prices in the case of MIT. However, they all have a similar picture for the development of global energy in the next two decades: fast increases in renewables, relatively constant contributions from nuclear and hydro, continuing reliance on fossil fuels, flat or slightly declining coal use, slight growth in oil use, and a faster growth in natural gas use. While the projections for a share of renewables in 2040 differ from 6% to 13% (in part due to different reporting principles in different outlooks), these outlooks show that the current policies are not consistent with the stated de-carbonization goals as the world continues to rely heavily on fossil fuels.

3.2 Prescriptive Scenarios

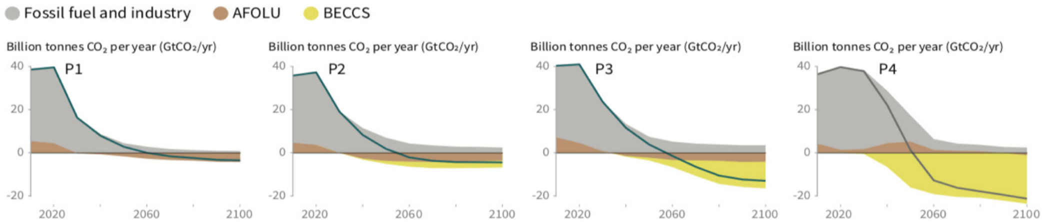
Prescriptive scenarios are important for an assessment of additional efforts required to achieve a certain goal. For example, IEA SDS sets the requirements to reach key energy-related goals of the UN sustainability agenda, namely an early peak and subsequent reduction in emissions, universal access to modern energy by 2030, and reduction in air pollution. IEA states that a trajectory for emissions in the SDS is consistent with reaching global "net zero" CO_2 emissions in 2070 and it results in a 66% chance of limiting the global average temperature rise to 1.8°C above pre-industrial levels (or a 50% chance of a 1.65°C stabilization). Similarly, other researchers have shown that scenarios with high shares of renewables would enable meeting climate targets (e.g., Oei et al. 2020; Breyer et al. 2020).

The goals usually refer to the endpoint of a scenario, such as a temperature target. However, there are many ways—or scenario paths—for achieving any one temperature outcome. The political, technological, and economic developments and associated risk drivers (e.g., which sectors and regions bear the most emissions reductions, or which energy technologies win out in different economies) can be distinctively different between pathways with the same outcome (MIT 2019). Figure 7 shows the four very different pathways to the same target of 1.5°C stabilization (IPCC 2018). It emphasizes the importance of using a range of scenario paths than relying on a single scenario for a stated goal. Developing families or suites of paths can serve to define "envelopes" of transition pathways, which in turn can illuminate the range of plausible impacts on energy systems.

There are other important characteristics of prescriptive energy-climate scenarios. Political and market pressure for a transition toward a low-carbon economy, and the resulting degree of stress on fossil fuel companies, can take many forms. Emissions mitigation in any country will ultimately be the product of an amalgamation of policy levers—including carbon taxes or a cap-and-trade system, product mandates such as fuel efficiency standards, subsidies for renewables, regulations, and bans—adopted by multiple jurisdictions. Climate-economy models require a quantitative representation of the cumulative pressure these measures would create.

While some simulation models, such as the World Energy Model used by the IEA, might explicitly cover a wide variety of these levers, others, including many optimization models, might require a single representation of policy pressure in order to allocate computational power toward other sectors, land use, or Earth systems (MIT 2019). This is most commonly modeled as a "carbon price," or an additional cost of emitting CO_2, generally expressed in $/ton. However, this modeled "carbon price" is an approximate cost. Great care should be taken when accounting for the intertwined consequences that such a tax would have on energy markets or government decisions.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
└ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
└ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
└ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
└ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
└ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
└ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
└ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
└ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
└ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
└ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
└ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km²)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b | Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM.3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socio-economic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (Figure SPM.3a). {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

FIGURE 7

Carbon dioxide emission pathways to meet 1.5°C target.

Source: IPCC (2018, 14-15).

The mix and pace of actions that will need to be taken in the next several decades to reach specific climate outcomes by 2100 are heavily influenced by assumptions about technological developments, some of which are not expected until the latter half of the century. Models often have to "force" outcomes by making assumptions about the invention, advantageous economics, and rapid scale-up of certain technologies (e.g., long-term energy storage, carbon capture and storage, bioenergy with carbon capture and storage, and other negative emissions technologies), many of which are currently unproven at scale, uneconomical, of questionable public acceptance, or otherwise problematic (MIT 2019, Braunger and Hauenstein 2020). Such assumptions can be obscured in scenario analyses that focus on the first half of the 21st century. This presents a challenge for energy companies as they try to anticipate the types of energy and fuels that will be required to stay competitive while meeting environmental requirements.

Shell Sky scenario (Shell 2018) provides an example that examines the challenge of moving to an energy system with net-zero CO_2 emissions and gradually eliminate emissions from deforestation by midway through the second half of the century (specifically by the year of 2070). Figure 8 shows the emission trajectory in the Shell Sky scenario that envisions a rapid energy transition to the low-carbon sources. The Sky scenario includes the current energy demand growth in the emerging economies and a steady strengthening of the pledges that countries made under the Paris Agreement process up to 2025–2030.

From 2030 the scenario assumes a target-driven approach that results in substantial electrification of energy use and scaling up of low-carbon technologies, like wind and solar. Hydrocarbons continue to play a role in some sectors like heavy-industry processes and heavy-duty transport. Methane emissions from oil and natural gas industry are substantially reduced by following best practices to mitigate them. In the later part of the century, carbon capture and storage (CCS) technology is widely employed both on fossil fuels and bioenergy.

As mentioned in Section 2, global energy-related CO_2 emissions have grown to about 34 Gt in 2018. The emissions in the Sky scenario are projected to grow to about 36.5 Gt in 2025–2026 and then they start to decline. The rate of decline accelerates after 2030 and the decline rate in 2035–2070 (-0.9 Gt/year) exceeds the rate of increase in energy-related CO2 emissions in 2000–2015 (+0.7 Gt/year).

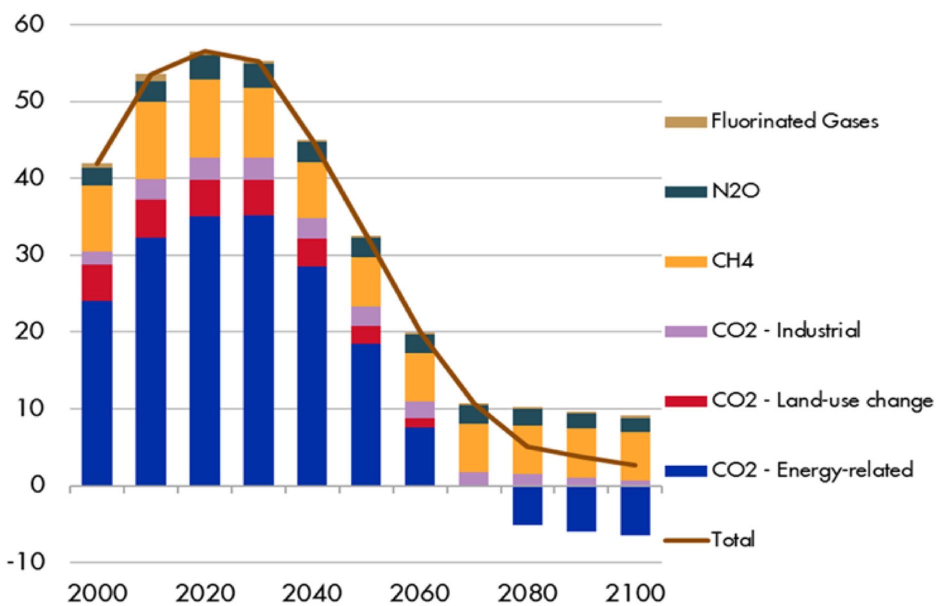


FIGURE 8

Global GHG emissions (Gt CO_2e) in Shell Sky Scenario.

Source: Paltsev et al (2018).

Figure 9 provides the temperature results of several scenarios with different assumptions about the land-use CO_2 emissions. The Mountains and Oceans scenarios assume the same land-use emission profiles. For the Sky scenario, four land-use CO_2 emission profiles were created (see Paltsev et al (2018) for a description of the Mountains and Oceans scenarios and details about land-use modeling). Two of these land-use variants consider enhanced use of land for carbon mitigation. These two scenarios with nature-based solutions (NBS) involve reforestation, reduced deforestation, better forest management, and other land related activities. These scenarios are called as Sky+Restoration NBS and Sky+Extra NBS. A wide deployment of land management practices is assumed after 2030 and a gradual exhaustion of new options by the end of the century. A third scenario, called Sky without NBS, keeps land-use emissions at a current (2015) level. All four variants of the Sky scenario (Sky, Sky without NBS, Sky+Restoration NBS, Sky+Extra NBS) are below 2°C. Additional NBS actions reduce the surface temperature increase and the Sky+Extra NBS scenario is approaching 1.5°C above the pre-industrial levels by 2100.

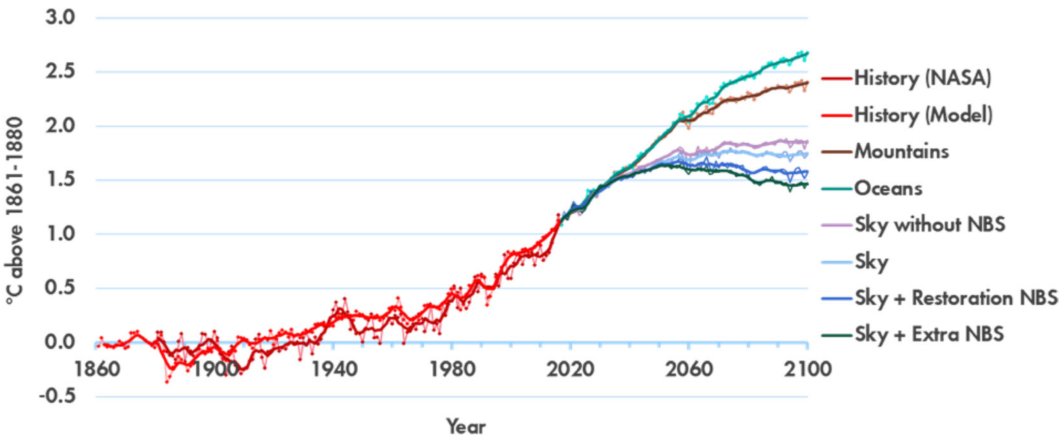


FIGURE 9

Temperature Implications.

Source: Paltsev et al (2018).

We now turn to assessing the implications of the 2°C targets for the fuel composition of the global energy system in the next two decades. As mentioned, there are numerous pathways to reach this goal, so the outlooks may be on a different underlying emission trajectory, but it is still useful to compare the energy mixes compatible to aggressive climate mitigation goals. Figure 10 shows a projection of the global primary energy use up to 2040 in the Shell Sky scenario (Shell, 2018). The base year (the latest reported historic data) for Shell Sky is 2015. "Other renewables" category in the Shell Sky scenario includes solar, wind and geothermal. It is the fastest growing energy source from 2015 to 2040 with an increase at a factor of 15.3 between these years. Renewables share in the total energy grows from 1.5% in 2015 to 17% in 2040. Fossil fuels in the Shell Sky scenario reduce their share from 81% in 2015 to 61% in 2040. Relative to the 2015 levels, coal use is reduced by 19% by 2040, oil use is reduced by 1.5%, and natural gas use is increased by 22%. The global energy use increases by 31% from 2015 to 2040 to about 17,900 mtoe.

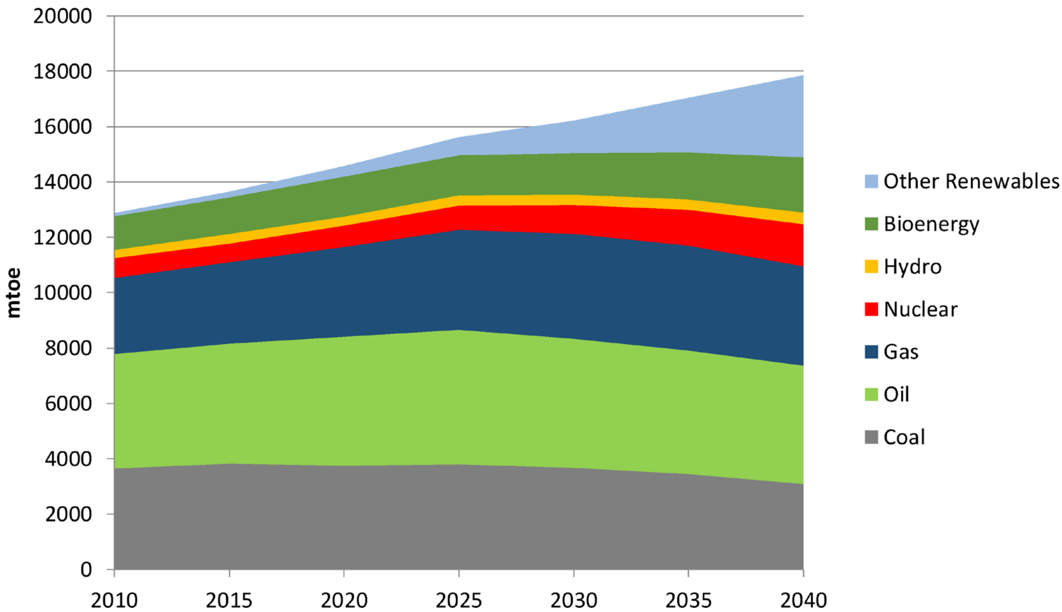


FIGURE 10

Global primary energy projection in the Shell Sky Scenario.

Data source: Shell (2018).

Figure 11 shows a projection of the global primary energy use in the IEA SDS. "Other renewables" category is again the fastest growing energy source. It increases 7.6 times between 2018 and 2040 (in comparison to 4.5 time in STEPS). Renewables share in the total energy grows from 2% in 2018 to 17% in 2040 (in comparison to 7% in STEPS). Fossil fuels in this scenario reduce their share from 81% in 2018 to 58% in 2040. Relative to the 2018 levels, coal use is reduced by 62% by 2040, oil use is reduced by 32%, and natural gas use is reduced by 3%. The global energy use is reduced by 7% from 2018 to 2040 to about 13,300 mtoe.

BP (2019b) provides projections for the Rapid Transition Scenario up to 2040 (Figure 12). "Other renewables" is the fastest growing source of energy, with an increase by a factor of 11.5 from 2017 to 2040 (in comparison to 6.5 times in the Evolving Transition Scenario). Its share in the total energy grows from 3% in 2017 to 26% in 2040. Fossil fuels reduce their share from 88% in 2017 to 59% in 2040. Global coal use in the BP Rapid Transition Scenario is reduced by 71% between 2017 and 2040. Oil use is reduced by 15% in the corresponding period, while natural gas usage still grows by 38% between 2017 and 2040. The global energy use grows by about 20% from 2017 to 2040 to about 15,700 mtoe. BP's decarbonization projections show a somewhat different picture for the future global energy mix in comparison to the IEA's Sustainable Development Scenario, but it is close to the view in the Shell Sky scenario.

Comparing the prescriptive scenarios described above, a trajectory to de-carbonization is rather different between these three forecasters. Shell's reduction in coal use is smaller (19% reduction by 2040) in comparison to BP (71%) and IEA (62%). The difference is driven by two factors: by an assumption by BP and IEA about more aggressive near-term mitigation actions in comparison to Shell (which assumes Paris Agreement NDCs for 2025-2030); and more optimism about carbon capture and storage (CCS) technology by Shell. Shell projects about 2.2 Gt CO_2 captured in 2040 and 5.2 Gt CO2 in 2050 (for consistency with other outlooks,

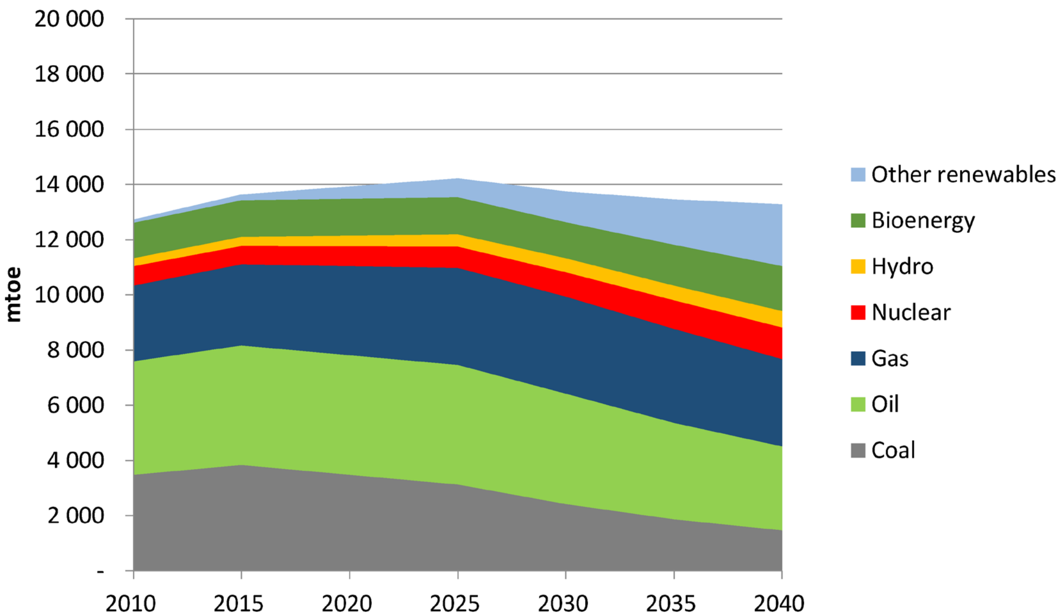


FIGURE 11

Global primary energy projection in the Sustainable Development Scenario of the 2019 IEA World Energy Outlook.

Data source: IEA (2019).

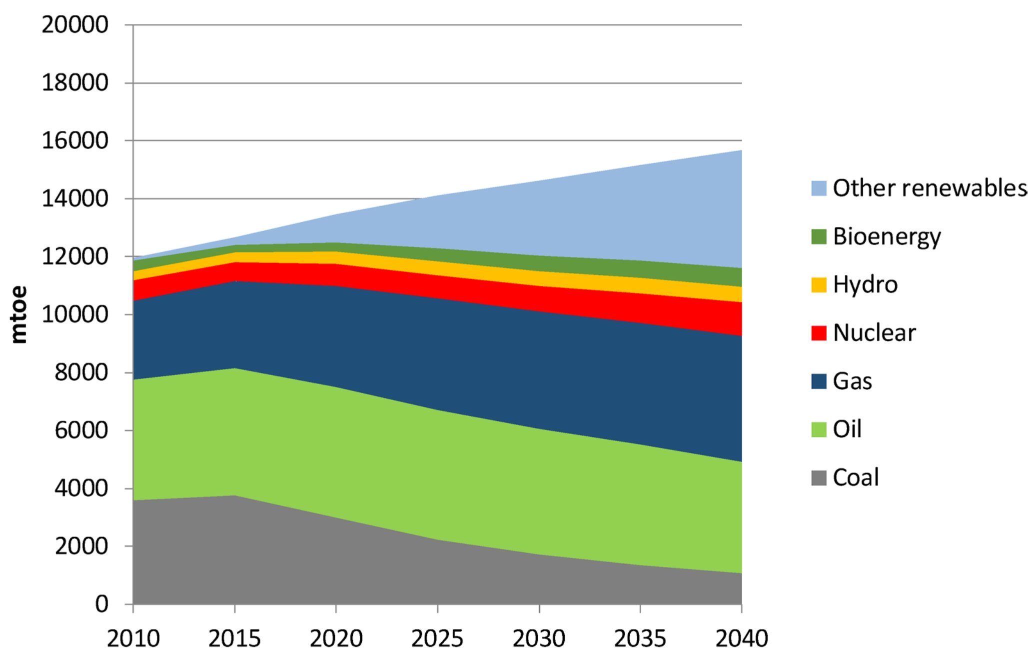


FIGURE 12

Global primary energy projection in the Rapid Transition Scenario of the 2019 BP Outlook.

Data source: BP (2019b).

in this paper we focus on reporting up to 2040), while IEA SDS scenario reaches 2.8 Gt CO_2 captured in 2050.

Natural gas use is rather constant over time in the IEA projection (only 3% reduction by 2040), but it grows in Shell (22% increase) and BP (38% increase) scenarios. Oil use is rather constant in Shell (only 1.5% reduction), but it is reduced faster in BP (15% reduction) and IEA (32% reduction) scenarios. All three outlooks envision a substantial increase in the share of renewables in the primary energy mix (17% in the Shell scenario, 17% in the IEA scenario, and 26% in the BP scenario). While both Shell and BP foresee an increase in the total global primary energy use by 2040 (by 31% and 20%, respectively), the IEA's prescriptive scenario forecasts a 7% decrease. These rather different views from the well-established and reputable forecasting groups about the global path to de-carbonization brings a caution to a treatment of prescriptive scenarios in terms of their robustness. This is in contrast to a relative agreement between forecasting agencies on the impacts of the current policies (as described in Section 3.1).

Another point to note is that all annual outlooks (from one edition to another) have a tendency to increase their long-term projections for renewables. For example, IEA in their Sustainable Development Scenario has increased the global amount of renewable energy in 2040 by 6.8% from their 2017 edition of the Outlook to the 2018 edition of the Outlook. The amount of renewables has been further increased by 4.7% in the 2019 Outlook. Other outlooks have similar dynamics about the renewables.

4. ILLUSTRATIVE EXAMPLE OF LONG-TERM ENERGY-CLIMATE SCENARIOS: MIT JOINT PROGRAM OUTLOOK

In this section, we expand a discussion of the features of the MIT Outlook (MIT Joint Program, 2018) that offers an example of long-term projections for energy, emissions, and the resulting climate variables such as temperature, precipitation, sea level rise, and ocean acidity. MIT Joint Program Outlook provides several 2°C and 1.5°C scenarios. Figure 13 presents the projections for the 2°C Tax Scenario from the MIT Outlook. The energy system evolution is similar to the IEA Sustainable Development Scenario with a sizeable impact on energy efficiency and total energy demand, substantial reduction in coal use and considerable increase in renewable energy by 2040. Oil use is decreased by 18% between 2015 and 2040, while the global natural gas use is almost unchanged in this period of time in this scenario.

Turning to other features that affect the de-carbonization pathways, MIT Outlook states that while the Paris Agreement focuses on 2°C and 1.5°C temperature targets, there remain several issues in establishing emissions pathways consistent with these goals. Foremost among these are uncertainties in the Earth-system response to a specific emissions pathway. Then there is the question of what is meant by "well-below" 2°C. Finally, there is the question of linking near-term targets with the long-term goal; doing more in the near term leaves more room in the future for hard-to-abate emissions, while betting on future zero or negative emissions technologies means more headroom in the near-term for countries to gradually transform energy, industry, agriculture and other sectors to zero-GHG technologies.

There are also possibilities of "overshoot" scenarios, where temperature rise above a level consistent with a long-term goal, but then fall back to that level in later years. These scenarios have been of particular interest in the case of the 1.5°C target because of the challenge of reducing emissions enough in the near-term to meet that goal. Figure 14 shows a set of simulations determines emissions paths consistent with staying below 2°C with a 50-50 chance (solid lines

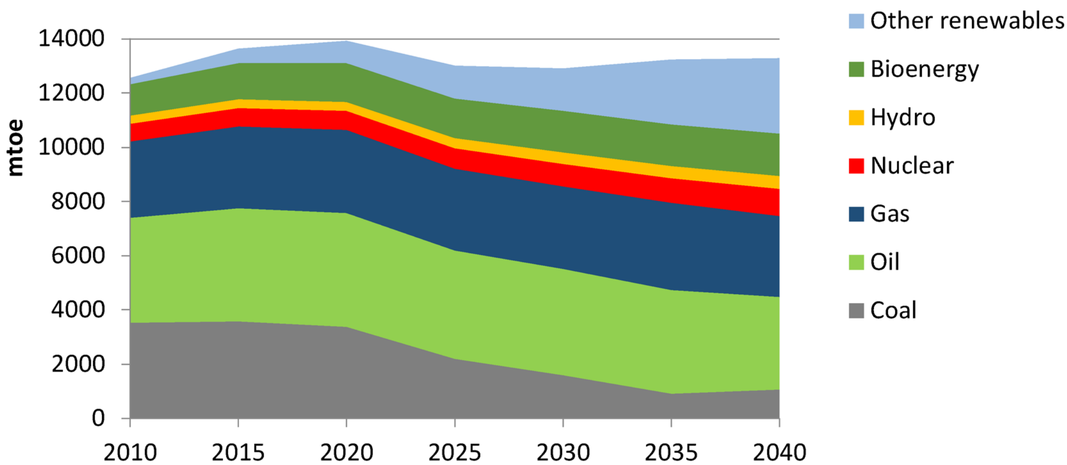


FIGURE 13

Global primary energy projection in the 2°C Tax Scenario of the 2018 MIT Joint Program Outlook.
Data Source: MIT Joint Program (2018).

on the left panel of Figure 14). Included are two stabilization pathways, one in which an optimal global carbon tax is implemented in 2020, the other in 2030, assuming that the NDCs from Paris have set the path through at least 2025. The needed initial tax, assumed to rise at 4% for the rest of the century, is $85 if started in 2020, or $122 if delayed until 2030 (in 2015 dollars). These simulations suggest that the emissions path associated with the Paris NDCs is basically inconsistent with the 2°C target. It is certainly possible to achieve that target, but an economically optimal path would indicate that emissions should immediately fall, and then continue to decline.

If the world waits to act until 2030, the emissions need to be somewhat lower for the rest of the century—not much lower as there are 70 years to make up the difference—but it would then require an even sharper drop once the global policy is in place. The median temperature peaks at 2°C by design. Given uncertainty in climate-system properties, the temperature rise could be, at the extremes, somewhat less than 1.5°C, or as much as 2.5°C. Staying below 2°C with only a 50-50 chance leaves open the chance of the temperature being well below 2°C or even 1.5°C, but this seems unlikely to be consistent with Paris Agreement language. The IPCC has defined different degrees of likelihood—and their definition of "likely" is an outcome with greater than 66% probability, i.e., at least a 2/3 likelihood (or 2-in-3 chance).

The dashed lines on the left panel of Figure 14 show the emissions scenarios making it "likely" that the increase is less than 2°C. These scenarios require an even greater emissions reduction starting immediately or in 2030, and a higher initial tax ($109 in 2020, $139 in 2030, in 2015 dollars). To assess uncertainty, a 400-member ensemble of the Integrated Global System Model (IGSM) was developed to assess a distribution of changes in temperature relative to1861–1880 (left panel of Figure 14). The "likely" scenarios result in a 50-50 chance of remaining below 1.8°C (light blue line, right panel of Figure 14), and about a 25% chance of remaining below 1.5°C. However, there is still about a 1-in-3 chance of temperatures above 2°C, but essentially all trajectories remain below 2.5°C. These scenarios are more consistent with the Paris Agreement language of "well below 2°C". Additional considerations related to

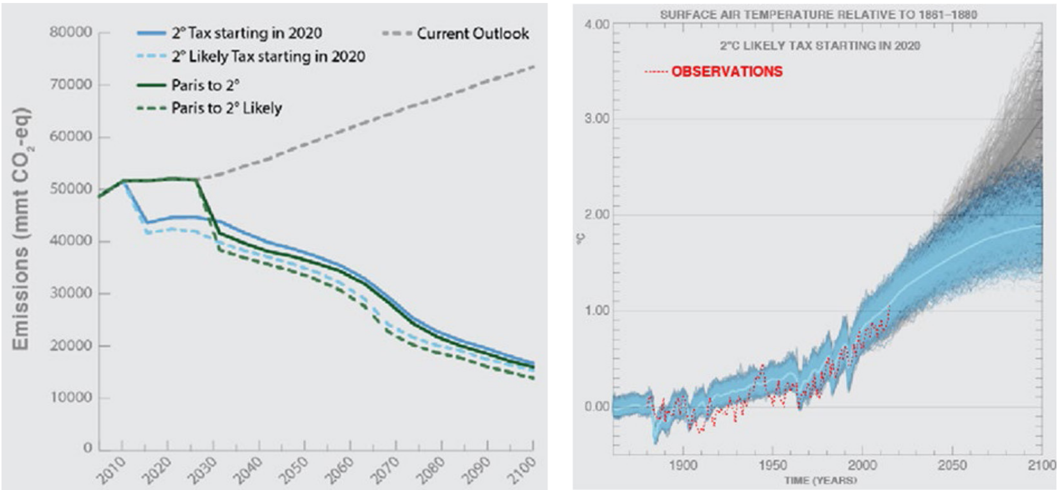


FIGURE 14
Global GHG emissions and the resulting temperature in the 2°C Tax Scenario of the 2018 MIT Joint Program Outlook.
Source: MIT Joint Program (2018).

food, water, energy and climate impacts are available in the MIT Outlook (MIT Joint Program 2018).

As for the energy projections for the 21st century, the exact energy mix depends on numerous aspects, such as available technologies, cost of competing technologies, how quickly new technologies can expand, policy instruments and their stringency, and many other factors. Figure 15 offers an example of a global power generation mix in the 2°C scenario from the MIT Outlook. In this scenario, the same overall emission profile is achieved in two variants: without a negative emission technology of bioenergy with carbon capture and storage (No BECCS); and with bioenergy with carbon capture and storage (BECCS) available.

The red vertical lines in Figure 15 illustrate the time period of projections discussed in Section 3. While the power generation mix up to 2040 is quite similar in these two settings, the technology deployment in the second half of the century is substantially different. The global trajectories for renewables, natural gas with CCS, and coal with CCS are heavily impacted by the availability of BECCS. Similar dramatic differences can be found with different assumptions about the long-term energy storage development (not shown here). Figure 15 provides an illustration that a technology mix may be quite different (over time and over different potential pathways for technology advances) even for the same emission mitigation scenario. For example, it shows that CCS is not a prominent technology in the global power generation in the next two decades, but it has a substantial contribution in the second half of the century.

It also shows that the seemingly winning in the medium-term technologies (wind & solar and natural gas in this example) may not be a dominant long-term solution for de-carbonization. Similar dynamics might occur in different sectors of the economy, like transportation, cement production, iron and steel and others. This simple illustration offers two observations. First, any energy projection for the second part of the century should be treated with a great degree of caution. Second, the exact contribution of particular technology depends on many economic and political variables and the policy and investment focus should be on targeting emissions reductions from any energy source, rather than trying to pick the long-term winners.

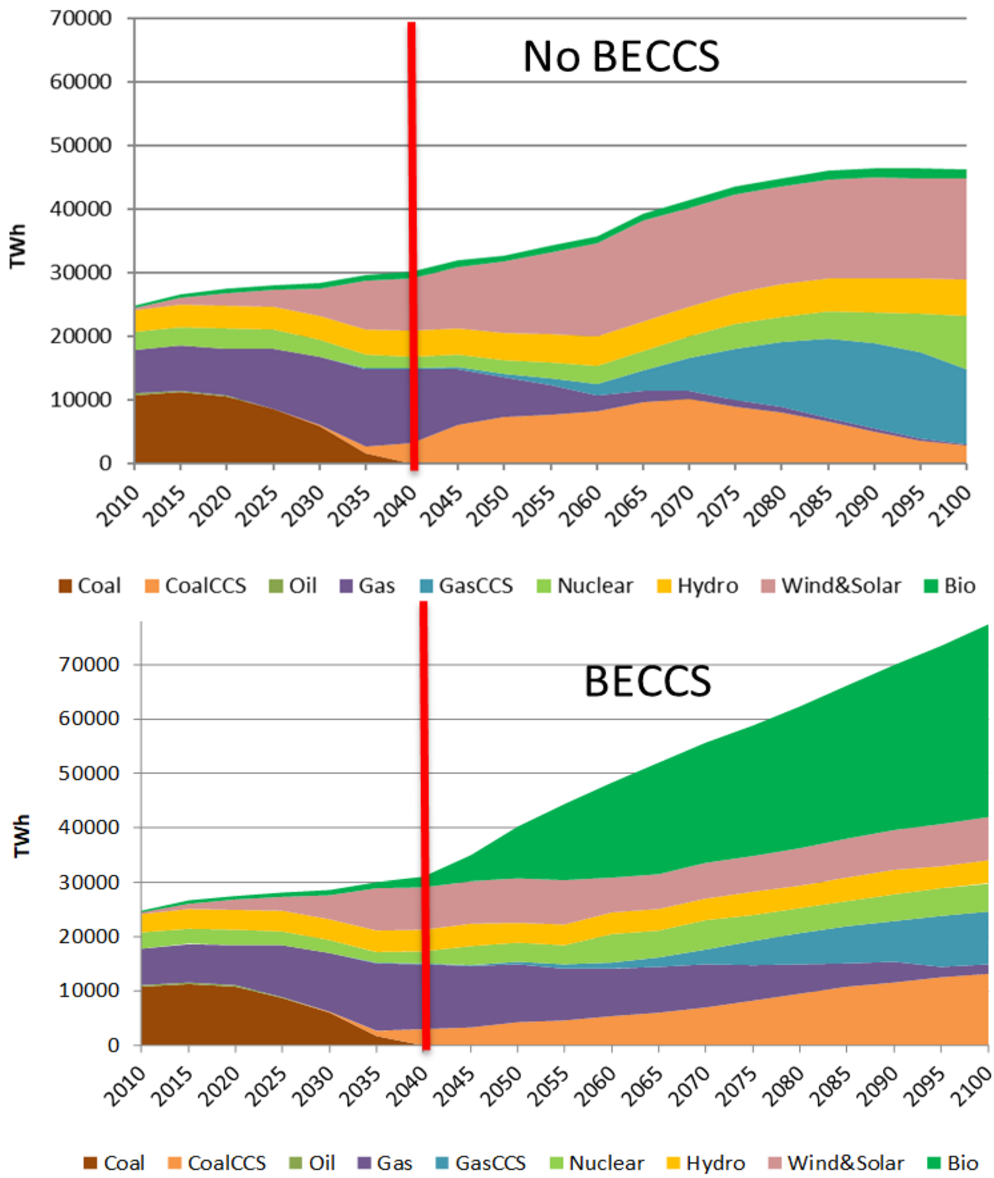


FIGURE 15

Global power generation mix in the 2°C Tax Scenario of the 2018 MIT Joint Program Outlook with different assumptions about technology development: without bioenergy with carbon capture (No BECCS); with bioenergy with carbon capture (BECCS).

5. CONCLUDING REMARKS

Projecting energy and climate is getting more challenging because of a clear divergence between descriptive (i.e., those that track the stated policies) and prescriptive (i.e., those that show a path to a particular target) scenarios. It is also getting more difficult to assess the credibility of numerous declarations related to the de-carbonization goals, such as aspirations to achieve full energy access in a few years, to reform energy prices, and/or to reach the net zero emissions in some countries and/or sectors. While all these are important goals, a history of successful implementation of similar declarations is rather weak. Among the examples of such a divergence between the stated goals and the reality is the U.S. Energy Independence and Security Act that included an aggressive schedule for the use of advanced biofuels through the Renewable Fuel Standard. The expected transition to the second-generation biofuels has not been realized and the U.S. government keeps issuing waivers from the requirements. There are numerous other examples where the stated declarations have not been achieved. At the same time, it is clear that the society demands a transition to low-carbon future, which makes longer-terms forecasts rather obvious (the world have to move to zero-carbon energy system), but the speed and fuel-specific directions of the transition and their implications for the next decade or two are quite uncertain.

Table 1 summarizes the results from the major energy outlooks for the shares of energy types in the global primary energy use. Under the current policy (descriptive scenarios), the fossil fuel share is projected to be reduced from the current contribution of about 80% to around 73-76% in 2040. In the scenarios consistent with the 2°C goal (prescriptive scenarios), the fossil fuel share is further reduced to about 56-61%. On the other hand, the share of wind and solar (which is the majority in the "other renewables" category) is increasing to 6-13% in the descriptive scenarios and to 17-26% in the prescriptive scenarios. While the shares of renewables differ between the outlooks (in part due to different accounting methods), none of the scenarios envisions the complete de-carbonization of energy in the next 20 years.

TABLE 1

Contribution (%) to global primary energy use in 2018 and 2040.

	Current (2018)	Descriptive Scenarios in 2040				Prescriptive Scenarios in 2040			
		IEA	ExxonMobil	BP	MIT	IEA	Shell	BP	MIT
Fossil Fuels	81%	74%	76%	76%	73%	58%	61%	59%	56%
Hydro	3%	3%	3%	5%	2%	4%	2%	3%	4%
Nuclear	5%	5%	7%	3%	4%	9%	9%	8%	8%
Biomass	9%	10%	8%	3%	9%	12%	11%	4%	11%
Other renewables	2%	7%	6%	13%	12%	17%	17%	26%	21%

Notes: BP does not include traditional biomass (which affects other shares). For consistency, nuclear and hydro for BP and MIT are adjusted to the IEA conversion factors. The "Other renewables" category includes solar, wind, and geothermal. Shares may not add up to 100% due to rounding.

While the fundamental uncertainties are unavoidable, some findings about the global energy system are quite robust. Coal (without carbon capture) does not have a sustainable future and many projections do not envision a wide deployment of carbon capture technology in the next 10-15 years (e.g., Hirschhausen, Herold, and Oei 2012; Oei and Mendelevitch 2016). However, longer-term forecasts rely on scaling-up carbon capture, utilization and storage for all carbon-emitting technologies (coal, natural gas, biomass). Natural gas seems to be a fuel with a rather positive outlook for the next couple decades, but then it faces the same fate as coal. Without carbon capture, natural gas is unsustainable for achieving the de-carbonization goals. Oil consumption will be affected by potential solutions in transportation sector, especially in heavy-duty, marine, and air travel segments. Some innovative approaches (like a system-wide use of hydrogen) may change the dynamics for oil dramatically. Energy efficiency improvements and demand-side management offer great opportunities for speeding up low-carbon transition, but the exact magnitudes about the feasible and economic actions related to them differ substantially between different experts. One clear winner is renewable (solar and wind) energy, where the costs have fallen substantially and the holding issues related to intermittency and long-term energy storage receive an enormous attention from the researchers and innovators. The optimism about the successful solution of the long-term energy storage varies among the experts, but a current consensus is that it would not be completely resolved in the next couple decades.

In this situation, rather than been informed by a single or several scenarios, a range of projections that encompass plausible futures provides a good guidance for a strong decision-making. Given the diversity of scenario paths, scenario outcomes, scenario producing model methodologies and modelers, the formal adoption or standardization of a particular scenario path, would appear unlikely. Growing demands from the financial community and shareholders to assess the risks related not only to a transition to a low-carbon society, but also the physical risks associated with climate change, call for a set of energy-climate projections that represent a system of human-Earth interactions. We offer an example of such approach where an integrated team of natural and social scientists studies the interactions among human and Earth systems to provide a sound foundation of scientific knowledge to aid decision-makers in confronting future food, energy, water, climate, air pollution and other interwoven challenges.

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