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Future energy: In search of a scenario reflecting current and future pressures and trends

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To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at

Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—*Ronald G. Prinn,*
Joint Program Director

Future energy: In search of a scenario reflecting current and future pressures and trends

Jennifer Morris^{1,2}, David Hone³, Martin Haigh³, Andrei Sokolov¹ and Sergey Paltsev¹

Abstract: Growing societal pressures, technological trends and government and industry actions are moving the world toward decarbonization and away from the “business-as-usual”. As such, the concept of a single/obvious “business as usual” or “reference” scenario is no longer relevant. Instead, there are multiple plausible futures that should be explored. We contribute one such scenario that carefully considers emission-reduction trends and actions that are likely in the future, absent globally coordinated mitigation effort. We explore the long-term implications for energy, emissions, and temperature outcomes if the world continues to address climate change in the way it has so far—through piecemeal actions and growing social and technological pressures. This *Growing Pressures* scenario results in a central scenario outcome of about 3°C of surface temperature warming, which is higher than the “well below 2°C” level aspired by the Paris Agreement, but lower than many widely used “no-policy” scenarios. Ongoing and growing pressures of change, the roots of which are clearly visible today, could deliver a plausible energy transition scenario to near zero emissions that plays out over the coming century. While a more aggressive transition is clearly required, this finding highlights the need to bring actions forward in time to achieve an improved outcome making use of clearly identifiable policies and technologies.

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1. Introduction

The Paris Agreement has set the goal of limiting global average surface temperature warming to “well below” 2°C (UN, 2015), and there has been a growing emphasis on limiting warming to 1.5°C (IPCC, 2018). Much research focuses on what it would take to meet these temperature targets—the amount of emissions reductions, the required energy transition, the cost of achieving the goals, etc. Mitigation challenges are usually assessed as a comparison between a “no policy”, or “business-as-usual” scenario and the required targets (e.g. IPCC, 2014; Kriegler *et al.*, 2014; Riahi *et al.*, 2017; Dellink *et al.*, 2020). The “business-as-usual” approach shapes intuition about the size of the challenge through graphical and verbal presentations contrasting the “business-as-usual” trajectory with particular temperature goals. This practice was established several decades ago, when it was relatively easy to create a “no climate policy” scenario projection because the policies and societal pressures in many regions of the world were mild or non-existent.

With growing pressure from society, more and more government and industry actions are moving the world towards decarbonization and away from the “business-as-usual”. Societal pressures and technological trends drive a reinforcing mechanism for action: pressure to pursue low-carbon solutions results in a growing array of low-carbon options, which in turn generates more pressure to employ those options. The result is changes from previously established expectations regarding “business-as-usual” development. In this context, a traditional approach of measuring mitigation efforts against some “worst case” scenario can be rather misleading. There are substantial uncertainties in how future technologies, policies and regulations, stability of nations, economic growth, and other aspects of human development will evolve, and with a curtailed resumption of global activities following the COVID-19 pandemic, these uncertainties are even greater. As such, there is no single “business as usual” scenario. Therefore, we argue that the new reality calls for moving away from traditional analysis of scenarios relative to “business-as-usual” scenarios or “references” and instead focusing on exploring multiple scenarios of plausible futures.

Indeed, the appropriateness of “no-policy” scenarios as a point of comparison for mitigation targets has been questioned, and some analysts have moved away from this practice. For example, the International Energy Agency (IEA, 2019) uses “Current Policies” and “Stated Policies” scenarios, and the United Nations Environment Programme’s Emissions Gap Report (UNEP, 2019) compares countries’ emissions-reduction pledges with global pathways that limit warming to well below 2°C, focusing on the gap between the two. Grant *et al.* (2020) offer a set of scenarios for mitigation analysis, along with suggestions

for the appropriate use for each. The authors argue that there are limited circumstances where a no-policy scenario is appropriate because “there is no future which does not involve substantial disruption, whether from climate policy or climate impacts”, or technological change. Therefore, a no-policy scenario represents a world which is non-existent, and comparison to such a scenario “risks overemphasizing the scale of the challenge.” Similarly, Hausfather and Peters (2020) implore people to stop using “worst case” scenarios, such as RCP8.5 from the IPCC’s Fifth Assessment Report (AR5) (IPCC, 2014), as a “business-as-usual” scenario, and to instead develop scenarios with more realistic trends.

In this paper, we add to existing sets of plausible future scenarios, a scenario that carefully considers emission-reduction trends and actions that are likely in the future, absent globally coordinated mitigation effort. Our scenario considers *growing pressures from society and future technology trends* that steer the energy system away from fossil fuels and captures current and expected future momentum across different drivers to reduce emissions and fossil fuel use. This “Growing Pressures” scenario requires making assumptions about how social, political, business, technological, and other trends will evolve over time, taking into consideration possible actions and policies on local and national levels. In this scenario we do not impose global carbon pricing as is assumed in the majority prescriptive scenarios to achieve particular climate targets, such as 2°C or 1.5°C (Paltsev, 2020; IPCC, 2014). While we support the notion that global carbon pricing is widely viewed as the most efficient way of addressing global climate change, the current trends in global climate policy allude to a good chance that there will never be a truly global carbon price.

Over the last decades, the world has seen an array of fragmented policies, regulations, technology developments, business commitments and social pressures. At the same time, globally coordinated climate policy designed to achieve “well below 2°C” (e.g., via global carbon pricing) is still largely absent. In light of this, we create a scenario that explores the following question: If the world continues to address climate change in the way it has so far (piecemeal actions and social/technological pressures that grow over time), what are the long-term implications for energy, emissions, and temperature outcomes? We present one view of a plausible estimate, along with a set of sensitivity cases.

We take a narrative approach, considering a wide variety of developments and commitments over the last decades and how we might reasonably expect those to evolve in the coming decades. The *Growing Pressures* scenario reflects the progress that has been made, and highlights the need to bring actions forward in time to achieve an improved outcome. It allows an assessment of the gap between the outcomes

achieved by trends we can plausibly expect into the future and the 2°C and 1.5°C goals the world has set for itself.

Our *Growing Pressures* narrative results in a central scenario outcome of around 3°C of surface temperature warming, which is not sufficient to achieve the long-term goals of the Paris Agreement, but it also does not lead to higher outcome results given the current state and pace of the energy transition and pressures from society. It should be noted that our projected path is defined by continued and growing societal pressure and action on the climate change threat, not complacency. As such, it presents a roadmap of an energy transition that could be further accelerated in pursuit of the Paris goals to limit the increase in temperature to “well below 2°C” relative to pre-industrial levels.

In Section 2, we offer a narrative behind our *Growing Pressures* scenario that considers a variety of factors that have impacted the energy system over the last decades and will continue to drive its evolution into the future. In Section 3, we introduce the energy-economic model that is then used in Section 4 to quantify the storyline and identify the implications for energy, emissions and global temperature. Section 4 also explores key sensitivities around the main narrative as well as climate-related uncertainty. In Section 5, we conclude.

2. A 100 Year Narrative

There have been changes in the energy system since the start of the 21st century, albeit not at anything like the pace required to meet the long-term goal of the Paris Agreement to limit average surface temperature warming to between 1.5°C and 2°C. Although a surge in coal use in China and India has driven the growth in global emissions, emissions growth has been less dramatic in other parts of the world, and emissions have fallen in a handful of developed countries (primarily the original Kyoto group) (see **Figure 1**).

Overall, emissions growth since 2000 has been tempered by substantial growth in natural gas supply as a substitute for coal, an order of magnitude increase in non-hydro renewable electricity generation (but still representing only 10% of global generation), a significant cost reduction in solar PV and wind technologies, the arrival of the electric car and some large-scale grid battery storage. Other developments are emerging within the areas of hydrogen production and use and electrification of industrial processes, but these are not yet substantive on a global scale. More distant opportunities may exist with synthetic fuels and the known unknown remains nuclear fusion. The sum total of all these changes may be modest over the past twenty years, but the transition started from a very small base. It is now gathering pace such that over the course of the next 100 years very substantial change is expected.

Unlike any other issue that society has confronted, the physical reality of a changing climate has become a catalyst to drive long-term and persistent change in society and in our energy system. As the global average surface temperature rises and the impacts become increasingly visible, the need for energy transition will consistently return to the spotlight as other issues come and go. Transition will be forced by policy change, activism and business necessity to respond to changing demand patterns and consumer pressure. Many countries, states, cities and companies have established long-term net-zero emission goals, and while promises may not always be kept, many actions will be carried forward. These pressures and actions could drive a transition toward near zero emissions over the course of a century or so.

Society is also dealing with changes in the way it functions. Digitalization of supply chains, services and work patterns is leading to a reorganization of the global economy and paving the way towards further electrification of the final energy mix. Some of these changes were set running during the dot-com period in the late 1990s, but the majority are manifestations of little more than a decade of change. This trend has been accelerated through necessity by the COVID-19 pandemic, but irrespective of the current push, a century of digital momentum will also bring profound change in society and very likely the energy mix it requires.

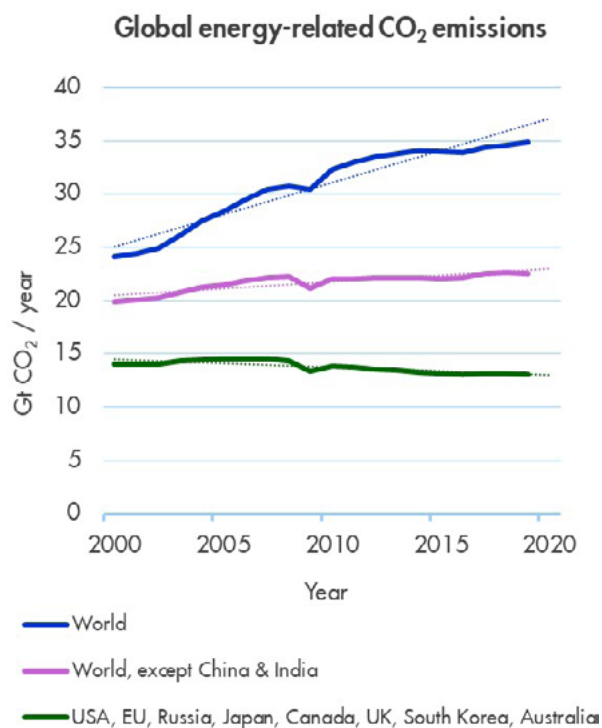


Figure 1. Energy-related CO₂ emissions. (Source: IEA and Shell analysis.)

Underpinning the energy transition is a confluence of multiple important factors:

- Climate changes;
 - ◆ Global surface temperature continues to rise, and impacts become more apparent.
 - ◆ Sea level keeps rising with visible consequences.
- Activism rises;
 - ◆ Voter pressure on cities, states and countries to develop 'green' policies.
 - ◆ Shareholders pushing companies to take on net-zero emission goals and targets.
- Local and national governments pursue (piecemeal) interventions;
 - ◆ Ongoing actions under the UNFCCC under the banner of the Paris Agreement and the emergence of net-zero emissions (NZE) as a framing concept.
 - ◆ Incentives and mandates drive down the cost of new energy technologies and lead to further uptake.
 - ◆ Large established NZE policy frameworks continue to operate (e.g. EU, California) and some new NZE policy frameworks emerge (e.g. China by 2060).
- Technology marches on;
 - ◆ Renewable energy access becomes cheaper.
 - ◆ Developments in physics, chemistry and materials sciences (e.g. PV, storage).
 - ◆ Rapid and broadening digitalization of society.
- Markets rule;
 - ◆ Financial markets distance themselves from fossil fuel investments, but particularly coal, and climate-related financial disclosures bring transparency.
 - ◆ Demands by businesses and consumers for lower carbon footprint products and some preparedness to pay for this.
 - ◆ Development of markets to support low-carbon investment (e.g. nature-based solutions).
 - ◆ Alternatives to coal, oil and gas becoming increasingly competitive.

While each of these will undoubtedly vary over time, their ongoing combined effect gives rise to a scenario of continuous change and transition. Here we offer a plausible energy transition scenario that plays out over the coming century, not through globally coordinated climate policy designed to achieve 2°C or 1.5°C (e.g. via global carbon pricing), but through persistent piecemeal action linked to the factors outlined above. The storyline behind our scenario is described below.

2.1 The Storyline

The trend throughout the 2010s of falling costs for renewable energy deployment continues through to the middle of the century. Governments at federal, state and city level remain under constant pressure from activists, NGOs and climate concerned voters to back this technology pathway through mandates, some modest pricing mechanisms in some countries, grid infrastructure and direct incentives (e.g. tax credits) for deployment. A plateau is eventually reached in scale, technology, underlying science and unit efficiency. While the pace of change may not be at the rates seen in the 2010s, by 2050, the cost of renewable energy deployment should fall by at least a further 25% when compared with 2020. Large scale solar PV and offshore wind rollout in the range of two to three cents per kilowatt hour would be commonplace. A similar trend emerges with energy storage, driven by necessity given the renewables deployment and employing a diverse range of technologies, bringing the system cost for electricity generation to a level that competes with natural gas in many circumstances and locations.

During the 2050s and 2060s a spate of new energy storage technologies emerges, catalysed by a burgeoning aviation industry (that has long overcome the 2020 pandemic impacts) that is under intense societal pressure to manage emissions and is looking to utilise electricity beyond very short haul routes. Scale up in the 2070s in combination with solar PV modules brings the system cost of electricity generation down further, outcompeting all other forms of generation.

But cost is not the only driver of transformation in the electricity system. During the 2020s just a handful of new coal fired power stations can gain both regulatory approval and financial backing in OECD countries, but with the arrival of the 2030s this ends. With rising renewables deployment, dispatch of thermal power stations becomes increasingly problematic going into the 2030s and 2040s, undermining the economics of these units. By 2070 as age also takes its toll on existing facilities, the last remaining coal fired power stations in the OECD are closed.

Coal remains a popular investment in China, India, Africa and parts of Asia right through the first half of the century, but financing becomes increasingly problematic and renewable alternatives compete. The clean air experienced in many cities during the COVID-19 crisis creates pressure on new developments in the early 2020s, which continues to build as environmental and climate impacts become more discernible. The late 2040s see the last of the new coal fired power stations built in these regions and age inevitably starts to take its toll on the installed fleet. By the early part of the 2090s coal has almost completely vanished from the global electricity mix and by 2100 it has departed the scene.

One technology to manage emissions that doesn't emerge at scale is carbon capture and storage (CCS). Although the technology matures and some projects may be developed over the years, the lack of a focused policy approach combined with the increasing competitiveness of renewable energy means that extensive use of CCS never eventuates. But it remains a viable alternative for niche industrial applications where demand for low carbon footprint products is important.

Natural gas progresses through a similar transition, but the driver for change is more cost based with system costs for renewables and storage falling sufficiently to compete. Natural gas continues to be utilised for grid stability but over time load factors fall to such an extent that new facilities are hardly built. Eventually the grid relies on older gas facilities running for a small number of hours per year. By 2050 there is little new natural gas investment in OECD countries and during the 2070s new natural gas investment diminishes globally, both for generation and new production fields. Natural gas use in industry extends into the 22nd century but by 2130 is ultimately limited to petrochemical feedstock for its carbon molecules.

The increasing availability of competitive renewable power generation and energy storage, the price stability it offers, and the underlying corporate social responsibility push to reduce emissions through the purchase of renewable electricity leads to an increasing trend towards electrification throughout society. In some locations the trend towards electricity is also assisted by favourable policy developments such as renewable energy tax benefits, pushed by climate activists and voters.

As the climate warms and many more cities experience extreme temperature days (>40°C) in the summer, with a worrying but growing handful also experiencing very extreme temperatures (45-50°C) at least once a summer, air conditioning becomes very popular. Dual cooling and warming electric systems dominate for reasons of cost and convenience, which progressively removes natural gas and heating oil from domestic use. By the 2060s home heating is electric almost everywhere, with biomass use in some locations (e.g. rural Sweden). Convenience also plays a role, with electric induction stovetops for cooking and efficient heat pumps for managing temperature in homes both entering widespread use. Combustion of fuels in homes begins to disappear in many urban settings from the 2040s onwards.

From 1960 to 2020 the global rate of electrification was steady at about 2% points per decade, leading to 20% of electricity in final energy by 2020. During the 2020s this starts to increase and passes 3% points per decade by 2040. By the 2070s the increase has reached 4% points per decade. It means that by 2150, electricity makes up over two thirds of the global final energy mix.

An important mid to long term driver for industrial electrification comes from industrial companies in the EU facing both national legislation and regional directives to reach net-zero emissions by 2050 as well as needing to achieve their own corporate pledges. Although varying levels of commitment by successive governments lead to waxing and waning of the pressure over time, widespread efforts to electrify various processes or convert them to hydrogen-based systems lead to processes such as hydrogen smelting of iron ore. Large-scale hydrogen production via electrolysis using renewable energy becomes a compelling choice for meeting net-zero targets in the 2030s and 2040s, accelerating the trend, building on a significant German stimulus emerging from the pandemic recovery. As renewable electricity becomes cheaper and extensively deployed globally, these innovations are adopted more widely, leading to substantial industrial change in OECD countries through the 2070s and eventually throughout the world by 2110 as existing production facilities are re-vamped and renewed and new ones built under a more carbon aware financial framework. Increased consumer demand for green products also drives this process, a trend that started prior to 2020 with companies such as Apple using only recycled aluminium.

A further important catalyst was the decision in the early 2020s by the London Metal Exchange to launch a platform to trade 'low-carbon' aluminium mostly produced with renewable energy, marking the first time a metal is traded based on its environmental footprint in the exchange's 143-year history (Financial Times, 2020). This trend is expanded to other metals and commodities over the ensuing years and the early price premium that emerges encourages big producers in India, China and the Middle East to install suitable facilities.

One area where electricity comes into its own is surface transport. Throughout the 2020s passenger vehicle manufacturers introduce a wide variety of models and compete on vehicle range and size. As a result, the uptake of electric vehicles begins to take shape. This is helped by some countries introducing phase out incentives for older internal combustion vehicles if the switch to electric is made and others introducing bans on the sale of internal combustion engine cars at various points from 2035 to 2050. Cities help the process by introducing low emission then zero emission driving zones in key areas. The C40 group of cities becomes increasingly bold in its actions as the market delivers the solutions they need. In 2025 London restricts the Square Mile to electric vehicles only, but quickly expands the zone in the years that follow.

But it isn't until the late 2040s when a tipping point is reached as manufacturers start deciding to exit the internal combustion market completely, reminiscent of the General Motors decision to abandon right-hand drive vehicle

manufacturing in 2020. The lower manufacturing costs for all parts of the vehicle except the battery, simplicity of after sales service and much smaller work forces linked to the R&D process leads to these decisions. During the 2070s internal combustion engine vehicle sales end globally and the era of these vehicles' drifts to a close.

Road freight transport is more difficult to dislodge. The weight and cost of a battery required for long distance haulage and the time required for recharging limits electricity to urban heavy transport, such as buses, delivery vans and municipal vehicles. Electricity continues its creep into the urban sector, pushed by city authorities extending low emission zones and by innovative companies offering an increasing range of electric options. The same is true for agriculture, with electric farm machinery becoming pervasive in OECD countries by 2050 (John Deere, 2020). Although there are few internal-combustion based urban trucks, vans and farm vehicles remaining by the 2070s, the long-distance haulage fleet has remained largely in the fuel world, but particularly in regions where long-distance haulage is commonplace. Nevertheless, there is some electric creep into this sector as well as battery technology improves.

In the 2030s and 2040s as electric cars begin to deploy at scale into the passenger vehicle market, biofuels that are released from that market due to reduced E10-gasoline (i.e., gasoline with 10% blending of ethanol) demand move into the diesel fuel market, albeit with additional conversion processing. This helps to reduce emissions in the haulage sector and provides an important boost for the biofuel industry. But public pressure leads to increasing scrutiny of biofuel crops, with NGOs making use of AI and satellite data to effectively monitor global crop coverage, which in turn limits the overall biofuel fuel pool. So, this pathway undergoes change as well.

Haulage companies respond to both city emission restrictions and companies shifting their supply chains to a zero-emission base for reasons linked to corporate social responsibility and consumer demand. Electrification creeps into the lighter end of the road haulage fleet and through the 2030s and 2040s hydrogen fuel cell trucks begin to appear for larger vehicles, with early fuel networks appearing in California and Germany. But the transition is slow, and it is not until much later in the century that electricity and hydrogen dominate the haulage sector.

After the COVID-19 crisis in 2020 the aviation industry begins its path to recovery and climate activism promptly resumes. Because of the pandemic, new investment is initially limited and the anticipated early transition to electric planes for short haul use does not emerge. But as the industry resumes its growth path and activism prevents major airport expansion, short haul flights with under 100 passengers come under pressure to move away from

major hubs due to a lack of landing and take-off slots, leading to a boom in smaller regional airports linked to hub satellite airports. This is ideal territory for the emergence of a cost competitive and viable commuter electric plane in the 2030s, although its initial impact on jet fuel demand is minimal. Nevertheless, a few smaller airframe manufacturers appear, and a competitive market develops, progressively improving on passenger capacity, comfort and range. Later in the 2040s these smaller companies become targets for the likes of Boeing and Airbus.

But there is no shift in emissions on long-haul flights until much later in the century when a variety of technologies merge to deliver new thinking on air frame design and propulsion. This arrives at a timely moment as the cost of supplying high grade hydrocarbons from crude oil for one sector with a very specific requirement is starting to become burdensome. This marks the beginning of the end for crude oil exploration, extraction, refining and shipping. The first of a new generation of planes appear in 2080 and by 2130 the global aviation fleet is completely transformed.

By the early decades of the 22nd century, even in a world where global climate action never accelerates to the pace required for the Paris Agreement, the last remaining energy use demand for fossil fuels is collapsing. The fossil fuel demand tail is a long one and stretches well into the century, but is hardly noticeable in terms of atmospheric impact.

3. The Model

We seek to quantify this storyline with formal energy-economic modelling and identify its implications for global temperature. To do so, we employ the MIT Integrated Global System Model (IGSM) framework, which links the Economic Projection and Policy Analysis (EPPA) model, a multi-sector, multi-region, computable general equilibrium (CGE) model of the world economy to the MIT Earth System Model (MESM) of intermediate complexity. EPPA determines the amount of emissions of greenhouse gases (GHGs) and other pollutants associated with human activity, which is then passed to MESM to determine the implications of those emissions for temperature.

The EPPA model represents 18 regions of the world (see Figure S1 in Supplementary Material) and a number of sectors, including those related to fossil fuel extraction, energy-intensive industries, other manufacturing, services, transportation, electricity generation, agriculture and households (see Chen *et al.*, 2016 for more information about the model). Many low- and zero-carbon options are represented in the model, including a suite of electricity generation technologies such as wind, solar, biomass, nuclear and CCS (for information about cost and penetration rate assumptions see Morris *et al.* 2019a and 2019b), liquid biofuels, and electric vehicle options for household transportation. For this work, additional

electricity-based technology options were added to the industrial and commercial transportation sectors, as well as for final and intermediate demand.

For its base year data, the EPPA model uses the GTAP dataset (Narayanan *et al.*, 2012), which provides a consistent representation of energy markets as well as detailed data on regional production, consumption, and bilateral trade flows. The model is calibrated to economic and energy data from IMF (2019) and IEA (2019) for 2010 and 2015 and then it solves in 5-year time steps, traditionally to 2100. This analysis commenced before the COVID-19 pandemic and does not include energy system impacts related to it. Given the 130-year time frame, we do not see this as consequential to the outcome.

For this work, we extended the model horizon to 2150 to explore the potential for climate stabilization beyond 2100. To do so, we extended the default exogenous trends in EPPA for population and GDP, as well as other exogenous parameters such as autonomous energy efficiency improvements and urban pollutants. The assumed global population and GDP paths are shown in **Figure 2** (with additional detail in the Supplementary Material). For population, we use our standard assumptions to 2100 based on UN (2019) and then apply the growth rate from 2095 to 2100 to the rest of period (2100-2150). The exception is Africa, for which we slow population growth after 2100. For GDP beyond 2100, we assume it continues to grow but the growth rate slows in all regions.

As a starting point, we first ran a typical “no policy reference” scenario, which we call *Historical Trends*. This scenario does not include the Nationally Determined Contribution (NDC) targets of the Paris Agreement or any future climate policy. Scenarios like this are commonly used in the assessment of climate targets (e.g. IPCC, 2014). They result in unfettered continued use of fossil fuels even as other energy sources, such as renewables, emerge. Even scenarios that account for the Paris NDCs, but assume no

further climate policy, tend to continue into the future the trends we have seen historically in terms energy and fossil fuel production and use (e.g., IEA 2019 “Stated Policies”, BP 2019, Exxon 2019, MIT 2018).

The primary energy and electricity generation mix associated with the *Historical Trends* scenario are shown in **Figure 3**, and reflect a persistent use of fossil fuels.

The emissions associated with this scenario are shown in **Figure 4** for GHGs and for total CO₂ (fossil, industrial and land use), and the resulting temperature results are shown in **Figure 5**. Emissions flatten out toward the end of the century and even start to decline after 2100, reflecting primary energy use that flattens out and involves a growing share of alternatives to oil (e.g. bio-oil). This growth in oil alternatives is due to eventual oil supply constraints which increase the price of oil, allowing alternatives to compete in some regions, particularly China. Still the temperature continues to rise steadily, reaching 3.7°C by 2100. The temperature continues to rise rapidly after 2100 (the furthest projected year for most models), reaching 5.3°C in 2150 with still no sign of stabilizing. In the 50 years between 2100 and 2150, temperature increases an additional 1.6°C, which is more than the total temperature increase targeted by the Paris Agreement.

This scenario presents a depressingly wide gap between where the world is headed in the absence of global policy action and the near-and long-term Paris goals. However, such a path does not account for continuing cost reductions in low- and zero-carbon technologies, persistent social pressure for climate action and green products, commitments by governments and businesses, or the increasingly difficult financing of fossil-based projects.

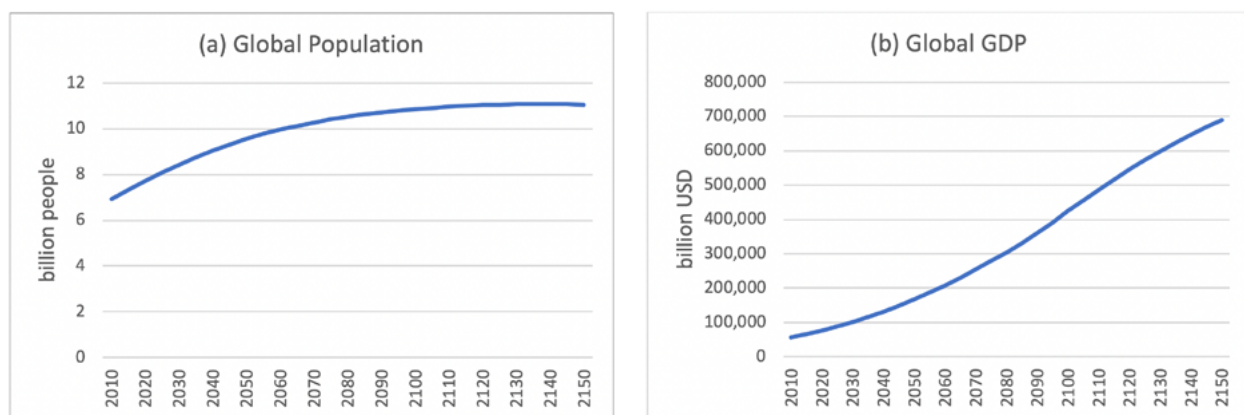


Figure 2. Global population (a) and GDP (b) to 2150.

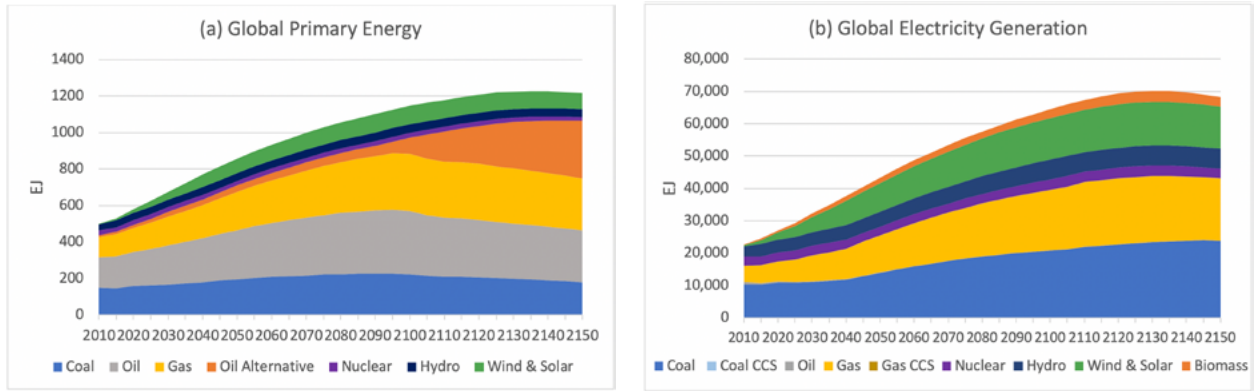


Figure 3. Global primary energy (a) and electricity generation mix (b) under the *Historical Trends* scenario.

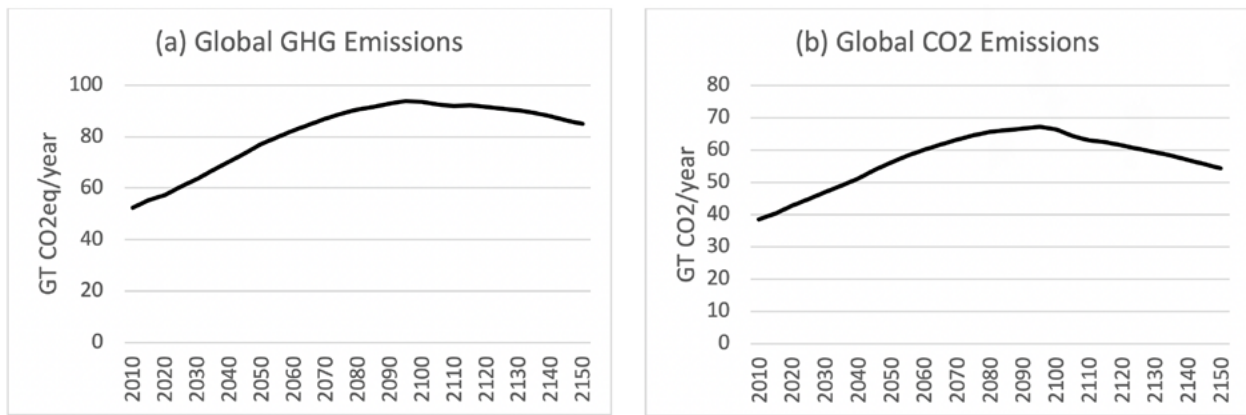


Figure 4. Global emissions of greenhouse gases (a) and CO₂ (b) under the *Historical Trends* scenario.

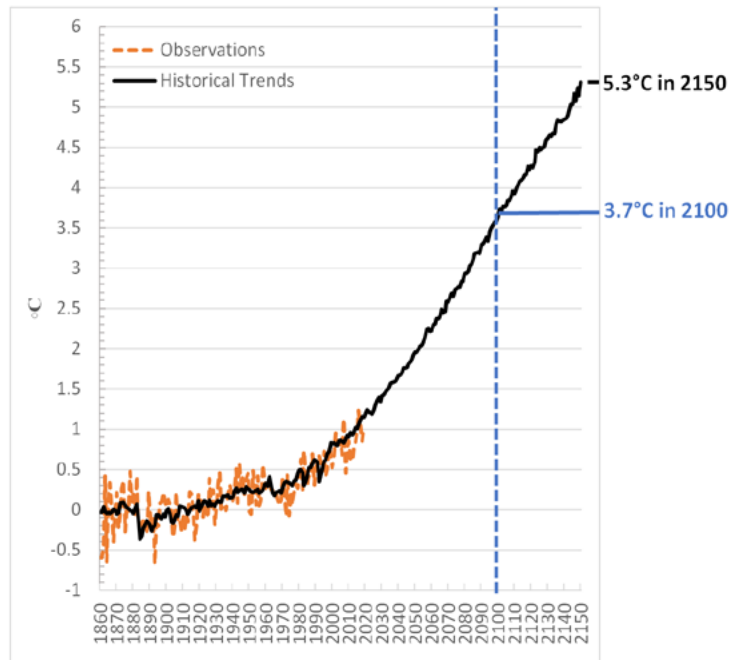


Figure 5. Global annual mean surface air temperature relative to pre-industrial levels (1861-1880 mean) under the *Historical Trends* scenario.

4. Quantifying the Transition

4.1 Defining the *Growing Pressures* Scenario

To quantify the narrative described in Section 2, we conduct a series of model runs. We start from the *Historical Trends* scenario described above, and successively add components of the narrative until we create a scenario that fully captures the narrative—the *Growing Pressures* scenario. The set of main scenario elements is described in **Table 1**. Consistent with the narrative above, the *Growing Pressures* scenario does not employ global carbon pricing designed to achieve the Paris goal, but rather a series of industry/country/region-level actions that lead to the shift away from fossil fuels (e.g. mandates, regulations, cost reductions, etc.). Further, we explore the transition in the absence of other significant constraints, whether on fossil resources or environmental. If either of those factors play a significant role, then they will further accelerate the transition away from fossil fuels.

Scenario Elements 1 and *4* reflect the narrative about the falling costs for renewable energy and energy storage. In *Scenario Element 1*, the cost of wind and solar technologies are assumed to fall by 1% per year, reaching a floor in 2050 of 25% below their 2020 costs. *Scenario Element 4* assumes a cost-competitive scaled energy storage technology is available by 2075, which fully resolves renewable intermittency challenges. The assumption is that deployment driven by commercial projects and fragmented policies (e.g. tax credits, renewable portfolio standards, feed-in tariffs, research and development, etc.) lead to these falling costs.

Scenario Element 2 builds on *Scenario Element 1* and phases out¹ coal generation, with the phase out occurring on different timeframes in different regions. OECD countries are the first to stop building new coal generation. China, Africa and India are the last. Coal generation disappears globally by 2090. These phase outs are assumed to be driven by increasing difficulty securing regulatory approval and financial backing, the competitive cost of renewables, growing demands for clean air, and in some cases governmental bans.

Scenario Element 3 adds to *Scenario Element 2* the phase out of natural gas generation, with developed countries no longer building baseload natural gas generation capacity by 2050, and the rest of the world stopping by 2070. While some gas generation continues to be used to backup renewable generation, baseload gas generation disappears globally by

1 While the term “phase out” can be interpreted as a deliberate and forced reduction, here we use it in the modelling sense in that we have phased out certain energy types in the model as supported by our narrative in Section 2.1, which makes assumptions as to what drives the phase outs (e.g. falling costs of competing technologies, government regulations, industry/business commitments, consumer pressure, financing challenges, etc.).

2105. These phase outs are assumed to be driven by the competitive costs renewables and energy storage, which cause the load factors for natural gas to such an extent that new facilities are hardly built.

The narrative about widespread electrification is reflected in *Scenario Elements 5, 6, 7 and 8*. *Scenario Element 5* focuses on energy intensive industries, assuming they begin to deploy green technology—likely electrification or hydrogen, but also potentially CCS—by 2050. The assumption is that industrial companies in the EU facing national and regional directives to reach net-zero emissions by 2050 lead the way in efforts to electrify various processes or convert them to hydrogen-based systems (e.g. electrolysis using renewable energy). These innovations spread globally as the cost of renewable energy falls. Energy-intensive industries are largely electrified by 2075 in the OECD, and by 2110 in the rest of the world.

Scenario Element 7 incorporates the electrification of final demand, assuming that globally coal is phased out of final demand by 2030, gas by 2060 and oil by 2090 as home heating and cooking shift to electricity. *Scenario Element 8* assumes fossil fuels are phased out of intermediate demand (e.g. use as inputs into production) globally by 2130, largely being replaced by electricity.

Scenario Element 6 focuses on the phase out of refined oil, much of which is related to transportation. We assume electric vehicles take over for internal combustion vehicles for personal transportation by 2060 globally. Urban heavy transport, such as buses, delivery vans and municipal vehicles as well as farm machinery also electrify. Long haul trucking faces greater challenges, but implements a combination of electric vehicles, biofuels and hydrogen. Aviation is the most challenging to decarbonize, and is not transformed until 2120 or beyond.

Scenario Element 9 adds in reductions in non-CO₂ GHG emissions. We assume reductions in CH₄ and N₂O similar to the Shell Sky scenario (Shell 2018; see Supplementary Material). These reductions are driven by the shift away from fossil fuels throughout the economy, and changes in agricultural and various industrial practices as well as diets.

All scenario elements together create the *Growing Pressures* scenario, a plausible energy transition scenario that captures current and expected future momentum across different drivers to reduce emissions and fossil fuel usage.

The GHG and CO₂ emissions paths for each of the scenario elements are shown in **Figure 6**. Sequentially adding additional elements of the narrative allows us to identify areas that have the largest impact on emissions reductions. The falling cost of renewables (*Scenario Element 1*) has virtually no impact on emissions. This is due to a rebound effect: cheap renewable electricity leads to less fossil fuel use in electricity, which leads to falling costs of fossil fuels and

Table 1. List of scenario elements building up to the *Growing Pressures* scenario that quantifies the narrative

Element Description	Scenario Description	Discussion
1 Cost of renewables falls over time	Wind and solar costs fall by 1% per year, reaching a floor of 75% of their 2020 cost by 2050 USA, EUR, CAN, ANZ: no new by 2020; no vintage by 2040 JPN: no new by 2030; no vintage by 2080 RUS, ROE: no new by 2040; no vintage by 2080 CHN: no new by 2045; no vintage by 2090 Rest: no new by 2050; no vintage by 2090	Assumes that deployment driven by government policies (e.g. mandate, tax incentives, etc.) lead to these falling costs.
2 Phase out of coal electricity		Coal generation phase out occurs on different timeframes in different regions. OECD countries are the first to stop building new coal generation. China, Africa and India are the last. Coal generation disappears globally by 2090. These phase outs are assumed to be driven by increasing difficulty securing regulatory approval and financial backing, the competitive cost of renewables, growing demands for clean air, and in some cases governmental bans.
3 Phase out of gas electricity	Gas generation (except renewables backup) phases out Developed: no new by 2050; no vintage by 2090 Developing: no new by 2070; no vintage by 2105	Developed countries no longer build baseload natural gas generation capacity by 2050, and the rest of the world stops by 2070. While some gas generation continues to be used to backup renewable generation, baseload gas generation disappears globally by 2105. These phase outs are assumed to be driven by the competitive costs of renewables and energy storage, which cause the load factors for natural gas to fall to such an extent that new facilities are hardly built.
4 Energy storage solution	Cost-competitive technology to fully resolve renewable intermittency challenges (e.g. storage) available by 2075	During the 2050s and 2060s a spate of new energy storage technologies emerges. Scale up in the 2070s in combination with solar PV and wind brings the system cost of electricity generation down further, outcompeting all other forms of generation.
5 Electrify energy-intensive industries	Energy-intensive industries with green technology (e.g. green electricity or hydrogen) emerge by 2050	Scalable solutions emerge during the 2040s in areas such as the EU for major industrial processes, such as iron ore smelting. But they take decades to deploy globally, given the slow turnover rate of big industrial facilities.
6 Phase out refined oil	EVs take over ICEVs for personal transportation by 2060 globally. Carbon-free alternatives to refined oil (e.g. bio-oil, EVs, hydrogen) take over in Developed countries by 2100 and Developing countries by 2120	Refined oil has the longest fat tail of demand. We assume EVs replacement with ICEVs is aided by government policies. Urban heavy transport, such as buses, delivery vans and municipal vehicles as well as farm machinery also electrify. Long haul trucking faces greater challenges, but implements a combination of electric vehicles, biofuels and hydrogen. Aviation is the most challenging to decarbonize, and is not transformed until 2120 or beyond.
7 Phase out fossil fuel demand	Globally, coal out of final demand by 2030, gas by 2060 and oil by 2090	Combustion of fuels in homes begins to disappear in many urban settings from the 2040s onwards. Convenience and cost allow electric-based heating and cooking to progressively remove natural gas and heating.
8 Phase out fossil inputs	Fossil energy out by 2130 globally	All production processes and sectors eventually seek to replace fossil inputs with alternatives, mainly electricity.
9 Non-CO ₂ GHG reductions	Reductions in CH ₄ and N ₂ O similar to the Shell Sky scenario Growing Pressures Scenario	The economy-wide shift away from fossil fuels, combined with changes in various industrial practices, agricultural practices, and diets also leads to reductions in non-CO ₂ GHGs such as CH ₄ and N ₂ O. All elements together create a plausible baseline energy transition scenario that captures current and expected future momentum across different drivers to reduce emissions and fossil fuel usage.

Notes: USA = United States; EUR = European Union; CAN = Canada; ANZ = Australia and New Zealand; JPN = Japan; RUS = Russia; ROE = Rest of Europe; CHN = China. All EPPA regions are defined in Figure S1 in Supplementary Material. Shell Sky scenario is described in Shell (2018), see Supplementary Material for profiles of CH₄ and N₂O.

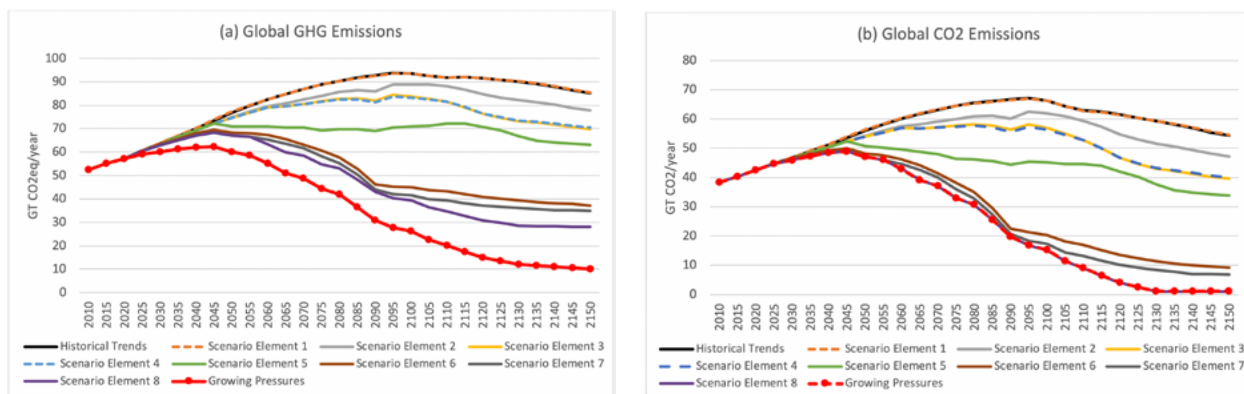


Figure 6. Global emissions of GHGs (a) and CO₂ (b) in a series of scenarios building up to the *Growing Pressures* scenario described in the narrative.

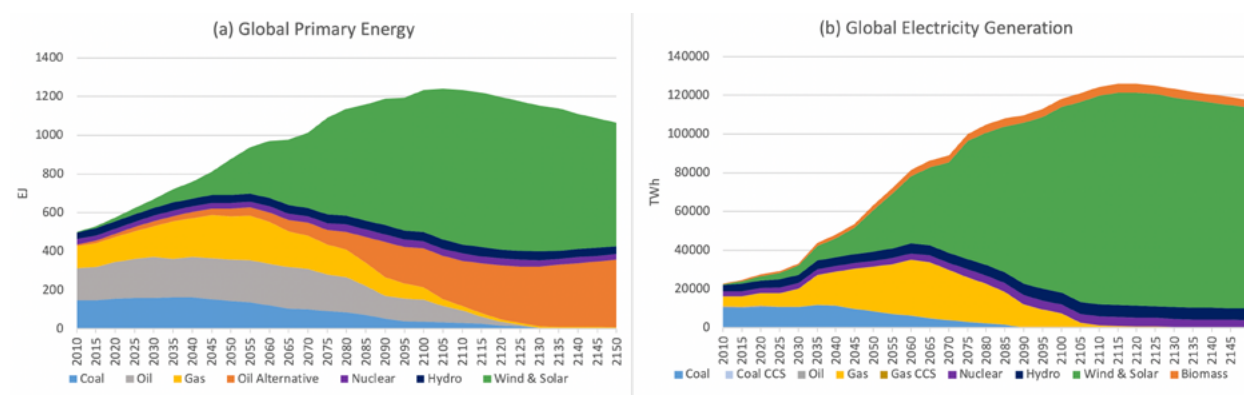


Figure 7. Global primary energy (a) and electricity generation (b) mix under the *Growing Pressures* scenario.

therefore more fossil fuel use in other sectors. We see the same story under *Scenario Element 4* in which cost-competitive energy storage leads to a massive increase in renewable electricity, pushing fossil fuels out of electricity generation, but increasing their use in other sectors. Figure 6 also shows that cleaning up the electricity sector alone has only a small impact on overall emissions reductions, highlighting the importance of decarbonization in other sectors. We also see that electrifying (or pursuing other low-carbon options in) energy-intensive industries (as we have imagined in *Scenario Element 5*) can lead to more emissions reductions earlier in the century. The gradual reduction in refined oil demand (*Scenario Element 6*) has by far the largest impact on emissions reductions, reflecting oil's pervasive use throughout the global economy. Phasing fossil fuels out of final demand (*Scenario Element 7*) has a small emissions impact. Replacing fossil fuel inputs into production (*Scenario Element 8*) has a sizeable impact. These actions lead to essentially zero CO₂ emissions by 2130. However, global GHGs are almost 30 Gt in 2130 and beyond. Adding in the assumption that non-CO₂ GHGs (e.g. CH₄ and N₂O from agriculture) will also be reduced (*Scenario*

Element 9, the *Growing Pressures* scenario) brings global GHG emissions to about 10 Gt—still not zero, but close.

The primary energy and electricity generation mixes for the final *Growing Pressures* scenario are shown in **Figure 7**. Although fossil fuels ultimately disappear from the global primary energy mix by 2130, it is a long, drawn-out process, with global reductions largely taking place after 2060. “Oil Alternative”, a category representing a combination of biofuels, electrification and hydrogen which substitute for refined oil, grows after that point. There is also a massive increase in renewable energy as electrification becomes widespread, driven by global electricity systems dominated by renewable generation. The global electricity mix shows a slightly faster transition than in primary energy, and is nearly decarbonized by 2100. However, natural gas generation continues to play an important role, continuing to grow through about 2065, after which no new capacity is built, retirements of old capacity occur, and renewables with an energy storage solution become increasingly cost competitive.

Figure 8 shows the temperature implications of the *Growing Pressures* scenario compared to the *Historical Trends*

scenario as well as a *Paris2C* scenario designed to meet the Paris NDC targets in 2030 and then pursue a global carbon price consistent with achieving 2°C by 2100 with a 66% probability. Under the *Growing Pressures* scenario, the increase in global temperature stabilizes at 2.8°C by 2150, a full 2.5°C lower than where the *Historical Trends* scenario ends up in 2150 as it continues an upward trajectory.

To be clear, a lot of action needs to take place for the *Growing Pressures* scenario to be realized—a summary is provided in **Figure 9**. Continued and growing social, political, business and technology pressures can drive these actions toward a low-carbon world.

Of course, temperature stabilization at 2.8°C above preindustrial levels does not match the goals of the Paris Agreement (see **Figures 8 and 10** for a comparison of temperature impacts and emissions pathways between the *Growing Pressures* scenario and the *Paris2C* scenario). However, the pathway described shows the significant progress that has been made in recent years in redefining our collective future. With the exception of aviation, the scenario makes use of a set of technologies and changes in energy use that are visible now, rather than just imagined as necessary. In addition, the path laid out in the *Growing Pressures* scenario

provides a roadmap of an energy transition that could be accelerated, particularly with global coordination and carbon pricing, in order to get closer to the Paris Goals.

4.2 Key Sensitivities

While we formulated in Section 4.1 the main driving forces that lead to the *Growing Pressures* scenario (shown in Figure 9), the exact timing and magnitude of those actions are subject to uncertainty. To explore the sensitivity with respect to our main assumptions, we conducted five sensitivity cases (see **Table 2**) related to the phase out of refined oil, the electrification of energy-intensive industries, and actions in developing regions (India and Africa).

As described in Section 4.1, in the main version of the *Growing Pressures* scenario we envision that developed regions will move to carbon-free alternatives to refined oil by 2100 and the rest of the world completely switches to carbon-free alternatives to refined oil by 2120. Since the phase out of refined oil is critical to the timing of the transition (see Figure 6 for the change in emissions trajectory between *Scenario Element 5* and *Scenario Element 6*), we test alternative cases regarding the oil phase out.

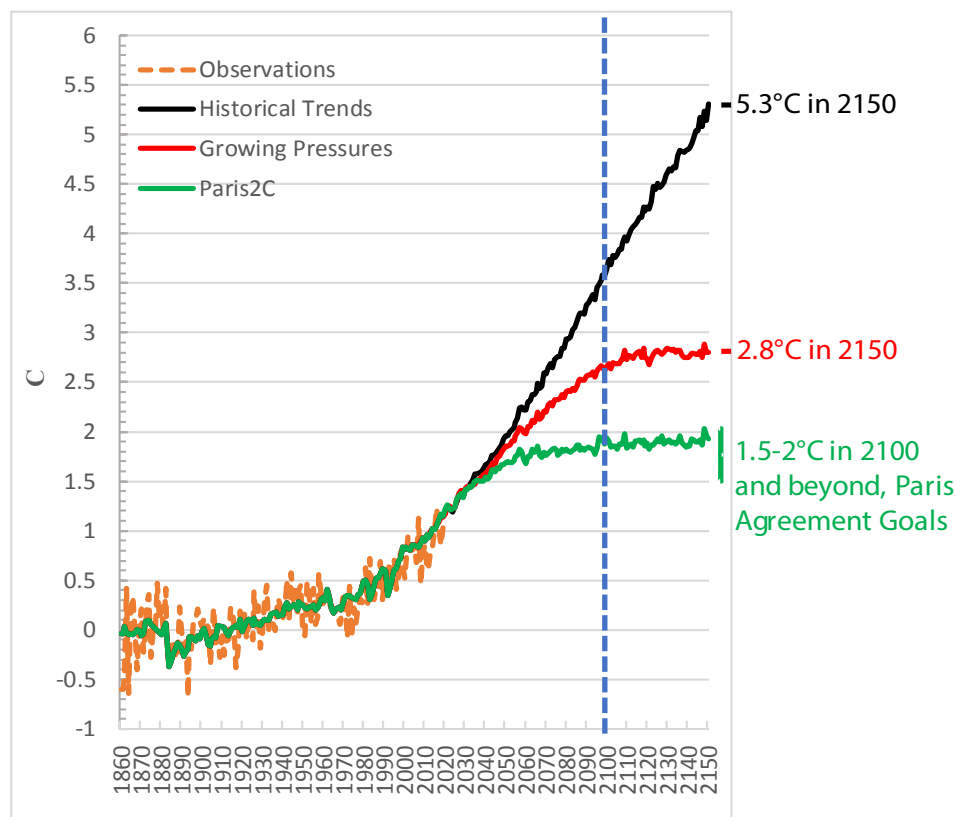


Figure 8. Global average surface air temperature relative to pre-industrial levels (1861-1880 mean) under the *Growing Pressures* scenario, the *Historical Trends* scenario and *Paris2C* scenario.

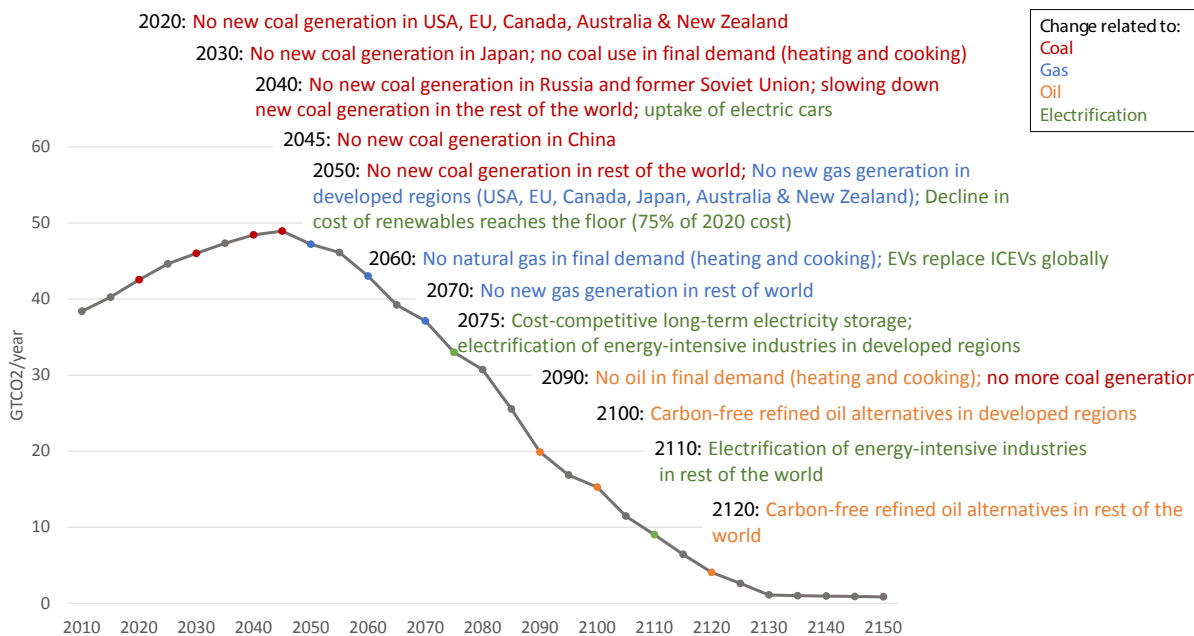


Figure 9. Summary of assumed actions driving the *Growing Pressures* scenario.

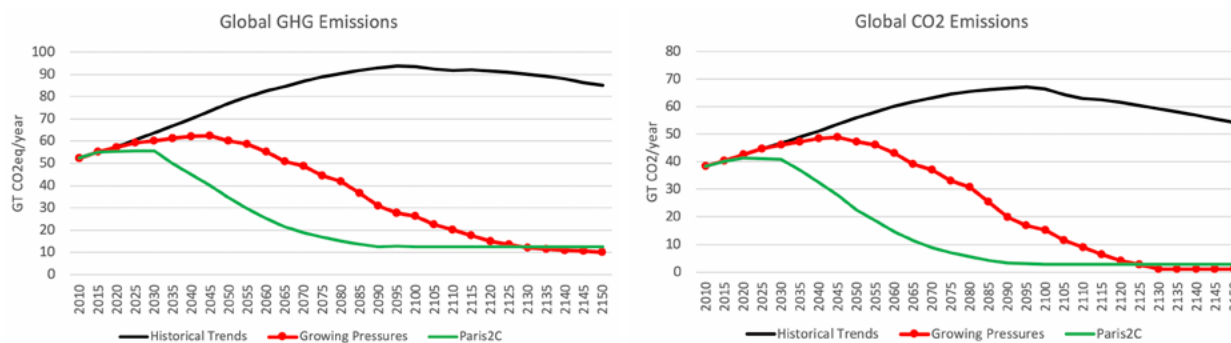


Figure 10. Global emissions of GHGs (a) and CO₂ (b) under the *Growing Pressures* scenario, the *Historical Trends* scenario and *Paris2C* scenario.

Table 2. Sensitivity Scenarios: Variations of the *Growing Pressures* (GP) scenario.

Scenario	Description
<i>GP_SlowOil</i>	Slower phase out of refined oil
<i>GP+FastOil</i>	Faster phase out of refined oil
<i>GP_LessEINT</i>	Only 50% energy intensive industry electrified
<i>GP_NoAFR</i>	Africa takes limited action to reduce fossil fuels
<i>GP_NoAFR_NoIND</i>	Africa and India take limited action to reduce out fossil fuels

In the *GP_SlowOil* scenario, we delay the phase out of refined oil and assume that even by 2150 there are pockets of the global economy that continue to rely on refined oil. In this case, development of alternatives for oil in commercial transportation (particularly in long-haul trucking, shipping, and air travel) prove to be more difficult and/or expensive than imagined in the main version of the *Growing*

Pressures scenario. In contrast, in the *GP+FastOil* scenario the progress with oil alternatives is more advanced, and by mid-century a substantial deployment of carbon-free alternatives to refined oil is taking place. This scenario is supported by the recent announcement by major energy companies (BP, Shell, Total, and others) to search for the solutions to become “net-zero” emissions by 2050. Here we

assume that other companies join the pledges and alternative options are deployed more quickly. However, given the prevalence of oil in the global economy, we assume that a faster oil phase out requires additional action beyond what might be assumed in our *Growing Pressures* scenario.

We also test a scenario where it is more difficult to remove fossil-based inputs to energy-intensive industries than imagined in the *Growing Pressures* scenario (through electrification or use of “green” hydrogen, or, alternatively, by using CCS technology to capture emissions). In this scenario (called *GP_LessEINT*), only 50% of energy intensive industry activities are electrified by 2110.

Additional scenarios explore cases in which the low-carbon transition is delayed in some developing regions. We use examples of Africa and India as populous regions with substantial low-income populations that may pursue other development objectives and stay with fossil fuels, perhaps because of domestic availability. In these cases, these regions still experience the cost declines in renewable generation and energy storage technologies, and face increasing barriers (e.g. financing costs) to fossil electricity generation. However, they do not pursue direct restrictions on fossil energy use, such as limiting the ability to purchase an internal combustion vehicle. While we consider unlikely the situation of a fragmented world where these regions would forever continue using oil and oil-based technologies while the rest of the world has moved on to newer and cleaner alternatives, these sensitivity cases provide us with useful benchmarking. As an example, to continue making use of gasoline through to the end of the century and beyond, certain countries would need to develop a domestic vehicle production industry as we envisage a world in which the current global manufacturers have opted to move on to electric vehicle technology.

The CO₂ emissions paths associated with each sensitivity scenario are shown in **Figure 11**, and their temperature implications are provided in **Figure 12**. As expected, delays in the low-carbon transition increase the global CO₂ profiles and the resulting temperature.

The *GP_SlowOil* scenario increases global CO₂ emissions relative to the *Growing Pressures* scenario throughout the time horizon and as a result the temperature increase in 2150 ends up at just over 3°C, and by that time the temperature is not stabilized but continues to rise. This is compared to

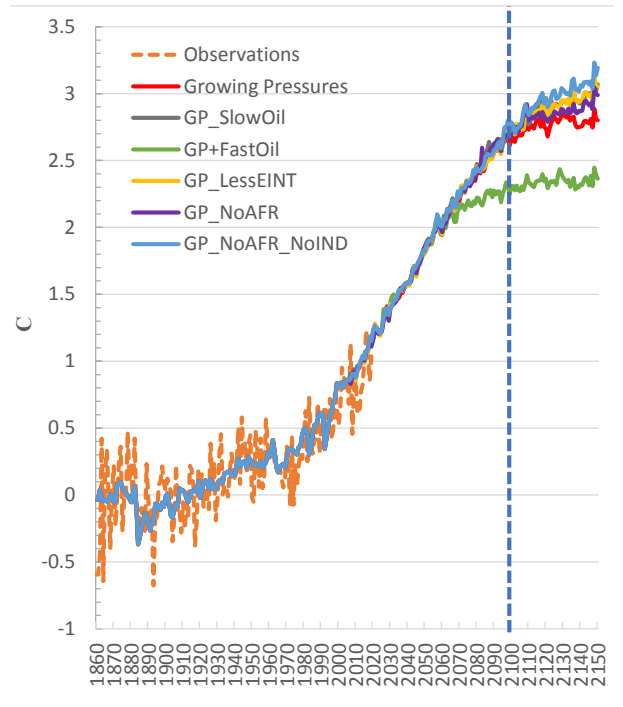


Figure 12. Global average surface air temperature relative to pre-industrial levels (1861-1880 mean) under the *Growing Pressures* scenario, and its alternative variations

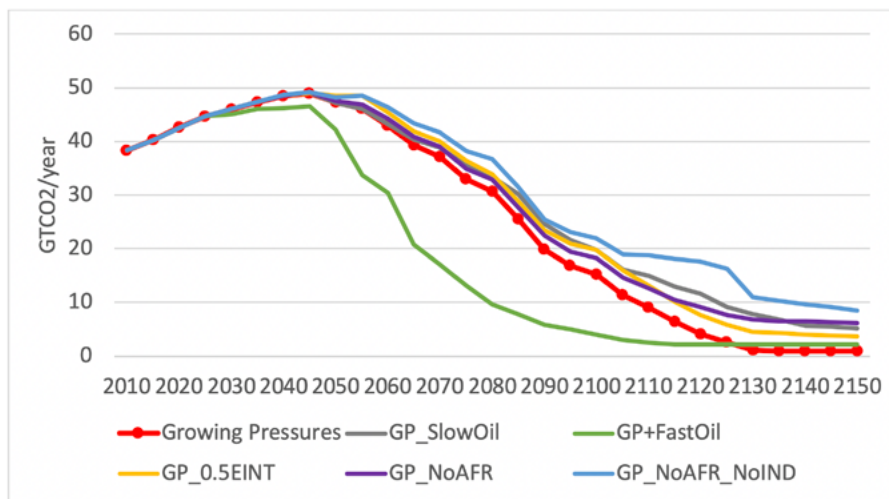


Figure 11. Global CO₂ emissions in the *Growing Pressures* scenario (red line with round markers), and its alternative variations.

a stabilization at 2.8°C in the *Growing Pressures* scenario. In contrast, in the *GP+FastOil* scenario global CO₂ emissions are significantly reduced. The emissions trajectory is slightly lower than the *Growing Pressures* scenario between 2025 and 2045 and then emissions fall dramatically through 2110, where they remain close to zero (at about 2 Gt CO₂) through 2150. This dramatic change in emissions is reflected in the temperature increase, which stabilizes at about 2.4°C. In the *GP_LessEINT* scenario, emissions are increased relative to the *Growing Pressures* scenario, and as a result the global temperature increase ends up at just over 3°C in

2150. Limited decarbonisation activities in Africa also lead to a similar temperature increase. Among the sensitivity cases that we have tested, the largest temperature increase (3.2°C by 2150) is in the scenario when both Africa and India pursue limited decarbonisation activities.

The results described above are driven by the changes in the global primary energy mix. **Figure 13** illustrates these changes in the cases with different phase out trajectories for refined oil. In the *Growing Pressures* scenario, oil is removed from the global energy mix in 2120, while in the *GP_SlowOil* scenario oil lingers through 2150, reflecting its continued use

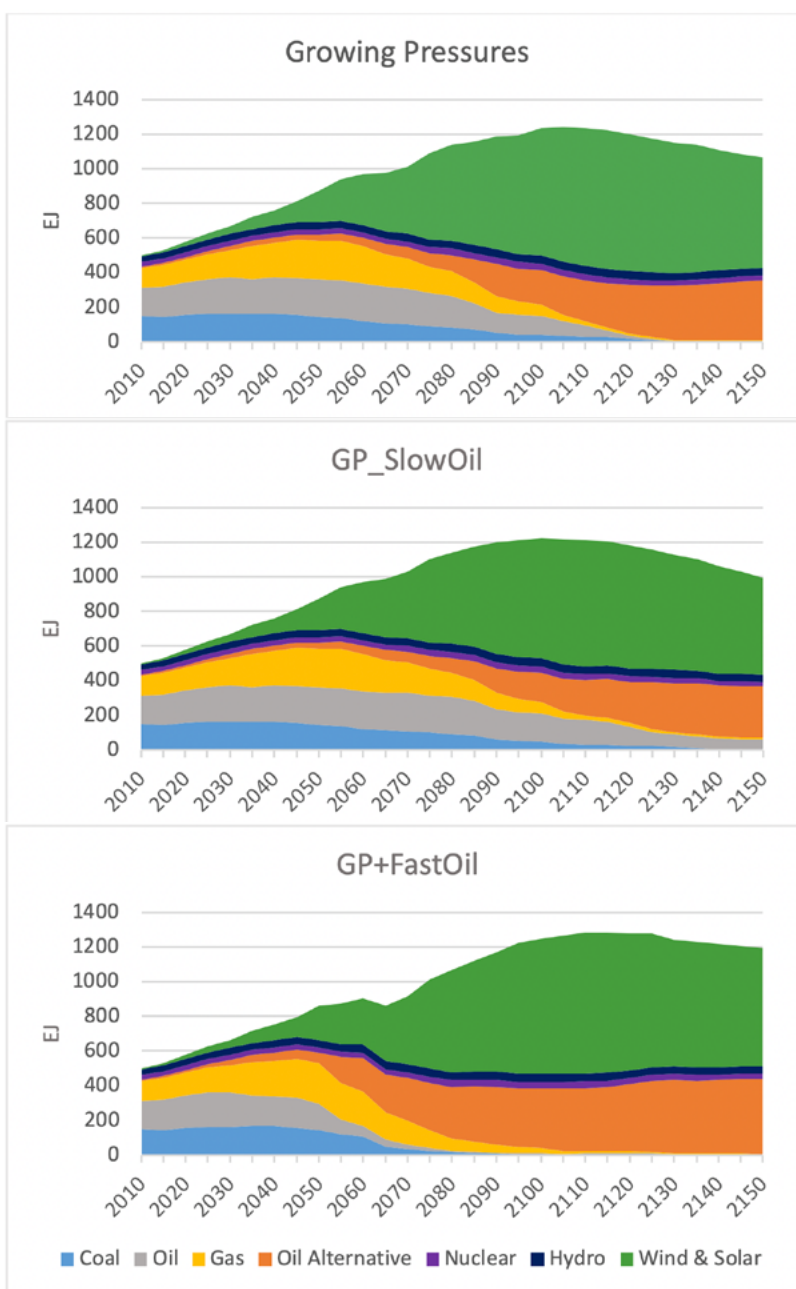


Figure 13. Global primary energy mix under different assumptions about the phase out of oil.

in some sectors (e.g. air transport) and some regions (e.g. Africa and the Middle East). In the *GP+FastOil* scenario, oil is significantly reduced by 2055 and phased out by 2080. These sensitivity cases indicate how important phasing out oil is to long-term climate stabilization goals. This suggests the need for more aggressive actions to develop and deploy technologies, fuels and infrastructure that enable the transition away from refined oil at a faster pace.

When Africa does not take aggressive decarbonisation actions, it has a starkly different primary energy mix (see **Figure 14**). In comparison to the *Growing Pressures* scenario, where the continent is almost fully electrified by 2120-2130, in the *GP_No AFR* scenario it continues to employ coal, oil and gas and uses far less renewables. As a result, Africa's emissions are significantly higher and about double from 2020 to 2150 (see **Figure 15**). While in the *Growing Pressures* scenario Africa's CO₂ emissions approach zero after 2100, in the *GP_No AFR* scenario the emissions in 2050-2150 are relatively stable at about 6

GtCO₂/year. With a rapidly growing population in Africa, stabilizing emissions is an important milestone. However, decarbonisation actions in Africa need to be enhanced to reach the temperature goals of the Paris Agreement.

In the case where India is slow to adopt the low-carbon technologies that are pervasive elsewhere, it continues its use of fossil fuels to an even greater extent than Africa. This is seen in its primary energy mix which uses large amounts of oil and coal (see **Figure 16**), and is particularly stark in its electricity generation mix which is dominated by coal instead of renewables (see **Figure 17**). These changes result in rising emissions that end up over four times higher than 2020 levels by 2150 (see **Figure 18**). These differences in India, together with the differences in Africa, translate to an increase in global temperature by 3.2°C by 2150 (as depicted in Figure 12).

Our sensitivity analysis provides a quantification of the impacts from relaxing or tightening key assumptions in the *Growing Pressures* scenario. It shows that even with

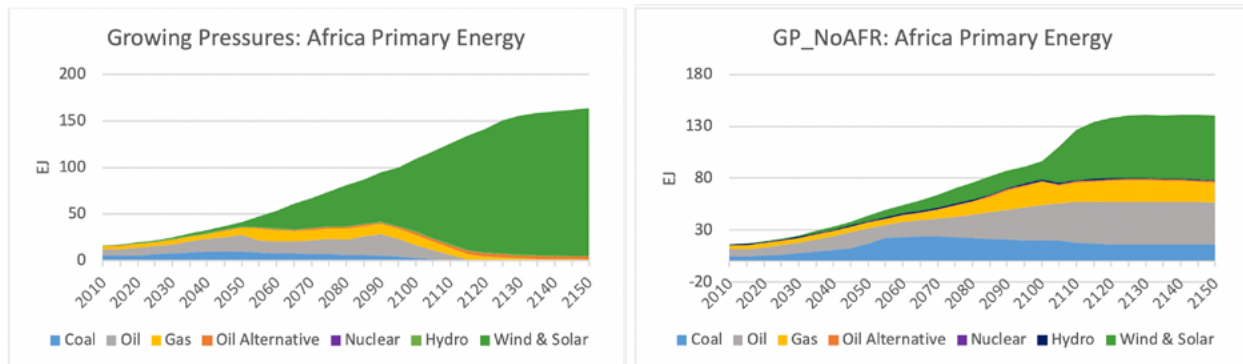


Figure 14. Primary energy mix in Africa in the *Growing Pressures* scenario and the *GP_NoAFR* scenario in which Africa takes limited action to reduce fossil fuels.

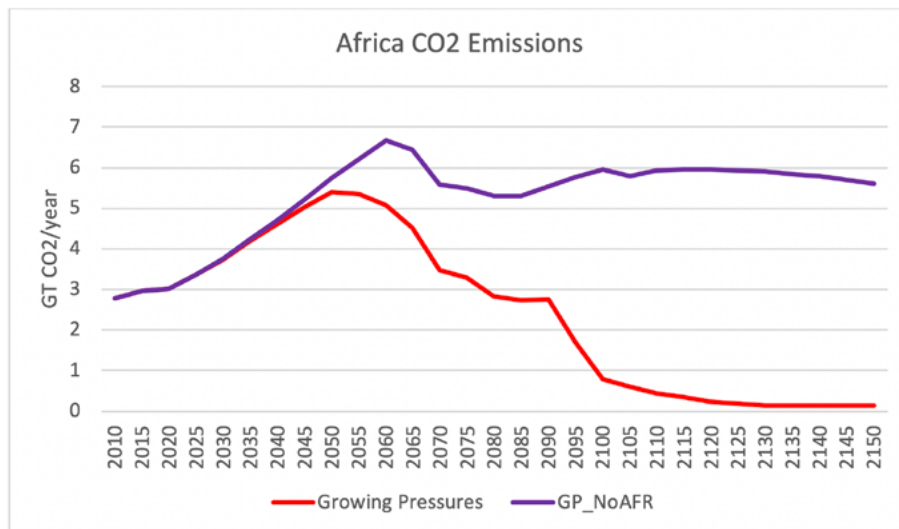


Figure 15. CO₂ Emissions in Africa in the *Growing Pressures* scenario and the *GP_NoAFR* scenario in which Africa takes limited action to reduce fossil fuels.

less courageous assumptions about future decarbonisation actions, the global temperature increase could be bounded to about 3°C, not 5°C or more (as suggested by RCP8.5-like trajectories). Our assessment also indicates areas to focus actions in order to put the world on a trajec-

tory that could align with the long-term goals of the Paris Agreement - namely the use of refined oil, energy-intensive industries, and action in key developing regions. Faster decarbonization in those areas could put more aggressive climate stabilization targets within reach.

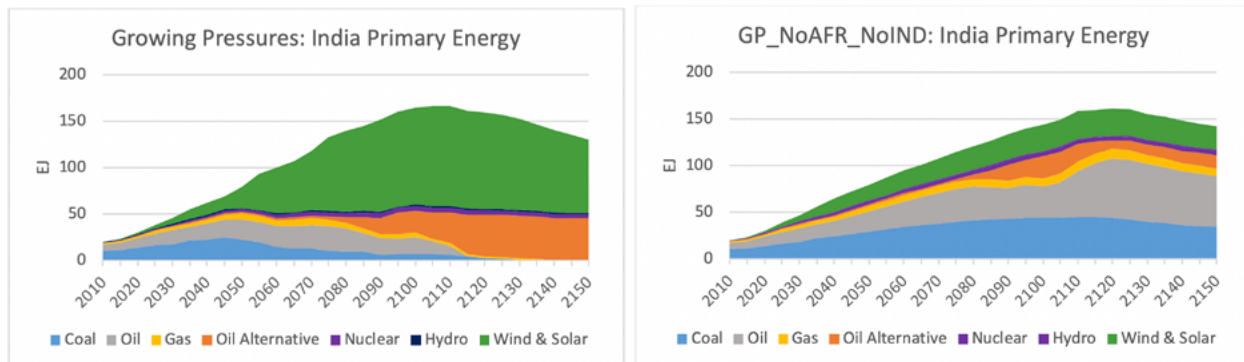


Figure 16. Primary energy mix in India in the *Growing Pressures* scenario and the *GP_NoAFR_NoIndia* scenario in which India and Africa take limited action to reduce fossil fuels.

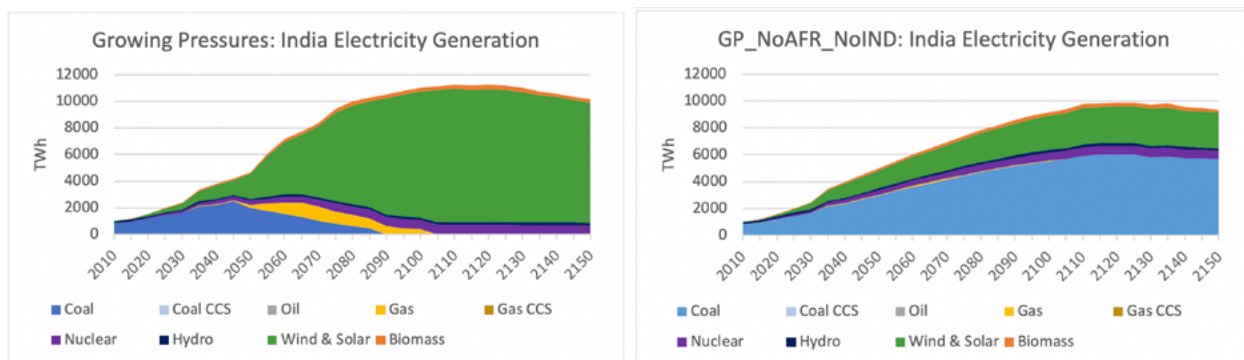


Figure 17. Electricity generation mix in India in the *Growing Pressures* scenario and the *GP_NoAFR_NoIndia* scenario in which India and Africa take limited action to reduce fossil fuels.

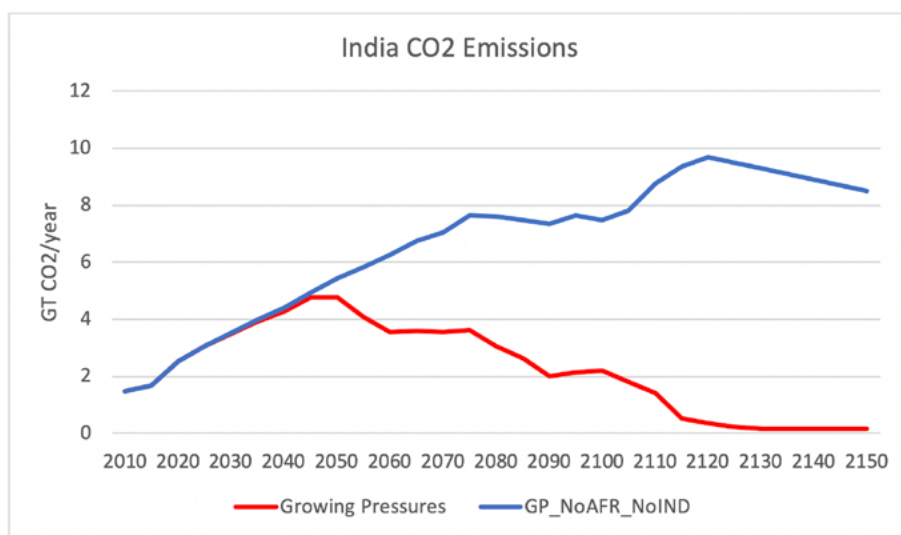


Figure 18. CO₂ Emissions in India under the *Growing Pressures* scenario and the *GP_NoAFR_NoIND* scenario in which India and Africa takes limited action to reduce fossil fuels.

4.3 Climate-Related Uncertainty

Temperature outcomes are not solely determined by the emissions trajectory, but also by the climate response to those emissions, which is uncertain. To account for this climate-related uncertainty, we run 400-member ensembles of the MIT Earth System Model (MESM) (Sokolov *et al.*, 2018) based on probability distributions for climate sensitivity, ocean heat uptake and aerosol forcing (Libardoni *et al.*, 2018). Accounting for uncertainty in the climate response to the emissions from the *Growing Pressures* scenario, gives a 90% probability bound of 2150 temperature increase of 2.24-3.51°C (see **Table 3**).

Figure 19 shows the 90% probability bound for temperature under the *Growing Pressures* scenario, as well as under the *GP_NoAFR_NoIND*, *Historical Trends* and *2C* scenarios. Of the alternative variations of the *Growing Pressures* scenario explored in Section 4.2, the *GP_NoAFR_NoIND* scenario has the highest temperature outcome (3.2°C) given median climate parameters, and the original *Growing Pressures*

scenario the lowest (2.8°C).² **Figure 19** therefore provides an image of the temperature range from the *Growing Pressures* scenario accounting for both scenario uncertainty and climate uncertainty. The 2150 temperature spans a range of 2.24°C (the lower bound of *Growing Pressures*) to 3.84°C (the upper bound of *GP_NoAFR_NoIND*). This range is an important reminder that a given emissions trajectory cannot guarantee a temperature outcome. Rather, uncertainty in the climate system requires that actions be continually adjusted if a temperature target is to be met.

5. Conclusions

In a world with growing pressures toward decarbonization, there is no longer a single, obvious business-as-usual” or

² Although the *GP_FastOil* scenario has a lower temperature outcome than *Growing Pressures*, that scenario is considered as requiring action beyond what we consider in the *Growing Pressures* narrative. It is therefore a scenario between *Growing Pressures* and *2C*.

Table 3. Global average surface air temperature relative to pre-industrial levels (1861-1880 mean) under the *Growing Pressures* scenario at the end of the century (2091-2100) and for 2141-2150 for given percentiles when accounting for uncertainty in climate response.

	Temperature at Given Percentiles						
	5%	17%	33%	50%	66%	83%	95%
2091-2100	2.10	2.34	2.51	2.64	2.79	2.95	3.21
2141-2150	2.24	2.48	2.66	2.80	2.98	3.22	3.51

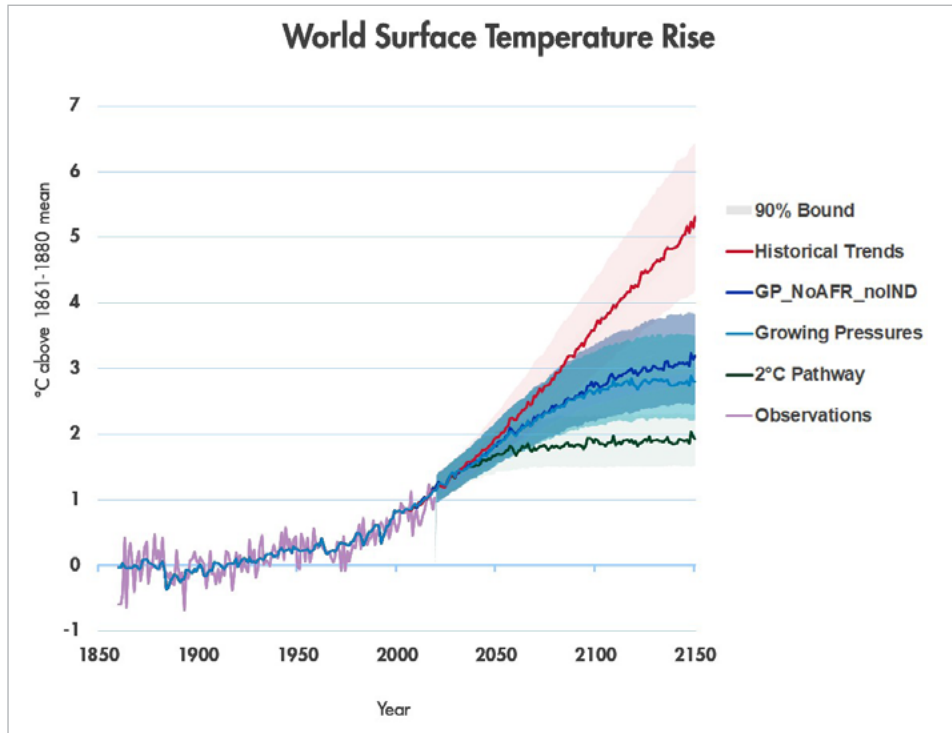


Figure 19.

“no policy reference” scenario. Instead, there is a range of plausible futures that should be explored. Researchers should think carefully about using a “business-as-usual” scenario and what it means. In particular, scenarios that continue historical trends of unfettered fossil fuel use no longer seem relevant when a shift toward a low-carbon society is already under way. We offer a scenario of a transition that reflects recent progress and pressures and how those might evolve at a natural pace into the future, absent globally coordinated mitigation effort. We consider a world that continues to address climate change in the way it has so far—through piecemeal actions and growing social awareness and technological advances.

This scenario takes into account the increasingly visible impacts of climate change that result in growing activism and demand for transition away from fossil fuels. Increasing pressure from voters, shareholders, consumers and investors prompt action by governments and businesses, steering investments away from fossil fuels. Technology and infrastructure investments and developments in renewables, energy storage, electrification, hydrogen and digitalization further push the low-carbon transition. In the scenario, these persistent and mounting pressures drive a series of plausible actions that lead to a transition that brings the global energy system to near zero emissions, and results in a global temperature increase of about 3°C above preindustrial levels.

The plausible actions involved in our scenario bring society closer to the long-term goals of the Paris Agreement. They also provide a roadmap of ways in which the transition could

be accelerated to bring the Paris goals within reach, and provide insight into the additional actions needed. Refined oil is highlighted as playing a particularly impactful role in the transition. Action in the forms of R&D, technology deployment, infrastructure development, policy incentives and business practices will all be essential to speed up the transition away from refined oil. Similarly, actions to help accelerate the decarbonization of energy intensive industries are needed.

A slower energy transition than imagined in our analysis for developing countries (such as African countries or India) is a real possibility. However, enabling an even faster transition in such countries is necessary for the Paris targets to be attainable. Global coordination to help such countries achieve important development goals in a sustainable way will therefore be critical. It is not enough to lead by example, it is necessary to transfer knowledge and available technologies to developing countries. Stepping up government actions, including deploying carbon pricing, supporting natural and geological carbon sinks, and facilitating lifestyle changes, are crucial for all regions of the world in order to accelerate the transition.

6. Acknowledgement

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Supplementary Material

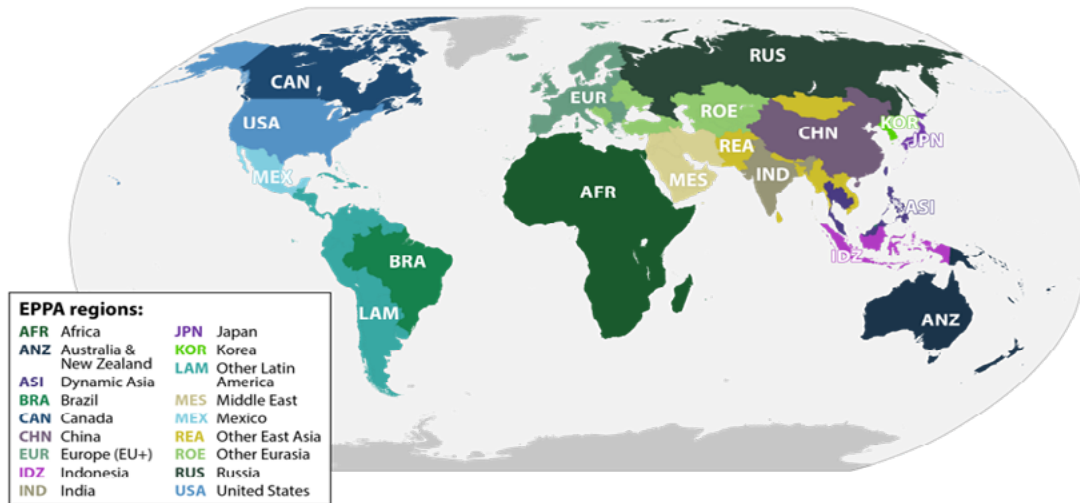


Figure S1. Regional representation in the MIT EPPA Model.

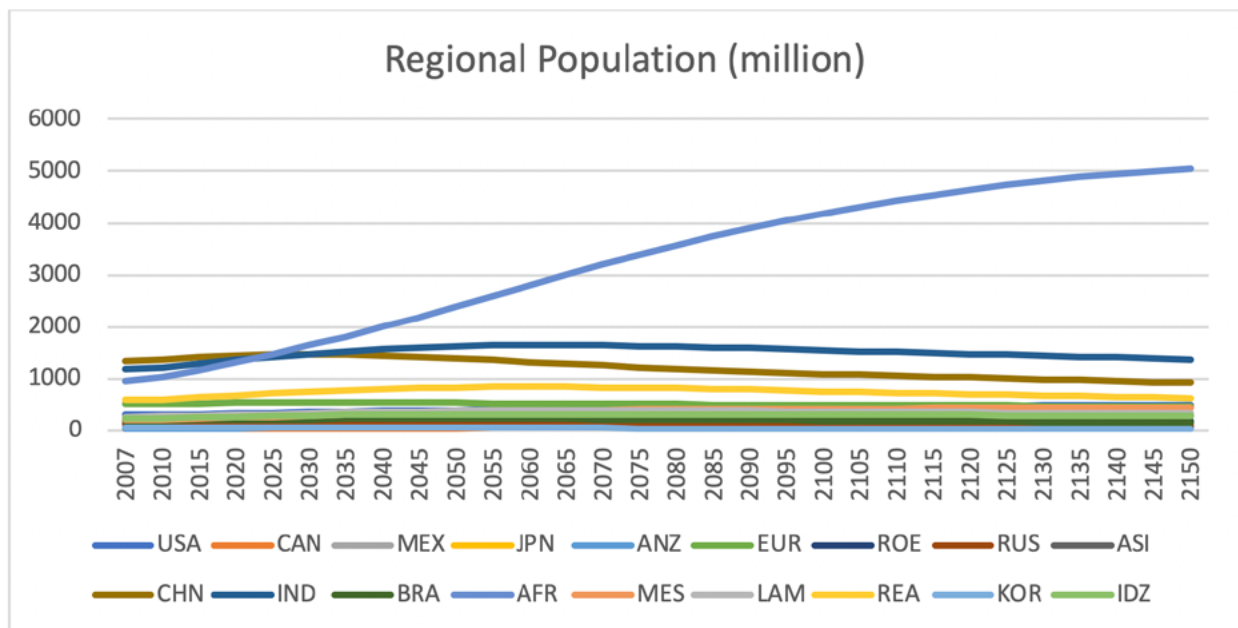


Figure S2. Assumed population projections by region in the EPPA model.

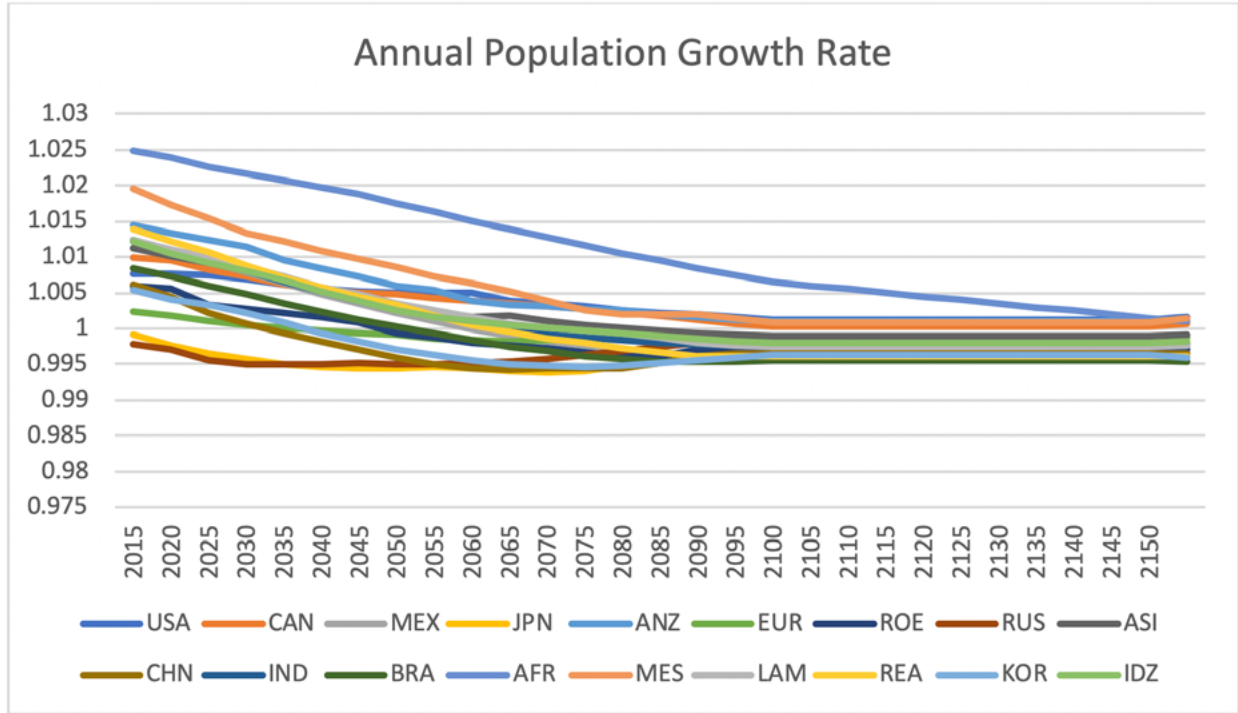


Figure S3. Assumed population growth rates by region in the EPPA model.

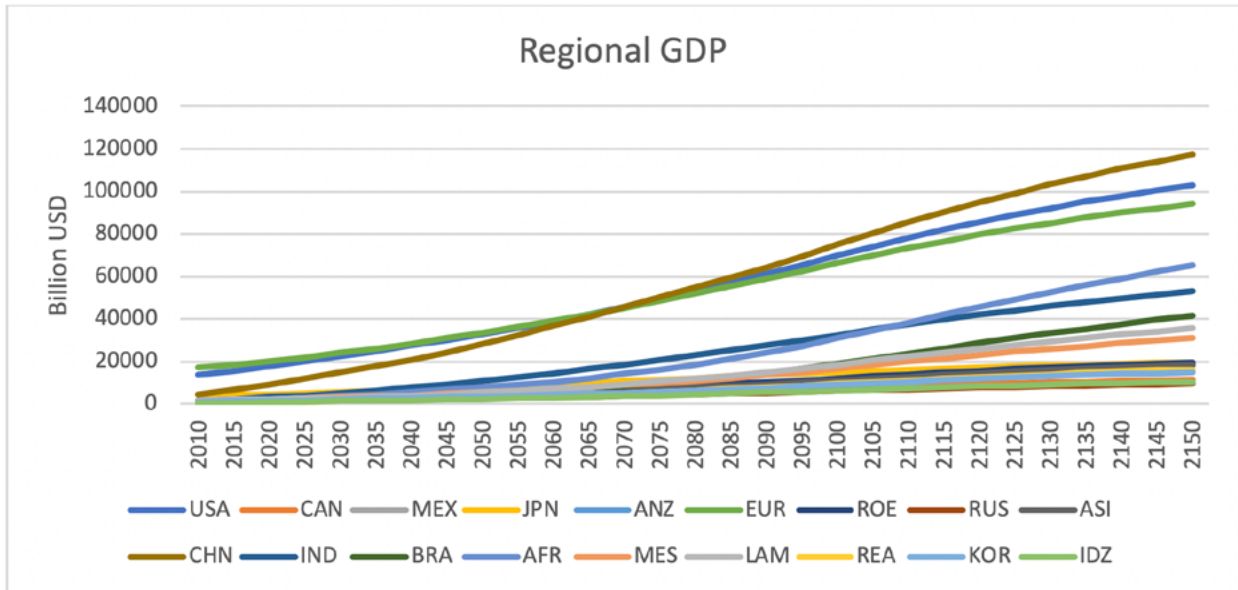


Figure S4. Assumed GDP projections by region in the EPPA model.

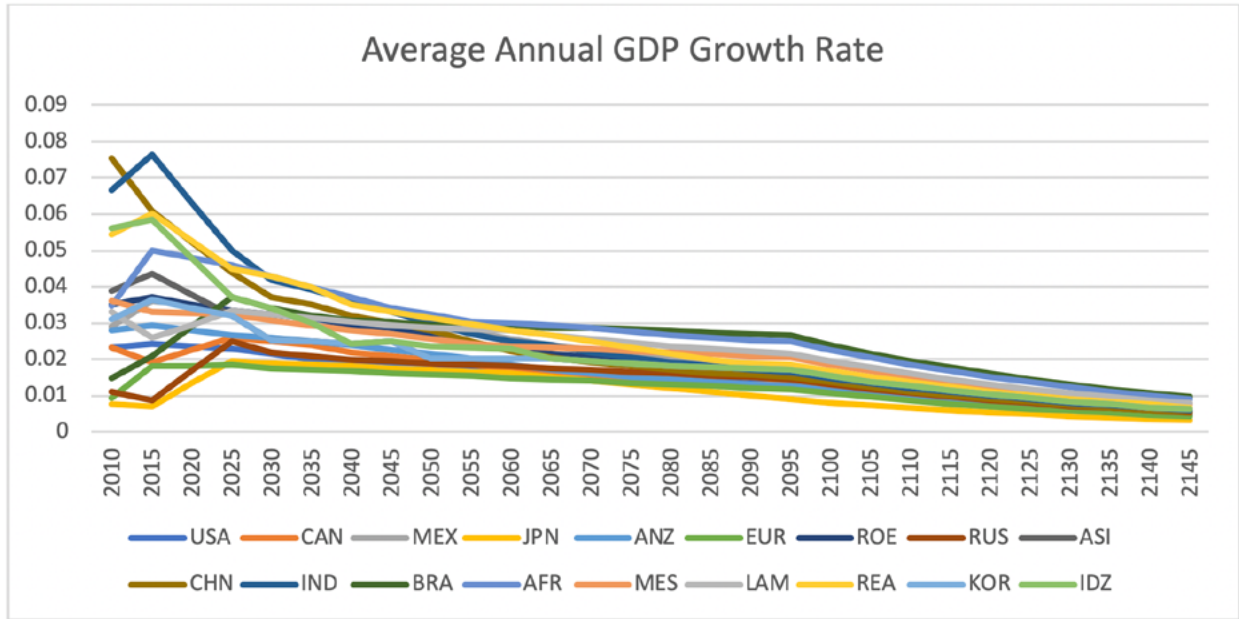


Figure S5. Assumed GDP growth rates by region in the EPPA model.

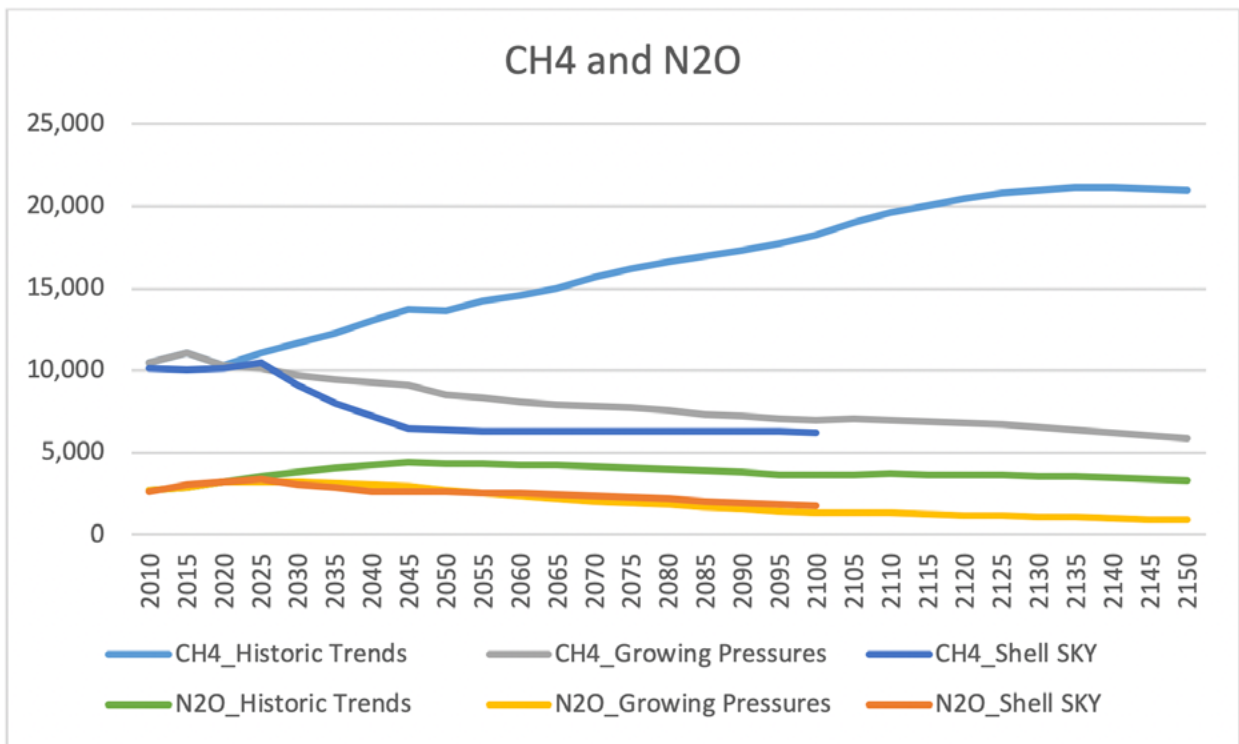


Figure S6. Assumed CH4 and N2O trajectories for *Historic Trends*, *Growing Pressures* and *Shell SKY* scenarios. The trajectories shown for *Growing Pressures* are used for *Scenario Element 9* (as described in the main text in Table 1).

Table S1. Assumed actions driving emissions reductions, including for methane (CH₄) and Nitrous Oxide (N₂O), in the Shell SKY scenario. These actions drive the Shell SKY CH₄ and N₂O trajectories shown in Figure S6.

Gas	Sector	Actions assumed between 2020-2070
Carbon dioxide	Cement	<ul style="list-style-type: none"> • Progressive substitution away from cement in buildings • Some substitution away from limestone as a feedstock, e.g., using fly-ash • Using carbon capture and storage (CCS)
	Industrial (process emissions)	<ul style="list-style-type: none"> • Using CCS
	Agriculture	<ul style="list-style-type: none"> • Eliminating deforestation for land gain • Implementing soil carbon programmes, e.g., no-till farming, land-use rotation
	Urbanisation and development	<ul style="list-style-type: none"> • Creating green cities through extensive tree planting • Maintaining green belts within and around cities • Avoiding city spread through higher density living • Addressing traditional biomass usage through modern access to energy programmes
Methane	Coal mining	<ul style="list-style-type: none"> • Reducing coal consumption • Implementing best practice for methane drainage and use in coal mines (e.g., UNECE Guidance) • Managing abandoned mines
	Oil and gas industry	<ul style="list-style-type: none"> • Reducing oil and gas consumption • Oil and gas industry leaders implementing best-practice from the 2020s, and all world production meeting best-practice by 2050
	Cattle farming	<ul style="list-style-type: none"> • Offering alternative products to consumers • Changing cattle diets to minimise methane
	Rice growing	<ul style="list-style-type: none"> • Reducing forced flooding in rice paddies
	Urbanisation and development	<ul style="list-style-type: none"> • Capturing methane from landfill
Nitrous oxide	Agriculture	<ul style="list-style-type: none"> • Implementing nitrogen fertiliser management, i.e., application rate, formulation (fertiliser type), timing of application, placement
	Industrial processes	<ul style="list-style-type: none"> • Implementing catalytic decomposition and thermal destruction techniques
Fluorinated gases	Various (e.g., IT industry, refrigeration, transformers)	<ul style="list-style-type: none"> • Progressive substitution away from PFC, HFC, and SF₆ • Using best practice management • Introducing recovery programmes for retired equipment (e.g., refrigerators, transformers)

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