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Energy, Climate, and Policy towards 2055: An Interdisciplinary Energy Outlook (DIW-REM Outlook)

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Energy, climate, and policy towards 2055: An interdisciplinary energy outlook (DIW-REM Outlook)

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Executive Summary and policy recommendations

- The energy system is subject to substantial uncertainty over the coming decades. Energy outlooks inform analysts and decision-makers about potential developments. Scenarios do not typically aim at predicting the future, but at giving bounds to the range of plausible developments. In other words, energy outlooks provide readers with information on how current drivers will manifest in specific futures.

- In a three-year study, we have composed an independent energy outlook, which focusses equally on “conventional” factors (i.e. technology development, climate policies) as well as more unconventional factors, such as (geo-)politics, the state of global governance, and the role of society. These factors were integrated in a multi-step process that featured expert-led qualitative analyses and quantitative energy sector modelling.

- The outlook contains four scenarios (base case ‘**Business as Usual**’, worst case ‘**Survival of the Fittest**’, best case ‘**Green Cooperation**’, and surprise case ‘**Climate Tech**’) that depict plausible alternative futures of global energy, climate, and policy. Each scenario contains a detailed storyline of the events between today and 2055, including figures for global energy production and consumption as well as the electricity mix. Moreover, this report presents energy system metrics for selected regions in more detail and includes a comparison with other prominent outlooks. We also discuss stranded assets in the fossil resource sector and the related risks that become apparent in our outlook.

The following conclusions and recommendations are found:

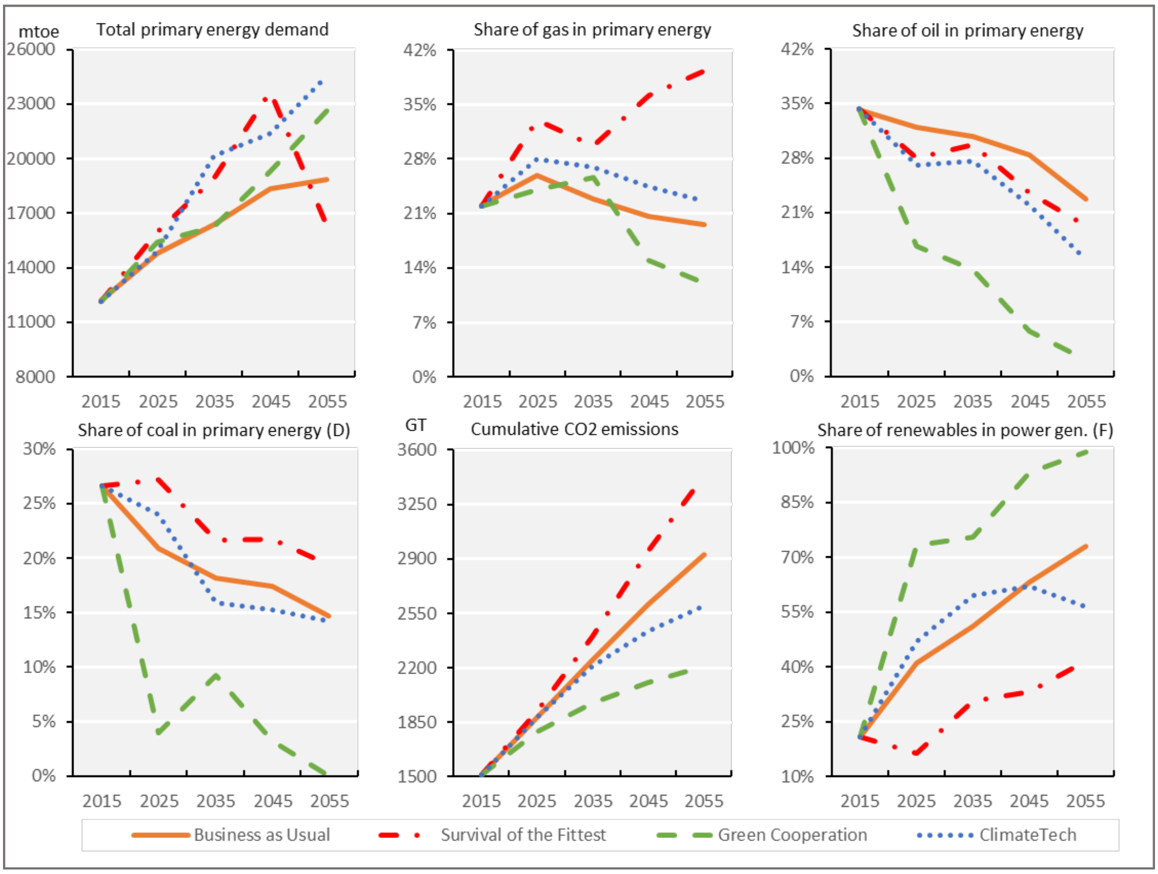
- A return to political isolationism is a critical risk for the energy transition: First, effective climate policies require international collaboration. Second, the energy transition depends on channelling investments into the ‘right’ directions, whereas lacking global coordination leads to ambiguous (technological) developments and competing technologies. Substantial increases in the global temperature risk to create massive refugee waves, further fuelling inter-regional tensions.

- Public opinion and societal transitions are an integral component of decarbonisation efforts. It is highly unlikely that technological progress alone will be sufficient to outweigh missing efforts to phase-out fossil fuel consumption. Deep decarbonisation necessitates a holistic transition that includes society.

- The integration of economic and energy-related objectives and incentives (e.g. poverty alleviation, infrastructure modernisation, and private investment) is crucial. Technology transfer, the creation of incentives, and geopolitical reconciliation are necessary for a successful global transition.

- Energy importers need to consider the exporters' perspectives. Asset stranding, that is the depreciation of assets due to sudden policies or market disruptions, is a risk for fossil-fuel dependent economies with limited diversification of exports and of fiscal budgets. There is a high risk for market rebounds and increasing political tensions that can damage decarbonisation efforts and fragile security environments alike.

- We find that some metrics commonly used for assessing the state of decarbonisation are unfit indicators. We show that, especially, the share of renewables and electricity consumption are improper indicators, as the trends of increasing electrification and rising renewable energy generation are also ongoing in the scenarios with increasing emissions. Instead, we advocate for direct metrics (e.g. the rate of emissions, see Figure below) or a set of multidimensional indicators, as we present them as part of our outlook.



1 Introduction: The history and theory of scenarios

Van Notten (2005, p. 7) defines scenarios as "consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action". They differ from other methods, mainly in the type of questions. While contingency planning focuses on 'what if?' questions by presenting a base case and an exception (or contingency), "scenarios explore the joint impact of various uncertainties which stand side by side as equals" (Schoemaker, 1995, p. 26). Scenario building also differs from sensitivity analysis with regards to how uncertainty is approached. While the former generally considers simultaneous modifications of several variables, sensitivity analysis only focuses on the effect of modifying one variable while keeping everything else unchanged.

Although some suggest that scenarios date back to the 19th century and military strategists such as von Clausewitz (Bradfield et al., 2005), the use of modern scenario techniques started after the Second World War. Rand Corporation was among the first organisations to provide scenario-based services for the Pentagon. Herman Kahn, a top strategist for Rand in the 1950s, was the one to begin developing scenarios that altered the US military's approach to thermonuclear war, most notably in consideration to 'thinking the unthinkable', which allowed for alternative strategies to annihilation or surrender (ibid., p. 798). Methods used at the time ranged from Delphi techniques to cross-impact matrices.

In the 1960s and 70s, scenario development finally emerged as a tool not only for public policy but also for strategic corporate purposes. Wack (1985, p. 73) explains the emergence of so-called 'scenario planning':

'Beginning in the late 1960s and early 1970s, Shell developed a technique known as "scenario planning." By listening to planners' analysis of the global business environment, Shell's management was prepared for the eventuality—if not the timing—of the 1973 oil crisis. And again in 1981, when other oil companies stockpiled reserves in the aftermath of the outbreak of the Iran-Iraq war, Shell sold off its excess before the glut became a reality and prices collapsed.'

Hence, scenario planning allowed Shell to respond quickly to the oil crises of 1973 and 1981. It contributed to the company becoming one of the stronger "Seven Sisters". The original *raison d'être* of scenario planning was, therefore, to help (corporate) decision-makers open their minds to improbable future developments contingent on previously 'inconceivable or imperceptible' change (Wilkinson and Kupers, 2013, p. 118).

Scenarios, in this sense, need to be distinguished from other future-oriented methods, most importantly from forecasting methods and other prediction-oriented techniques. The latter seek to predict the future with the utmost accuracy and answer the question 'What will happen?'. Given the highly complex nature of a system such as that of global energy, which sits on the interplay of dozens if not hundreds of parameters, that quest is most likely bound to fail.

Instead, scenario analysis considers the questions 'What can happen?' and, in certain applications, 'What should happen?'. Scenarios, as Wilkinson and Kupers (2013, p. 121) describe it, "are intended to set the stage for a future world in which readers imagine themselves as actors and are invited to pay attention to deeply held assumptions about how that world works. What happens at a scenario's horizon date is not as important as the storyline's clarity of logic and how it helps open the mind to new dynamics". Therefore, the "strength of scenarios is that they do not describe just one future, but that several realisable or desirable futures are placed side by side." (Mietzner and Reger, 2005, p. 235). In this context, and opposed to forecasting, the term "plausibility" is more central than "probability" (Derbyshire, 2017). Scenarios, hence, explore the range of plausible futures rather than necessarily aiming at finding the most probable one of them.

Forecasting, in contrast, is based on computer simulations and tends to reason from continuous developments and linear processes, which does not allow the outlook to reflect discontinuity, whether in the form of sudden technological breakthroughs, economic booms and busts, or a geopolitical shift (Söderholm et al., 2011; Van Notten, 2005). Scenario studies are intrinsically better suited, if not for anticipating sudden changes, at least for facilitating early response systems to them. Therefore, scenarios are often equipped with diagnostic indicators, which help observers monitor the situation and reveal which scenario eventually unfolds (e.g. Heuer and Pherson, 2015).

Moreover, there is a seemingly small yet important distinction between scenario building and scenario planning. As summarised by Mietzner and Reger (2005, p. 223), "building scenarios means speculating about the uncertainty surrounding the future", whereas scenario planning is "a management technology used by managers to articulate their mental models about the future and thereby make better decisions" and thereby relies on the former as its foundation.

Ultimately, scenario building exercises rely on a smart balance between qualitative and quantitative information inputs that can tell "a story of how various elements might interact under uncertain conditions" (Schoemaker, 1995, p. 26). Nevertheless, the actual way of handling both inputs varies considerably and may range from thorough methods for including a multitude of drivers to the use of numerical models to combinations of them. Often, several scenarios are developed by the same institution at the same time, with the desire to englobe the largest plausible range of potential future realization.

This range of potential futures is often referred to as the 'scenario cone' or the 'cone of plausibility' (Figure 1), as the uncertainty (and, hence, the spread between the scenarios) increases over time (e.g. Amer et al., 2013). Scenarios are specific futures that typically lie in the area of plausible developments, which is to be distinguished from the probable developments. The latter are the futures that seem most likely based on a projection of the present. Either of these areas can or cannot overlap with the space of preferable scenarios, i.e. the developments and outcomes that are normatively desirable. Beyond the borders of plausible developments are the implausible but possible developments, which can be envisioned but do not seem reasonable from today's point of few. Even further outside the circle of plausible developments, we find the space of developments that are labelled as impossible to occur.

Still, an important dimension frequently side-lined in energy scenarios is social transition. Scenarios "barely take lifestyle sufficiency into account", although "sufficiency and changes in lifestyle should rather be embedded, discussed and quantified independently of technology decisions" (Samadi et al., 2017, p. 132). In the following outlook, we will see that this dimension is, at best, part of those scenarios that include a detailed analysis of their vision and drivers.

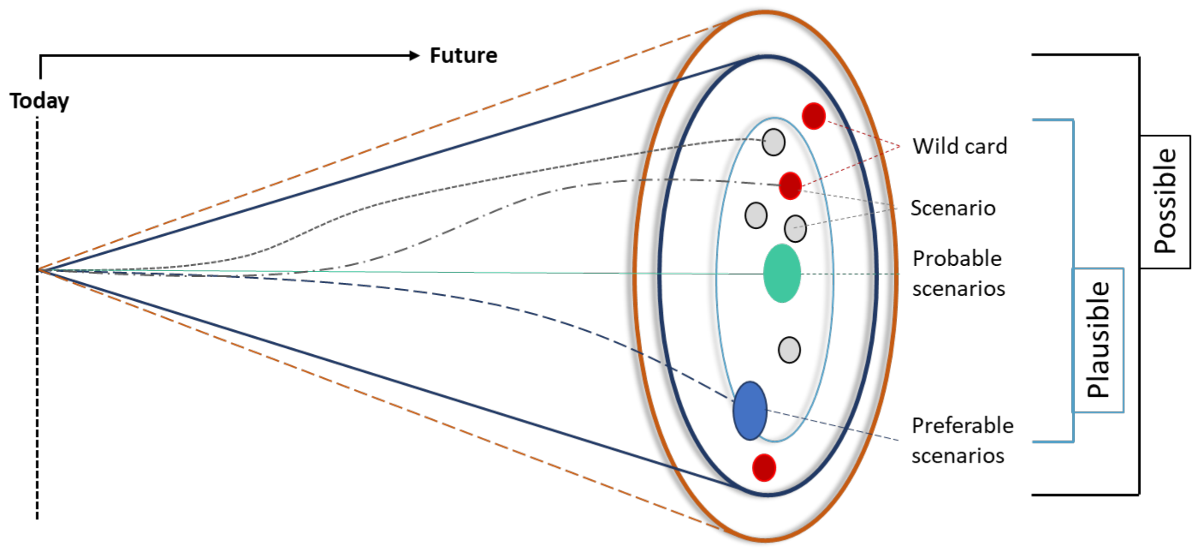


Figure 1: Illustration of the scenario cone

2 Overview

This report presents a novel and independent energy outlook[1] towards 2055. Similar to other prominent outlooks, such as the IEA's World Energy Outlook or the Royal Dutch Shell scenarios, our outlook illustrates possible global futures and provides readers with several insights on energy, climate, and interrelating fields.

The outlook is the result of a three-year study by the research group Resource and Environmental Markets at the German Institute for Economic Research (DIW-REM). Its development has been part of research projects for the European Commission and the German Federal Ministry of Education and Research. The scenarios (to which we refer as 'narratives') depict the broad range of plausible developments in the years to come (cf. Figure 1). Each narrative starts in 2015 and describes a plausible (but not necessarily probable) path of the world towards 2055. Precisely, the outlook comprises the following four scenarios:

- **Business as Usual:** A vision of the developments to happen if current trends are set to continue, i.e. the conflicting interests of various state and market actors in a tense (geo-)political environment lead to a diverse and ambiguous future energy system (which fails to curb emissions).
- **Survival of the Fittest:** A worst-case vision of a world that disaggregates into various competing (regional) actors, who show only little regard to decarbonisation efforts and instead ramp up previous commitments in fossil fuels, eventually leading to a consolidation of power before large-scale climate catastrophes disrupt the world entirely.
- **Green Cooperation:** A best-case vision of the revival of global cooperation and collaboration between different states and within them, which enables markets to allocate investments in the various technologies required to turn civilisation, society, and growth green.
- **ClimateTech:** A surprise-case vision (wild card) of a technology-centred world in the aftermath of sudden advancements in various energy and climate technologies, which ultimately succeed in curbing emissions but fail to address the underlying social and economic structures preventing deep decarbonisation.

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[1] To avoid confusion, we shall use 'outlook' to describe a set of scenarios that are generate by one source; and we shall use 'scenario' to describe a particular future.

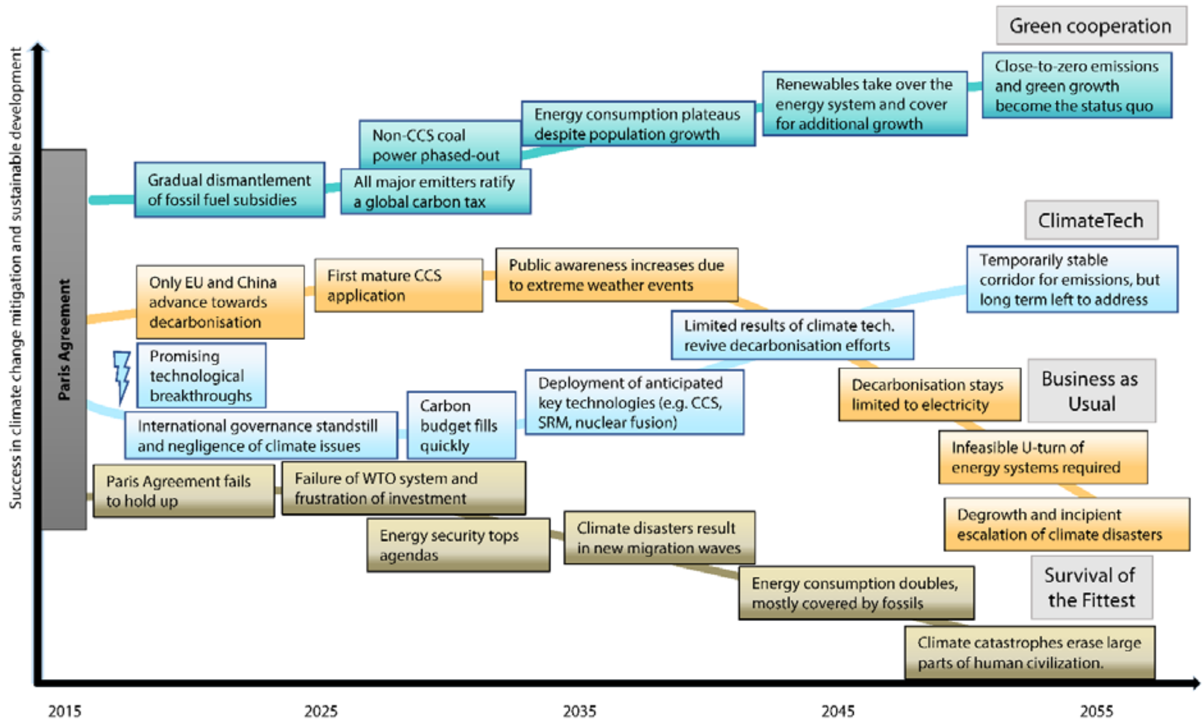

Figure 2: Illustration of the main developments over time in the four scenarios

Crucially, the scenarios were generated in a structured way and with a focus on factors beyond technology and economics. Instead, the narratives have a strong emphasis on the interdependencies between policy and politics, society, security aspects, and energy and climate aspects. Each one contains a detailed storyline of the developments from today until 2055 (see Figure 1 for an illustration of the main events) as well as figures for energy consumption and production as well as the electricity mix.

Our outlook is novel and complementary to previous efforts in three ways:

- This outlook combines both qualitative and quantitative methods with equal importance. This enables us to construct futures that are sophisticated elaborations of factors that are hard-to-measure (e.g. social transitions or geopolitics) but also strong in classical numerical dimensions (e.g. energy production and consumption). As a result, the narratives have a comprehensive character and provide better insight than outlooks that only focus on either side.
- The outlook is the product of independent research, which is why numbers and scenarios are unbiased of potential conflicts of interests, such as they could be present in a corporate environment.

- While most outlooks rely on simulations or linear optimisations, this outlook makes (rare) use of a complementarity model. Therefore, our quantitative analysis is better suited to give insights into actual (energy) market dynamics than other outlooks.

The remainder of this report proceeds as follows:

Section 3 covers the core of the outlook, i.e. the four narratives. After a brief overview, we present their qualitative storylines along with figures for global final energy consumption, global primary energy production, and the global electricity generation mix.

Section 4 summarises the figures for the global level and analyses them in the context of decarbonisation and the energy transition.

Section 5 continues the outlook by presenting and describing the regional figures for final energy consumption, primary energy production, and power generation mix in the European Union, the Middle East, South America, Asia-Pacific, and North America.

Section 7 proceeds with a comparison of our outlook to other prominent outlooks. The section elaborates on differences and similarities for the global numerical figures as well as regional metrics for Europe, Asia-Pacific, and North America.

Section 8 is a side-note dedicated to stranded assets, a topic of rising importance in the energy industry. The section introduces the issue and provides an index that indicates the risk for asset stranding in the Middle East, China, and South America, based on the outlook's numbers.

Section 6 provides qualitative and quantitative indicators for the scenarios, i.e. a set of diagnostic observables that enable readers to monitor the situation and track which scenario eventually unfolds.

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Methodological appendix provides further information on the methods that were used for generating this outlook.

3 The four narratives

3.1 Business as Usual

3.1.1 The Paris promise: between targets and ambitions in the 2020s

In the Business as Usual scenario, geopolitical tensions and localised conflict continue in the late 2010s and early 2020s, not only in the Middle East and Africa but also in OECD countries. While this geopolitical situation does not directly impact the accomplishment of climate targets set by countries in their NDCs, political priorities are diverted away from climate and energy issues.

The 2015 Paris Agreement was only a first step and poses several additional challenges: While ambitions on mitigation objectives are converging, much still needs to be done with regards to actual measures. The climate targets that were announced in the NDCs following the Paris Agreement are mostly met in the Business as Usual scenario. However, the re-evaluation of those targets and associated measures, agreed to take place every five years, brings only modest changes to the original ambitions of the signatory countries. Between 2019 and 2025, among the top 10 GHG emitters that signed the Paris Agreement, only the EU and China effectively scale up their efforts. Further questions relating to financing schemes to support developing countries' plans as well as frameworks that could foster technology transfers have yet to be addressed. Schemes such as the Green Climate Fund and the Global Environment Facility are present on paper but fail to kickstart effectively. This limited progress is connected to a general increase in struggles to find a global common stance: Many United Nations initiatives (including the UNFCCC) hold firm but face a cooling of international relations, a growing divergence in national interests, and thus, a weakening of their legitimacy and influence.

By the mid-2020s, carbon pricing is not enforced globally but instead relies on regional, national, and local implementation. EU policies for a green transition become more stringent although political differences and national interests mean a decarbonised Europe is still far from a reality. The United States does not witness major changes with regards to the pace of clean energy deployment. Country-wide carbon pricing remains absent, and the regional extent of decarbonisation efforts is heterogeneous. Some states rely on cap-and-trade initiatives, but others refuse to introduce new bills, often due to pressure from large upstream (fossil fuel) and downstream (conventional) energy companies, which continue to be crucial to many local economies.

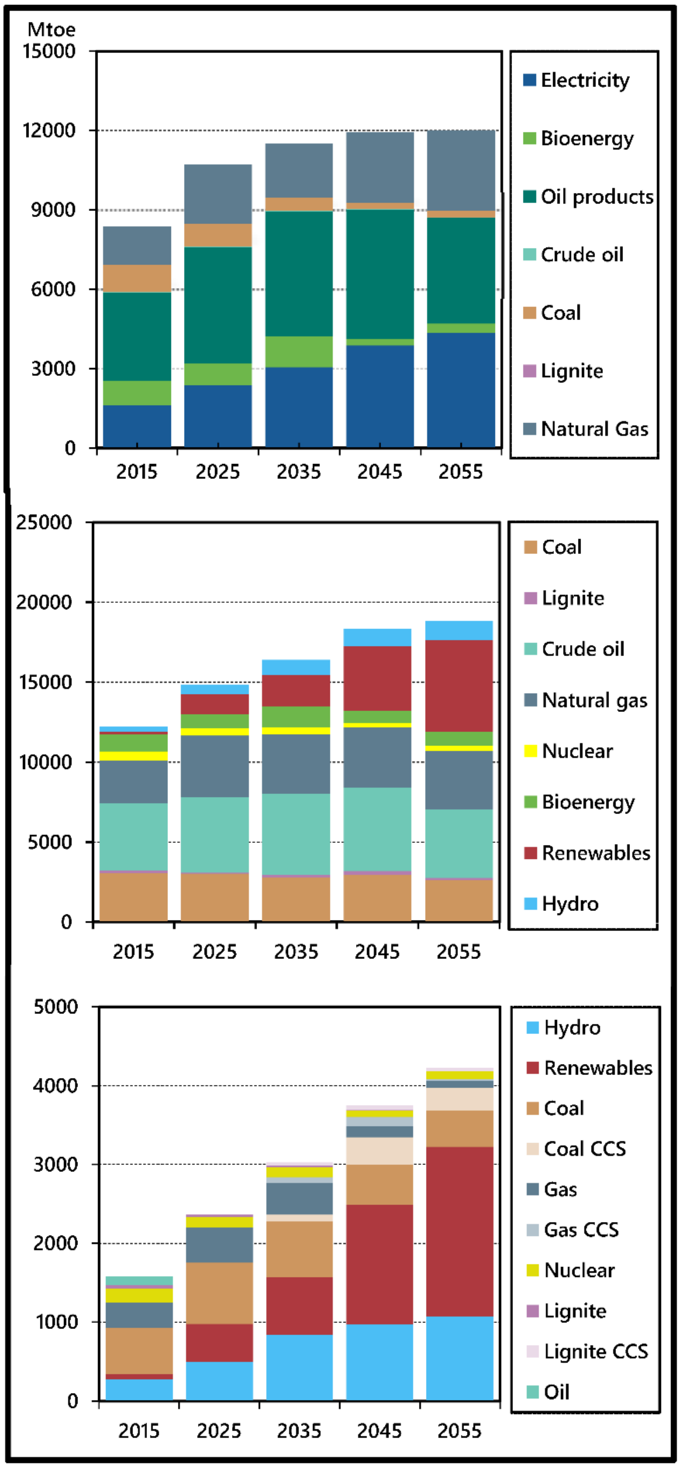

Figure 3: Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Business as Usual

Regional initiatives, being more modest than initially hoped for, do not spur the investment in R&D and the deployment of renewable energy generation and energy efficiency necessary to tackle the growth of energy demand in much of the developing world. As a result, the carbon intensity in emerging economies increases in the next decades. India's climate policy makes incipient progress through stricter vehicle standards and gas power plants. However, emissions from coal-fired electricity generation rise steeply and make India one of the world's largest polluters. More generally in the Global South, the diffusion of zero-emission micro-grid installations, targeted green investment programmes, and a significant amount of new hydropower projects (whether through private actors or multilateral development banks) do not suffice to curb carbon emissions in these regions. Distributional questions regarding the North-South divide remain unsolved, driving most of the Global South into prioritising energy security rather than global sustainability.

This trend is partly offset by more climate-friendly developments among several large polluters. China consolidates its role as a green force within a polycentric Asia and thereby becomes a pillar for future international climate cooperation. However, despite large investments in renewable energy generation and stagnating coal demand, fossil fuels remain an integral part of the Chinese energy system.

The MENA region takes a more pro-active stance towards decarbonisation with an increased number of initiatives towards clean energy, especially for net importers of fuel. For exporters, these initiatives remain mostly symbolic, and an effective move towards deep economic and energy sector reforms is constrained by conflicting interests with the regional fossil fuel sector, which becomes ever more dependent on domestic consumption.

Despite the absence of a global carbon pricing mechanism, and heterogeneous, largely insufficient schemes for supporting investments in renewable energies in the first decade of the scenario, some developments favour a future reduction in global GHG emissions. For example, while global demand will not yet have switched away from coal by the 2020s, new solutions start to emerge at the turn of the 2030s, for instance in the form of the first mature carbon capture and storage (CCS) applications and efficiency increases for renewable technologies.

Altogether, the 2020s see renewable energy and fossil fuels co-exist. Transport, especially in the Global South, depends on fossil fuels, whereas the diffusion of electric vehicles accelerates slowly in many industrialised economies. Despite significant advances towards decarbonisation in China and Europe, disruptive changes in conventional energy systems are virtually absent. Fossils still dominate in the rest of the world, supported by the absence of joint political action or technological advances.

3.1.2 Catching up after 2030?

The pace of the global energy transition accelerates somewhat in the 2030s and 2040s as a consequence of stronger climate change effects and technological advances. The number and magnitude of extreme weather events such as droughts, wildfires, storms, and excessive precipitation grows. North America is among the regions that are increasingly hit. This leads to a gradual change in public perception and eventually redirects the U.S. federal leadership towards a stronger stance on climate policy. These fresh ambitions enable a new and significant multilateral push towards decarbonisation, in which all large emitting countries take part. This effort comprises coordinated action to decrease carbon leakage, stricter national climate policies, and financing schemes for supporting climate adaptation. However, the agreements continue to lag behind initial expectations in a world order that has never fully moved on from political tensions between major powers. They merely lead to a stagnation of fossil fuel consumption rather than a shift in the global energy system, among other reasons due to the continued absence of a global CO_2 price.

Concerning technological advances, the transport sector is subject to substantial changes, with electric vehicles experiencing significant cost decreases by the late 2020s, although wide-scale deployment only takes place in the following decade. Traditional combustion-engine cars persist in many parts of the globe. Freight and air travel do not undergo any significant changes. Renewable electricity generation becomes increasingly cheaper relative to electricity generation from coal and gas. CCS enters power generation on a larger scale, yet the technology stays expensive and its efficiency remains below expectations. Over time, renewables and, to a lesser degree, CCS dominate the global fuel mix and cover the steep increase in electricity demand from all sectors towards 2050. Other technologies, such as nuclear fusion, are far from commercially available, although research into those technologies nevertheless continues. Global substitution of fossils by renewables only takes place in power generation and in the 2040s. Examples of deep decarbonisation in industry and transport are rare, which is why fossil fuels are still essential, partly due to the availability of CCS technology. Nevertheless, efforts finally lead to stagnation of fossil fuel production and consumption despite global population growth.

Global collective action for climate change mitigation still operates within a UNFCCC-type framework. However, the associated emission reduction is too low and comes too late: by this point, not only a smooth transition but a U-turn in the energy system and disruptive shift to negative net emissions would be necessary to have a chance at keeping cumulative emissions below the 2 °C limit.

The growing impact and quantity of extreme weather events crucially raises awareness among the public and decision makers. However, fears of too harsh and expensive reactions by fossil fuel owners – threatened by asset stranding – and a lack of common ground in dealing with distributional questions on a global scale lead to a reluctance to enact a profound transition in the energy system and fuel-dependent economies. The late re-invigoration of mitigation efforts is too little, too late to prevent the intensification and surge in – still localised – climate change-induced catastrophes towards 2050 and beyond. As a result, multiple regions of the world are about to enter a period of de-growth, as adaptation costs escalate globally.

3.2 Survival of the Fittest

3.2.1 A world apart

In the Survival of the Fittest scenario, policy making in Europe and North America becomes increasingly influenced by protectionist and nationalist interests. Hence, their relevance in the international economic governance system declines in the 2020s, making any multilateral process much less likely to bring efficient results. Agreements on trade and economic cooperation are instead determined within regions, thus accelerating the transition to a polycentric world order dominated by regional powers.

Influenced by a rationale rooted in isolationism, the United States drastically reduces its efforts in the Middle East and Eastern Europe around 2020. Its reduced military presence in the Middle East especially leads to a disaggregation of alliances into competing local factions. These developments have a direct effect on the economic and political stability of oil exporters, including the Gulf States, which become ever more vulnerable to global economic conditions. Political struggles eventually lead to the disaggregation of the Gulf Cooperation Council, and a climate of tension and hostility characterises *a gulf apart*. This even leads to localised instances of military confrontation, and the conflict expands to the wider Middle East and North Africa. Fuelled by mounting tensions on domestic fronts, exporters fail to achieve a common stance on oil policy. Without the leadership of Saudi Arabia, OPEC continues to exist on paper, but it fails to establish a common output policy.

Therefore, and despite conflict and insecurity, global oil and gas output is only subject to mild disruption. Instead, each country engages in a self-preserving and short-term oriented approach, and the absence of coordination leads to a surge in production and a drop in oil prices.

At the same time, conflicts erupt elsewhere. Among them, in the South China Sea, isolated yet violent confrontations take place between China and a coalition of smaller countries backed by the United States. Although both powers avoid the escalation to open conflict, the continued struggle severely damages relations between China and the US, reducing their diplomatic ties to a minimum.

Conflicts in the South Caucasus also put a strain on European solidarity. The continent is divided into “hawks and doves” over how to best deal with Russia. Weakened transatlantic relations leave Europe and the U.S. alienated, and European decision makers are torn when it comes to redefining alliances. Between *rechtsruck* and *realpolitik*, a fragmented Europe has little basis to form common foreign or fiscal policy. This limits economic progress and the possibility to mediate in international conflicts. Global tensions also heighten concerns over Europe's access to affordable and secure energy, moving decarbonisation out of focus in the 2020s. Based on the principle of the lowest common denominator, a fragmented Europe continues to cooperate on advancing the energy transition although at a slower pace and with weaker ambitions.

3.2.2 International climate policy at a standstill

The Paris Agreement fails to hold, as (supply) security trumps climate policy on the national agendas of fuel-importing countries, while multilateral diplomacy quickly erodes due to a general sense of mistrust. This leads to a global institutional order in which the UNFCCC loses its legitimacy. In parallel with Australia, Latin America, Russia, South Africa, and multiple Southeast Asian suppliers, the U.S. ramps up coal production, consolidating the fuel as the pillar of many countries' energy systems. An even larger surge takes place in the natural gas sector, whose importance increases to meet the steep increase in modern industry and residential energy needs in the absence of a global transition to electricity.

Green transformation efforts become increasingly dependent on informal alliances and bilateral relations. China, in ever-closer cooperation with the EU, continues to gain importance in this regard, consolidating agreements on technology transfers, green investments, and development programmes, not only with European countries but also with parts of the developing world. Chinese infrastructure investments are on the rise in Africa and Asia alike. The objectives behind these moves are diverse but mostly directed towards filling the vacuum left by the weak international system, thereby consolidating the role of China as the (supra-) regional hegemon.

Global economic growth slows down from the early 2020s onwards, in large part due to the failure of the WTO system and the re-enforcement of trade barriers and protectionist policies. The pro-autarkical regulations and a lack of support for coordinated projects lead to a frustration of private investment, which drifts away from technological innovations in the fields of energy generation, efficiency, storage, and CCS as well as the transport sector. Thus, in the 2030s, the rate of technological progress slows down, deployment of new technologies lacks support, and the private sector altogether fails to propose adequate solutions for mitigating climate change.

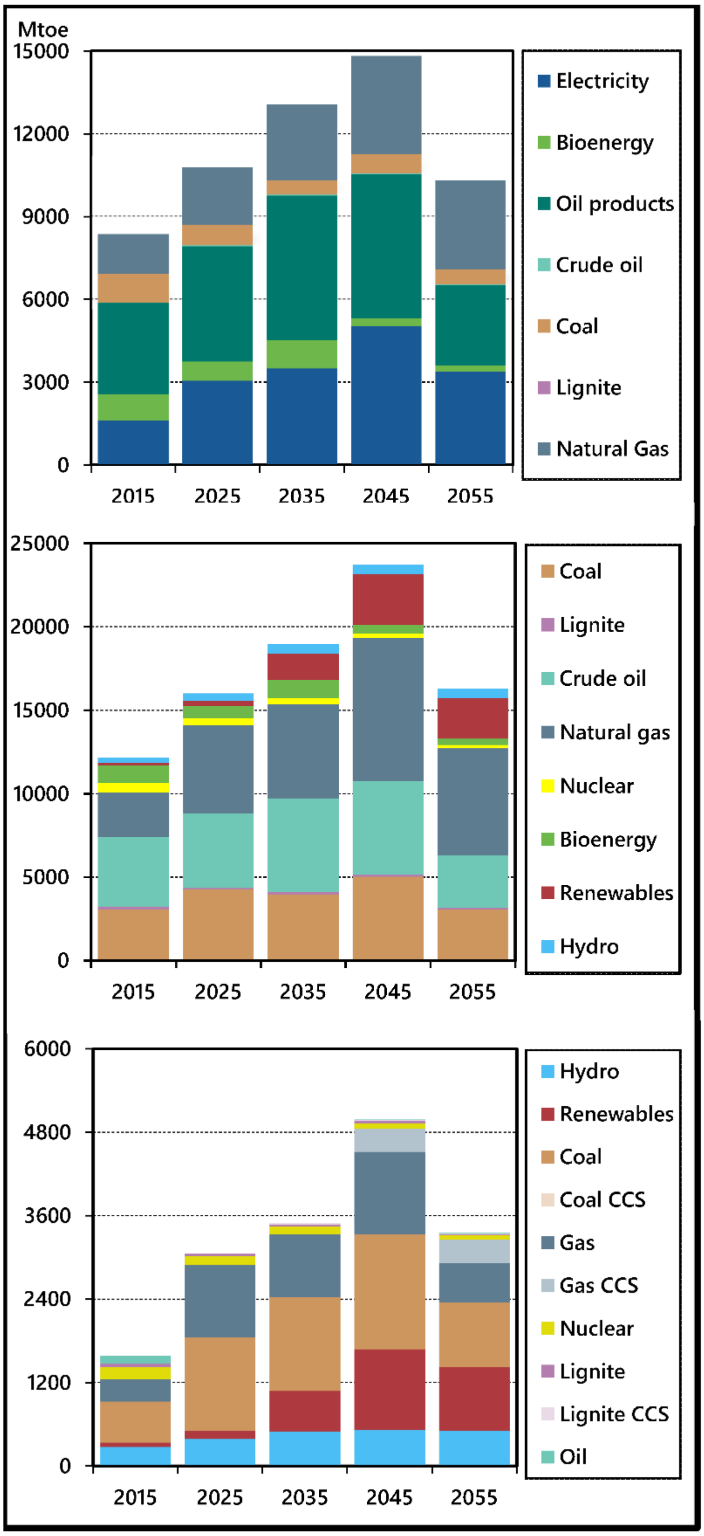

Figure 4: Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Survival of the Fittest

Instead, increased global competition in fossil fuel extraction and the widespread deployment of coal and gas power plants lead to efficiency gains in conventional fuels and technologies. Energy consumption increases continuously and almost doubles until 2045. The composition of demand follows "traditional" (i.e. fossil-intensive) growth patterns without much technology switch. The (moderate) increase in global electricity generation also sees a somewhat growing role for renewables, but the vast majority is met by conventional power plants.

While concerns over national security hamper international climate negotiations, energy security and air and water quality also rank high on the agendas of many countries. For some large net-importing economies, most notably Europe and China, public health issues start to play a major role in energy policy considerations in the 2030s. This leads to a re-orientation of their focus on domestic resources, with a strong emphasis on solar and wind power, while at the same time ensuring higher end-use efficiency. North America also continues to rely strongly on its domestic unconventional oil and gas reserves, further driving up global fossil fuel demand. However, this trend is partially offset by some cities and state-level actors which push for a green transformation. This Quixotic approach creates an atmosphere of clean enclaves, which further cement heterogeneity and divergence within the continent.

Without strong international organisations to coordinate policies tackling energy consumption or end-use efficiency, the 2 °C carbon budget is met early in the 2030s. Therefore, in the following decades, climate change-related catastrophes become frequent. The persistent absence of international cooperation between states and the diversion of public spending away from potential mitigation or adaptation measures further hinder financial and technological transfers to the countries most affected. The developments fail to create the necessary global common sense of solidarity since estranged governments oppose free-rider gains and focus on local adaptation measures.

As a result, climate change becomes an influential factor for international migration in the late 2030s and leads to a multiplication of security threats. Not unlike the refugee crisis in the mid-2010s in Europe, albeit on a larger scale, a new wave of mass migration overwhelms international assistance and further fuels state-on-state as well as domestic conflicts. This new migratory crisis and the resulting tensions further hinder government responsiveness in many host countries, thereby delaying any concerted climate change measures even further, and increasing adaptation costs drastically.

In the endgame, towards 2050, global warming is out of control and results in large-scale natural catastrophes globally. Whereas the richest nations are forced to afford the exploding costs of adapting to this world and pay significant shares of their GDPs to survive, vulnerable regions that cannot afford these measures become uninhabitable. Regional wars over remaining resources add to an extraordinary high number of human casualties that results from the unprecedented floods, droughts, and storms. With the death of roughly one third of humanity and the massive destruction of productive factors, the world will see veritable global de-growth, de-industrialisation, and, therefore, a slump in energy production and consumption. Survival of the Fittest sees the world as we know it cease to exist.

3.3 Green Cooperation

3.3.1 Clean Peace

In the early years of the Green Cooperation scenario, decades of conflict in the Global South push northwards, transported by migration and market turbulence. Societies in the Global North are increasingly tense and see a quick rise in nationalist and reactionary forces, which begin to gain the upper hand throughout Europe and North America. However, this eventually causes a strong push-back by a revived liberal civil society which elects a new generation of progressive leaders into office. Aiming to rebuild their societies and end conflicts, this young class of leaders values the potential losses from non-cooperation in an interdependent world more highly than the prospective gains through confrontation.

Therefore, this scenario sees a quick return to peace where conflicts soon de-escalate in key geopolitical regions such as the Middle East, South Caucasus and the South China Sea. The international order is characterised by a strong stance against sedition and discord, which moves rather fiery regional players to set conflicts aside. Some internal power disputes remain, e.g. in the Greater Middle East, but the frequency and scope of armed conflict diminish and do not resurge throughout the 2050s, in large part due to a continued common policy of conciliation among the world's major powers.

The effects on international relations and fossil fuel prices are mixed. On the one hand, the phase-out of armed conflicts in the Middle East is accompanied by renewed dialogue between the major players in OPEC. As relations between Saudi Arabia and Iran normalise, oil-producing countries are finally able to reach an effective and long-lasting agreement on withholding production. This has nevertheless only limited influence on oil and gas prices because consumption in many net-importing countries decreases due to technological advances and a shift to alternative energy sources from the 2020s onwards. While North America becomes increasingly energy self-sufficient, Europe, India, and China benefit from the détente, which allows them to consolidate their security of supply, for example through the diversification of gas imports. Growing fossil fuel demand in Sub-Saharan Africa is the main counterbalancing force against this trend in the first decade of the outlook period, driven by fast economic growth as well as rising demand for transport fuels.

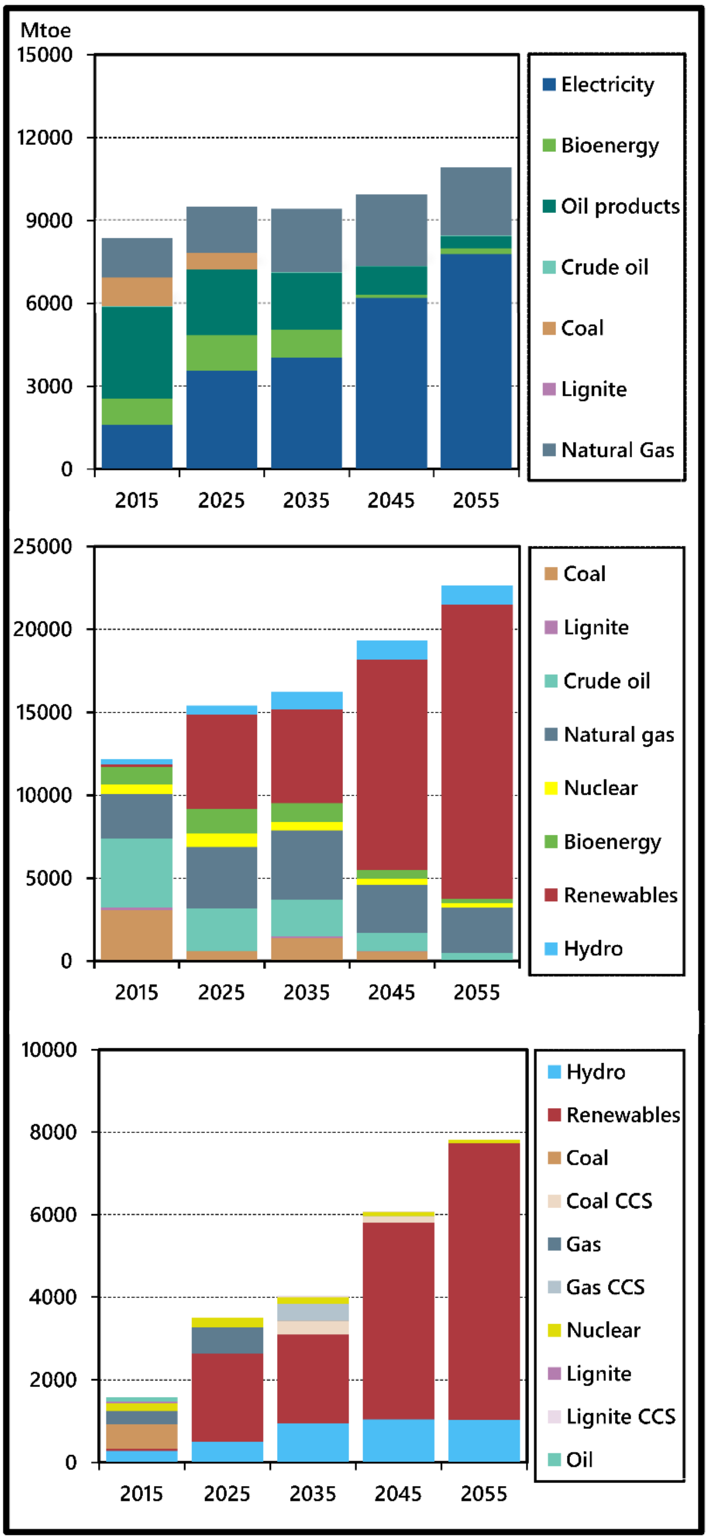

Figure 5: Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Green Cooperation

With security and economic concerns diminishing, internationally coordinated efforts towards climate change mitigation gain momentum. The 2015 Paris Agreement is upheld, and the emission reduction targets are tightened in the 2020s. The first half of the 2020s furthermore sees a paradigm shift, so that decarbonisation and poverty alleviation are increasingly considered as dual objectives. Also, national economies become increasingly interconnected, thus allowing for better-integrated energy systems and greater international cooperation on mitigation measures overall. Throughout the 2020s, this new dynamic contributes to the fast dismantlement of fossil fuel subsidy programmes as well as to a linkage and expansion of emission trading schemes, thus allowing for an increase in climate policy ambition and a reduced cost of emission mitigation in the following decades.

As a result, decarbonisation policies support innovation and sharp decreases in costs for renewables, and their fast deployment leads to a successive phase-out of fossil fuels. In the 2030s, the global electricity mix is coal free and dominated by renewables, which have been the focus of public and private investment as opposed to CCS technology. However, CCS only plays a temporary role by extending the phase-out of fossil fuels into the 2040s. The use of oil products is substantially decreased as well, in particular due to strong policies that push towards an early transition of the transit sector.

3.3.2 The future of green synergies

While the role of central governments remains crucial for the global energy transition in the next decades, more and more solutions are being put forward through other channels, involving not only the private sector but also transnational bodies, cities, and consumers. The global transition, therefore, lives off synergies that are reached by combining top-down approaches, mostly in the form of strict carbon taxation and green subsidies, and bottom-up action from all actors. For transition economies, the scenario foresees an increased role for multilateral development banks and micro-finance programmes. Ensuring near-universal energy access under clean standards becomes a focus of these initiatives for much of rural Africa and South-East Asia, where, despite a reduction in conflicts, state capacity remains limited. Distributed generation and decentralised renewable energy solutions leapfrog the slow-moving deployment of centralised power and rapidly accelerate energy access. As a result, infrastructure, private sector investment, and productivity improve quickly from the mid-2020s onwards in the Global South. Generally, there is less need for energy infrastructure (expansions) in this scenario due to the substantial success of energy efficiency efforts in all energy consumption sectors compared to the Business as Usual scenario. Therefore, despite rapid population growth, final energy consumption first plateaus in the 2030s. Subsequent increases are of only a modest nature and covered almost entirely by growth in clean electricity, which largely dominates the global energy mix in the 2040s.

Prosumers gain importance and consolidate the image of responsible citizens, thanks to matured decentralised system designs, the availability of microfinance in developing countries, and policy support schemes, as well as harmonised legal frameworks. Hence, in the 2020s and 2030s, prosumers become a key driver of the Asian energy transition and contribute to the switch away from dirty electricity sources in other fossil fuel-dependent regions.

Finally, the interconnectedness of economies and the political support for a global energy transition lead to an acceleration of the integration of national energy agendas. Early progress towards a global carbon tax is made in the early 2020s and initially only ratified by a handful of nations. However, the group widens quickly and includes all major emitters by the 2030s.

The scenario period witnesses an intense urbanisation process, both in the Global South and in OECD countries. However, energy efficiency efforts are sizeable, and much of the energy demand in the urban buildings and transport sectors is met by clean solutions, thus avoiding a lock-in of carbon-intensive infrastructure in developing regions. In many growing cities, urban density enables the integration of district heating and cooling networks fuelled by low-carbon energy sources or waste heat from industrial plants. New building materials, which are the result of the large-scale support for R&D, allow for the construction of new megacities without a large carbon footprint.

As low-carbon urban mobility becomes a top priority, electric vehicles take over the streets in the 2020s, but large investments in new and innovative modes of mass public transit prove the only way to manage the quick growth of cities sustainably. Major cities, therefore, push towards bans or strong restrictions on private car traffic, which are welcomed by their inhabitants.

This is part of an overall shift in individual behaviour which results from a symbiosis of policy, culture, and technology. Progressive cities welcome the international climate efforts and vie in the creation of green urban ecosystems whose leitmotif is the urban oasis: a modern and efficient yet green utopia. The rapid improvement in living conditions, especially in areas that observed high rates of air pollution, seizes citizens' imaginations and improves public awareness of environmental issues drastically. With the change in generations, a close-to-zero-emission environment becomes the *status quo* in most developed countries. Some latecomers still exhibit higher emission levels but pledge improvements beyond 2050. Increased specialisation, lower risk, and large public programmes lead to a culture of investment and research which allows progress in numerous key technologies that enable an affordable transition to this clean, modern vision, such as 3D and 4D printing, novel materials, and quantum computing.

Thanks to early, widespread, and deep emission mitigation, climate change only has localised impacts in the medium run, to which the international community reacts promptly with financial and technological transfers and adaptation measures. By 2050, all these factors combined will have led to the achievement of an inclusive renewable energy transition, which prevents extensive global warming. In combination with further advances in negative emission technologies beyond 2050, green growth has become a reality.

3.4 ClimateTech

3.4.1 Time is on my side

Similarly to the Business as Usual scenario, diplomatic relations between the large regional powers remain steady over the outlook period of this scenario. Geopolitical tensions and localised conflict in the late 2010s and 2020s worsen human and economic conditions across the globe. The international governance system comes to a standstill at the turn of the 2020s at the expense of climate and energy issues, in part due to the failure of any major actors to take the lead in multilateral, rule-based (international) institutions.

However, and at the same time, research into climate intervention shows promising results, so technologies such as carbon capture and storage (CCS) and solar radiation management see their performances increasing while costs are cut. Although these technologies are still at an early stage of development in the 2020s, their perceived benefits alone significantly affect climate policy in the following years. News of the forthcoming technical revolution generates an atmosphere of public euphoria that is fortified with the widespread perception that climate questions are already solved.

Although not seconded by scientists, politicians rejoice in the diminished pressure to decarbonise their respective economies and divert political effort to other topics such as economic growth. Therefore, the global economy remains strong over the entire outlook period, accompanied by significant worldwide population growth in Africa and South-East Asia. However, economic development remains unequal, due to an international order that continues to be tense and does not provide a vital setting for balanced free trade and technology transfer. Despite the loss of focus on climate policy, environmental policy becomes important as public health is another topic rejuvenated by a public that expects a transition to a clean lifestyle.

The loss of momentum in decarbonisation policy making combined with the frustration of diplomatic relations between the large global powers affects international climate negotiations. While the Paris Agreement leads to a deceleration in fossil fuel consumption growth until 2035, progress soon slows down, as the initially formulated NDCs are not followed by more ambitious pledges. This failure in emissions reduction is also due to rapidly rising energy demand driven by population growth and urbanisation. Some isolated attempts at climate change mitigation in the first half of the outlook are, however, noteworthy: Europe scales up its ambitions, and China exploits the tech dawn to finally move beyond the production of cheap tradeables. On this course, China redefines its comparative advantage and is determined to take the global lead as an R&D powerhouse.

A Business-as-Usual world with the (absent) climate policy of Survival of the Fittest and technological ambitions beyond Green Cooperation establishes an energy system that exhibits a steep growth in demand, rapid technological change, and uneven developments. Throughout the first half of the outlook, strong gains in fossil fuel demand nearly double final energy consumption, and medium-paced growth in the electricity sector comes with new renewables and conventional plants alike. As a result, GHG emissions increase dramatically and exceed the Business as Usual case dramatically. With internationally concerted efforts to tackle CO_2 emissions facing a dead end, the 2°C carbon budget is nearly spent by the early 2030s, thus inducing more frequent extreme weather events.

3.4.2 A tale of sulphates and nucléocrates

Final breakthroughs in key climate and energy engineering technologies in addition to various forms of geo-engineering are seen in the 2030s. However, these adolescent technologies still teeter into the wider energy system on their quest for an ultimate role.

First, direct air capture witnesses sharp cost cuts due to the development of modular units that enable quick deployment. Although initially the efficiency and applicability of the technology is still limited, direct air capture soon becomes the symbol of omnipresent action to tackle emissions, as the (now smaller) devices are installed virtually everywhere. Air capture is furthermore favoured by decision-makers for its ability to capture not only emission flows but also stocks. The social acceptance of underground CO_2 storage comes hand in hand with the air capture technology development, as the rapid development of commercial CO_2 use, in particular in the chemical industry takes place.

A second key technology, solar radiation management (SRM) receives a spike in attention during the 2030s. In the public eye, the technology is celebrated as the liberator of humanity from climate change due to its potential to have a large and lasting effect on emissions. Nevertheless, after a multitude of tests during the first years of its availability, scientists begin to warn that SRM, and more specifically aerosol sulphate, may deplete ozone and bring significant changes to the hydrological cycle. While these warnings are initially unheeded by politicians, the effects become discernible and measurable, affecting nearly all kind of maritime value creation. Also, specific SRM techniques threaten to be developed into weapons, thereby violating the 1976 Environmental Modification Convention. As a result, the unilateral use of SRM is eventually prohibited and only scaled up slowly within multilaterally concerted initiatives.

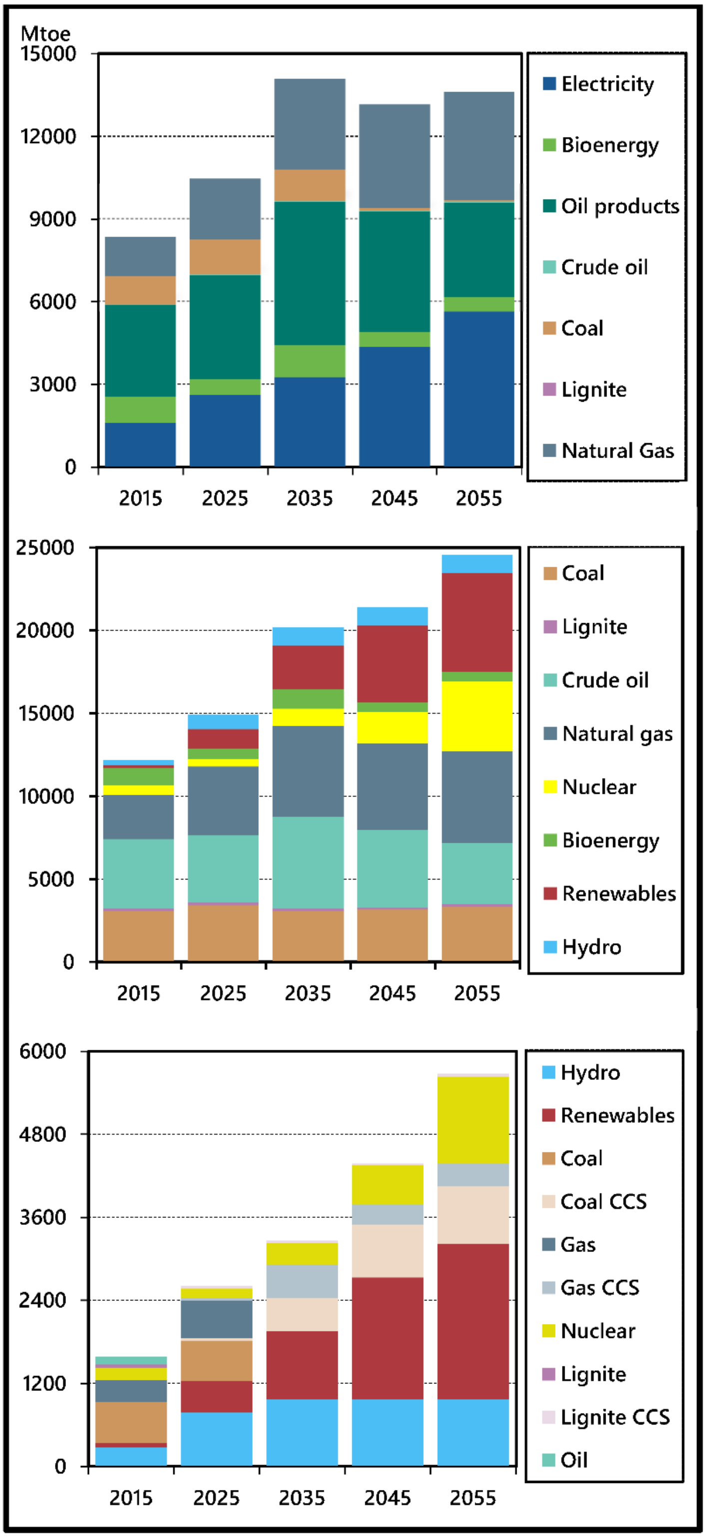

Figure 6: Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in ClimateTech

To control the risks associated with the novel technologies, new institutional frameworks for international cooperation emerge. Novel multilateral funding sources, such as development banks for supporting improvements in climate engineering, are created within the framework of the UN, whose political influence decreased significantly over the previous decades. At the same time, a new intergovernmental body, inspired by the International Atomic Energy Agency, is founded to promote the safe use of climate engineering and provide international safeguards against its misuse.

As climate engineering affects emissions but ultimately falls below the enormous initial expectations, the reopened discussion about climate change mitigation sheds light on the elephant in the room: Energy consumption has risen at a pace that the still-incipient climate technologies fail to compensate. However, increasingly extreme weather events and widespread coverage of the rise and fall of hopes for adaptation-based solutions have created a broad awareness of climate change. Therefore, the re-empowered international community manages to commit to a global CO_2 cap. However, numerous exemptions are given and remain a common practice because of fears for national industries and the presence of emission reduction technologies. Nevertheless, the energy system in the 2040s experiences a reduction in fossil-fuel consumption and witnesses the death blow for direct coal usage, though natural gas and crude oil remain crucial in the final energy mix. Priority is given to completing the decarbonisation of electricity.

One of the technologies that sees sudden advances is nuclear fusion. Although, particularly during the 2030s, the technology's value is questioned due to high costs, its promise to break the energy trilemma by providing affordable, secure, and clean energy in the long run is a tempting vision. Especially China, which is responsible for much of the research during the 2020s that finally leads to a breakthrough, is set to supply the majority of its exponentially growing electricity demand with nuclear fusion. The decision to go all-in on this technology is, in the early stages, mostly aimed at turning it into the greatest Chinese export. Its mesmerising effect on politicians creates a new generation of nuclear advocates who seek to pressure the "new saviour" of energy and climate into global power grids at any cost. However, the 2030s see virtually no application of the technology outside of China. Finally, towards 2050, more mature reactors are installed in other energy systems, despite continued controversies regarding their actual potential. However, outside of China, whose nuclear elite refuses to question the technology, applications remain limited.

Elsewhere, cost cuts and novel technologies turn renewables into the major source of electricity with a global share of roughly 50%. The other half of electricity demand is met by nuclear energy and highly efficient CCS coal and natural gas power plants, which profit from strong R&D investments even after their mature emergence around 2030. As a result, over all five decades of the outlook, there are only minor changes in global fossil fuel production except for a surge in the production of natural gas.

Altogether, the numerous breakthroughs – a consequence of both fortune and significant investments – buy time and lessen the burden of the energy transition, but eventually both decarbonisation and adaptation measures are necessary. The resulting system succeeds in curtailing emissions and in preventing large scale climate catastrophes. Nevertheless, the negative emission technologies fail to provide a robust counterweight to the lagging decarbonisation and lack of behavioural shifts. Hence, the emission trajectory is inherently fragile concerning population and economic growth beyond the outlook period. This world can only be sustainable if technological progress continues to outrun growth.

4 Analysis of the global level

The comparative assessment of emissions, energy service consumption, and electricity generation (Figure 7) shows discrepancies but also similarities between the four scenarios.

The four trajectories of final energy consumption show a substantial divergence, with only modest increases in Green Cooperation, a stagnation of demand starting in 2025 in Business as Usual, and strong increases in ClimateTech and Survival of the Fittest. The two latter scenarios outgrow Business as Usual in terms of energy consumption by twofold in 2035 and 2045, respectively. Energy demand in ClimateTech is then disrupted by the shift towards stricter climate policies. In contrast, energy consumption growth in Survival of the Fittest is only brought to an end by the global collapse induced by the climate catastrophe.

More homogenous development occurs for in electricity sector, albeit with some variation. All scenarios witness a large increase in power demand by 2035 that exceeds a 50% increase compared to 2015 and even reaches a fourfold increase by 2045 in Green Cooperation. In the 2020s, all four scenarios still lie in a similar range and experience a – more or less pronounced – first wave of electrification of the economy. Then, however, the gap between the scenarios widens. In Green Cooperation, the green transition moves beyond energy and merges with a holistic change in technology and society into a *smart world*. Survival of the Fittest sees the second-largest increase in power demand (before its eventual collapse) which, however, is the outcome of absent energy efficiency measures and unlimited growth. This suggests that the electrification of the economy – sometimes understood as an indicator of how well energy transition and climate change mitigation succeed – may be misleading in this regard. Business as Usual and ClimateTech show somewhat lower electricity growth at first, although slow system decarbonisation and new technologies lead to higher growth rates towards the end of the scenario period for the latter.

CO_2 emission trajectories reveal deeper insights. The quick global shift towards (green) cooperation in the corresponding narrative results in a U-turn for CO_2 emissions, which have their largest drop during the 2020s. Despite later increases in energy demand, emissions fall continuously and reach approximately 20% of today's levels by 2050. Negative emission technologies do not play a major role in this scenario. On the other end of the scenario spectrum, the rampant growth of (non-clean) consumption leads to emission peaks that outsize current emissions by more than 60% in Survival of the Fittest. In this scenario, isolationism and the meltdown of the global order work as catalysts for climate change that accelerate the path towards a climate catastrophe of unparalleled extent.

For Business as Usual and ClimateTech, the (net) CO_2 emission trajectories are less self-explanatory. Stagnating energy demand and meagre, apathetic decarbonisation efforts prevent further escalation of emissions but fail to yield substantial reductions. Hence, Business as Usual can be understood as a postponed Survival of the Fittest, where energy production patterns and cumulative emissions are on a pathway to exceeding the 2 °C target towards the end of the scenario period and a sustainable solution remains out of sight. Despite the surge in consumption, emissions in ClimateTech only rise modestly until the 2020s and see sharp cuts afterwards. This is first a result of the large-scale deployment of negative emission technologies (that account for roughly one-third of emission reduction), but is also an outcome of the powerful advances made towards low-carbon electricity generation in later years. Although the scenario fails to decarbonise final consumption, the enhanced technology portfolio succeeds in achieving an almost CO_2-free power sector until 2035. This is very much opposed to Business as Usual and Survival of the Fittest, which undergo some decarbonisation effort in the power sector but fail to achieve even this goal. Nevertheless, cumulative emissions in ClimateTech are far from the very low levels of Green Cooperation, and an emission path that stagnates at 50% of today's values may still fail to address the long-term climate needs adequately, especially given continued population growth.

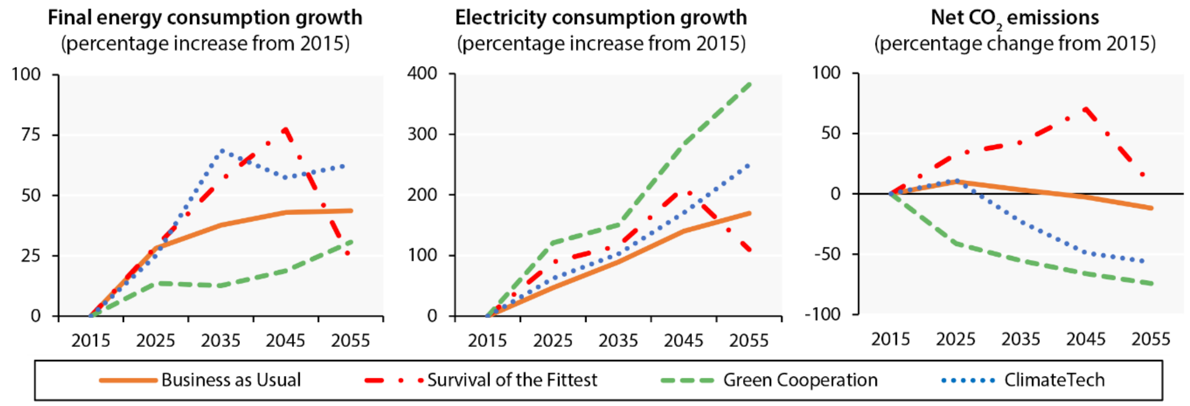

Figure 7: Final energy consumption (left), electricity consumption (middle), and CO_2 net emissions (right) as percentage changes from 2015 values compared between the scenarios

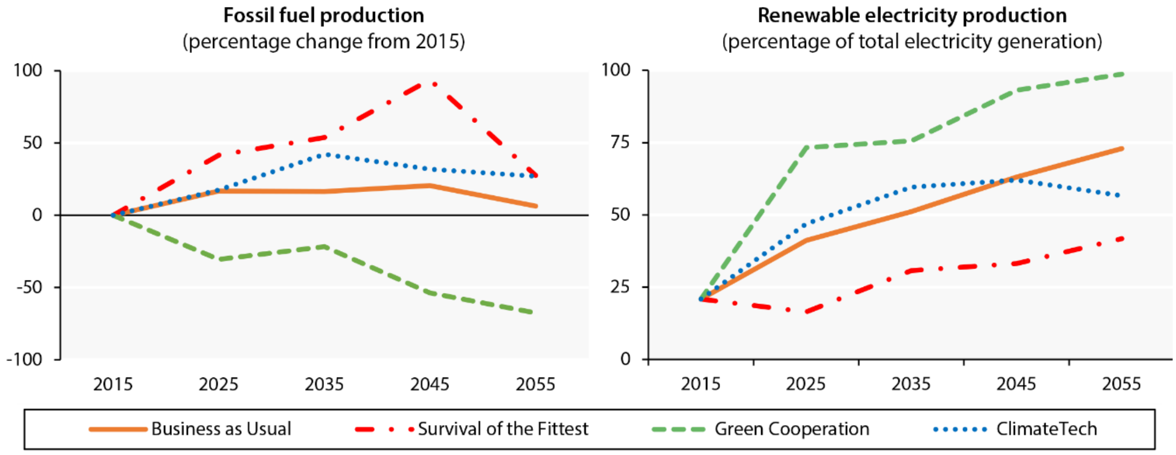

Figure 8: Fossil fuel production (left, as percent of 2015 values) and renewable electricity generation (right, as percent of total electricity) compared between the scenarios

Renewables take over massive shares of the electricity mix in all scenarios, but to varying extents (Figure 8). While Green Cooperation develops towards fully-renewable power generation by 2055, Survival of the Fittest sees the smallest share of renewable energy (which nevertheless reaches almost 50%).[2] Therefore, and similar to the conclusions on energy consumption, the share of renewables can be a misleading indicator when evaluating whether the world is on a successful path to climate change mitigation. Business as Usual and ClimateTech develop similarly, but low-carbon CCS plants and nuclear fusion technology in ClimateTech mean Business as Usual ultimately falls behind.

The development of fossil fuel extraction (Figure 8) gives a diverse picture of modest-to-substantial increases over time, while only Green Cooperation exhibits major cuts. However, even in this case, fossil fuels are only cut back to approximately 30% of current production, as natural gas fuels the hardest-to-electrify industries, and a small share of oil production also remains. In contrast, in Survival of the Fittest there will be a surge in the production of fossil fuels that reaches almost double the current production levels in the 2040s. ClimateTech produces more fossil fuels than Business as Usual due to the strong reliance on CCS and negative emission technologies that lead to higher fossil fuel reliance.

[2] The share of renewables is the only trajectory in Survival of the Fittest that seems unaffected by the global collapse; this is because the *fittest*, who survive in the eponymous scenario, eventually include large regions such as Europe and China, that invest large amounts in renewable technology long before the 2050s.

5 Regional analyses

The following section describes energy system figures for five selected key regions: Europe, the Middle East, North and South America, and Asia-Pacific. For each case, we provide numbers for final energy consumption, primary energy production, and the electricity generation mix.

5.1 Europe

Final energy demand in the European Union (Figure 9) shows only slight variation between the scenarios. In all cases, the outlook shows a modest increase in demand towards 2025 and a subsequent stagnation in Business as Usual as well as further minor increases for the other scenarios. The composition of demand does not exhibit large variation either: All scenarios foresee further electrification of demand. While electricity becomes the single most dominant demand component in Green Corporation, natural gas remains a significant source of energy, especially for transport and industry. Oil products are mostly phased out towards 2050. These developments are connected to both tougher climate policies, which are assumed for every scenario to varying extents, and the low opportunity cost for renewable energy in Europe.

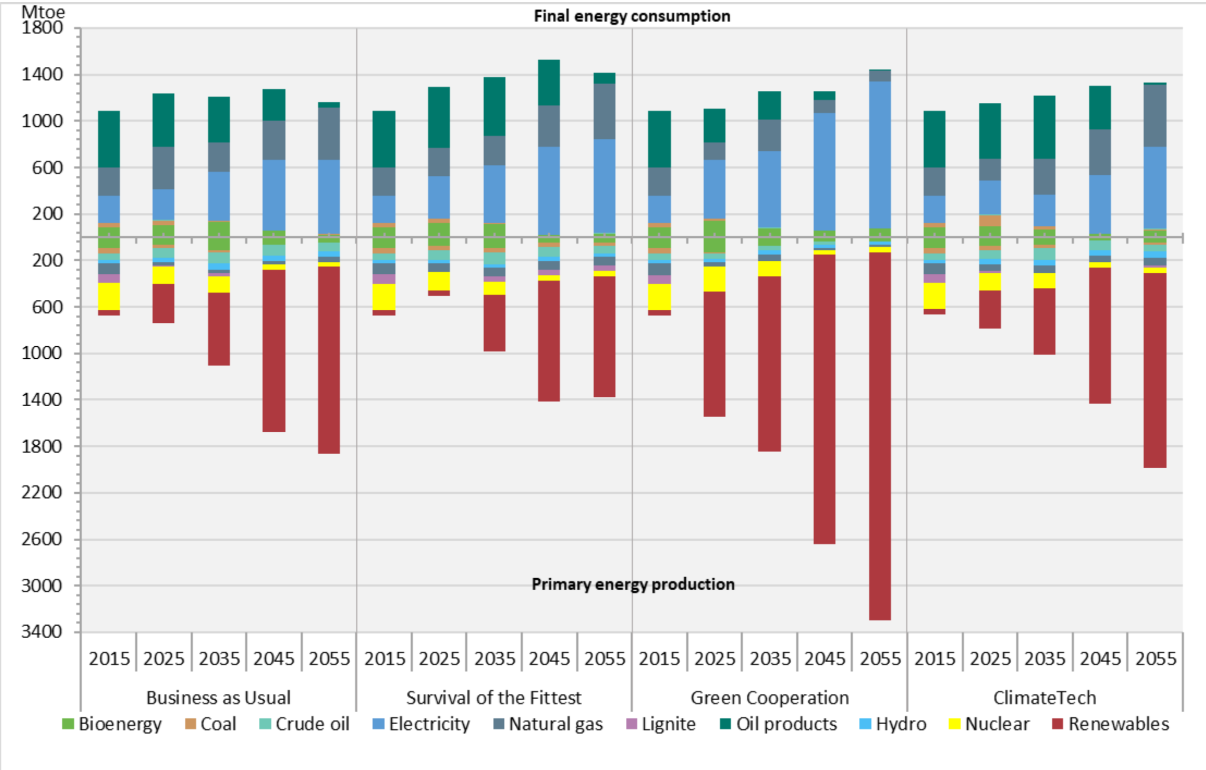

Figure 9: Final energy consumption (top) and primary energy production (bottom) for the European Union

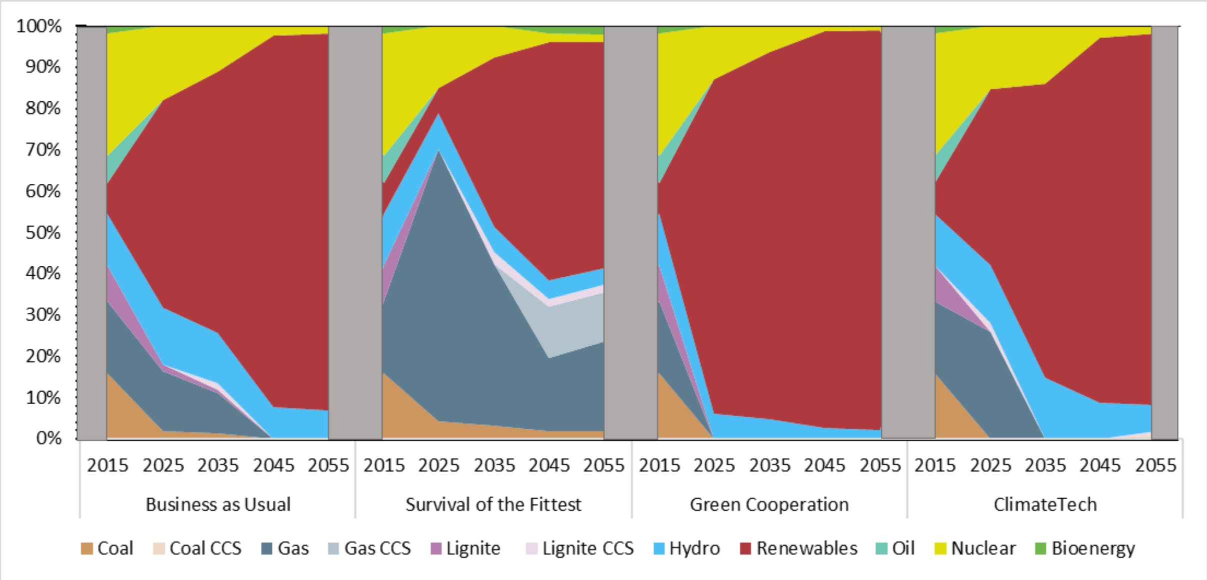

Figure 10: Electricity mix for the European Union in the four scenarios

Not surprisingly, a similar picture emerges for the power sector (Figure 10). All scenarios exhibit visible growth in renewable technologies and consider them the dominant technologies by 2055. The only exception is Survival of the Fittest, which balances between natural gas and renewables as main electricity sources. In all scenarios, electricity from nuclear power plants is gradually phased out; however, they are set to maintain a particular share of the power mix. This is mostly the result of existing infrastructure and political inertia (*la nucléocratie*).

5.2 Middle East

The scenarios foresee different changes in the magnitude of the regional energy demand (Figure 11), but no significant discrepancies in the very composition. All scenarios but Green Cooperation consider an increase in demand, reflecting (population) growth and urbanisation albeit virtually no integral policies to decouple either from energy demand. As discussed in the literature (Hochman and Zilberman, 2015; Zaklan et al., 2018), the vast reserves of oil make the region prone to a coupling of energy supply with demand. Whatever global markets would not purchase is used domestically; this is especially the case in ClimateTech. The only exception to this is Green Cooperation, which sees a rapid electrification of demand and energy-saving measures to decouple regional development from energy intensity. Natural gas consumption increases considerably in all scenarios.

Crude oil production dominates primary energy supply from the region in all scenarios but Green Cooperation. However, the scenarios show almost no significant increases. To the contrary, natural gas production accelerates quickly in all scenarios but continues to stay the smaller of both industries. Renewable energy production only reaches significant values towards the 2050s in Business as Usual, and from the 2030s onwards, in Green Cooperation, where it replaces much of the crude oil supply.

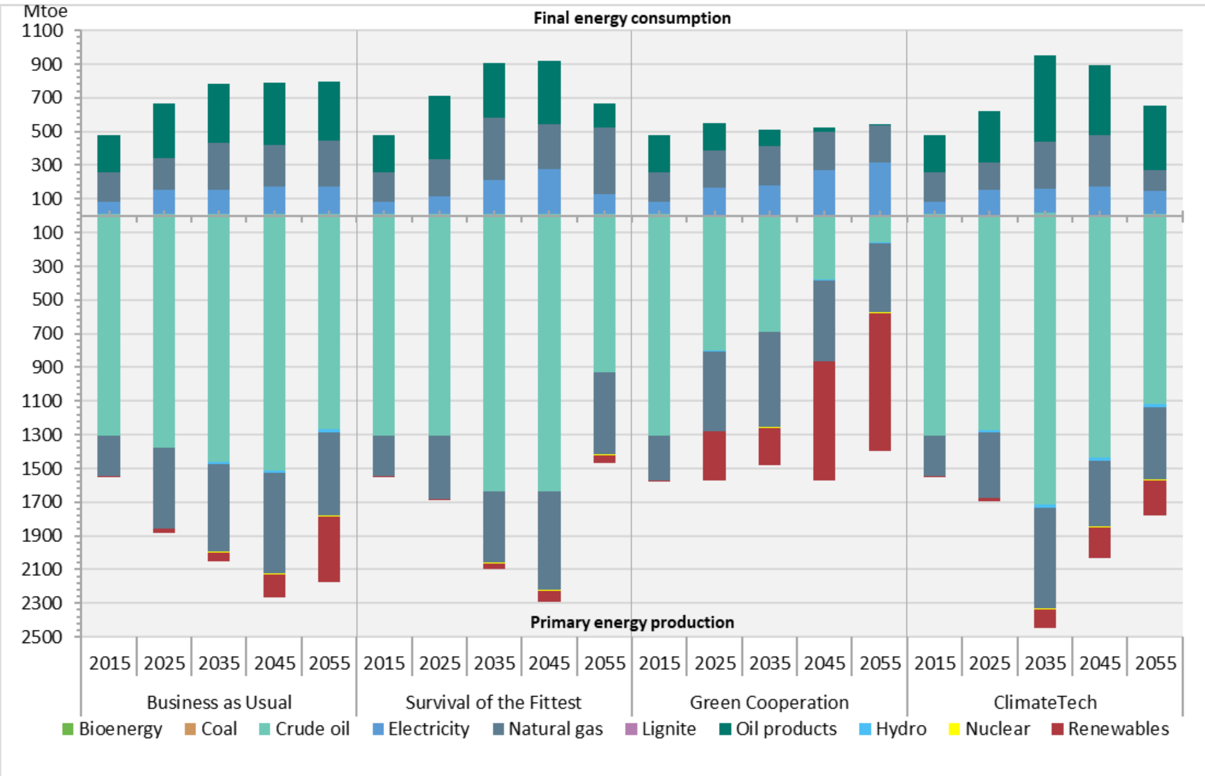

Figure 11: Final energy consumption (top) and primary energy production (bottom) for the Middle East region

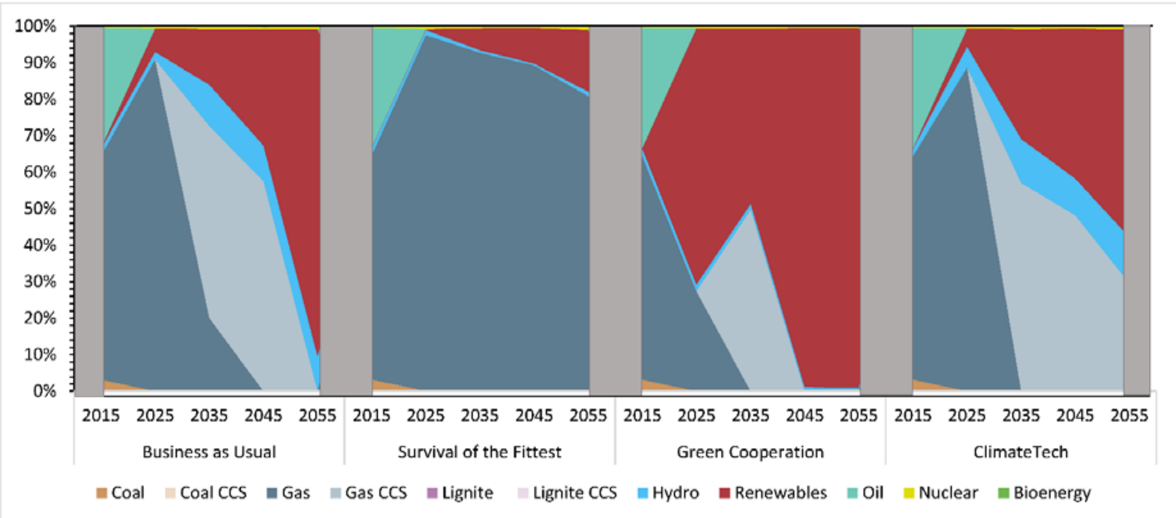

Figure 12: Electricity mix for the Middle East Region in the four scenarios

Regarding power generation (Figure 12), the variation between the scenarios stays limited. Oil-fired stations are phased out in all scenarios by the mid-2020s for economic reasons. Their replacement, however, are natural gas plants in all scenarios except for Green Cooperation, which sees a quick shift to renewables. In Survival of the Fittest, conventional natural gas continues to produce more than 80% of electricity even towards 2055, while Business as Usual and Climate Tech see a shift towards CCS-powered gas plants in the 2020s and 2030s, in addition to a large deployment of renewable energies towards the end of the outlook.

5.3 South America

Final energy demand in Latin America increases (Figure 13) in all scenarios towards 2025 but shows different trajectories for the years to come. Business as Usual foresees a stagnation of demand and a substitution of biomass consumption with electricity, while Survival of the Fittest and, even more, ClimateTech consider a quick acceleration of energy demand. Especially in ClimateTech, the direct usage of (domestic) oil products for the growing industry shapes this pattern. Nevertheless, the increase in electrification is visible in all scenarios. Overall, the region shows some of the clearest differences between the scenarios, which is largely connected to its status as an emerging region. In Survival of the Fittest, the region fails to secure its place among the fittest nations, and it perishes in large-scale natural catastrophes and intracontinental wars over remaining resources. In ClimateTech, however, the region grows at an uncontrolled pace, driven by the proliferation of (energy) technology.

However, the South American power sector (Figure 14) witnesses neither much change nor variety: In all scenarios, hydropower continues to be the dominant source of electricity. In almost all scenarios, hydro energy is aided by renewables (most noticeably in Green Cooperation, where they outgrow hydroelectricity towards 2050). In Survival of the Fittest, however, conventional coal and, to a lesser extent, gas supply nearly half the power sector in the mid-run). ClimateTech and Green Cooperation, instead, exhibit some CCS-based supply in the mid-term, and Business as Usual contains a phase-out of coal and gas, while some bioenergy plants are added in the 2040s.

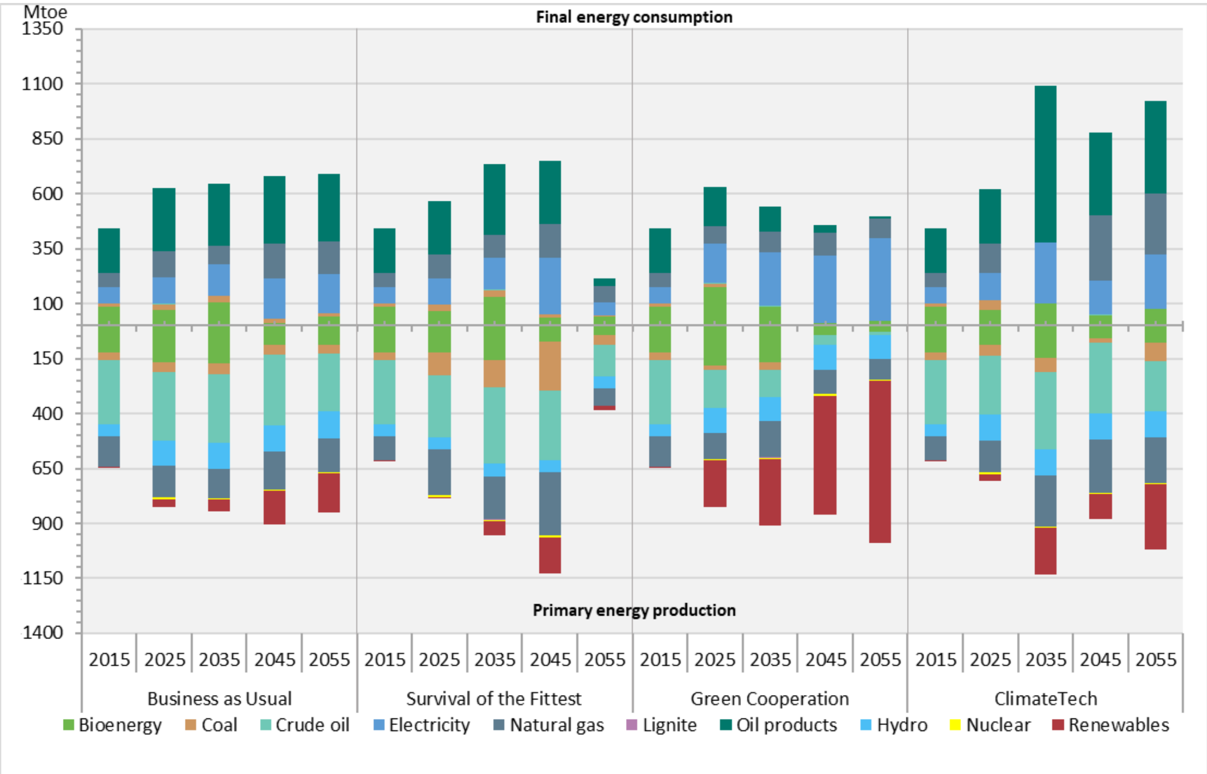

Figure 13: Final energy consumption (top) and primary energy production (bottom) for Latin America in the four scenarios

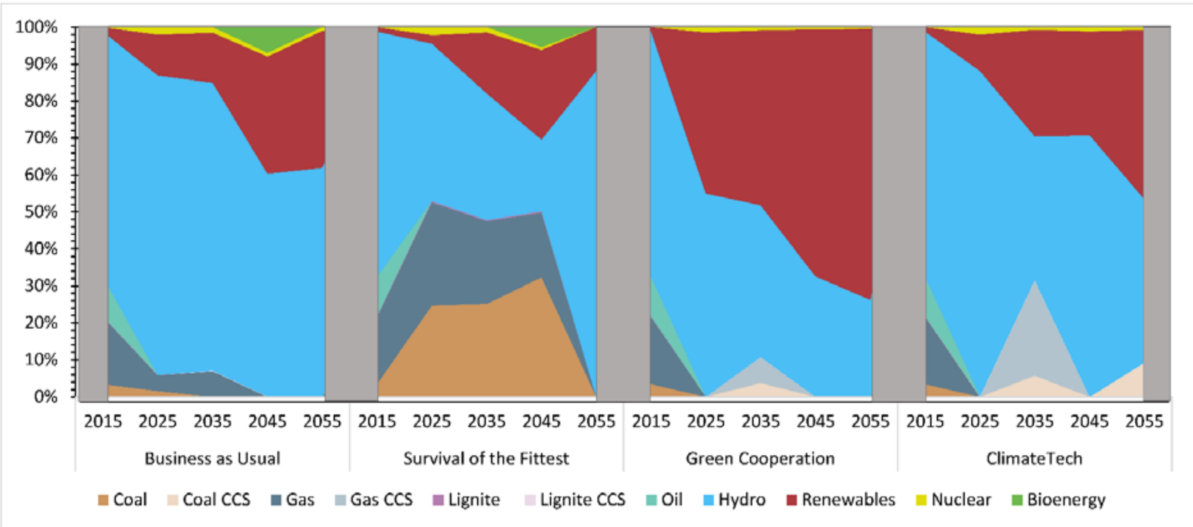

Figure 14: Electricity mix for Latin America in the four scenarios

5.4 Asia-Pacific

Energy demand in the Asia-Pacific region varies considerably between the four scenarios. In Business as Usual and ClimateTech, final energy demand increases steeply towards 2035 but stagnates afterwards. In the latter, however, the share of electricity outgrows the other sources.

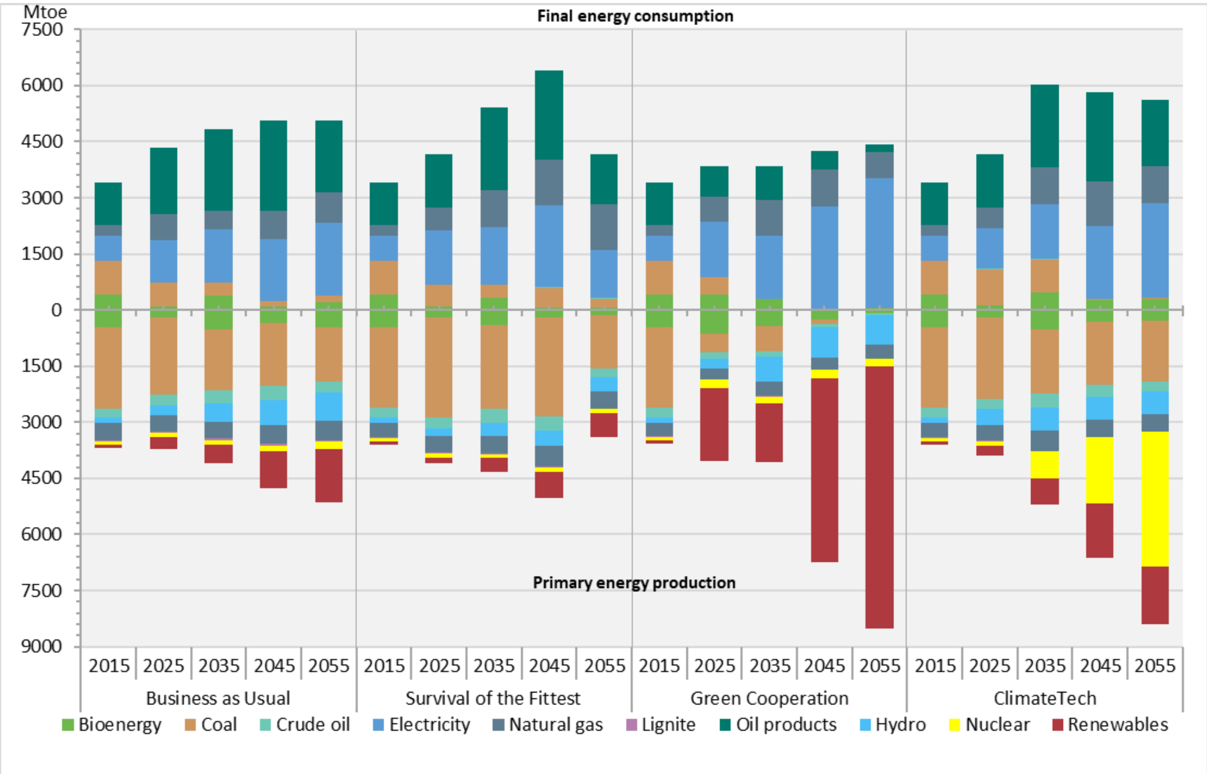

Figure 15: Final energy consumption (top) and primary energy production (bottom) for Asia-Pacific

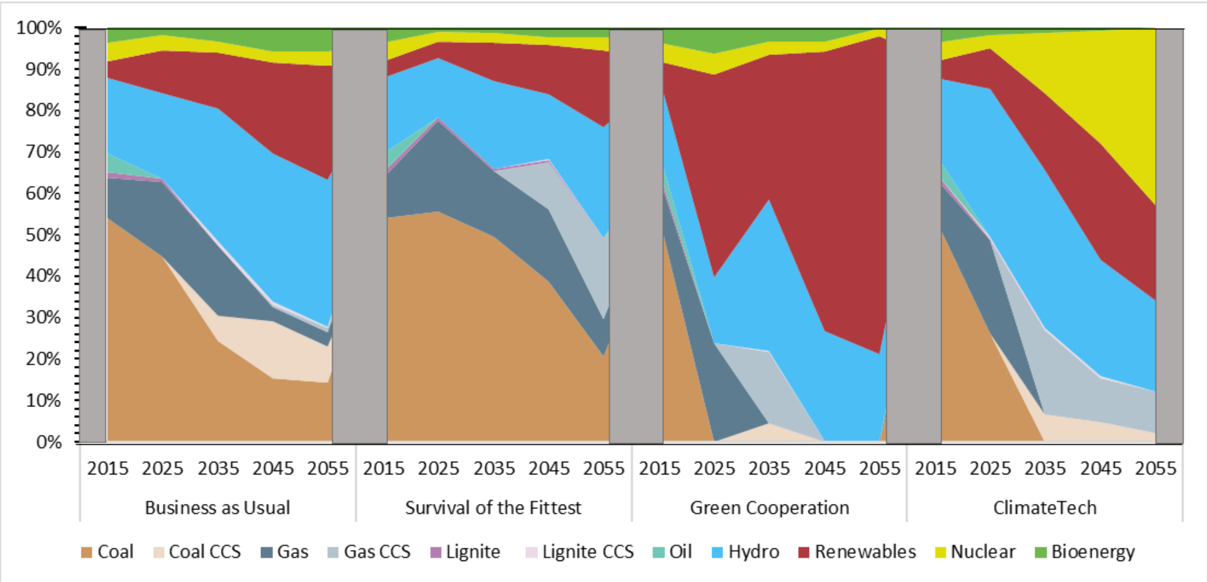

Figure 16: Electricity mix for Latin America in the four scenarios

In contrast, energy demand in Survival of the Fittest keeps growing until 2045, when coastal areas are entirely flooded, causing a noticeable drop in energy demand. Energy demand growth in Green cooperation occurs only moderately. Coal demand is phased out until 2030 in Green

Cooperation, whereas (industrial) coal consumption continues in Business as Usual and Survival of the Fittest even towards 2055.

Energy production, in contrast, shows a different picture. In all scenarios but Green Cooperation, coal production is mostly stable over the whole outlook, and there is virtually no change in the production of natural gas or crude oil. In Green Cooperation, renewable energies take over energy production. In ClimateTech, instead, Nuclear Fusion makes substantial gains from 2035 onwards.

Asia-Pacific exhibits a more diversified electricity generation mix than other regions, especially in Business as Usual and ClimateTech. CCS technology is crucial in the future power mixes for coal and gas; the only exception is Green Cooperation, which goes approx. 95% renewable. Conventional coal power only remains in the power mix of Survival of the Fittest (which foresees renewables and hydropower reaching only 30% of total power generation), and it is phased out in Green Cooperation by 2025. Nuclear power remains present in all scenarios, but most noticeably in ClimateTech.

5.5 North America

Energy demand in North America (Figure 17) continues to grow with a slow pace in all scenarios except for Survival of the Fittest, where total demand increases considerably. Business as Usual and Survival of the Fittest show almost no changes to the composition of final energy demand, while Green Cooperation and ClimateTech envision gains for electricity.

On the production side, crude oil and coal remain integral outputs of the North American economy. In Survival of the Fittest, US-American natural gas production outgrows the other industries. In Green cooperation only, all fossil industries grow back, and renewable energies take over. However, even in this setting, some residual oil and gas output remains in North America.

Power generation draws a similar picture. All scenarios but Green Cooperation exhibit very high shares of coal power even towards 2055 (however as CCS plants for the case of CliamteTech). Similarly, the share of renewable energies grows in all scenarios but exceeds 30% only in Green Cooperation.

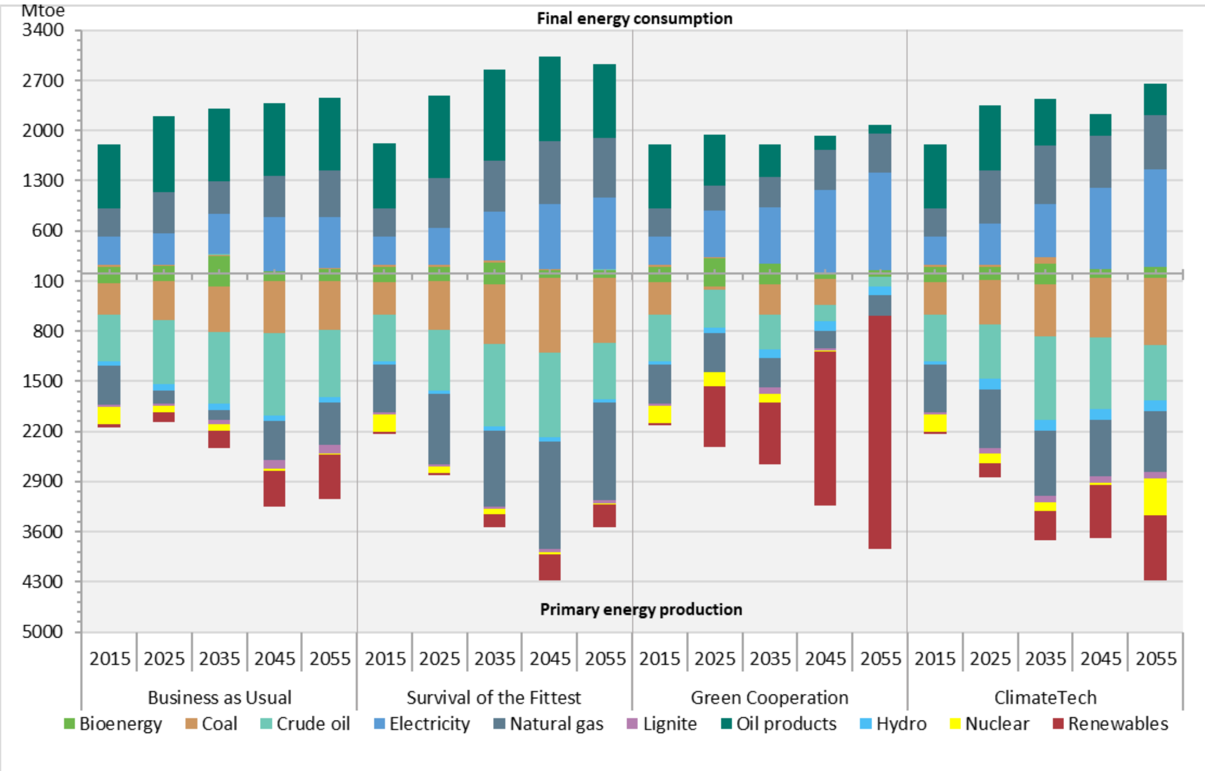

Figure 17: Final energy consumption (top) and primary energy production (bottom) for North America

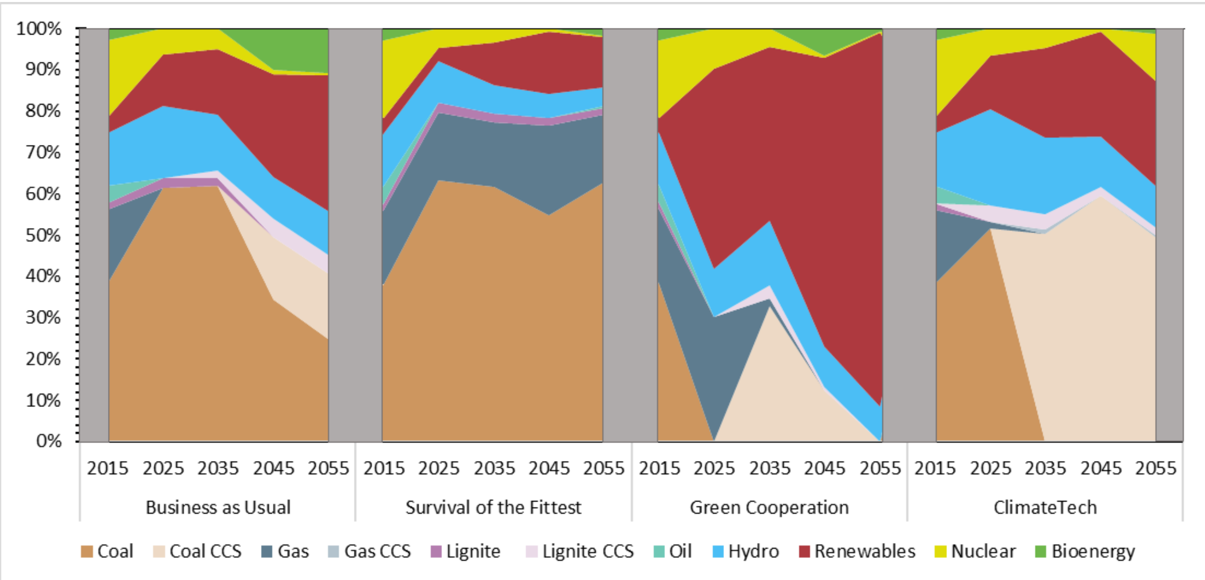

Figure 18: Electricity mix for North America in the four scenarios

6 Indicators

Indicators help identify each scenario and can be signals for which scenario eventually develops. They can "evaluate change over time", and have "diagnostic power" (Heuer and Pherson, 2015, p. 135). Indicators are unique and detectable manifestations for each narrative and can thereby serve as transparent early-warning signals for observers.

Table 1 contains carefully chosen qualitative indicators in different dimensions. Additionally, Figure 19 displays several quantitative indicators. Decision-makers and analysts can use these indicators to monitor the situation and detect which of the four narratives eventually unfolds.

The number of indicators for Survival of the Fittest and Green Cooperation is eventually higher, as the worst and best case have more unique identifiers than the Business and Usual and ClimateTech scenarios. The latter pair share a similar background, with the exception that ClimateTech includes a surprise event at the beginning of the period. Therefore, the number of unique identifiers for them is lower.

Table 1: Qualitative indicators for all four scenarios by dimension

Business as Usual	**Survival of the Fittest**	**Green Cooperation**	**ClimateTech**
		Social dimension	
Non-climate issues dominate the social discourse despite a general awareness of the climate crisis.	Climate change denial is omnipresent and echoed by many governments	Societies push towards decarbonisation and "green modernity", including significant lifestyle changes in the 2020s.	Climate targets are discussed mainly from a technology perspective
Social incohesion is a recognised issue but attempts to tackle it fail.	Xenophobia, chauvinism, and repressions against dissidents become widely accepted.	Increased social cohesion on a national and global level.	Social cohesion increases only on a national level.
		Technological dimension	
Innovations are not focussed on particular technologies but diverse and competing (Figure 19 panels I-L).	Increased innovations in fossil technologies (extraction, combustion, chemical use) (Figure 19, panels I-L)	Numerous innovations to implement and operate the circular economy, including new materials	Promising and sudden advances in novel energy and climate engineering (esp. CCS and negative emissions)
	Continued improvement of fossil fuel reserve exploration (Figure 19, panel K)	Energy innovations are limited to clean technologies (Figure 19, panels I-K)	High rate of innovation in various technologies (Figure 19, panels J and I-K)

	Mostly state-driven innovation to sustain energy security and revenues	Multinational, market-driven innovation incentivised by focussed global support schemes	
Economic dimension (incl. energy and resource markets)			
Coal phase-out in the 2030s in Europe, but not globally (Figure 19, panels D, G)	No coal phase-out (Figure 19, panels D, G)	Global coal phase-out in the 2020s (Figure 19, panels D, G),	(Coal) CCS plants substituting conventional power plants
Continued sophistication and diversification of the energy mix with dirty and clean sources (Figure 19, panels F, G)	Fossil fuel production is nearly doubled by 2040 (Figure 8)	Quick switch away from fossil fuels to renewables, especially in power (Figure 8, Figure 19, panels F, G)	Large-scale introduction of novel technologies such as nuclear fusion and direct air capture
Continued moderate growth in international trade	Policy-driven decline in international trade (tariff and non-tariff barriers)	Consumer-driven decrease of trade in goods (digitalisation and localisation of economies)	Promotion of trade in high-tech goods
	Escalating waste problems in the 2030s	Circular economy realised across all sectors during the 2030s	
	High and increasing global inequality (economy-wide)	Parallel advances in universal energy access, poverty eradication, and decarbonisation	
		Large role for decentralised energy	
Military and security dimension			
Current tensions extend beyond the 2030s but do not escalate.	Intensification and expansion of current conflicts	Quick de-escalation of major conflicts and tensions in the 2020s	Climate (engineering) enters military agendas
	Regional alliances and hegemons supersede global alliances (e.g. NATO)	Further globalisation of alliances and focus on conflict de-escalation	
	Escalating and frequent immigration border crises	Increasingly open borders, yet decreasing migration due to better conditions in the South	

Political dimension			
Private-sector interests constrain policy.	Authoritarian rule and isolationism become the status quo.	The policy process is inclusive and oriented towards (global) welfare, sustainability, and the long term.	Policy process increasingly dictated by technological requirements
Conflicts between different fields of policy (esp. social policy, economy, climate)	Policy-making pivots on few goals and the short term only.	"Unified wellbeing policy" replaces previously conflicting policy fields (e.g. economy, climate, society)	Industrial policy and climate policy merge increasingly.
		Abandoning of "materialist" metrics, including GDP	
Legal and institutional dimension			
Low (global) institutional innovation and change	Further regionalisation and divergence of institutions and legal systems (especially common law)	New forms of multilateral and multi-level cooperation regimes emerge in the 2020s (e.g. international cooperation of sub-national entities such as cities)	New institutions are created to internationally manage the use of novel (geo-engineering) technologies.
	Polycentric institutions	Focus of state institutions on environmental law	Focus on the sophistication and enforcement of technology law (esp. patents)
Environmental dimension			
GHG emission rates are largely constant over time at 2015-2020 levels (Figure 7, Figure 19, panel H).	GHG emissions rapidly escalate from 2025 onwards (Figure 7, Figure 19, panel H).	GHG emissions growth is stopped in the early 2020s and falls afterwards (Figure 7, Figure 19. panel H)	Moderate decrease of emissions, focus on negative emission technologies (Figure 7, Figure 19,panel H)
Climate disasters increase but do not lead to a global disruption by 2050.	Climate catastrophes destroy much of human civilisation around mid-century	Climate damage is localizsd and can largely be managed with adaptation measures	Climate disasters occur in the 2020s but do not increase in frequency or magnitude subsequently
	Climate policies only in Europe and China	Introduction of a global carbon tax	
Cultural dimension			
Urban and rural culture further diverge	Regional convergence of cultures	Cooperative decision-making on all levels (subnational, national, supranational)	Openness to controversial technologies (e.g. CO_2 storage, nuclear energy, new technologies)

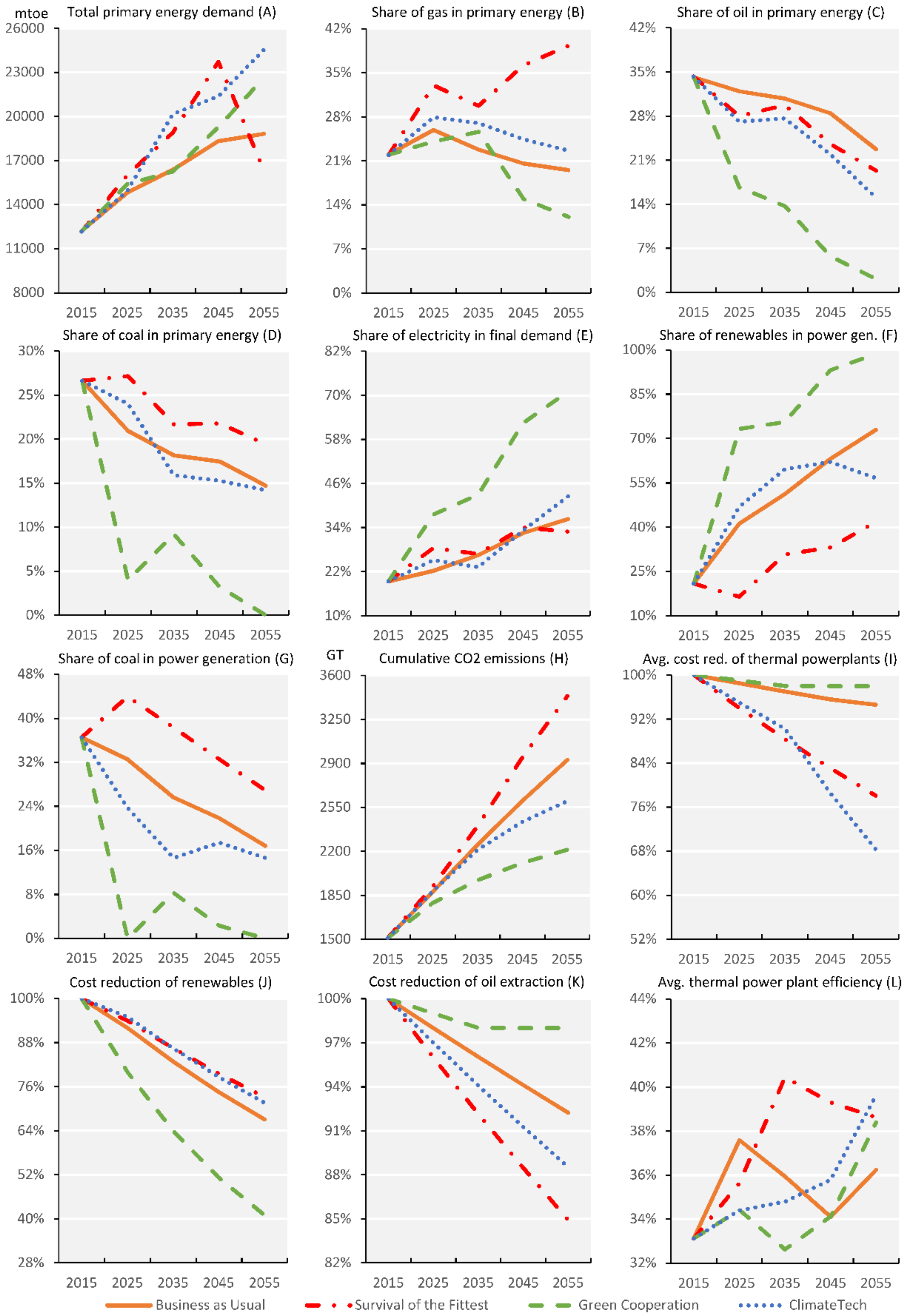

Figure 19: Quantitative indicators for all four dimensions

7 Outlooks compared

Energy scenarios have come a long way from their introduction in the 1960s, fighting their way into the very core of mainstream energy analysis. Several institutions, among them supranational bodies but also civil society organisations and private companies, prepare energy outlooks, which provide the basis for business and policy decisions. In recent years, scenarios also gained additional prominence in outlining possible paths to low-carbon futures and for monitoring the status of decarbonisation and climate change (Söderholm et al., 2011).

We use this section to provide a brief comparison of various prominent outlooks and to put our outlook into context. First, we consider the World Energy Outlook (WEO), which is published by the International Energy Agency (IEA) – an intergovernmental, public body established in the framework of the OECD – and arguably the most prominent energy outlook. We also consider the energy outlooks published by the World Energy Council (WEC), a global energy body with UN accreditation; the international oil companies Royal Dutch Shell, BP, Equinor, and ExxonMobil; as well as the research institution MIT; and the scientist-led civil society organisation Energy Watch Group.

- The IEA (2018) World Energy Outlook contains three scenarios: "Current Policies" and "New Policies", which assume a world with current and recently announced energy and climate policies, respectively, and "Sustainable Development", which assesses the pathway to universal energy access and climate change mitigation.
- Shell's scenarios – Shell (2013)'s "Ocean" and "Mountain" and Shell (2018)'s "Sky" – have dedicated storylines that feature detailed events and timelines on both global and regional levels. While Sky is a normative assessment designed to meet climate goals, Ocean and Mountain are positive assessments of the energy system.
- The WEC (2016) outlook contains three scenarios, which can arguably be understood as best ("Unfinished Symphony"), base ("Modern Jazz"), and worst case ("Hard Rock"). They are positive assessments of the energy system and mostly focussed on carrying forward current policy trends.
- The Equinor (2019) outlook has a very similar setup (best case "Renewal", base case "Reform", and worst case "Rivalry") and considers three worlds of global (non-)cooperation reflected in the energy system.
- The latest BP (2019) outlook features a base case projection ("Evolving Transition"), similar to the definition of the IEA WEO's Current Policies Scenario, and a number of scenarios

that consider slight variations: stricter climate policies (“Rapid Transition”), a positive shock on energy demand (“More Energy”), and the case of decreasing global trade and GDP (“Less Globalization”).

The remaining three examples are no outlooks in the previous sense of a line-up of futures, but each one contains one scenario only.

- The MIT scenario “Food, Water, Energy & Climate Outlook” (Chen et al., 2016) and the ExxonMobil (2018) outlook consider a continuation of current trends.
- The EWG scenario (Ram et al., 2019), on the contrary, is a normative scenario that assesses the pathway to a 100% renewable energy system

Figure 20 visualises global trajectories of the different scenarios. The three graphs show total primary energy demand, total coal demand, and electricity generation for the different outlooks, categorised into baseline projections (solid lines), best case projections (dotted lines), worst case projections (dashed line), and others (dash-dotted line).

Global total primary energy demand shows considerable variation between the scenarios but also some common characteristics. All scenarios witness major energy demand increases in the 2030s except for the best cases by Equinor and IEA’s WEO. Other than that, there is no apparent pattern towards 2050: Energy demand projections cover a wide range of possible developments, regardless of the scenario nature (except for the two scenarios mentioned before). Noticeably, all Shell scenarios project a steep growth in demand that is only seconded by our Green Cooperation and ClimateTech scenarios. A special and distinct case is the EWG projection, which operates in another order of magnitude and starts off approximately one-third below the other scenarios in 2015.

Global total coal demand projections diverge even more but along the lines of scenario natures. All best-case scenarios include significant drops in global coal demand, starting as early as 2020 and approaching zero towards 2050. The latecomer in this category is Shell’s Sky, which only begins to drop by 2040. Most base-case scenarios (ExxonMobil, MIT, Equinor, BP, DIW-REM) consider stagnating or slowly decreasing coal demand, and the worst-case scenarios move between a stagnation of coal demand and (for some even drastic) increases. There are, however, two major exceptions to this categorisation: First, Shell’s Oceans and Mountains scenarios present severe increases in coal demand. Second, WEC’s Unfinished Symphony mimics the trajectories of the best cases rather than other base cases.

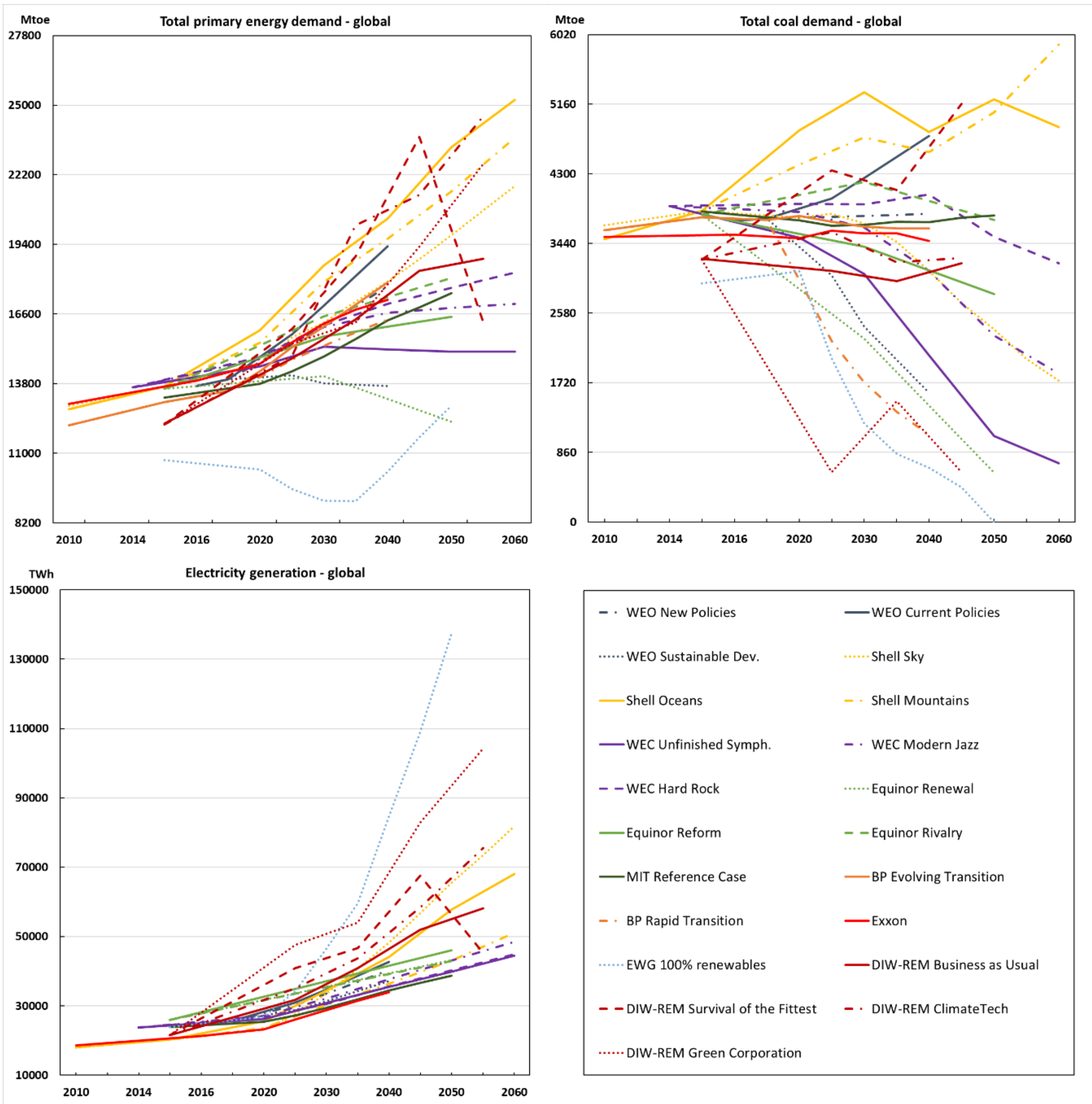

Figure 20: Global total primary energy demand, coal demand, and electricity generation compared
Note: DIW-REM electricity generation is adjusted to a common base year level

Global electricity generation, finally, resembles the conventional scenario cone: All scenarios (except for our DIW-REM Green Cooperation path) start on a common trajectory of moderate electricity growth towards 2020, followed by steeper growth towards 2030. Approaching 2040, the scenarios start to diverge: The EWG scenario considers an unprecedented and severe electrification boom, which exceeds a sevenfold increase between 2020 and 2050. Not far from that is our DIW-REM Green Cooperation scenario, whose 2055 number amounts to a fivefold increase from 2020. The remaining variation between scenarios, however, shows no structural characteristic with respect to institutions or scenario nature.

Furthermore, we compare the (available) outlooks for the key regions Europe (EU28, Figure 21) and Asia-Pacific (Figure 22).

The development of total primary energy demand in Europe is more driven by outlooks than by scenarios. For example, our DIW-REM scenarios all project significant growth in demand. Especially Green Cooperation projects a steep increase that exceeds today's levels by twofold, reflecting its concept of green growth. In contrast, the Shell scenarios follow a stagnating to increasing energy demand path, where Mountains comes closest to our scenario results. The EWG trajectory mimics its global counterpart and considers a late increase, and so does the MIT outlook. All other scenarios consider modest to substantial decreases in energy demand; reflecting strong efforts in energy efficiency; the most articulate example for this is Equinor's best case Renewal.

All outlooks show a common trend in European coal consumption, namely the decrease of coal use throughout the next decades. The most ambitious outlook is, again, DIW-REM, with all scenarios witnessing steep decreases in the 2020s. Green Cooperation eventually phases out coal by 2035, shortly before BP's Rapid Transition. After that, a cloud of best-case scenarios and Equinor's base case approach arrive at a complete coal phase-out before 2050. On the upper end of the range, worst-case scenarios only project a drop in coal production by approximately one half.

Electricity production offers the largest variety in European energy developments: EWG's renewable outlook and DIW-REM's Green Cooperation project a more-than-fivefold increase in power generation, while the entire IEA outlook considers a stagnation of European electricity generation. The remaining few scenarios that present disaggregated electricity generation are in between these two extremes.

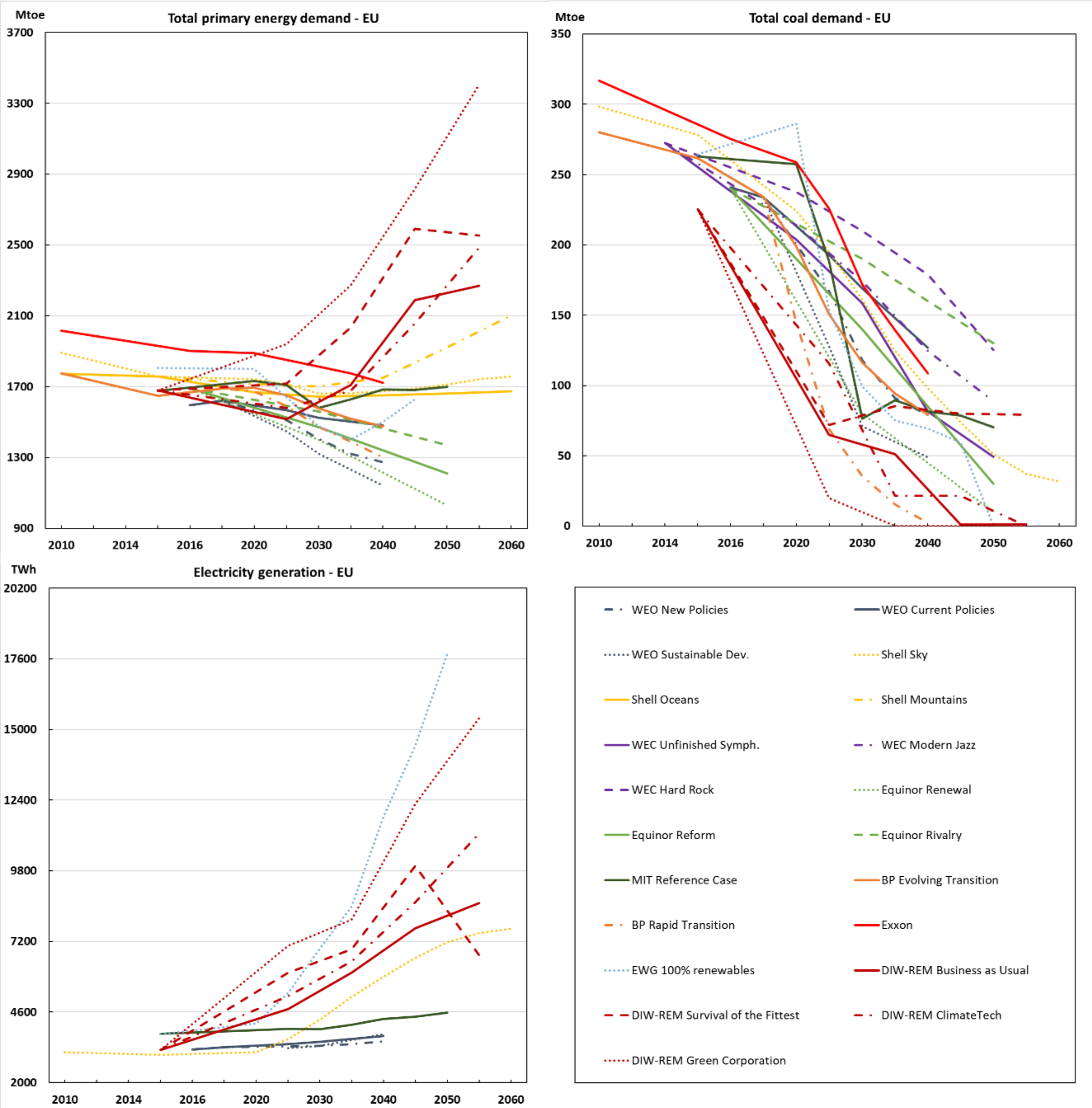

Figure 21: Total primary energy demand, coal demand, and electricity generation in the European Union compared
Notes: WEC numbers are adjusted to match the regional disaggregation "European Union"; DIW-REM electricity generation level is adjusted to a common base year level

Most scenarios show a steady increase of total primary energy demand in Asia and the Pacific region ("Asia-Pacific") in the 2020s and high-to-moderate increases in the 2030s. A general exception to this is the EWG outlook, where, again, the regional pattern mimics the global behaviour of an initial drop followed by a late increase. Also, the best cases of IEA and Equinor as well as the base case of DIW-REM show a stagnation (or even decrease) of energy demand in Asia towards 2040 and beyond, reflecting the decoupling of energy demand growth and economic growth. The highest projection comes from Shell's best case, which sees a constant path of demand growth. All other scenarios lie in between these values.

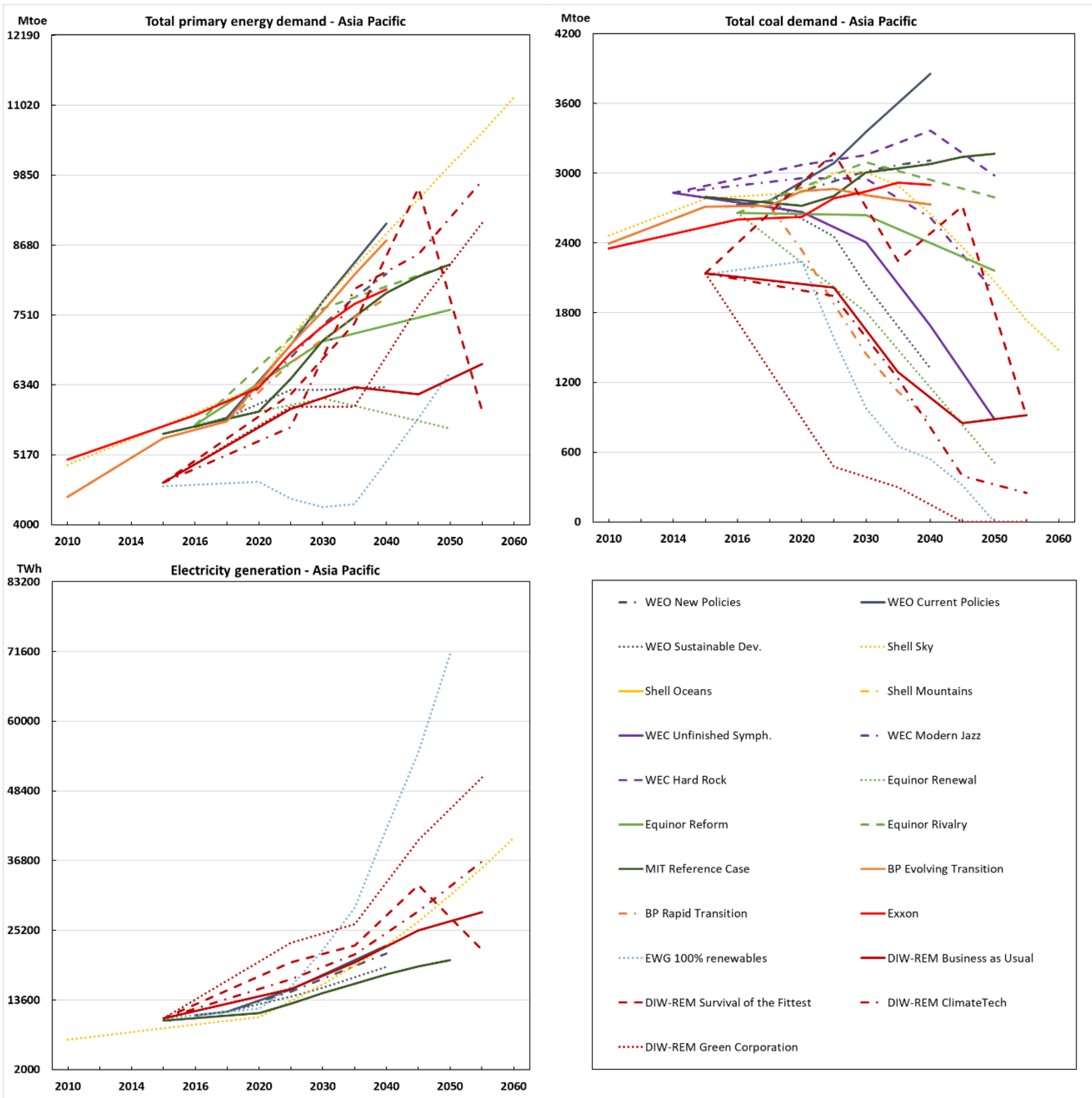

Figure 22: Total primary energy demand, coal demand, and electricity generation in Asia-Pacific compared
Note: Shell, Equinor, and BP numbers have been adjusted to match the regional disaggregation "Asia-Pacific" as defined by the IEA; DIW-REM electricity generation level is adjusted to a common base year level

The graph for total coal demand in Asia-Pacific shows considerable divergence. Both positive IEA WEO scenarios show considerable growth in coal demand, while most other base cases and worst cases consider a stagnation or only moderate increase. All best cases (and some other scenarios with stricter climate policies) hint at a tremendous decrease in coal demand, where

DIW-REM and EWG have the fastest phase-out and Shell's Sky initiates the path towards a phase-out only around 2050.

Asian-Pacific electricity generation, finally, shows a homogenous trend of a moderate increase in the 2020s and a more rapid ascent in the 2030s. Towards 2050, however, the spread between scenarios becomes broader again, with EWG and DIW-REM's Green Cooperation on the upper scale and the MIT outlook on the lower end.

Total North American primary energy demand (Figure 17) resembles again the conic shape discussed before: The divergence of scenarios increases over time and almost symmetrically in both directions. The lower end is filled by a cloud of best-case scenarios (EWG, Equinor, Shell, IEA), and our DIW-REM outlook takes the upper end of the range. The medium range is filled with all other scenarios and varies between slight decreases and slight increases in energy demand. ExxonMobil's outlook considers the highest demand growth among them, and Shell's Ocean and Mountains in addition to MIT and Equinor's base case come closer to the best-case scenarios.

Total North American coal demand presents our DIW-REM outlook as an outlier: All DIW-REM scenarios foresee an increase in demand, at least for the mid-term. This is connected to the strong role that the CCS technology plays in Green Cooperation and ClimateTech and to the dominant force of US energy independence for the other two. All other outlooks foresee modest to strong reductions in coal demand: Worst-case scenarios consider stagnating coal demand with some reduction (but small) towards 2050, while best-case scenarios and Shell's Mountains consider quicker decreases. Remarkably, towards 2060, Shell's Sky converges to a small, yet positive coal demand level, similar to the numbers of the WEC outlook that reaches Paris-compatible cumulative global emissions by then. This is an indicator that these scenarios also include negative emissions technologies, albeit without transparently mentioning it.

Electricity generation in North America shows more initial variation than its European and Asian counterparts. The DIW-REM scenarios, again, foresee large increases in the 2020s, while the outlooks of MIT and IEA as well as Shell's Sky project no changes at first. Towards 2030, however, the outlooks part again with different growth rates. IEA and MIT continue to stay close to today's values, while Sky eventually witnesses firm increases. The EWG outlook starts with slow increases but finally catches up with our outlook.

Figure 23: Global total primary energy demand, coal demand, and electricity in North America compared
Note: BP numbers are adjusted to match the regional disaggregation “North America”

8 Stranded assets in the Global South

8.1 Introduction

Asset stranding is an increasing concern for the energy sector. In its broadest form, the term describes "assets [that] suffer from unanticipated or premature write-offs, downward revaluations or are converted to liabilities" (Caldecott et al., 2013, p. 7). It can be the result of disruptive innovation (Green and Newman, 2017) or policies, particularly of environmental nature (Harnett, 2018). Stranded assets are connected to sunk costs and include all of their key characteristics (recoverability, transferability, longevity, and financing needs), but they describe a narrower phenomenon (ibid.).

Researching (potential) stranded assets and their effects has received attention in several academic fields over the past decade. Among them are, of course, energy and climate (e.g. Ansar et al., 2013), electricity (e.g. Saygin et al., 2019; Simshauser, 2017), resources (e.g. McGlade and Ekins, 2015; Muttitt, 2016), agriculture (e.g. Caldecott et al., 2013), as well as environmental and public economics (e.g. Baldwin et al., 2019; Rozenberg et al., 2018; Sen and von Schickfus, 2017; van der Ploeg and Rezai, 2018). Many contributions were made in finance and investment, but with a strong emphasis on the effects for and in developed economies (e.g. Andersson et al., 2016; Byrd and Cooperman, 2015; Byrd and Cooperman, 2018; Silver, 2017).

However, stranded assets have only received very limited attention by development researchers. Rare examples include Kalin et al. (2019) for the water sector, Comello et al. (2017) and Hoffmann and Ansari (2019) for mini-grids. This is very surprising given the potential effect that asset stranding has on the developing world. Low-income countries might eventually be hit hardest by conventional climate policy instruments (Dorband et al., 2019), and resource endowments prone to stranding are often located in the developing world (McGlade and Ekins, 2015). In this vein, Mercure et al. (2018) estimate a future global wealth loss in the range of US$ 1 to 4 trillion with tremendous distributional impacts (an excess burden for net exporters and benefits for net importers). Non-producing economies could also be hit: Asset stranding can produce a cascading effect, hitting downstream sectors and affiliated industries, such as the power sector and energy-intensive industries (Campiglio et al., 2017). On the other hand, successful transitions to greener economy models could eventually benefit developing economies. Carbon pricing, for instance, could finance infrastructure development (Jakob et al., 2016). As examples from the 19th and 20th century show, chances for the developing world do not depend solely on 'hard' factors (e.g. resources); instead, the institutional environment is a major determinant for economic resilience in the wake of change, i.e. the ability to adapt to changing global circumstances and prevent economic downturn (Zenghelis et al., 2018).

8.2 Assessing stranded assets

This subsection contains an assessment of asset stranding for the Middle East, China, and South America, based on our energy outlook. For this, we use a novel index that is tailored towards measuring asset stranding for the present framework. It reflects the risk that specific sectors are exposed to, and, hence, can give an indication where and to which extent asset stranding might occur. It ranges from 0 to 1, where a value of 0 would imply no risk of asset stranding and a value of 1 would imply that a sector deserves the utmost attention.

Table 2: Values for the stranded asset index
Rem.: 0 implies no risk, 1 implies maximum risk

	Coal	Crude oil	Natural Gas	Lignite	Average
Middle East	0.02	0.55	0.16	0.00	0.18
China	0.61	0.21	0.04	0.04	0.22
South America	0.18	0.48	0.16	0.03	0.21

Remarkably, the average (i.e. regional across all sectors) index is very similar for all three regions, ranging between 0.18 and 0.22. These values are rather low when considering the entire range of the index. While this does eventually imply that asset stranding might not be an existence-threatening risk to the respective regions, the results should by no means be understood as an all-clear for business as usual. First, readers should keep in mind that the index does not consider the whole economy in its sector-weighting mechanism. Secondly, the index does not consider downstream technologies (e.g. power plants). Thirdly, the values refer to the uncertainty in the development of the sectors, but the potentially certain component of trajectories (e.g. lower capacity usage in all scenarios because of technological progress).

Instead, the individual sectoral indices provide evidence that a large potential for devasting asset stranding exists in specific sectors. These are, at the forefront, the Middle Eastern crude oil sector, Chinese coal production, and the Latin American crude oil sector. Middle Eastern crude oil is eventually persistent in all the scenarios except Green Cooperation, but its global oil phase-out will hit the oil-dependent region hardly. China's coal sector is a very similar case: Coal supply accounts for the large majority of primary energy supply, and albeit gradual reduction in all scenarios, Green Cooperation eventually sees a phase-out by 2040. The case of Latin American crude is slightly different from the Middle East: The spread between the scenarios is even larger, as Latin American production virtually disappears in Green Cooperation, but the relative importance of oil is lower than that in the Middle East.

Indices for the natural gas sector are only small to modest for all regions. This results from two central factors: First, natural gas consumption continues in each scenario, which is why the sector's prospects are less uncertain. Second, none of the three regions is all-dependent on natural gas-supply: China's production is anyhow limited, and the other two regions produce large amounts of either crude oil or renewables, depending on the scenario. Clearly, this does not need to be the case for individual nations (e.g. Qatar). This remark is also central for the Latin American coal sector: Continent-wise, the index is low. However, (current and prospective) coal production is distributed unevenly across Latin American countries, which is why some (e.g. Colombia) will be hit significantly in Green Cooperation. Values for lignite are only barely above 0, as the sector's production is neither large in any of the regions, nor does any scenario foresee significant lignite supply in the future.

Nevertheless, in the presence of uncertainty, fossil-fuel exporters will always be in an adverse position, as a unilateral transformation away from fuel exports is likely to be economically harmful in the short-run. The institutional framework plays a dominant role in enabling or hindering a green transition. Middle Eastern economies are in adverse condition with rigid social contracts and are mostly unsuccessful in the factors that determine economic resilience and, thus, the prospects of and likeliness to engage in a green transition. China, on the contrary, offers many of the required factors to be able to adapt to a climate constrained world and is likely to engage a green transition, whose extent yet to determine and potentially to be influenced by policy-making. Latin American economies stand between both models and do not provide the same rigid institutional framework of the Middle East. However, human capital formation, innovation, and credibility in policy-making remain crucial issues that will determine whether the continent moves rather towards a green transition or if it will endure the risk of stranded assets.

9 Conclusions and lessons learnt

In this report, we have presented the DIW-REM outlook for developments of the global energy system and climate towards 2055. Moreover, we gave a brief comparison to other outlooks and discussion of the effects of the diverse developments in the fossil fuel sectors on asset stranding in resource-dependent countries.

The following conclusions and recommendations apply:

- A return to political isolationism is a critical risk for the energy transition: First, effective climate policies require international collaboration. Indeed, recent theoretical and empirical research shows that an at least partial transition is bound to happen due to market developments (especially cost reductions), and some climate action will happen even unilaterally. However, finding economic solutions to the global carbons problem requires multilateral, global efforts, since actors will often have unilateral incentives to deter costly transitions. Moreover, and second, the energy transition depends on channelling investments into the 'right' directions. Despite the importance of state actors, who set aims and policies, it will be non-state actors that implement a transition eventually. The availability and cost of certain (cleaner) technologies is the most important variable for private actors. Therefore, targeted research and development, supported by multilateral state initiatives (e.g. under the UN framework), are a crucial tool to direct market actors in the right direction. Otherwise, lacking global coordination will lead to ambiguous (technological) developments and competing technologies. An unsuccessful transition, stranded assets, and wasteful research expenses may be the consequence. Lastly, substantial increases in the global temperature risks to create massive refugee waves. These waves would further fuel inter-regional tensions, potentially leading to even more isolationism and cementing existing carbon lock-ins.

- Public opinion and societal transitions are an integral component of decarbonization efforts. First, the outlook shows that a solely technical transition may succeed in preventing an immediate escalation of the climate crisis, but it will typically not manage to provide a stable corridor for the long run. Second, conflicting interests on all levels of society as well as incohesion provide strong barriers to transition. An inclusive society that shifts its opinion towards transition is necessary to create the holistic change that is required to overcome the inertia of the current system.

- The integration of economic and energy-related objectives and incentives (e.g. poverty alleviation, infrastructure modernisation, and private investment) is crucial. On a global level, energy access and economic development in the Global South remain urgent needs that are bound to put additional pressure on the carbon budget. Historical questions of distributive justice between Global North and South risk to create a kicking-away-the-ladder narrative in energy-related issues. Therefore, for a successful transition, nations of the Global North will not only have to decarbonise within their borders, but they will be required to take an active role in green growth in the Global South. This push for inclusive, sustainable development includes but is not limited to technology transfer, the incentive design, and geopolitical reconciliation. Moreover, fossil-fuel sectors in resource-rich regions will require special emphasis by the international community, since economies and social contracts may depend on them. Asset stranding, which is the depreciation of assets due to sudden policies or market disruptions, is a risk for fossil-fuel dependent economies with limited diversification of exports and fiscal budgets. There is a high risk for market rebounds and increasing political tensions that can damage decarbonisation efforts and fragile security environments alike. Also, industrialised countries will need to make sure that the transition does not create an excessive burden for lower-income groups.

- We find that some metrics commonly used for assessing the state of decarbonisation are unfit indicators. We show that, especially, the share of renewables and electricity consumption are improper indicators, as the trends of increasing electrification and rising renewable energy generation are also ongoing in the scenarios with increasing emissions. Monitoring the transition and designing policies solely based on these indicators risks wrong assessments and biased action. Instead, we advocate for direct metrics (e.g. the rate of emissions, see Figure below) or a set of multidimensional indicators, as we present them as part of our outlook.

Concerning the methods of foresight analysis and complementarity modelling of the global energy system, the following lessons learnt can be drawn:

- Scenario planning is a useful tool. However, foresight analysis is rather short-term oriented (usually 5-6 years ahead) and needs to be adapted for long-term analyses. The adaptation then is similar, if not equal, to the scenario planning method which is employed by Shell, and to a weaker extend by the World Energy Council and the IEA.

- Taking into account a large variety of sectors, factors, as well as societal and political dimensions allows detecting interlinkages and feedback loops beyond the energy sector. For the question of global decarbonization of the energy system, it is particularly necessary to account for geopolitics and societal developments.

- Equilibrium (complementarity modelling) of energy systems allows for including market features such as imperfect competition. However, the mathematical complexity of the method requires to reduce the data complexity (e.g. the number of energy consumption technologies). Moreover, in the multi-period setting, this modelling setup tends to replicate existing systems with similar structures over time, as opposed to (linear) optimisation methods which may also include substantial structural breaks (extreme solutions, such as the complete abandoning of a particular technology or fuel).

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Methodological appendix

A1 Generating scenarios

The outlook is based on a sequential application of qualitative methods and quantitative energy modelling (Figure 24). First, we develop qualitative storylines using multiple scenario generation. Second, we use parameters derived from the qualitative storylines in the numerical energy and resource market model Multimod to quantify the energy and climate aspects of the storylines. Third, we integrate the quantitative model results with the storylines to obtain comprehensive, fully-fledged narratives that describe energy and climate but also consider the societal, political, security and technology aspects. Details on the method can be found in Ansari and Holz (2019).

Figure 24: Illustration of the methods

The first step uses scenario foresight à la Burrows and Gnad (2018), which relies largely on Heuer and Pherson (2015) and Pherson and Pherson (2016). The process is distinct from both forecasting, which aims to provide bounded statements about the (mostly short-run) future, and predictions, which are definite statements about the future. The foresight process generates scenarios for "exploring different possible futures, the levers that bring them about and the interactions that arise across a complex [....] system" (International Energy Agency, 2018, p. 23). It is a "reframing process" that involves exploiting insights to thinking about the future (Burrows and Gnad, 2018, p. 14). The scenarios encompass the complexity of human systems by working in the STEMPLE+ analytical framework: **s**ocial, **t**echnological, **e**conomic, **m**ilitary/security, **p**olitical, **l**egal, **e**nvironmental, plus others (e.g., cultural, psychological).

Precisely, the foresight process involves four steps which are done in mixed desk research with group work in a scenario workshop[3]. First, and prior to the workshop, the participants identify key assumptions (Table 3) and discuss them at the workshop in addition to the definition of

[3] The scenario workshop, hosted in November 2016 in Berlin, was moderated and facilitated by Oliver Gnad. Participants were approx. 30 experts from different areas and sectors. Details on the course of the workshop and its intermediate results can be found in the Appendix of Ansari et al. (2018)

prevailing megatrends. The accepted assumptions provide a framework of unchallengeable rules for the scenario generation. Second, the participants perform a structured brainstorming and clustering of the research question ("What are the drivers of the renewable energy transition until 2050?") in the STEMPLE+ framework. The results are key drivers (Table 4), which have a critical influence on the system. Third, participant groups develop plausible alternative futures by combining logically consistent drivers in a 2 x 2 matrix. Each collusion of two driver realisations produces an initial scenario, which is to be described, characterised, and evaluated by the group. After the workshop, initial scenarios are collected, clustered, and checked for consistency. These clusters are the raw narratives that include sets of drivers and rough chronologies of events in the respective scenarios. Fourth, the raw narratives are elaborated in desk research, and "diagnostic" (Heuer and Pherson, 2015, p. 135) indicators for each raw narrative are identified and validated.

Table 3: Megatrends and key assumptions

Megatrends and key assumptions	
Population growth and urbanisation	Despite shrinking fertility rates in many industrialised countries, the world and especially the Global South continue to see high rates of population growth and urbanisation. Although the pace may decrease in the decades to come, the world will move closer towards the milestone of 10 billion humans.
Energy cost declines	The cost decline of energy technologies – especially renewables but also others – observed in the past decades will continue. The gradient of future cost development may differ across technologies.
Fossil fuel availability	Reserves of fossil energy carriers remain high despite ongoing extraction. Current production levels could be maintained for more than a century thanks to continued exploration and improvement of extraction technologies. Therefore, global supply-induced production peaks throughout the scenario outlooks are improbable.
Economic integration	The global economy is deeply interconnected on various levels, including virtual layers (e.g. banking) and physical layers (e.g. trade, multinational supply chains). Trade barriers and protectionist policies may affect the extent of economic interlinkage, but the overall integration is unalterable.

Table 4: Drivers in each scenario

	Business-as-usual	Survival of the Fittest	Green Cooperation	ClimateTech
Drivers				
Climate change impact	Global and gradually increasing	Global and quickly accelerating	Only localised	Only localised
International cooperation	Mixed	Minimal	Close	Mixed
Social welfare-coherence	Mixed	High inequality	Low inequality	Mixed
Innovation in finance models	Low	Low	High	High
Influence of the fossil fuel sector	High	Very high	Low	Mixed
State of security and geopolitical stability	Mostly stable	Unstable	Stable	Stable
Rate of innovation	Mixed	Low	High	Very high

In the second step of our analysis, we quantify the scenario trajectories. For this purpose, we use the energy and resource market model Multimod. In the sense of Sovacool et al. (2018), Multimod is a simulation with elements of hybrid models and agent-based approaches: The model describes the energy system as the outcome of profit-maximising actors along the supply chain and utility-maximising customers. The system is bound by numerous constraints (such as balancing conditions or capacity and reserve restrictions), and outcomes are given as the economic (partial) equilibrium of all markets involved. The model has a global focus and includes different fuels with multiple value-chain steps and differentiated demand sectors. Unique features include imperfect competition as well as endogenous investments and fuel substitution. For this study, Multimod (originally a mixed complementarity problem) was reformulated into a convex quadratic optimisation problem, using the method described by Baltensperger et al. (2018). We use the model to obtain key variables (energy production and consumption, CO_2 emissions, infrastructure investment) that match the setting of the storylines.

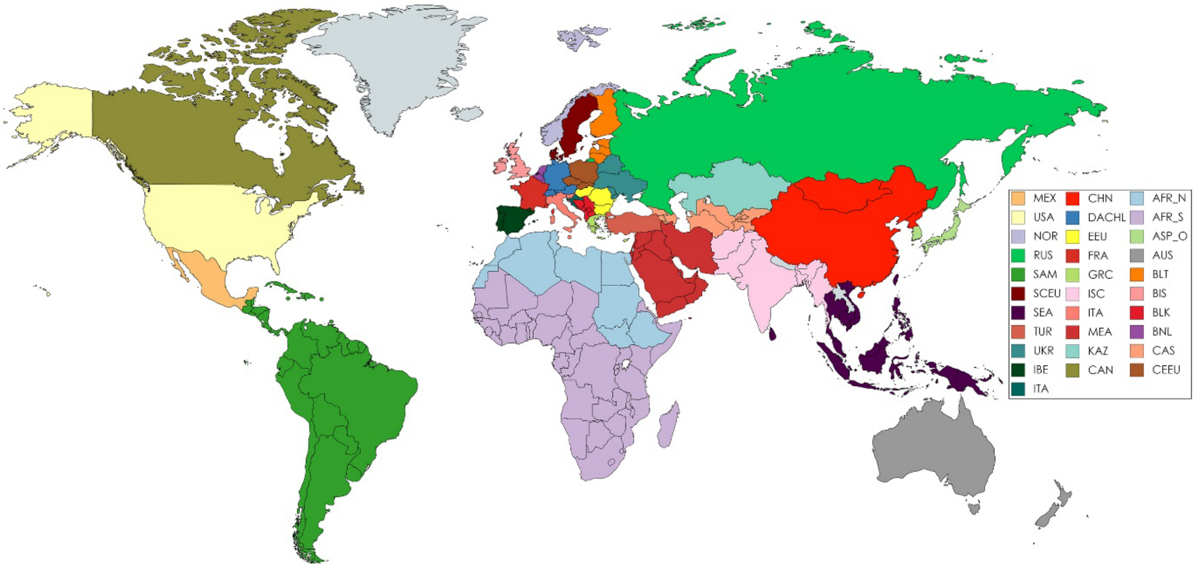

Figure 25: Overview of the regional disaggregation

The model proceeds in ten-year steps from 2015 to 2055. The world is disaggregated into 30 nodes, which represent geographic entities (illustrated by Figure 25). These nodes are home to the different actors along the energy value chain (see Figure 26: suppliers (upstream), service providers (midstream), and consumers (downstream). Our version of the model covers natural gas, coal, lignite, and crude oil on the fossil fuel side as well as hydro, biofuels[4], other renewables (solar / wind / geothermal), and nuclear energy on the upstream level. While some of these fuels can be used directly, others need to be processed first and can be transported via various modes.

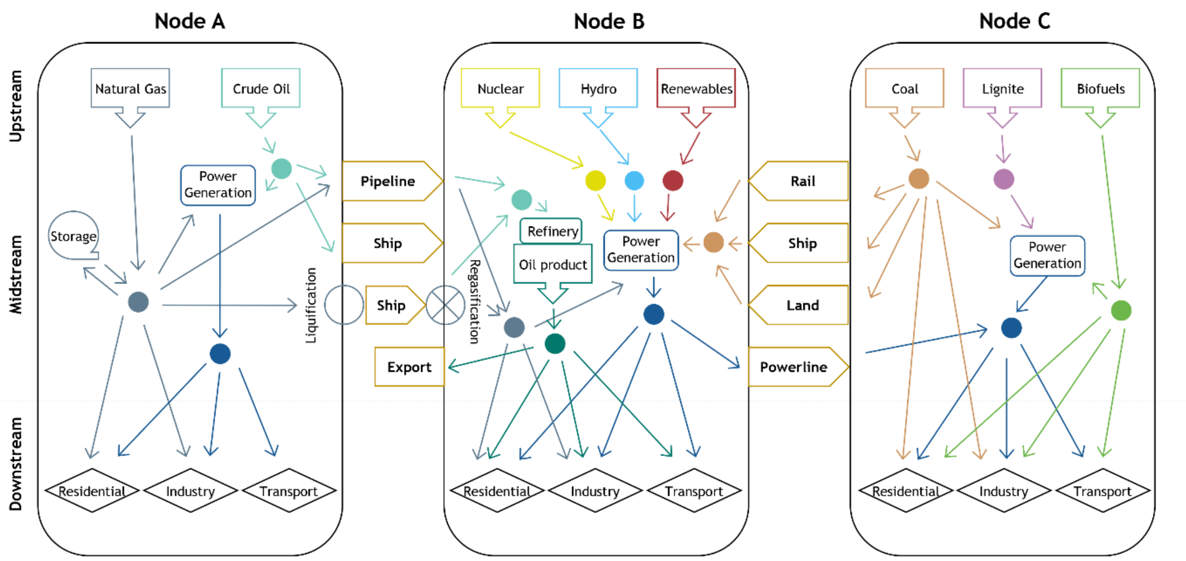

Figure 26: Illustration of the modelled value chains

[4] Biofuels are defined according to International Energy Agency (2017a) and cover both primitive biomass as well as processed biofuels.

The setup also includes energy storage and LNG infrastructure. Certain producers – here, a limited number of oil and gas producers (OPEC members, Qatar, Russia) – can exercise market power in a Cournot fashion, i.e. they choose their supply in anticipation of each other's actions. We distinguish three separate and individual demand sectors (residential, industrial, transportation), which are represented by their individual demand function in each node. Emissions are computed for each action (production, service, and consumption of specific fuels) along the supply chain.

A2 Stranded assets index

The stranded assets index reflects the risk that specific sectors are exposed to. It implies, to which extent asset stranding needs to be considered (and, thus, policy intervention may be necessary) for each case study region and fossil fuel sector. It ranges from 0 to 1, where a value of 0 would imply no risk of asset stranding and a value of 1 would imply that a sector deserves the utmost attention.

$$I_{s,f} = \sqrt{\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f} * \text{share}_{s,f}}$$

$$\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f} = \frac{1}{(\text{card}(Y)-1)} \max_{\substack{i,j \\ i \neq j}} \left\{ \sum_{\substack{h \in H \\ y>1}} \left(\text{util}_{y,s,f,i} - \text{util}_{y,s,f,j}\right) \right\}$$

$$\text{share}_{s,f} = \frac{\sum_{\substack{h \in H \\ y>1}} q^P_{y,h,s,n,d,e,argmax(\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f})}}{\sum_{\substack{h \in H \\ y>1 \\ f \in F}} q^P_{y,h,s,n,d,e,argmax(\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f})}}$$

Precisely, the index measures the uncertainty of a certain sector (i.e. specific fossil industry in a specific country) and weights it with the relative importance of the sector. We compute the index $I_{s,f}$, as the geometric average of the uncertainty in capacity utilisation $\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f}$ and the relative share of the sector $\text{share}_{s,f}$.

The first part, the uncertainty in capacity utilisation $\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f}$, is given by the largest possible, time-averaged divergence in capacity utilisation between any two scenarios. In other words, this part of the index considers the difference between the highest possible capacity usage in the sector and the lowest possible one and frames the difference as potentially stranded assets. This mimics the idea that stranded assets are unanticipated write-offs to (productive) assets: $\Delta_{\text{avg}}^{\text{max}}\text{util}_{s,f}$ takes the scenarios as given and measures the range of uncertainty in the usage of productive capacities $\text{util}_{y,s,f,i}$.[5]. However, and not downplaying localised effects, this will only be of minor interest, if the corresponding sector shows no importance in the overall (energy) economy. Therefore, $\text{share}_{s,f}$, the second factor in the index, measures the relative share that the sector has in overall national energy production accumulated over the outlook period. Hence, the index increases in a larger share of the sector, as asset stranding becomes most dangerous if an essential part of the economy were hit.

A3 Data structure and sources

We use a dataset named *30 nodes plus*, which is an extended and updated version of Huppmann and Egging (2014)'s dataset, to which we refer for a general and more comprehensive overview. An overview of the most important sources for input data is given in Table 5. The dataset makes extensive use of the DIW Berlin sector-level models and databases.

In a nutshell, the model translates detailed information for a base year, reference points for the future, and techno-economic specifications of the supply chain into energy system and market outcomes as the result of the objective-oriented interaction of all market actors. In detail, the model requires disaggregated energy balances for a base year, operational costs for production (i.e. a quadratic function in our version) and (linear) costs for all energy services, investment costs for the expansion of production and energy service capacities as well as their limits (e.g. possibilities for new transport routes or power plants), resource reserves, efficiency values, (seasonal) reference demand[6] values, depreciation rates, and greenhouse gas emission values for each action. The model then computes a single equilibrium solution for all periods, nodes, and actors. This solution contains quantities and flows for production, consumption, conversion, storage, and transport as well as investments in all infrastructures. Additionally, the model determines end-use costs, prices, emissions, and welfare.

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[5] In case all scenarios are considerably similar (at least in terms of capacity utilisation), the sector does not face much uncertainty. Instead, no matter the future, the sector faces a similar trajectory, which is why there would not be a major risk of asset stranding. However, in the case of at least two scenarios diverging significantly (e.g. Green Cooperation foresees almost no utilisation of present capacities and Survival of the Fittest foresees a high capacity utilisation), that sector's future would be highly uncertain, increasing the risk of stranded assets.

[6] There is a central difference between having an eventual demand level and a reference demand point as input. Models that use final demand levels as input fix the final quantities exogenously. Hence, such a model is not economic in the sense that the model does not replicate a market action with price and quantity as endogenous variables. In contrast to that, a reference demand point (including a reference price) refers to a single and specific point on the demand curve, which is used to extrapolate the remainder of the curve. Hence, while choosing and varying the reference demand point influences the eventual demand, it does not determine it. This is done endogenously in the interplay of supply and demand.

Regarding demand, the model distinguishes three separate and individual sectors (residential, industrial, transportation), which are represented by their own demand in each node. Multimod requires reference demand values for each node, sector, and period, which are central to the model's automatic calibration and work as key parameters for calibrating the different scenarios. For the year 2015, fixed demand values are taken from International Energy Agency (2017a). Regarding future periods (i.e. 2025, 2035, 2045, 2055), we derive baseline demand values from the numerical results of Chen et al. (2016)[7] and process them into growth rates per decade. Then, we alter and differentiate these growth rates to reflect the four storylines. The final reference demand values for future periods are then obtained by multiplying the corresponding growth rates with the (fixed) base year demand.

Table 5: Main sources for sectoral input data

<table>
<tr><th></th><th>Production costs</th><th>Production capacities</th><th>Transport, processing</th><th>Reserves</th><th>Emissions</th></tr>
<tr><td>Coal</td><td colspan="4">Holz et al. (2016)</td><td rowspan="6">Burandt et al. (2018); Huppmann and Egging (2014)</td></tr>
<tr><td>Gas</td><td colspan="4">Egging and Holz (2019); Holz et al. (2017)</td></tr>
<tr><td>Oil</td><td>Aguilera (2014); Ansari (2017)</td><td>Ansari (2017); International Energy Agency (2017b)</td><td>BP plc (2017); Huppmann and Egging (2014)</td><td>BP plc (2017)</td></tr>
<tr><td>CCS</td><td colspan="4">Holz et al. (2018); Mendelevitch and Oei (2018); Oei and Mendelevitch (2016)</td></tr>
<tr><td>Renewables</td><td colspan="4">Burandt et al. (2018); Huppmann and Egging (2014); Ragwitz et al. (2012)</td></tr>
<tr><td>Power</td><td>Gerbaulet and Lorenz (2017); Löffler et al. (2017)</td><td>Huppmann and Egging (2014); Löffler et al. (2017); Wealer et al. (2018)</td><td>Burandt et al. (2018); Huppmann and Egging (2014); Löffler et al. (2017)</td><td>Huppmann and Egging (2014)</td></tr>
</table>

The four scenarios vary along several parameters that are chosen to mimic the settings and series of events of the storylines. As elaborated above, this includes reference demand values, but also the availability and costs of (new) transportation forms (e.g. in Survival of the Fittest, increased geopolitical tensions and isolationism restrict the use and expansion of multilateral pipeline projects, while numerous new transportation methods are open to investment in Green Coop-

[7] The MIT Joint Program on the Science and Policy of Global Change provides an independent forecast for primary energy use and electricity production as well as generation mix.

eration). Of course, climate policies vary widely between the scenarios; for reasons of smoothness of calibration, they were modelled as emission caps in all scenarios[8]. Another set of parameters fitted to the storyline's centres around technological development and its consequences. All scenarios feature cost declines and efficiency increases, but their extent and focus differ. Table 6 illustrates some of the key differences between the scenarios.

Table 6: Main sources and assumptions for the narratives
p.d.: per decade

	Business as Usual (BaU)	Survival of the Fittest (SotF)	Green Cooperation (GC)	ClimateTech (CT)
Base year demand: International Energy Agency (2017a) Base reference demand trajectory: Chen et al. (2016)				
Carbon limit (based on 2015 values)	Europe and (South-) East Asia start 2025, tightened by 20% and 8%, p.d.; others start in 2035, tightened by between 2% and 8% p.d.	Only in Europe and East Asia, tightened by 10% and 6% p.d. respectively	Global cap from 2025 onwards (based on BaU values for 2025), tightened by 25% p.d.	Global cap from 2035 onwards (based on 90% of BaU values for 2025), tightened by 15% p.d.
Trade routes	Routes between continents (e.g. extensive African-European power transmission) and tense regions (e.g. Iran to India pipeline) unavailable	Same as in BaU; Additionally, interregional trade is strictly limited (e.g. no Russian exports to Europe)	Intercontinental infrastructure and networks crossing previously tense regions become available	Same as in BaU
Novel technologies	CCS available after 2030	CCS available after 2030	CCS available after 2030	CCS after 2020 (emission reductions 25% p.d.); nuclear fusion after 2030 (50% p.d. reductions over current nuclear plants); Negative emission technologies after 2030

[8] Since we assume perfect foresight and complete information in the model setup, there is no difference between the effect of a carbon tax or a cap.

Reference demand	Continuation of current trends	Expansion of electricity and transportation demand; Continued industrial coal demand; diminished demand post-2050	Strong expansion of electricity; decreasing fossil fuel; Universal energy access phases out raw biomass demand	Expansion of demand until 2035 similar to SotF; later decreasing fossil-fuel demand
Costs for renewables	8% decline towards 2025; 10% p.d. afterwards	2% less decline than in BaU	20% decline p.d.	1% less decline than in BaU
Costs for hydrocarbons & thermal power plants	Only minor changes	3-8% p.d. lower extraction and conversion costs; 5-10% p.d. conversion efficiency gains (incl. CCS)	Only minor changes	4-6% p.d. lower conversion costs and higher conversion efficiency; 17% p.d. lower CCS costs
Hydrocarbon exploration	Moderate exploration and reserve increases	Strongest exploration and reserve increases	No further exploration	Strong exploration and reserve increases

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