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Between stranded assets and green transformation: Fossil-fuel-producing developing countries towards 2055

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ABSTRACT

Climate-related asset stranding refers to the depreciation of assets – such as resource reserves, infrastructure, or industries – resulting from the unanticipated changes, such as the tightening of climate policies. Although developing countries – especially fossil-fuel exporters – may be most concerned by this issue, its analysis in development (economics) has so far been limited.

We aim at enhancing the understanding of stranded assets by investigating its relevance in the resource sectors of three case study regions –the Middle East, China, and Latin America. For this, we analyse the regional dimensions of four interdisciplinary global energy scenarios. Specifically, we extract results from a numerical energy model (energy production, energy consumption, electricity generation) for the three regions and introduce a novel index for stranded assets. The index identifies which fossil fuel sector in each region is most prone to asset stranding and should receive the most attention from national and international policymakers.

We find that considerable uncertainty exists for the Chinese coal sector as well as the Middle Eastern and Latin American crude oil sectors. We finally put our results into perspective by discussing aspects that are closely related to stranded assets for resource-rich economies such as the uncertainty in global energy and climate policy, the resource curse and diversification, economic resilience, and unequal burden-sharing of climate policy efforts between industrialised economies and latecomers. We conclude that China is more likely to engage in a green transformation than the Latin Americas or, still less, the Middle East.

1. Introduction

A new spectre is haunting the fossil-fuel dependent world: asset stranding. In its broadest meaning, the term 'stranded assets' describes "assets [that] suffer from unanticipated or premature write-offs, downward revaluations or are converted to liabilities" (Caldecott, Howarth, & McSharry, 2013, p. 7). Stranded assets are connected to sunk costs and include all of their key characteristics (recoverability, transferability, longevity, and financing needs), but describe a narrower phenomenon (Harnett, 2018).

Stranded assets can result from disruptive innovation (Green & Newman, 2017) or policies, particularly of an environmental nature (Harnett, 2018); however, they are particularly relevant in context of climate change mitigation. With the Paris Agreement, it has become clear that some form of climate policy will be implemented, and future revenues from fossil fuels could decline and eventually disappear. This is a new risk for sectors that were, for a long time, safe *cash cows* for resource-endowed countries. In the future, domestic reluctance to engage in climate change mitigation might be unable to shield fossil-fuel sectors from the effects of climate policies and technological spillovers in globalised markets.

Researching (the potential for or effects of) stranded assets has received attention from different academic fields and sectors over the past decade. At the forefront is electricity sector research (e.g. Simshauser, 2017; Simshauser & Akimov, 2019), including regional studies on stranded assets in Latin America (Binsted et al., 2019; González-Mahecha, Lecuyer, Hallack, Bazilian, & Vogt-Schilb, 2019), China (Yuan, Guo, Zhang, Zhou, & Qin, 2019), and India (Gadre & Anandarajah, 2019; Yang & Urpelainen, 2019). Several contributions were made in finance and investment, but with a strong emphasis on the effects for and in high-income economies

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(e.g. Andersson, Bolton, & Samama, 2016; Byrd & Cooperman, 2018; Silver, 2017). Researchers have furthermore analysed stranded assets in resource sectors (e.g. McGlade & Ekins, 2015; Muttitt, 2016), agriculture (e.g. Caldecott et al., 2013), as well as environmental and public economics (e.g. Kalkuhl, Steckel, & Edenhofer, 2019; Sen & von Schickfus, 2019; van der Ploeg & Rezai, 2018).

However, (climate-related) stranded assets (and stranded resources, in particular) have only received limited attention from development researchers so far. In a first attempt, Bos and Gupta (2019) review how the sparse literature on stranded assets on the one hand and climate change on the other can be linked to sustainable development. Other examples (without a direct reference to climate change) include Kalin et al. (2019) for the water sector, and Comello, Reichelstein, Sahoo, and Schmidt (2017) and Hoffmann and Ansari (2019) for rural electrification.

The limited number of contributions is very surprising given the potential effect that climate-change-related asset stranding could have especially on the developing world. Despite a legal nexus between Sustainable Development Goals (SDGs) and the Paris Agreement (Gupta & Arts, 2018), climate policy may potentially slow down poverty eradication (Campagnolo & Davide, 2019). The export of fossil fuels has been crucial for many resource-rich economies, and resource endowments prone to stranding are often located in the developing world (Jakob & Hilaire, 2015; McGlade & Ekins, 2015). In this vein, Mercure et al. (2018) estimate future global wealth loss in the range of US$ 1 to 4 trillion with tremendous distributional impacts. Similar to Bazilian, Bradshaw, Goldthau, and Westphal (2019), they show that while importers may benefit, resource exporters bear a heavy burden from carbon reduction. However, economies without fossil-fuel endowments 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, Godin, & Kemp-Benedict, 2017). Climate policy effects on these sectors are bound to have a disproportionate impact on the developing world (Kefford, Ballinger, Schmeda-Lopez, Greig, & Smart, 2018), and conventional instruments may eventually hit low-income countries hardest (Dorband, Jakob, Kalkuhl, & Steckel, 2019). Ultimately, in the presence of weak institutions and special social contracts, shifting economic structures and revenues caused by climate policy and stranded assets could disrupt stability and (regional or even global) security (Ansari, 2016; Bazilian et al., 2019; Helm, 2017; Van de Graaf, 2018).

On the other hand, successful transitions to greener economy models could eventually benefit developing economies. Clean energy programs have significant potential for poverty alleviation (Liao & Fei, 2019), green technologies provide opportunities for new industries (Khalili, Duecker, Ashton, & Chavez, 2015), and defying comparative advantage can actually bring benefits (Lectard & Rougier, 2018). Moreover, opportunities 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, Fouquet, & Hippe, 2018).

Therefore, we investigate the potential for climate-related asset stranding – and green transformations – in three selected regions by presenting, analysing, and reflecting on four interdisciplinary global energy and climate scenarios. As extreme visions of 2055, these scenarios spell out some specific realisations in the range of plausible alternative futures by defining certain trajectories, downside risks, and new trends for the years to come. The four scenarios (base case 'Business-as-usual', worst case 'Survival of the Fittest', best case 'Green Cooperation', surprise case 'Climate Tech') were established as storylines in a foresight exercise for multiple scenario generation and then quantified in Multimod, a cutting-edge multi-fuel multi-sector energy systems model (Ansari & Holz, 2019; Ansari, Holz, & Al-Kuhlani, 2019).

Specifically, we present the numerical results (energy production, consumption, and transformation) for three case study regions: the Middle East, China, and Latin America. Furthermore, we deepen the discussion on stranded assets by introducing a novel index, calculated from the model results. The index identifies which fossil-fuel sectors in the three regions may be most prone to climate-related asset stranding and deserve the greatest attention from both national and international policy-makers. We supplement this analysis with a discussion on the push and pull factors towards a green transformation in the case study regions.

Our article aims at introducing the important (and inevitably controversial) concept of stranded assets to development researchers. Therefore, the study relates to both the literature on energy systems and on the development of research-rich economies. By using our own scenarios for regional analyses as well as the novel stranded asset index, we present fossil futures in the case study regions from a new angle. Moreover, we aim at providing researchers and decision-makers with insight into where the risk for asset stranding is highest and where attention is most needed.

The remainder of this paper proceeds as follows: First, we elaborate on the method that was used to generate the global framework scenarios, the setup of the partial equilibrium model Multimod, and our stranded assets index. Then, the paper continues with a brief synopsis of the global framework, before focusing on the regional analysis and findings from the stranded asset index. Subsequently, we discuss selected issues that influence the behaviour of fuel exporters – the prospects of a green transformation, the status of economic diversification, economic resilience, and the challenges from an unequal burden-sharing in climate change mitigation. We close the paper with a summary of our findings.

2. Methods

We analyse the results of four holistic narratives on energy and climate towards 2055 regarding the (dis-)incentives for major fossil-fuel producers to participate in a transformation of the energy sector and economy.

2.1. The global frame

The global frame is provided by four holistic narratives. These are the result of a three-step procedure that unites qualitative and quantitative methods. A detailed description of the individual steps can be found in Ansari and Holz (2019). In a first step, we establish qualitative storylines using scenario foresight. Secondly, we extract key parameters from the different storylines and compute results for energy and climate with the numerical model Multimod. Lastly, in a partially iterated process, we check for consistency between storylines and model results and finally integrate both to holistic narratives.

This approach aims at moving beyond the shortcomings of many scenario-related studies (see e.g. De Cian et al., 2018; Moallemi & Malekpour, 2018; Sharmina et al., 2019). Depending on the exact model, conventional numerical outlooks in the energy sector are based on detailed representations of energy infrastructure or market formations (Subramanian, Gundersen, & Adams, 2018); however, and as such, they rarely go beyond a simple extrapolation of the past and continuation of current trends. Yet, the energy system itself encompasses various dimensions and is contingent on a multitude of influences and drivers, many of which lie outside of the realm of engineering and sometimes even economics (Miller, Richter, O'Leary, & Science, 2015).

The first step – the qualitative analysis – 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 (Mietzner & Reger, 2005). 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), 2018, p. 23). It is a "reframing process" that involves exploiting insights to think about the future (Burrows & 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).

More precisely, the process involves four steps which are done in mixed desk research with group work in a scenario workshop[1]. The group work is designed to overcome the cognitive limitations and biases of individuals. First, and prior to the workshop, the participants identify key assumptions and discuss them at the workshop, in addition to the definition of prevailing megatrends. The accepted assumptions provide a framework of unchallengeable rules for the scenario generation. Second, the participants perform a structured brainstorming of the research question ("What are the drivers of the renewable energy transition until 2050?") in the STEMPLE + framework. This step involves both silent and group brainstorming as well as clustering. The results are key drivers, which have critical influence on the system. Third, participant groups develop plausible alternative futures by combining logically consistent drivers. Each collusion of two driver realisations produces an initial scenario, which is 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.

In a second step, we implement the raw narratives in the numerical energy and resource market model Multimod, to which the next subsection is dedicated. For this, we extract key variables along the four raw narratives, adapt the input parameters to mimic the settings of each storyline, and calibrate the model to match the events. The input parameters to be varied along the scenarios include reference demand, production and transportation costs, and technology availability and efficiency, as well as the availability of certain transport routes. Of course, climate policies vary greatly between the scenarios. Model results include a full numerical description of the energy system, including energy production and consumption, as well as capacity investments and trade flows.

In the last step, 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 technological issues. This integration aspect involves checking both results and storylines for consistency.

2.2. Modelling approach for energy system variables

We use a game theory approach to energy and resource markets to investigate how the energy system in certain regions could develop under different scenarios. In particular, we adopt *Multimod*, a numerical, spatial, partial equilibrium model of the global energy system (see e.g. Huppmann & Egging, 2014; Oke, Huppmann, Marshall, Poulton, & Siddiqui, 2018). Appendix A contains a technical description of the model.

Our approach is to model the (global) energy system as a game with multiple classes of players located in the various regions of the globe (so-called nodes). From a microeconomic perspective, each node contains markets for different energy carriers[2] (see Fig. 1). The energy carriers considered by the model are natural gas, coal, lignite, and crude oil on the fossil side as well as hydro, biofuels and other renewables (solar / wind / geothermal) and nuclear energy on the upstream level. Some energy resources can be used directly, others need to be processed first (electricity from all fuels and oil products from crude oil). Transportation, processing, and energy storage is provided by the respective service agents.

In every node, supply-side players extract (primary) energy resources and seek to maximise the discounted sum of annual profits from sales to consumers worldwide. The latter aim at maximising their utility from the consumption of energy services. Consumers are separated into three different kinds of players with separate utility functions, representing individual demand sectors (residential, industry, transport). Moreover, markets contain service agents (international transporters, power plant and refinery owners, and energy storage owners) who maximise the sum of annual profits from offering their services to the market.

Solving the model now amounts to determining the open-loop[3] Nash equilibrium of a deterministic, discrete-time, finite-horizon, non-cooperative, one-stage game. The solution to the game is an equilibrium in which no market participant (suppliers, services agents, consumers) has an incentive to unilaterally deviate from his equilibrium actions, given the other participants' actions.

2.3. Calculating the risk of stranded assets

The definition of asset stranding given in the introduction is merely a meta-definition, as the topic is overly broad and research is still in its infancy (Caldecott, 2018). Therefore, approaches to measuring stranded assets vary significantly and, in many examples, still reflect the early stage of the field. IRENA (2017) contains a broad, yet not comprehensive, survey of the literature and their approach to (measuring) stranded assets. Other examples include Pfeiffer, Hepburn, Vogt-Schilb, and Caldecott (2018), who consider the difference between baseline projections and alternative projections that meet climate goals in energy models, and Lewis, Voisin, Hazra, Mary, and Walker (2014), who carry out algebraic elaborations for different value streams between the baseline of IEA assumptions and strong climate policies. Löffler, Burandt, Hainsch, and Oei (2019) also make a scenario-based assessment, but they introduce limited foresight and imperfect planning into their model. Most authors employ the Value at Risk approach in different settings (e.g. Dietz, Bowen, Dixon, & Gradwell, 2016; Spedding, Mehta, & Robins, 2013). Some macroeconomic assessments also model stranded assets explicitly, e.g. as an asset stock that varies with different policy settings (Van der Ploeg & Rezai, 2016). Besides these, most assessments of stranded assets are rather qualitative (Buhr, 2017; Schlösser, Schultze, Ivleva, Wolters, & Scholl, 2017), including structured workshops (Bang & Lahn, 2019).

For this study, we propose a novel index that is tailored towards measuring stranded assets in our scenario framework. It reflects the risk to which specific sectors are exposed, and, hence, can give

[1] 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.

[2] Energy carriers are energy forms (e.g. electricity) or energy-containing substances (e.g. coal), which will ultimately be converted to energy services (e.g. heat, work).

[3] In an open-loop game, players cannot observe the actions of their opponents.

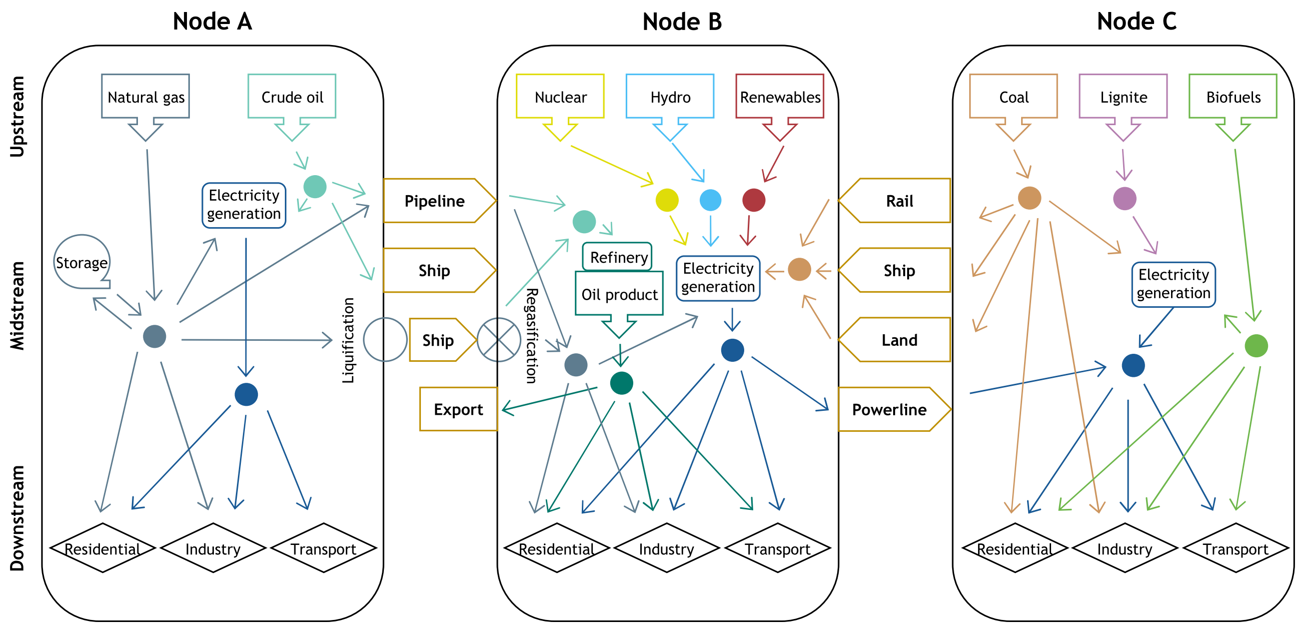

Fig. 1. Illustration of the value chain in Multimod. Based on Ansari and Holz (2019).

an indication of where and to wat extent asset stranding might occur. The index is calculated 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 is at high risk of a stranding of its production and infrastructure assets. Appendix A contains a summary of the notation.

Specifically, for each specific fossil industry in a specific node (region), the index $I_{s,f}$ measures:

- the sectoral uncertainty, proxied by the largest possible average difference in capacity utilisation between any two scenarios ($\Delta^{\max}_{\text{avg}}\text{util}_{s,f}$), and
- the relative importance of that sector, proxied by the share of that fuel in all domestic energy production ($\text{share}_{s,f}$).

$$I_{s,f} = \sqrt{\Delta^{\max}_{\text{avg}}\text{util}_{s,f} * \text{share}_{s,f}} \tag{1}$$

$$\Delta^{\max}_{\text{avg}}\text{util}_{s,f} = \frac{1}{(\text{card}(Y) - 1)} \max_{i,j,i \neq j} \left\{ \sum_{\substack{y \in Y \\ y > 1}} |util_{y,s,f,i} - util_{y,s,f,j}| \right\} \tag{2}$$

$$\text{share}_{s,f} = \frac{\sum_{\substack{h \in H \\ y > 1}} q^P_{(\cdot),\,\text{argmax}(\text{avg}(\text{util}_{s,f}))}}{\sum_{\substack{h \in H \\ y > 1 \\ f \in F}} q^P_{(\cdot),\,\text{argmax}(\text{avg}(\text{util}_{s,f}))}} \tag{3}$$

We compute the index, according to (1), as the geometric average of both components.

The first part (uncertainty in capacity utilisation $\Delta^{\max}_{\text{avg}}\text{util}_{s,f}$) is a proxy for stranded assets. It is given by the largest possible time-averaged absolute divergence in capacity utilisation between any two scenarios over all time periods $y \in Y$ (2). In other words, we first compute the average spread of production capacity utilisation (in absolute values) between any two pairs of scenarios; then, we choose the biggest average difference among them. This approach reflects the idea that stranded assets are unanticipated write-offs of (productive) assets:$\Delta^{\max}_{\text{avg}}\text{util}_{s,f}$takes the scenarios as given and measures the range of uncertainty in the usage of productive capacities $\text{util}_{y,s,f,i}$[4].

However, such uncertainty would only be an economy-wide concern, if the sector, and hence its capital stock, occupies a significant share of the domestic (energy) production. Therefore, $\text{share}_{s,f}$, the second factor in the index, measures the relative share the sector has in overall national energy production accumulated over the outlook period. Eq. (3) uses the scenario with the highest utilisation rate (indicated by $\text{avg}(\text{util}_{s,f})$) for this. Hence, the index increases in a larger share of the sector, as asset stranding would become a greater problem if an essential part of the economy were hit.

Lastly, we vary the time frame Y that is considered by the index. First, we compute the index for the entire period from 2015 to 2055. Then, we compute index results only considering the mid-term (i.e. model results for 2025 and 2035) or the long-term (i.e. model results for 2045 and 2055). Situations are possible in which the pair of most distinct scenarios (reflected in $\Delta^{\max}_{\text{avg}}\text{util}_{s,f}$) differs between mid-term and long-term, which is why the index for the entire period is not necessarily the mean of the other two numbers.

3. Four narratives for global energy

Using the three-step approach described in Section 2.1, we establish four distinct scenarios for the global energy system. This section gives a brief account of the four narratives, while their full (global) account can be found in Ansari et al. (2019). The narratives

[4] If all scenarios are extremely 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 that at least two scenarios diverge 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.

do not aim at predicting the state of the global energy system by the year 2055 but rather give bounds to the range of plausible alternative futures by defining certain trajectories, downside risks, and new trends that could significantly affect developments in the years to come. Fig. 2 illustrates the main events in the four narratives, and Fig. 3 depicts selected key indicators of energy and climate.

- **Business as Usual:** The Paris Agreement is widely respected and fulfilled but not succeeded by more ambitious aims. Increasing, carbon-intensive energy demand can only partly be offset by progress towards decarbonisation in some emerging economies and the EU. Increased public awareness following an intensification of weather events accelerates the pace of global energy transition towards 2030. However, inertia from conflicting interests between and within nations cannot be overcome, leading to limited decarbonisation efforts and incipient degrowth and climate disasters towards 2055.
- **Survival of the Fittest:** Increasing (geopolitical) tensions contribute to an erosion of the international order, which brings international climate policy (besides isolated initiatives) to a halt. A lack of investment and technology cooperation depress the development of clean energy, and fossil fuels witness a new age. As a result, climate disasters cause new migration waves, further fuelling isolationism. Finally, the acceleration of emissions leads to climate catastrophes in the 2050 s, and only the richest nations are able to afford adaptation measures.
- **Green Cooperation:** Supported by a stabilisation of international relations and greater cooperation, climate policy soon becomes an international focus area. Poverty eradication and climate change mitigation are understood as dual objectives, and large technology transfer and multilateral development initiatives help to spur leapfrogging in the developing world. A holistic transition in society, technology, and policy takes place and enables green modernity, in which least-emission standards are the status quo. Consequently, the world enters a trajectory of green growth.
- **ClimateTech**: Decarbonisation efforts weaken as decision-makers anticipate promising technological advances in energy and climate engineering. While some technologies eventually prove useful, others bear dangers and require the re-empowerment of international bodies to provide regulation. Although this provides new momentum for decarbonisation, actual efforts remain limited as fossil fuel producers' interests remain integral for many nations, and others turn technologies into dogmas (such as China's ambition in nuclear fusion). Towards 2055, the world is in a temporarily stable emission corridor, but long-term issues (such as the effects of population growth) remain to be addressed.

4. Four different energy futures in the developing world: The Middle East, China, and Latin America

4.1. Regional energy systems

The following subsections provide an overview of the scenario results for the three case study regions – the Middle East, China, and Latin America. We present model results for the regional energy systems, i.e. primary energy production, final energy consumption, and the electricity generation mix. Model results are differentiated by scenario and period. A brief discussion of the results provides insights into the (variety of) futures into which the respective energy systems can develop. The results are then used in the subsequent discussion of whether each region is more likely to turn to a future of fossil fuels or a green transformation, and to what extent uncertainty can result in asset stranding.

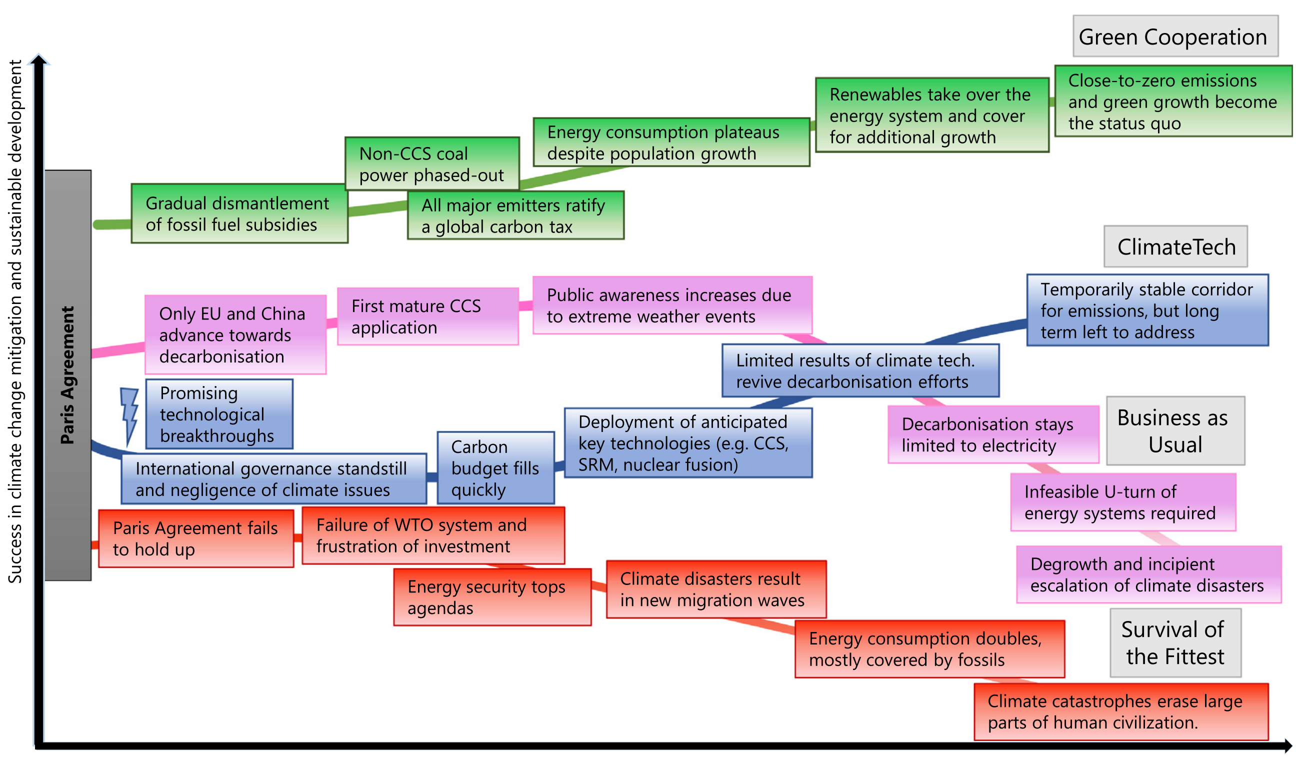

Fig. 2. Timelines of the four narratives. Based on Ansari et al. (2019).

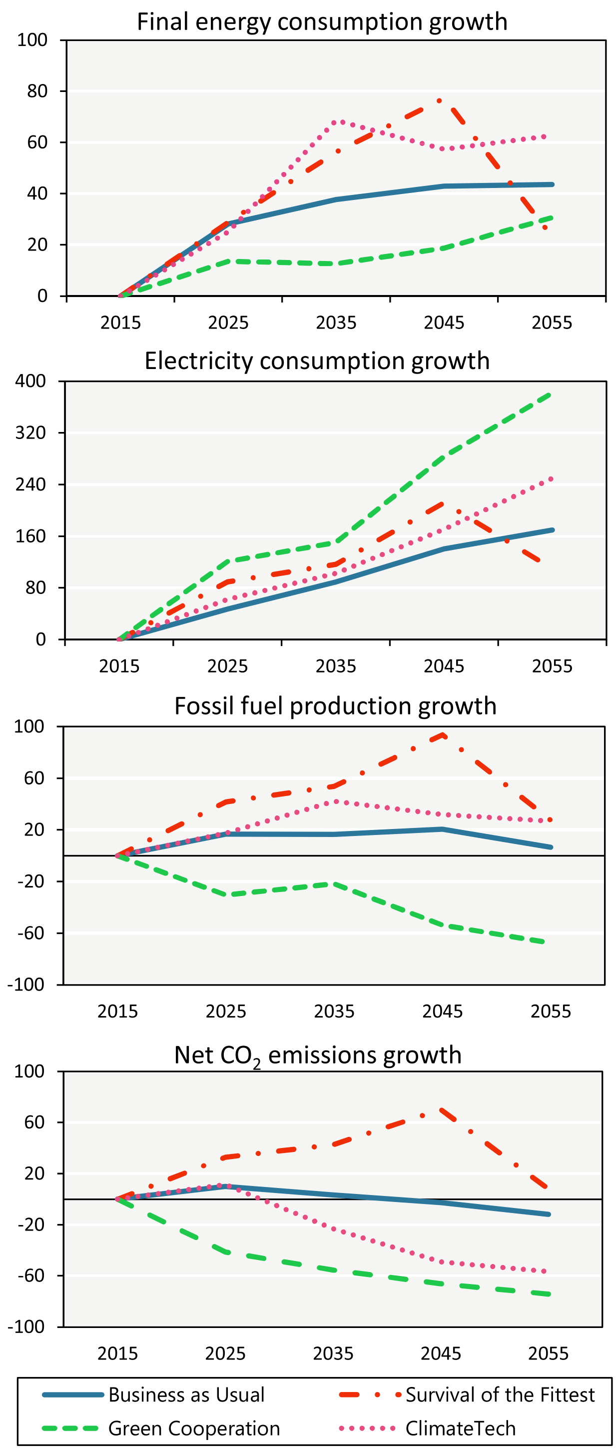

Fig. 3. Growth rates of global key indicators in the four narratives (in % changes from 2015 values). Based on Ansari et al. (2019).

4.1.1. The Middle East

The Middle East[5] has long been an idiosyncratic and special place in the global energy economy. Approximately one-third of the global crude oil production originates in the region, in addition to significant natural gas exports. Still, besides climatic similarities and governments which are either absolute monarchies or malfunctioning democracies, there are few similarities between the different nations of the Middle East. Past and present energy producers range from the world's richest nations (e.g. Qatar, UAE) to its least developed countries (e.g. Yemen). While some Middle Eastern nations are large energy exporters (e.g. Saudi Arabia, Iraq), others are strongly dependent on fuel imports (e.g. Jordan, Lebanon).

The scenarios foresee different changes in the magnitude of regional energy demand (Fig. 4), but no large discrepancies in its very composition. All scenarios but Green Cooperation consider an increase in demand, reflecting (population) growth and urbanisation, albeit with virtually no integral policies to decouple either from energy demand. As discussed in the literature (e.g. Hochman & Zilberman, 2015) its vast oil reserves make the region prone to the coupling of energy supply with demand. Whatever global markets do 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 in the region in all scenarios (except Green Cooperation) but sees almost no significant increases. On the contrary, natural gas production accelerates quickly in all scenarios but continues to remain the smaller of the two industries. Renewable energy production only reaches significant levels towards the 2050 s in Business as Usual, and from the 2030 s onwards in Green Cooperation, where it replaces much of the crude oil supply.

Regarding power generation (Fig. 5), the variation between the scenarios stays limited. Oil-fired stations are phased out in all scenarios by the mid-2020 s for economic reasons, leaving behind unused capacities. 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 gas-fired power plants with CCS in the 2020 s and 2030 s, in addition to a large deployment of renewable energies towards the end of the outlook period.

4.1.2. China

China's vast economic expansion over the past decades has shaped an equally expanded energy system. China is both a major producer and consumer of fossil fuels. Heretofore, its most relevant energy resource is coal, which makes up the majority of its present production but also of its direct (final) and power-based consumption. These high coal consumption levels especially mean China is affected by air pollution issues, but an increasing tendency towards stricter environmental regulations has been apparent over the past five years. Besides coal, China is a high consuming country for oil and natural gas. Despite considerable crude oil and (to a lesser degree) natural gas production, China is a net importer of both resources.

On the demand side (Fig. 6), variation between the different scenarios is only modest, and trends differ in pace rather than shape. All scenarios witness a phase-out (or at least drastic reduction) of direct coal usage and the massive electrification of the country, especially Green Cooperation and ClimateTech. The presence of natural gas increases in the 2020 s and 30 s. However, while this trend continues in Survival of the Fittest, the other scenarios foresee a stagnation or even slight decrease in demand towards the 2050 s. The consumption of oil products does not exhibit strong growth rates in the mid-term and even displays diminishing rates towards the long-term.

Primary energy supply, however, differs considerably between the scenarios. All scenarios but Green Cooperation consider

[5] In our model, the node 'Middle East' includes the Arabian Peninsula (Saudi Arabia, Yemen, Oman, UAE, Kuwait, Qatar, Bahrain), the Levant (Jordan, Lebanon, Syria, Palestine, Israel), Iraq, and Iran.

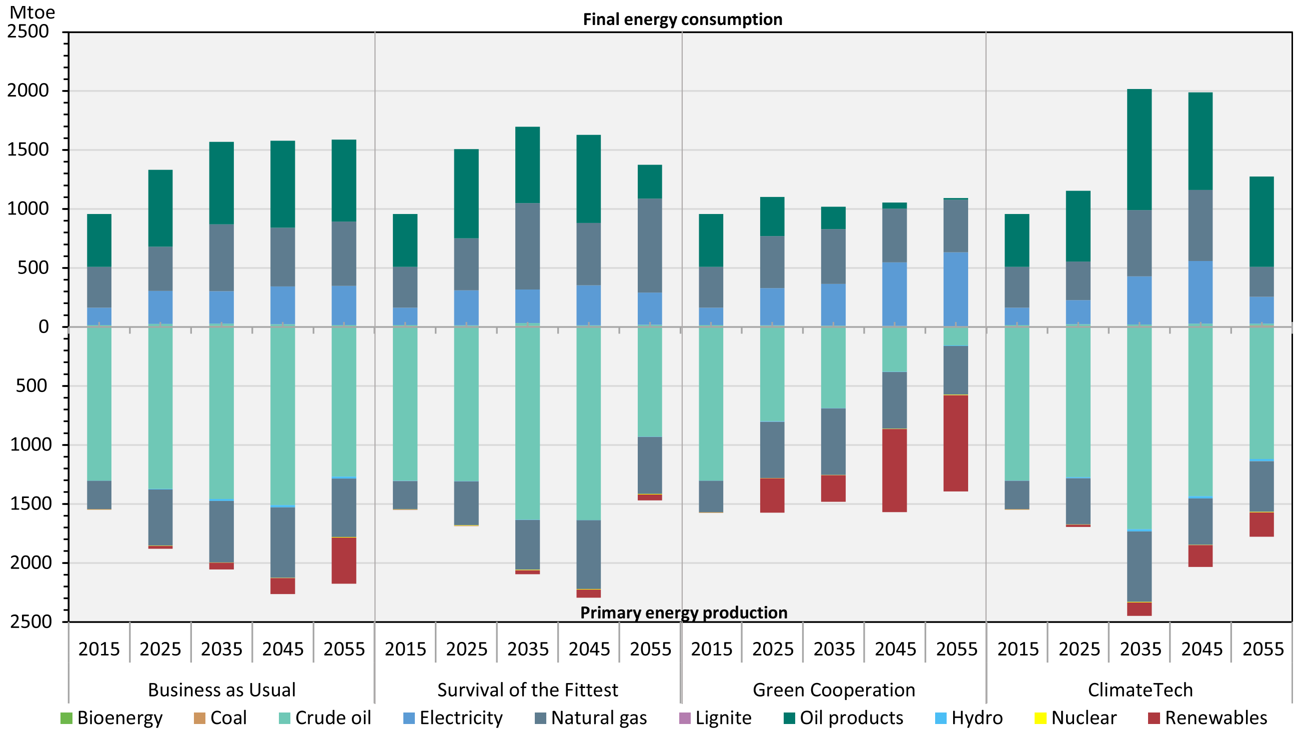

Fig. 4. Final energy consumption (top) and primary energy production (bottom) for the Middle East region in the four scenarios.

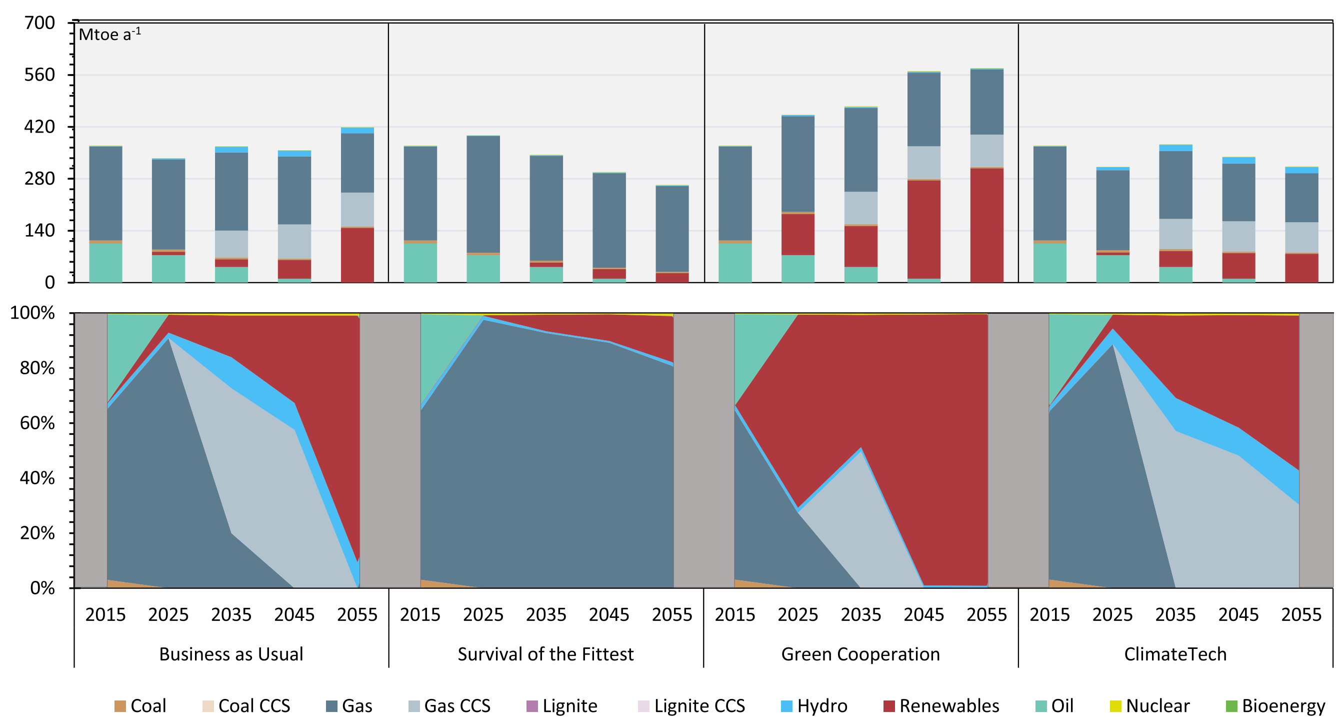

Fig. 5. Power plant capacities (top) and electricity mix (bottom) for the Middle East region in the four scenarios.

shrinking but still dominant coal production over the outlook period. Other fossil-fuel sectors remain nearly unchanged in these scenarios. In Green Cooperation, however, large volumes of renewables enter the energy system, starting in the 2020 s and surpassing 50% of supply by 2045.

The Chinese power sector (Fig. 7) exhibits drastic changes. In all scenarios, the importance of conventional coal-fired plants decreases significantly. While a share of approximately a quarter remains in Business as Usual and Survival of the Fittest, a phase-out is completed in Green Cooperation and ClimateTech by 2025 and 2035, respectively. The role of hydropower persists, while some gas-based power is added to the system in all scenarios (but to varying extents and, if beyond 2035, mostly in connection with CCS). In Green Cooperation, massive gains are made by renewables, and ClimateTech sees the drastic expansion of nuclear energy.

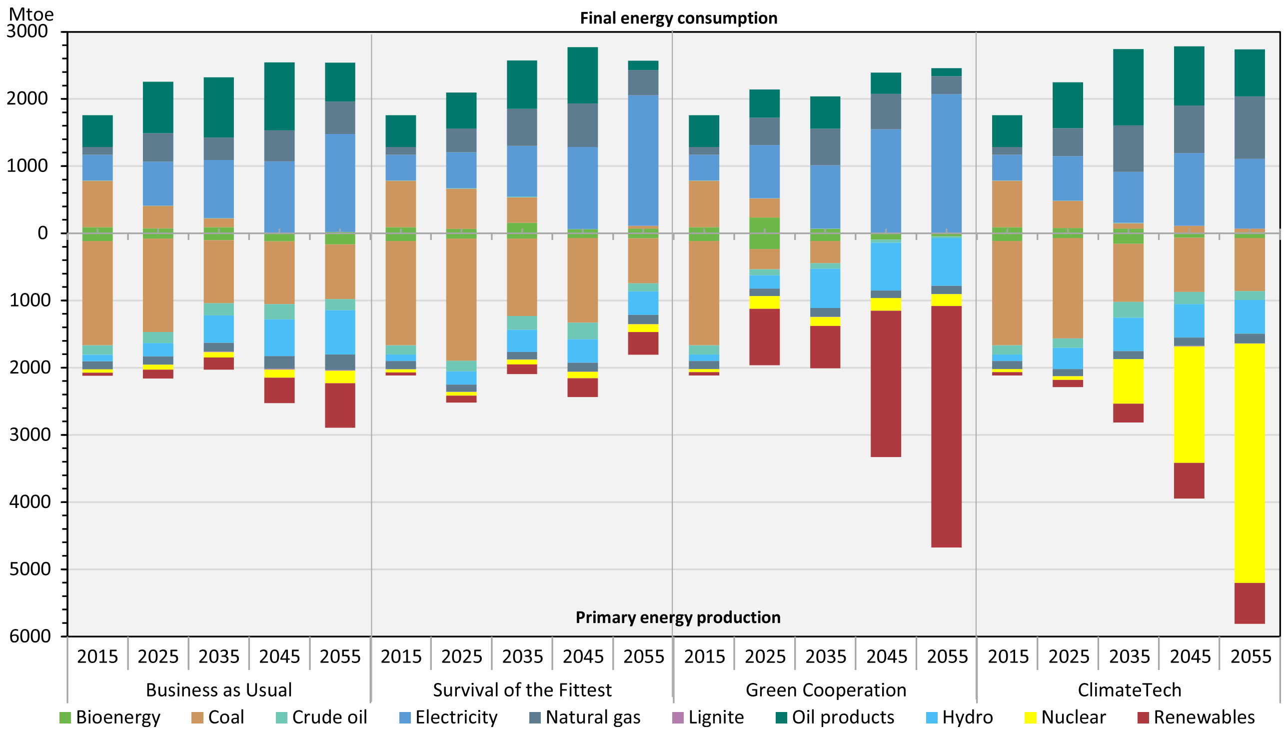

Fig. 6. Final energy consumption (top) and primary energy production (bottom) for China in the four scenarios.

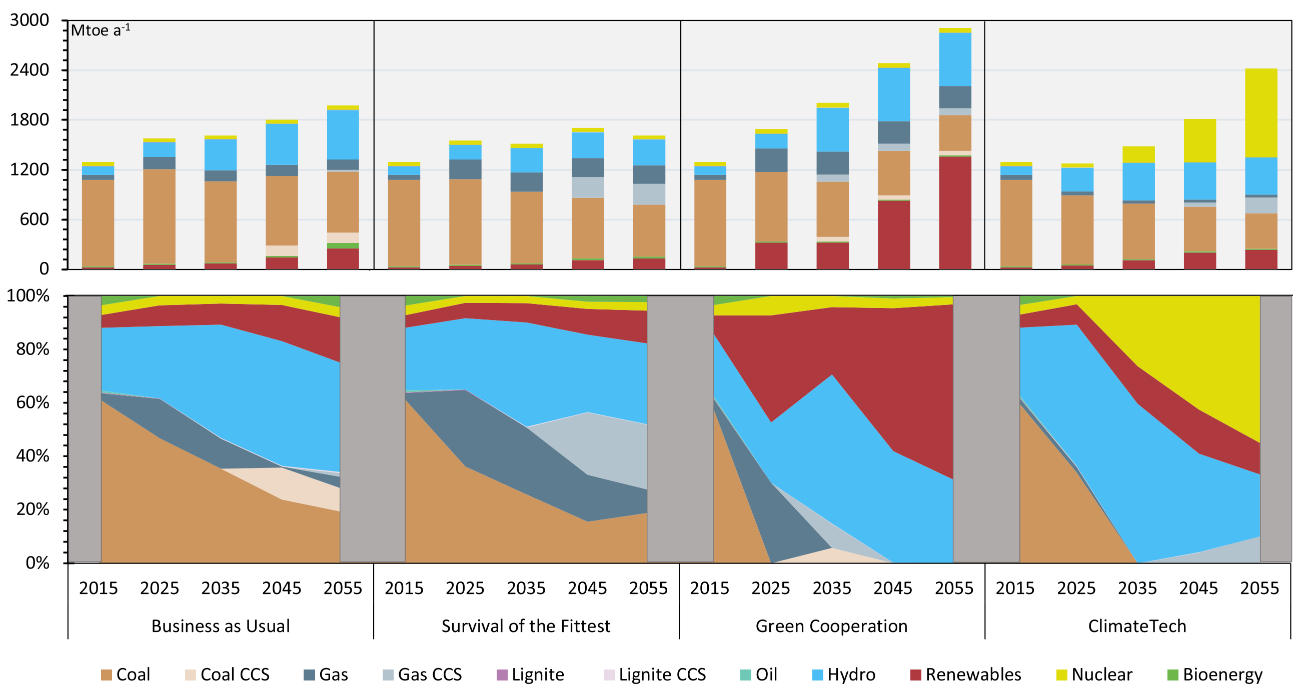

Fig. 7. Power plant capacities (top) and electricity mix (bottom) for China in the four scenarios.

4.1.3. Latin America

Final energy demand in Latin America[6] increases in all scenarios towards 2025 but shows different trajectories for the years to come (Fig. 8). Business as Usual foresees the stagnation of demand and a substitution of biomass consumption with electricity, while Survival of the Fittest and, even more so, ClimateTech, project a fast acceleration in energy demand. Especially in ClimateTech, the usage of (domestic) oil products for the growing industry shapes this pattern. Nevertheless, increasing electrification also raises the importance of electricity in terms of final energy demand.

The South American power sector witnesses neither many changes nor variety: In all scenarios, hydropower continues to be the dominant source of electricity (Fig. 9). In almost all scenarios, hydro energy is complemented 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, natural gas supply nearly half the power sector in the mid-run). ClimateTech and Green Cooperation, instead, show some CCS-based supply in the mid-term, and

[6] In our model, the node 'Latin America' includes all South American nations (excluding Mexico) as well as the Caribbean island nations.

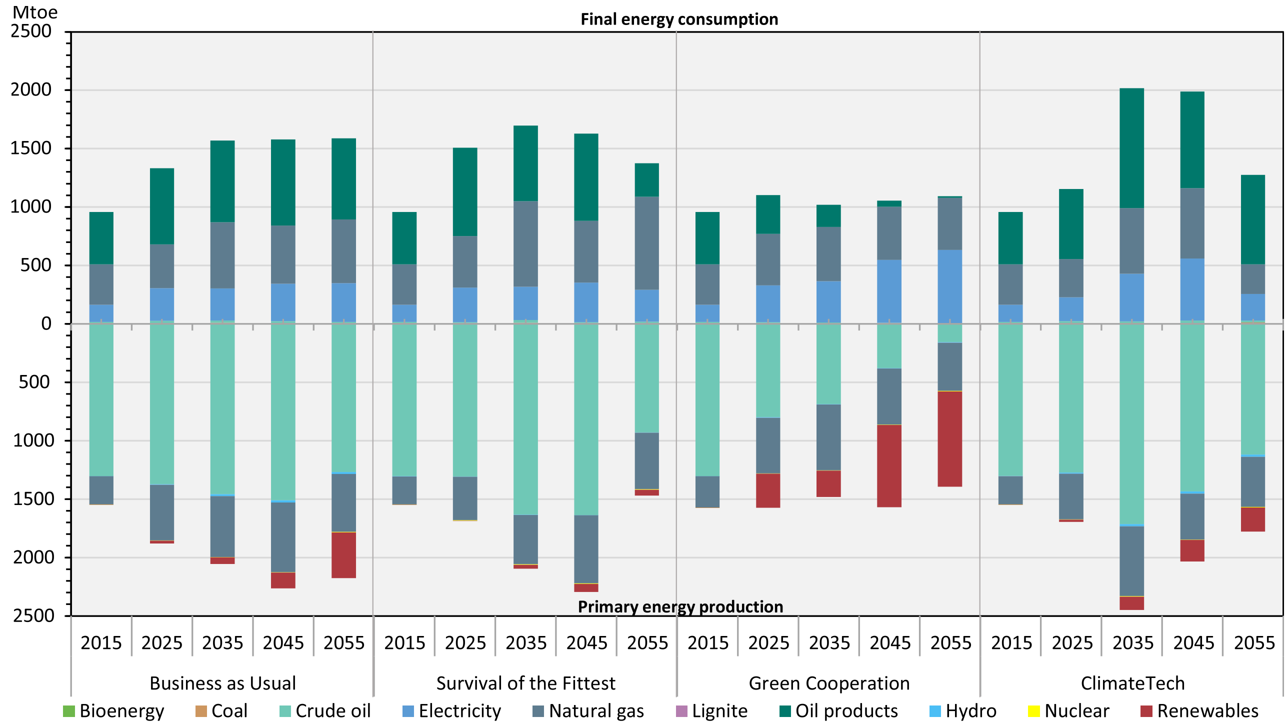

Fig. 8. Final energy consumption (top) and primary energy production (bottom) for Latin America in the four scenarios.

Business as Usual contains a phase-out of coal and gas, while some bioenergy plants are added in the 2040's.

4.2. Asset stranding compared

Table 1 provides the values of the stranded asset index for each case study region and sector, separated into mid-term effects until 2035 (i.e. including the modelling results for 2025 and 2035), long-term effects (i.e. including the modelling results for 2045 and 2055), and effects over the entire modelling period.

The average across all sectors is remarkably similar for all three regions, ranging between 0.18 and 0.22. These values are rather low, considering the entire range of the index. While this implies that asset stranding might not be a widespread risk to the respective regions, the results should not 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-weighing mechanism. Secondly, the index does not consider downstream technologies (e.g. power plants). Thirdly, the values refer to the stranding risk from uncertainty in the development of the sectors

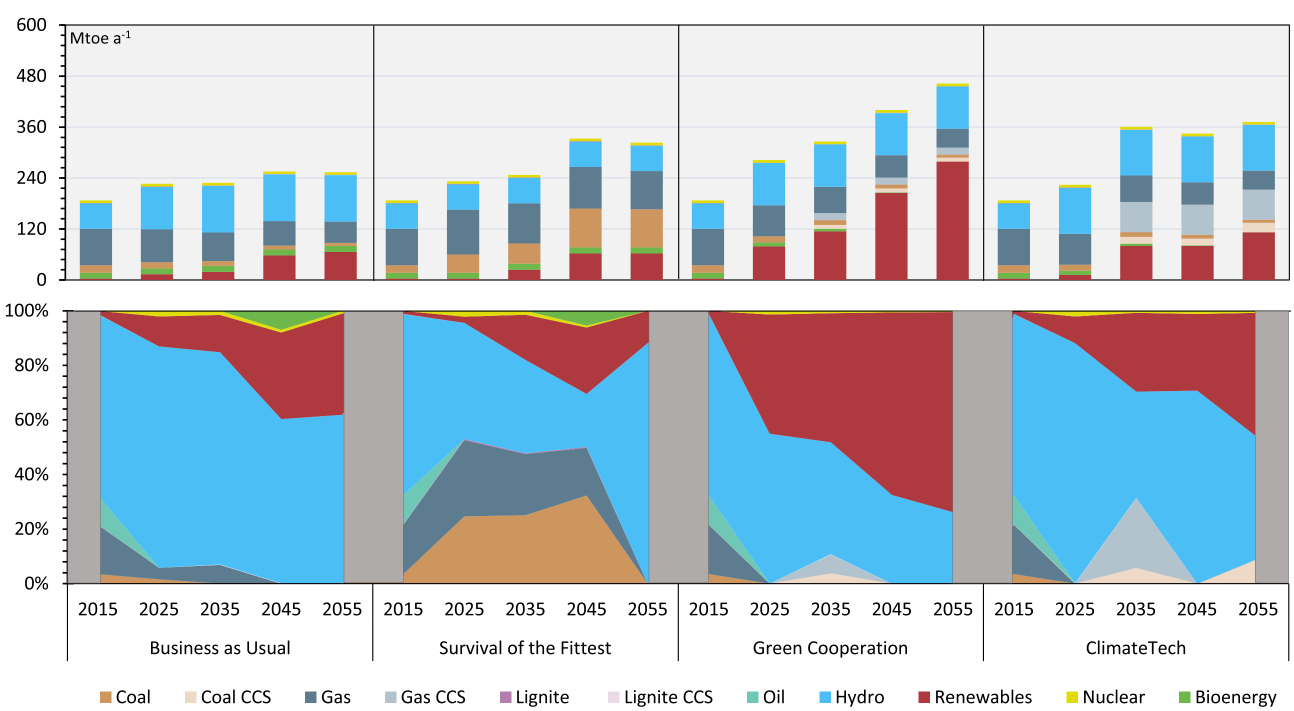

Fig. 9. Power plant capacities (top) and electricity mix (bottom) for Latin America in the four scenarios.

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

		Coal	Crude oil	Natural gas	Lignite	Average
Middle East	Until 2035	0.02	0.49	0.24	0.00	0.19
	After 2035	0.02	0.59	0.28	0.00	0.22
	Total	**0.02**	**0.55**	**0.16**	**0.00**	**0.18**
China	Until 2035	0.60	0.19	0.05	0.03	0.22
	After 2035	0.61	0.23	0.03	0.04	0.23
	Total	**0.61**	**0.21**	**0.04**	**0.04**	**0.22**
Latin America	Until 2035	0.27	0.39	0.12	0.03	0.20
	After 2035	0.23	0.55	0.19	0.02	0.25
	Total	**0.18**	**0.48**	**0.16**	**0.03**	**0.21**

but not potentially certain components of trajectories (e.g. lower capacity usage in all scenarios because of technological progress).

For individual sectors, the index confirms a large potential for asset stranding. At the forefront for this are the Middle Eastern crude oil sector (0.55), Chinese coal production (0.61), and the Latin American crude oil sector (0.48). Middle Eastern crude oil is eventually persistent in all scenarios but Green Cooperation; however, a global shift to renewables ultimately comes with a widespread oil phase-out that hits the oil-dependent region hard. China's coal sector is a very similar case: Coal supply accounts for the majority of primary energy supply, and despite a 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; however, the relative importance of oil is lower than in the Middle East, which is why the index exhibits lower values.

Index values for the natural gas sector are only small-to-moderate for all regions and do not exceed 0.3. This results from two central factors: First, natural gas consumption continues in each scenario (although to varying degrees), which is why the sector's prospects are less uncertain. Second, none of the three regions is completely dependent on natural gas supply: China's production is limited anyhow, and the other two regions also produce large amounts of either crude oil or renewables, depending on the scenario. Clearly, this would not be the case for individual nations (e.g. Qatar). This also applies to the Latin American coal sector: The region-wide index is low; nevertheless, coal production is distributed unevenly across Latin American countries, which is why some countries would be hit significantly in Green Cooperation (e.g. Colombia). Values for lignite are barely above 0, as the sector's production is not high in any of the case study regions, nor does any scenario foresee significant lignite supply (and, hence uncertainty) in the future.

Regarding the timing of stranded assets, the values for up to and after 2035 do not show major differences. Most long-term values are slightly more elevated (about 0.05 above the values for the mid-term) and reflect the increased uncertainty over time that is inherent to scenarios (typically referred to as the 'scenario cone', see Amer, Daim, and Jetter (2013) and Ansari, Holz, and Al-Kuhlani (2020)) An exception to this is Latin American coal, which exhibits a slightly higher (0.05 difference) index for the mid-term. The only sectors with larger differences between mid-term and long-term are the Middle Eastern and the Latin American crude oil sectors (differences of 0.10 and 0.16, respectively), whose risk increases significantly over time. This finding is connected to the amplified variation in crude oil production towards 2055 in the different scenarios.

5. Resource exporters in the face of uncertain climate policy

As the index-based analysis has shown, each of the case study regions contains at least one sector that is subject to significant stranded asset risk. Hence, greening the economy and phasing-out fossil resource sectors in a structured (planned) way has advantages for resource owners. It would considerably reduce the uncertainty of future capacity utilisation and future revenues and, thereby, contribute to economic stabilisation.

Countries may even find new comparative advantages in a decarbonised world. Due to its unique capabilities surrounding technology commercialization and manufacturing-related innovation (Nahm & Steinfeld, 2014), China has a comparative advantage in the production of photovoltaics (Algieri, Aquino, & Succurro, 2011; Zhu, Xu, & Pan, 2019). Moreover, given their vast natural endowment in solar radiation, Middle Eastern countries could become large exporters of solar energy to Europe (Hepbasli & Alsuhaibani, 2011; Pazheri et al., 2011; Trieb, Schillings, Pregger, & O'Sullivan, 2012). Latin America has similar prospects, for instance in the biofuel sector (La Rovere, Pereira, & Simões, 2011).

However, although renewables and other new technologies have become cost competitive, they often still require higher upfront investment than older (often dirty) technologies (Fankhauser & Jotzo, 2018). Yet this is not the only reason why countries have only little incentive to turn away from their natural endowments, despite the prospects of tightening climate policies. It is crucial to accept that the transformation of resource-rich economies is entirely different from greening a resource importer (see e.g. Okereke et al., 2019). Although defying a comparative advantage in primary resource sectors can help sophisticated exports (Lectard & Rougier, 2018), there is no doubt that fossil-resource owners receive substantial revenues from exports in addition to the provision of domestic energy security.[7] Unilateral transitions, especially away from the export of fossil fuels, are unlikely to foster economic improvements – at least not in the short run.

Among the numerous push and pull factors that may either loosen or strengthen the carbon lock-in that resource suppliers face, the following subsections discuss four selected factors in more detail. These are uncertainty on the eventual trajectory of global energy and climate, resource dependency, economic resilience, and the inequal prospective burden sharing.

5.1. Uncertainty in energy and climate policy

Bos and Gupta (2016) argue that stranded assets are not yet considered a major issue. Even without resorting to climate-change scepticism, the eventual direction of energy system and climate policies is uncertain. Energy outlooks[8] confirm that current global trends are not in line with the Paris Agreement but will instead lead to increasing emissions from growing fossil-fuel con-

[7] One should keep in mind that fossil resource endowment does not necessarily and automatically lead to domestic supply security because many fossil fuel rich countries in the developing world do not host large processing capacities to produce the final consumption energy commodity (e.g., refinery capacities for crude oil in Latin America) or the final consumption infrastructure (e.g., natural gas, which is hardly consumed in developing countries).

[8] Energy outlooks are (groups of) scenarios that explore the future of energy and related fields. They can depict future trajectories that extrapolate current trends, "*what-if?*" settings, best and worst cases, and pathways towards reaching certain goals. Outlooks are relevant for decision-making in business and policy.

sumption (see e.g. Ansari et al., 2020; Paltsev, 2017; Weber et al., 2018). Moreover, even some Paris-compliant scenarios actually depict futures with growing fossil-fuel markets, often under the assumption of carbon capture and negative-emission technologies (Ansari et al., 2020). Hence, stranded assets are a risk for resource owners but no certain future.

So far, we have observed that this uncertainty has led governments to doubt the extent to which climate policies will eventually affect the future of fossil fuels and, hence, their revenues. However, in this paper, we show that the risk of asset stranding is very present and must be considered by policymakers. As shown in Ansari et al. (2020), our scenarios are exemplary but by no means unique in the large variation that they foresee between different – plausible – futures. These ultimately depend on the climate policy ambition but also on a multitude of other (political, social, technological, etc.) factors (see Section 2.1).

5.2. The resource curse and diversification

Regardless of stranded assets, it is well known that resource dependency bears numerous disadvantages. The Dutch Disease, i.e. de-industrialisation and real-exchange-rate overvaluations (Corden & Neary, 1982; Van der Ploeg & Venables, 2013), damage caused by volatile macro-indicators (Clements, Lan, & Roberts, 2008; Cavalcanti, Mohaddes, & Raissi, 2015), and institutional failure (Acemoglu, Verdier, & Robinson, 2004; Collier & Hoeffler, 2005) are summarised under the term 'resource curse' (Ross, 1999; Van der Ploeg, 2011). Recent turbulences in resource markets raised awareness of policy-makers in resource-rich countries once more in the wake of 2014′s oil price crash, for instance, when even wealthy Arab Gulf states saw their fiscal budgets being tightened (Ansari, 2017; Nusair, 2016).

The diversification of economies and energy systems is, therefore, increasingly seen as a key objective for many resource-rich economies (Alsharif, Bhattacharyya, & Intartaglia, 2017; Lectard & Rougier, 2018). However, tracking its progress is not a trivial task, and misconceptions are widespread. First, setting diversification on the political agenda or naming it as a policy goal is often (mis)understood as progress, although developments do rarely exceed this initial step. For the case of Saudi Arabia, for instance, diversification has been a part of development plans since the 1970 s, although achievements until now have been very limited (Albassam, 2015).

Second, it is hard to find a clear-cut indicator to measure resource dependency, as it can take different forms. Table 2 shows a selection of such indicators for particular countries in our case study regions and beyond. While the share of natural resource rents in GDP is the most intuitive indicator, its numbers can be misleading. Kuwait and Iraq, for instance, range above 30%, but other resource exporters exhibit surprisingly low rates (e.g. 3% in Bahrain and Colombia, 5% in Nigeria, and a modest 11% in the UAE). These numbers suggest that the corresponding countries have successfully diversified. However, the share of fuels in exports and the share of resources in government revenues – indicators that measure the diversification of exports and state finances respectively – reveal that this is not the case. Colombia's coal exports make up more than 50% of total merchandise exports, and oil accounts for as much as 96% of Nigerian exports. The UAE, which is frequently dubbed a very diverse economy (Flamos, Roupas, & Psarras, 2013), and Bahrain receive more than two-thirds of their public budget from resources. For Saudi Arabia, this number exceeds 90%. Therefore, diversification and dependence have to be understood as issues beyond the sectoral composition (as given by GDP shares), while export and budget can create significant lock-ins. We will discuss these issues further in the next subsection. For China, all indicators are eventually low, reflecting the that its resource sector is large in absolute terms but represents only a portion of its large economy.

Table 2
Fossil-fuel dependency for selected case study and other countries. Data: World Bank, IMF, EITI, ICTD.

Country	Natural resource rents 2016 (% of GDP)	Fuel exports 2016 (% of merchandise exports)	Resource revenues 2014 (% of total government revenue)
Algeria	12.3	94	52.8
Azerbaijan	15.4	87.5	67.6
Bahrain	3.2	55	88.6
Brunei	14.7	87.9	n/a
Cameroon	5.9	6.2	26
China	1.1	1.3	n/a
Colombia	3.4	50	19.3
Ecuador	3.8	33.1	28.9
Egypt, Arab Rep.	3.1	16.4	n/a
Indonesia	3.1	19.3	20.4
Iran, Islamic Rep.	13.5	67.4	n/a
Iraq	31.3	99.9	92.4
Kazakhstan	12.4	60.7	51.6
Kuwait	32.6	89.7	89.7
Mexico	2.3	4.9	n/a
Nigeria	4.9	96.3	53.9
Norway	4.1	53	24.5
Oman	19.7	62.53	42.6
Qatar	15.4	81.55	52.7
Russian Federation	8.8	47.19	n/a
Saudi Arabia	20	74.53	93.4
United Arab Emirates	11.4	20.23	68

Third, the diversification of resource-exporters' energy systems towards higher shares of renewables is slow. Ultimately, drawing revenues from fossil fuels is a stronger deterrent for investment in renewables than just consuming them (Fadly, 2019). In a generalised form, this often referred to as the 'carbon curse' – fuel-rich countries being destined to have higher CO2 emissions (Friedrichs & Inderwildi, 2013). Resource exporters often resort to controversial fuel subsidies for poverty eradication and the distribution of resource rents (Fattouh & El-Katiri, 2017). The carbon lock-in thus goes beyond the extractive industry and often includes oil-and-gas-dependent households, the transport sector, and domestic industries (Bos & Gupta, 2018). However, even decreasing these subsidies and/or investing in renewables do not necessarily contribute to decarbonisation. Environmental goals are often envisioned (Salam & Khan, 2018), but freeing production capacities for profitable exports is often the more integral aim of such measures (Blazquez, Manzano, Hunt, & Pierru, 2019).

5.3. Economic resilience of fossil-fuel producers

There is, clearly, no automatic mechanism that necessarily leads to economic downturns in response to global climate policy and/or asset stranding. Zenghelis et al. (2018) emphasise the role of adaptability and flexibility for economic resilience and the determining role played by institutions. Such economic resilience enables economies to adapt to new circumstances (such as a climate-constrained world) without major interruptions to their economic prosperity. This is largely an institutional issue, as "the biggest risk [...] tends to be vested interests capturing institutions and generating economic inertia. Strong and credible policies backed by public support are often prerequisites to overcoming such obstacles." (ibid., p. 70). They list factors that enable economic resilience and, thus, increase the potential for green transformations. A country is more likely to be resilient to shocks to its resource sector if it is able to promote (ibid.):

a) Policies that promote human capital,
b) Policies that support innovation,

c) Policies that are believable and credible;
d) productive, low-carbon infrastructure, i.e. low-emissions utilities and transport networks that support business-making and offer flexibility,
e) a willingness to take on entrenched interests,
f) a deepening of the financial sector,
g) the ability to recognise and address distributional issues,
h) openness to international markets (which can make a country more "sensitive" to volatility but also supports innovation).

In the Middle East, performance in these factors that enable economic resilience is limited at best. Human-capital formation receives considerable (public) investment, but results remain poor (Assaad, 2014); similar issues haunt knowledge production (Hanafi & Arvanitis, 2015). Infrastructure quality is divergent across the region but of insufficient quality in many areas; co-dependently, intra-regional trade is shockingly low, primarily due to non-tariff barriers (Malik & Awadallah, 2013). In general, trade, financial deepening, credible policy-making, and a willingness to pursue political reform are strongly constrained by high rates of (grand) corruption and mostly inefficient autocratic regimes. Social contracts in the Arab world, often in the form of authoritarian bargains, lead to tremendous inertia and burden all economic sectors (Assaad, 2014; Hinnebusch, 2019). Distributional issues are only tackled as far as stability, contingent on the fulfilment of these social contracts, is concerned.

Therefore, the current focus of regimes on generating revenues to finance social contracts constitutes a vicious circle that may ultimately prove fatal. Existing, rigid social contracts require resource rents, without which stability might be endangered (cf. Ansari, 2016). However, these rigid social contracts are also the very factor that prevents countries from creating the institutional framework necessary to develop economic resilience and, hence, reduce rent dependency. A depreciation of either productive assets or resource reserves may, thus, push fiscal states to their limits and erode social contracts. Hence, considering both institutional background and vast resource reserves, it is hard to envision the Middle East engaging in a transformation away from fossil-fuel based economic models.

China, in this regard, has a different position: Regardless of the numerous issues with China's streamlined and centralised system, it has enabled the country to grow into a flexible and innovative economy. China is strongly export-oriented and invests strongly in human capital formation, innovation, and infrastructure. Although its institutional and societal factors (i.e. the recognition and addressing of distributional issues, as well as the willingness to take on entrenched interests) must be viewed critically, China's policy-making is very credible. Moreover, good access to financial resources and/or a soft budget constraint in state-owned businesses as well as an increasing availability of infrastructure (including low-carbon infrastructure, e.g. for electric mobility) are additional factors that enable China to engage in an anticipatory planning process for industrial innovation and design of a green transformation (also see Nechifor et al., 2020 in this issue). As shown by our four scenarios, a systematic reduction of carbon-intensive industries is most likely for the Chinese energy system compared to the two other case study regions, given the trajectory of increased environmental protection that China has started to move on for the past few years, e.g. with its emissions trading scheme (Jotzo et al., 2018).

Nevertheless, the effects of China's planned economy are not solely beneficial for engaging in a green transformation. Cross-sector problem solving, including climate change mitigation, proves challenging in the country, as the economic (and political) framework is more effective towards measures for individual sectors (Richerzhagen & Scholz, 2008). Endowed with strong institutional and political hierarchies, decentralisation – despite the country's size and limited capacities for law-and-decision-making on the local level – has profited corruption (ibid.). Yet, overall, both our model results for the energy system and China's institutional background make a green transformation appear more likely (e.g. Burandt, Xiong, Löffler, & Oei, 2019).

Latin America, in turn, is a very heterogeneous region, also in the indicators suggested by Zenghelis et al. (2018). However, Latin American countries can be considered as exemplary of yet another model of political and economic governance than the two other case study regions. Although Latin America does not suffer from the same institutional rigidities as the Middle East, its low development level is a strong inhibitor to effective climate policy (Clarke et al., 2016). Therefore, innovation, human capital formation, policy credibility, and the provision of (low-carbon) infrastructure remain important challenges to solve. Similarly, at least for some countries in the region, a lower level of participation in international markets as well as a more difficult access to financial markets effectively pose challenges for a green transformation. Moreover, limited state capacities and corruption are detrimental for the Latin American governments' ability to take on entrenched interests.

Still, accountability is higher in the region than in the Middle East or China, and the recognition and addressing of distributive issues receives more attention. In sum, however, challenges seem to prevail in Latin America and achieving a green transformation will be a hard task.

5.4. Unequal burden-sharing

Our analysis has shown that resource-rich developing and emerging economies bear a high burden of climate change mitigation, i.e. they must engage in a substantial transformation of energy systems and economies compared to a business-as-usual scenario. Declining fossil-fuel production implies forgoing vast economic rents that may contribute to poverty eradication and growth. In contrast, for industrialised economies – of which many are fuel importers –, the burden of climate change mitigation is mostly limited to technological change (e.g. electrifying industry or traffic) and some stranded assets in the fossil-fuel processing industry (e.g. refineries and power plants).

First-comers to development have grown based on extensive resource extraction and carbon emissions, and their carbon footprint is generally higher than the footprints of most latecomers. Bos and Gupta (2019) highlight that that developing and emerging economies use their resources later but are subject to the request not to use them; this contrasts with "industrialized countries [having] deforested, built dams, and used fossil fuels to develop, but latecomers [...] being discouraged from engaging in these activities – thus limiting their scope to develop." (p. 6). Policies directed against fossil fuels can hence be (mis)understood as an environmental *kicking away the ladder* (Chang, 2002) – developed countries with large financial and political capacities using their influence to strongarm developing economies into forgoing growth.

Therefore, developed economies are eventually responsible for alleviating latecomers from much of the burden of climate change. However, the low-income world has so far been largely excluded from having their interests measured and managed in the climate-finance meta-system (Farbotko, 2020). Financial transfers to resource-owning countries are frequently discussed but remain highly unlikely (Bos & Gupta, 2019), and previous attempts on a smaller scale already failed (Sovacool & Scarpaci, 2016). Technology transfers to development latecomers are a crucial further measure to realise an inclusive global transition but ultimately rare (Pickering, Betzold, & Skovgaard, 2017). Beyond the resource sector, industrialised countries instead hamper green transformations, as their dirty industries are increasingly relocated to the developing world (Asghari, 2013).

Moreover, the energy transition implies significant geopolitical losses for fuel-producing latecomers, while industrialised importers gain power instead. Van de Graaf (2018) predicts that Saudi Arabia, Venezuela, Brazil, and Nigeria are the big losers of a transition, while Europe and Japan win. Overland, Bazilian, Uulu, Vakulchuk, and Westphal (2019) have similar findings: Most Middle Eastern nations lose geopolitical importance, while most European economies gain. Their results for Latin America, however, are more ambiguous. Stegen (2018) eventually finds both winners and losers among latecomers; however, also he concludes that European countries are mostly winners of the energy transition. Regarding China, Van de Graaf (2018) and Stegen (2018) find an increase in geopolitical influence, while Overland et al. (2019) project that China will eventually lose power.

Without drastic and inclusive policies targeted at alleviating some pressure from fossil-fuel producers, two dangerous paths are possible. First, fuel exporters manage to become more efficient, sustain low market prices, and flood the world markets with carbon-intensive resources, ultimately derailing the energy transition. Second, climate policies are eventually stringent enough to isolate fuel producers, thus destroying their economies and causing poverty and chaos.

6. Conclusions and policy recommendations

In this paper, we have discussed the risks from stranded assets in the developing world and for fossil-fuel producers in particular.

The study has taken a closer look at the Middle East, China, and Latin America by analysing the results of four interdisciplinary energy and climate scenarios. We have presented and elaborated different futures for the energy systems in the three regions, before assessing the risk for stranded assets with a novel index based on the model results. We have eventually shown that the overall risk of asset stranding in all three regions is moderate on average. Nevertheless, the Middle Eastern and Latin American crude oil sectors as well as the Chinese coal sector are prone to asset stranding and deserve special attention from researchers and policymakers in the years to come.

Moreover, we have discussed various aspects of the decisions that countries face concerning whether to stay invested in the fossil-fuel sector, namely the prospects of a green transformation, the uncertain future of global energy, missing diversification, and economic resilience. 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 an important role in enabling or hindering a green transformation. Rigid social contracts and low economic resilience but also being a very efficient fuel supplier hinders development and green transformations in the Middle East. China, on the contrary, has many of the factors required to be able to adapt to a climate-constrained world and is more likely to engage in a green transition, whose extent is yet to be determined and can potentially be influenced by policymaking. Latin American economies stand between these models and do not possess the same rigid institutional framework as that of the Middle East, but other factors make its economic resilience ambiguous.

Our research has implications beyond the case study countries investigated in this paper. Indeed, the same risk of asset stranding in the fossil-fuel sector and the challenge to find a model for green growth applies to all fossil-fuel intensive countries. It extends to countries with recent fossil-resource findings such as "Ghana, Tanzania, Guyana and Mozambique, where there are hopes that fossil fuel discoveries will transform their economies." (Bradley, Lahn, & Pye, 2018, p. 2).

We are aware of several limitations to this study. The stranded asset index considers only the upstream industry and disregards asset stranding in downstream sectors or associated industries. The share that is used to weigh uncertainty considers only the share of primary energy production made up by the fuels. Weighing the importance of the revenues from these fuels in total economic income would be a plausible alternative, but one beyond the realm of our energy sector model. We stress that the index only hints at sectors that should receive special research and policy attention, and our model should not be misunderstood as a comprehensive measure for stranded asset. Lastly, we are aware that 'stranded assets' is a concept with various constraints. It requires numerous assumptions (including myopic foresight, the irreversibility of capital stocks, and fossil-based infrastructures), may be inherently paradoxical, and blurs the lines between science and politics.

In general, we are convinced that this study should be understood as an early contribution to the academic discourse on stranded assets in developing and emerging economies, rather than a final conclusion to the discussion. Eventually, our article shows that the issue is far from trivial, and that policy advice needs to consider the complexity of energy markets, institutions, growth, and international politics at the same time. It is most crucial that the stranding of resource reserves is not seen as the problem of individual countries but a challenge for the entire international community. If first-comers to development fail to alleviate the burden on fuel producers (and low-income countries in general), unsuccessful climate change mitigation on the one hand and widespread conflict and poverty on the other will be the consequence. Hence, the biggest challenge of today might be to tackle climate change without neglecting the latecomers to development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Model formulation

Like other complementary models and market games, Multimod defines actors in the energy system as agents of a market game in quantities who seek to maximise a certain objective function in anticipation of others' responses. Table 3 shows an

Table 3
Overview of the different agents and their optimisation problems.

Agent	Objective (Maximisation)	Constraints
Suppliers	Profits from the production and sale of fuels $\max_{q^P,q^A,q^C,q^{O-},q^{O+},q^D,z^P} \sum_{y\in Y,h\in H,n\in N,e\in E} \delta_y dur_h \bigl(\sum_{d\in D}\bigl[cour^S_{ysnd}\Pi^D_{yhnde}(\cdot)$ $+\bigl(1-cour^S_{ysnd}\bigr)p^D_{yhnsde}\bigr]q^D_{yhsnde} - \Bigl[lin^P_{ysne}q^P_{yhsne} + qud^P_{ysne}\bigl(q^P_{yhsne}\bigr)^2\Bigr] - \sum_{a\in A^+_{ne}} p^A_{yha}q^A_{yhsa} -$ $\sum_{c\in C} p^C_{yhnce}q^C_{yhsnce} - \sum_{o\in O^E_e}\bigl(p^{O-}_{yhno}q^{O-}_{yhsno} + p^{O+}_{yhno}q^{O+}_{yhsno}\bigr) - \sum_{g\in G} p^G_{yng} ems^P_{ysneg} q^P_{yhsne} - inv^P_{ysne} z^P_{ysne}\bigr)$	• Production capacity $q^P_{yhsne} \le avl^P_{yhsne}\bigl(cap^P_{ysne} + \sum_{y'<y} dep^P_{y'ysne} z^P_{y'sne}\bigr)$ • Storage balance $\sum_{h\in H^V_{vo}} dur_h q^{O+}_{yhsno} = \sum_{h\in H^V_{vo}} dur_h \bigl(1-loss^{O-}_o\bigr) q^{O-}_{yhsno}$ • Production capacity investment limits $z^P_{ysne} \le exp^P_{ysne}$ • Reserve limits $\sum_{y\in Y,h\in H} dur_h q^P_{yhsne} \le hor^P_{sne}$ • Nodal mass balance constraint $\bigl(1-loss^P_{sne}\bigr) q^P_{yhsne} - \sum_{d\in D} q^D_{yhsnde} + \sum_{c\in C,f\in E^{C-}_c} transf^C_{yncfe} q^C_{yhsncf} -$ $\sum_{c\in C} q^C_{yhsnce} + \sum_{a\in A^+_{ne}} \bigl(1-loss^A_a\bigr) q^A_{yhsa} - \sum_{a\in A^-_{yhsa}} q^A_{yhsa} + \sum_{o\in O^E_e}\bigl(q^{O+}_{yhsno} - q^{O-}_{yhsno}\bigr) = 0$
Transporters	Profits from transportation services $\max_{f^A,z^A} \sum_{y\in Y,h\in H} \delta_y dur_h \bigl(\bigl(p^A_{yha} - trf^A_{ya}\bigr) f^A_{yha} - \sum_{g\in G} p^G_{yng}$ $ems^A_{yag} f^A_{yha} - inv^A_{ya} z^A_{ya}\bigr)$	• Capacity restriction $f^A_{yha} \le cap^A_{ya} + \sum_{y'<y} dep^A_{y'ya} z^A_{y'a}$ • Capacity expansion limits $z^A_{ya} \le exp^A_{ya}$ • Market-clearing condition $\sum_{s\in S} q^A_{yhsa} = f^A_{yha}$
Power plant and oil refinery owners (Transformation operators)	Profits from electricity generation and refining $\max_{f^C,z^C} \sum_{y\in Y,h\in H,e\in E^{C-}_c} \delta_y dur_h \bigl(\bigl(p^C_{yhnce} - trf^C_{ync}\bigr)$ $f^C_{yhnce} - \sum_{g\in G} p^G_{yng} ems^C_{yceg} f^C_{yhnce} - inv^C_{ync} z^C_{ync}\bigr)$	• Capacity restrictions $\sum_{(e,f)\in E^C_c} transf^C_{yncef} f^C_{yhnce} \le cap^C_{ync} + \sum_{y'<y} dep^C_{y'ync} z^C_{y'nc}$ • Minimum shares of certain input fuels $shr^C_{ynce} \sum_{(e',f)\in E^C_c} transf^C_{ynce'f} f^C_{yhnce'} \le \sum_{f\in E^{C+}_c} transf^C_{yncef} f^C_{yhnce}$ • Capacity expansion limits $z^C_{ync} \le exp^C_{ync}$ • Market-clearing condition $\sum_{s\in S} q^C_{yhsnce} = f^C_{yhnce}$
Storage operators	Profits from storing energy $\max_{f^{O-},f^{O+},z^O,z^{O-},z^{O+}} \sum_{y\in Y,h\in H} \delta_y dur_h \bigl(\bigl(p^{O-}_{yhno} - trf^{O-}_{yno}\bigr) f^{O-}_{yhno} +$ $p^{O+}_{yhno} f^{O+}_{yhno} - \sum_{g\in G} p^G_{yng} ems^{O-}_{yog} f^{O-}_{yhno} - inv^O_{yno} z^O_{yno} - inv^{O-}_{yno} z^{O-}_{yno} - inv^{O+}_{yno} z^{O+}_{yno}\bigr)$	• Restrictions of the cumulative energy injections $\sum_{h\in H^V_{vo}} dur_h f^{O-}_{yhno} \le cap^O_{yno} + \sum_{y'<y} dep^O_{y'yno} z^O_{y'no}$ • Restrictions of the period-wise intake and outtake $f^{O-}_{yhno} \le cap^{O-}_{yno} + \sum_{y'<y} dep^{O-}_{y'yno} z^{O-}_{y'no} f^{O+}_{yhno} \le cap^{O+}_{yno} + \sum_{y'<y} dep^{O+}_{y'yno} z^{O+}_{y'no}$ • capacity expansion restrictions $z^O_{yno} \le exp^O_{yno} z^{O-}_{yno} \le exp^{O-}_{yno} z^{O+}_{yno} \le exp^{O+}_{yno}$ • market-clearing constraints for energy in- and outtake $\sum_{s\in S} q^{O-}_{yhsno} = f^{O-}_{yhno} \sum_{s\in S} q^{O+}_{yhsno} = f^{O+}_{yhno}$
Emission authorities	Profits from issuing emission permits[1] $\max_{f^C} \sum_{y\in Y,n\in N,g\in G} \delta_y \bigl(p^G_{yng} - tax^{glob}_{yg} - \sum_{r\in R_n} tax^{reg}_{yrg} - tax^{nod}_{yng}\bigr) f^G_{yng}$	• national, regional, and global greenhouse gas quota $\sum_{n\in N} f^G_{yng} \le quota^{glob}_{yg} + \sum_{n\in N} z^G_{yng} \sum_{n\in N_r} f^G_{yng} \le quota^{reg}_{yrg} + \sum_{n\in N_r} z^G_{yng} f^G_{yng} \le quota^{nod}_{yng} + z^G_{yng}$ • global market clearing condition $\sum_{h\in H,e\in E} dur_h \bigl(\sum_{s\in S} ems^P_{ysneg} q^P_{yhsne} + \sum_{s\in S,d\in D} ems^D_{ydeg} q^D_{yhsnde} + \sum_{a\in A^+_{ne}} ems^A_{yag} f^A_{yha} +$ $\sum_{c\in C} ems^C_{yceg} f^C_{yhnce} + \sum_{o\in O} ems^{O-}_{yog} f^{O-}_{yhno}\bigr) = f^G_{yng}$
Consumers	Utility from the consumption of energy services, weighted against fuel, emission, and end-use costs[2] $p^D_{yhnde} = eff^D_{ynde}\Bigl[int^D_{yhnd} - slp^D_{yhnd}\bigl(\sum_{s\in S,f\in E} eff^D_{yndf} q^D_{yhsndf}\bigr)\Bigr]$ $-eucc^D_{yhnde} - eucc^D_{yhnde}\bigl(\sum_{s\in S} q^D_{yhsnde}\bigr) - \sum_{g\in G} p^G_{yng} ems^D_{ydeg}$	

[1]Since the emission authority acts in a competitive market, the profit maximisation amounts to a welfare maximisation.
[2]The end-use costs are automatically calibrated by Multimod's auxiliary algorithm and mimic endogenous fuel substitution, as elaborated in the appendix of Huppmann and Egging (2014).

Table 4
List of sets, parameters, variables, and mappings in Multimod.

Symbol	Description	Symbol	Description
Sets			
$y \in Y$	years	$a \in A$	Arcs
$h \in H$	seasons	$c \in C$	transformation technology
$s \in S$	suppliers	$e, f \in E$	energy carriers/fuels
$n, k \in N$	nodes	$r \in R$	regions
$d \in D$	demand sectors	$g \in G$	emission types
$l \in L$	sector fuel mix constraints	$o \in O$	storage operators/technology
$m \in M$	transformation mix constraints	$v \in V$	loading cycles of storage
Parameters and functions			
dur_h	relative duration of season h (with $\sum_h dur_h = 1$)	$cap^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	service or production capacity
$\exp^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	capacity expansion limit	$inv^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	unit cost of capacity expansion
$trf^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	unit cost for service provision	$dep^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	Infrastructure depreciation rate
$loss^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	relative losses though service usage	$ems^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	unit emissions
$cost^P_{yhsne}\left(\hat{A}\cdot\right)$	production cost function	hor^P_{sne}	production horizon (reserves)
lin^P_{ysne}	linear term of the production cost function$(lin^P \geq 0)$	$transf^C_{yncef}$	transformation rate by technology c at node n from input e to output f
qud^P_{ysne}	quadratic term of the production cost function$\left(qud^P \geq 0\right)$	shr^C_{ynce}	minimum share of (input) fuel e by transformation technology c
$cour^S_{ysnd}$	Cournot market power parameter	$quota^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	quota for nodal / regional / global emissions
avl^P_{yhsne}	availability factor of production capacity	eff^D_{ynde}	efficiency of demand satisfaction of sector d by fuel e at node n
$\Pi^D_{yhnde}\left(\hat{A}\cdot\right)$	inverse demand curve of sector$d$	$eucl^D_{yhnde}$	linear end-use cost parameter
int^D_{yhnd}	intercept of inverse demand curve for fuel e at node$n$	$eucc^D_{yhnde}$	constant end-use cost parameter
slp^D_{yhnd}	slope of inverse demand curve for fuel e at node$n$	$shr^{(\hat{A}\cdot)}_{ynl}$	minimum share of sector fuel mix constraint l (in energy services)
δ_y	discount factor	$util_{s,f}$	share of production capacity eventually used
Variables			
$q^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	quantity produced / sold / interacting with service	$p^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	market-clearing price of fuel or service
$f^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	flow of energy or emissions	$z^{(\hat{A}\cdot)}_{(\hat{A}\cdot)}$	capacity expansion
Mappings			
$n, k \in N_r$	node-to-region mapping	$e^O(o)$	fuel stored by technology o
$r \in R_n$	region-to-node mapping	$o \in O^E_e$	subset of technologies storing fuel e
$a \in A^+_{ne}$	subset of arcs ending at node n transporting fuel$e$	$h \in H^V_{vo}$	mapping between loading cycle and hour/day/season
$a \in A^-_{ne}$	subset of arcs starting at node n transporting fuel$e$	$v^H(h, o)$	loading cycle of hour/day/season (singleton)
$e \in E^A_a$	fuel(s) transported via arc a (singleton)	$e \in E^L_l$	fuel(s) that satisfies fuel mix constraint l
$n^{A+}(a)$	end node of arc$a$	$e \in \hat{E}^L_l$	fuel(s) that are included in fuel mix constraint l
$n^{A-}(a)$	start node of arc$a$	$e \in E^M_m$	fuel(s) that satisfies transformation mix constraint m
$f \in E^{C+}_c$	subset of output fuel(s)f obtained from transformation technology$c$	$d \in D^L_l$	demand sector(s) to which fuel mix constraint l applies
$e \in E^{C-}_c$	subset of input fuel(s) e for transformation technology$c$	$c \in C^M_m$	transformation technologies that satisfy transformation mix constraint m
$(e,f) \in E^C_c$	input/output fuel mapping of transformation technology$c$		

overview of the different agents and their respective optimisation problems. Furthermore, Table 4 contains a summary of the notation.

The model is solved by taking the Karush–Kuhn–Tucker conditions (KKTs) for all agents. The combination of all KKTs constitutes an equilibrium problem whose solution is equivalent to the Nash equilibrium of the game. To tackle the numerical complexity of the model, we eventually take the multivariate integral of all stationarity conditions and yield the objective function to a convex optimisation problem. Under the feasibility constraints of the KKT system, this convex optimisation has the same solution as the KKT system. We implement the convex optimisation in GAMS and solve it using the commercial solver CPLEX. Ansari and Holz (2019) cover the KKTs, the reformulation process, and the final set of equations.

Regarding an overview of the various data sources for the model, we refer to Ansari et al. (2019). For the demand, Multimod requires so-called reference demand[9] values for each node, sector, and period. For the year 2015, fixed demand values are taken from the International Energy Agency. (2017) (2017). Regarding future periods we derive base line values from Chen, Ejaz, Gao, Huang, Morris, Monier, Patsev, Reilly, Schlosser, and Scott (2016), process them into decade-wise growth rates, and alter these growth rates to reflect the scenarios. The model is calibrated with a discount rate of 5% per decade. Sector-specific data (e.g. costs, capacities, reserves, processing and distribution infrastructure) comes from recent scien-

[9] Reference demand refers to a specified reference point on a demand function (price and quantity) that is used to extrapolate a linear demand function, given an exogenous demand elasticity. Models that use final demand levels as inputs fix final quantities exogenously and do not treat price and quantity as endogenous variables. Hence, they do not represent an actual interplay between supply and demand. Fixing a reference demand, instead only fixes the demand *function*. Hence, varying the reference demand influences final demand but does not determine it. This is done endogenously by the interplay of supply and demand.

tific publications and DIW Berlin data documentation, in particular Egging and Holz (2016) for natural gas, Holz, Haftendorn, Mendelevitch, and von Hirschhausen (2016) for coal, Ansari (2017) for oil, Oei and Mendelevitch (2016) for carbon capture and storage, and Löffler et al. (2017) as well as Gerbaulet and Lorenz (2017) for electricity and renewables. This includes data on emissions, which are specified for different fuels and actions (i.e. the model accounts for emissions at each point of the value chain).

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