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Anticipating global energy, climate and policy in 2055: Constructing qualitative and quantitative narratives

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ABSTRACT

This study presents a set of novel and multidisciplinary scenarios ('narratives') that provide insight into four distinct and diverging yet plausible worlds. They combine qualitative and quantitative elements in order to reflect the interlinked and complex nature of energy and climate. We use the STEMPLE+ framework to include social, technological, economic, military (security), political, environmental, and cultural (+) dimensions in our narratives. We present the construction of the narratives, which started with the generation of qualitative scenario storylines using foresight analysis techniques, including a facilitated expert workshop. We then calibrated the numerical energy and resource market model Multimod to reflect the different storylines. Finally, we combined and refined the storylines and numerical model results into holistic narratives.

The study generates insights into the key assumptions and drivers of different pathways of (more or less successful) climate change mitigation. Moreover, a set of transparent and discriminatory indicators serves to identify which paths the world might take. They include quantitative results, e.g. emissions, energy consumption and electricity mix, as well as developments in the political or social sphere. Lessons learnt include the dangers of increased isolationism and the importance of integrating economic and energy-related objectives, as well as the significant role of civil society. However, we also show that the development of renewables and electrification are inappropriate indicators for a successful energy transition, as these trends are also consistent with emission-intensive scenarios.

1. Introduction

The global energy system is characterised by rapidly changing trends. Between the fast expansion of shale oil and gas in North America, the phase-out of nuclear energy in parts of Europe, the drop in global oil prices, and the Paris Agreement to combat climate change, the need to understand the underlying inter-linkages in energy and climate is apparent. Scenarios help us to gain an insight into possible transformation pathways, their drivers and long-term outcomes. Scenario planning helps to differentiate relevant signals from 'noise' and to identify the impact of today's emerging trends.

Qualitative scenario methods, on the one hand, enable the inclusion of a wide range of possibilities and factors, but fail to estimate the system-wide consequences and lack the precision of numerical results. Quantitative scenarios, on the other hand, deliver consistent and tangible results, but they are inherently bound by the modeller's assumptions and consider only simplifications of reality.

This study presents the methods and results of an interdisciplinary scenario-building study for the global energy system heading towards 2050, which combines quantitative modelling with qualitative foresight methods. Our four narratives (base case 'Business as usual', worst case 'Survival of the Fittest', best case 'Green Cooperation', and surprise scenario 'ClimateTech') describe distinct worlds, contributing insights for understanding if and how emerging trends today may signal forthcoming threats and opportunities. The narratives do not attempt to predict the precise state of the global energy system by the year 2055, but are rather four alternative futures showing plausible possible developments.

We use this approach to focus on dimensions that are rarely considered by purely numerical energy outlooks: changes to the global political order and geopolitics, the social aspects of climate objectives, and the resulting technological pathways. Climate policy, in particular, is a major determinant of the future energy system whose political and social perception is determinant on various external factors. Yet climate

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policy competes with other political objectives, and its political and social perception varies between different environments. Investors have an essential impact on trajectories, as innovation, learning effects, and cost reduction depend on them. This *imbroglio* may seem to consolidate system inertia and path dependency, but the mutual enforcement of (new) trends can also create the space for deviations from known trajectories.

Previous examples in energy for the integration of quantitative modelling with qualitative foresight were more limited in terms of their regional and/or sectoral scope, depth, and methods. They include studies of regional energy systems [1–3], sectors such as hydrogen energy [4], transportation systems and their energy demand [5,6], numerically-looser climate issues [7,8], generic socioeconomic transitions [9–12], and discussions for similar sectors such as land use [13]. Other processes of deriving holistic scenarios in the style of our study can be envisaged (e.g. [14–17]).

Discussions regarding the integration of concepts and methods are not new: [18] calls for understanding of the energy system as an integrated socio-economic system, and [19] emphasises the importance of multi-method scenarios that reflect on structural uncertainties such as energy governance. Exogenous determinants such as politics steer the energy system via technological change [20], governance capabilities [21], or spill overs from other policy fields [22]. Neglecting social aspects in future scenarios, for instance, may lead to an overestimation of the feasible action space [23], while conservatism in models due to a lack of interdisciplinary feedback may harm the implementation of the energy transition [24]. Therefore, approaches that refrain from crossing disciplinary borders can be considered entirely unsuitable for assessing energy futures [25]. The inclusion of qualitative methods may be the only way to address multiple major dimensions of uncertainty [26,27], but the eventual extent to which qualitative and quantitative methods can be combined is controversial. While [28] advocates for dialogue between modellers and practitioners, [29] suggests iterative approaches of (integrated assessment) modelling and social science research as a more fruitful approach than stakeholder consultation on modelling assumptions. [30] underlines that for each of the challenges associated with the energy transition, different model types are better suited, for example scalable linear programming electricity sector models for the analysis of increasingly decentralised electricity supply. Moreover, [31,32] propose agent-based modelling as the appropriate tool for investigating transitions and practical decision making. Instead, the rules of conventional numerical modelling can seem arbitrary to observers [33].

Our study bridges between qualitative and quantitative approaches with a three-step process. First, storylines and their underlying parameters (drivers, uncertainties, megatrends) are established in a scenario foresight exercise à la [34]. Second, we extract key parameters from the storylines and feed them into the global multi-fuel, multi-sector, energy systems model Multimod [35]. Lastly, we integrate qualitative storylines and quantitative model results to obtain holistic narratives that project energy and climate trajectories but consider societal, political, security, and technological aspects alike.

Our study contributes to the growing literature on bridging between quantitative modelling and qualitative social sciences research. The study is complementary to previous works with a strong focus on the quantitative side, such as the shared socioeconomic pathways [9,12], and it relies strongly on the STEMPLE+ framework. Our contribution is threefold. First, our narratives provide insight into four comprehensive possible futures for energy, climate, and their surrounding dimensions, including numbers for key variables in the energy system. Second, our study manifests the deep interlinkages between different spheres such as the energy system, politics, economics and society. Thirdly, we define a set of diagnostic indicators that provide a transparent early-warning system to alert us to which path the world might be heading down. With this, we provide insights of interest for both academia and policy; in the sense of [36], the narratives benefit both scenario explorers without an interest in modelling as well as data-driven modelling experts. Moreover, regarding the numerical work, this is the first major application of the method described by [37], which is used to reformulate a mixed complementarity problem (MCP) into a convex quadratic optimisation problem (QCP).

2. Methods

We apply qualitative methods and quantitative energy modelling sequentially to construct four distinct, comprehensive narratives of global energy and societal developments until 2055 (Fig. 1). 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

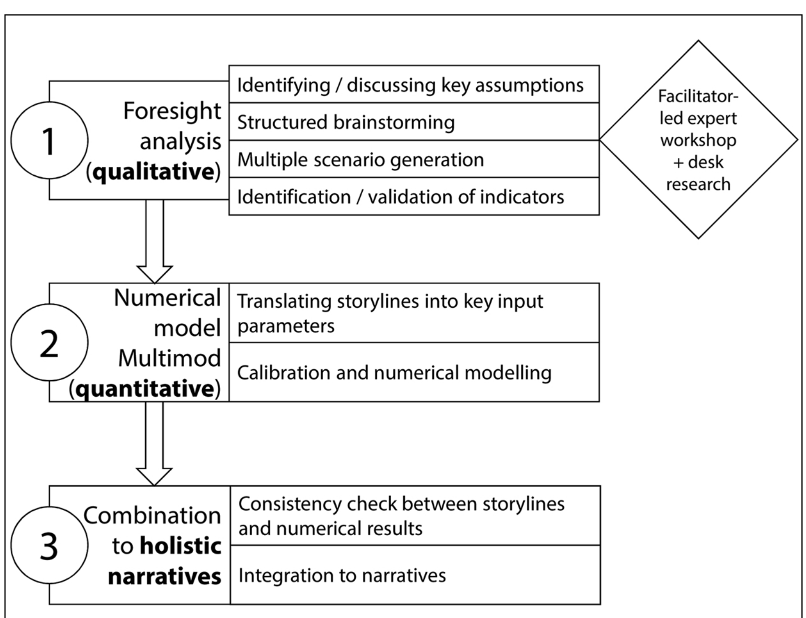

Fig. 1. Illustration of our three-step method to reach holistic narratives.

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.

2.1. Qualitative analysis: Scenario foresight

In the first step, we develop qualitative storylines that encompass broad societal developments until 2055. We use multiple scenario generation, also called scenario foresight. This is distinct from a "forecast" method as employed, for example, for business cycle outlooks, which provide bounded statements about future events and conditions in the short (or mid) term. Foresight is also different from "predictions", which are definitive statements about what will occur in the future. Rather, we develop and use scenarios in the sense of "exploring different possible futures, the levers that bring them about and the interactions that arise across a complex [….] system" [39,p. 23]. Foresight analysis helps with this exploratory analysis because it is in itself a "reframing process" that involves exploiting insights into thinking about the future [34,p. 14].

We address the complexity of human systems by working in the STEMPLE+ analytical framework. STEMPLE+ describes the dimensions included in our foresight considerations: **s**ocial, **t**echnological, **e**conomic, **m**ilitary/security, **p**olitical, **l**egal, and **e**nvironmental, plus others (e.g., cultural) [34]. These dimensions are not equally important in our analysis, due to its focus on energy and resource markets. Moreover, we expand the economic dimension to also include energy market considerations. The legal dimension also covers multinational organisations and the political dimension explicitly includes geopolitical issues.

We follow the method of [34], which relies to a large extent on [40,41].[1] This method involves a four-step foresight process and, in the sense of [38], fits most closely into the category of a narrative analysis that involves a focus group. In our foresight process, we mixed desk research with group work in a "scenario workshop". Participants in the scenario workshop were approx. thirty experts from different areas of energy, climate, and economics who are active in academia, media, the public sector, and industry.[2] The group work with a rather heterogeneous group aimed at overcoming some of the cognitive limitations and biases of individual analysts, in particular the tendency to think only about known phenomena and to exclude the (known and unknown) unknowns [34,40].[3] However, there are numerous challenges when working with participatory methods: results can be contradictory, hard to validate, or based on alternative realities [42]. We critically reflected on these challenges with the moderator and levelled out some inconsistencies in the post-workshop desk research phase.

More concretely, the following four steps in the process can be distinguished:[4]

1) **Identifying and discussing key assumptions**: Key assumptions are commonly accepted assumptions about major future developments ("truisms", [34,p. 13],) that serve as the rules and boundaries of the analysis. In this step, participants define assumptions that are unlikely to be challenged in the remainder of the foresight process. Additionally, this step primes participants for the later analysis by forcing them to reflect on cognitive biases. It was initiated with an online survey before the workshop and concluded during the first part of the workshop in a moderated discussion.
2) **Structured brainstorming** on the research question in the STEMPLE+ analytical framework: The research question given to the workshop participants was "What are the drivers of the renewable energy transition until 2050?" Preparatory brainstorming was already part of the online survey. At the workshop, participants engaged in multiple moderated stages of silent brainstorming, clustering and naming of "affinity groups", and subsequent group discussions (see [34] for more details). Key drivers were obtained from the clusters, which are critical influence factors that may eventually change the entire system. The workshop groups selected seven key drivers that are mutually exclusive and properly defined
3) **Multiple scenario generation**: In this step, storylines of plausible alternative futures were developed by the groups during the workshop. First, the participants identified the extremes of each driver (e.g. best and worst case), before combining the drivers to 21 pairs. Subsequently, participants analysed each pair in a 2 × 2 matrix (see [40,p. 146] for details) and identified four raw scenarios for each pair including simple, mutually exclusive storylines. Each storyline was described by a title and some main characteristics, as well as a brief analysis of the consequences of the future world described.- After the workshop, eleven relevant and consistent driver pairs were chosen, whose scenarios ("best case", "worst case", "surprise scenarios") were selected and combined into four clusters with common themes. These clusters yield the four final scenarios and feature the complex characteristics of their seven underlying drivers. Lastly, we composed storylines for these clusters, which include a chronology of events, explanations of factors and drivers, actors and trends, as well as a precise description of the final state in each scenario (by 2055, in our study). We conducted these post-workshop tasks with a smaller team of six; however, all workshop participants could in principle be involved, e.g. for obtaining feedback or providing direct contributions.
4) **Identification and validation of indicators**: For each scenario, "early warning" signals were identified. They help decision-makers and analysts detect which scenario is unfolding in the real world. Based on [34,40], each scenario is underpinned by a set of distinct ("diagnostic" [40,p. 135]) indicators: some phenomena that, for example, help us to notice emerging trends and to "separate relevant information from noise" [34,p. 15]. Also, for their unique and "diagnostic" character, indicators must be observable and collectable, valid, and reliable [40].

2.2. Quantitative energy modelling: Multimod

In the second step of our analysis, we quantify the scenario trajectories. For this purpose, we use the energy and resource market model Multimod (see Appendix B for technical details). In the sense of [38], 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 [37].

Multimod itself is also hybrid in the sense that it bridges between partial-equilibrium modelling (to account for strategic actions and infrastructure detail) and the broad scope of an energy system model (global scale and interdependencies). Different versions of the model,

[1] Oliver Gnad was the moderator and facilitator of the scenario workshop in November 2016 to which we refer.

[2] However, only four participants were female, and only two participants originated from the Global South. Public sector affiliates were advisory personnel, but no decision-makers participated.

[3] Correspondingly, the workshop ran under the title "From 'Known Unknowns' to 'Unknown Unknowns' – Uncovering Critical Uncertainties for the World Energy Future".

[4] More detail on the course of the workshop and its intermediate results can be found in the Appendix of [43]

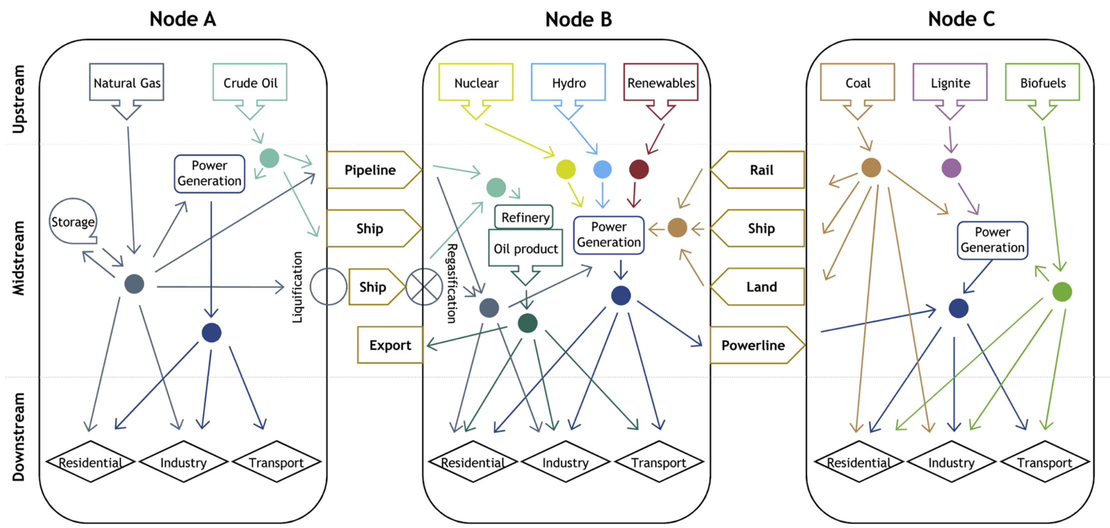

Fig. 2. Illustration of the geographical nodes defined in the data set.

initially developed and elaborated by [35], have been used in recent studies, e.g. of the global energy system [35] as well as North American natural gas [44,45] and crude oil [46,47] markets.

The global model is adapted and calibrated to express the settings of each scenario (see Appendix C for a more detailed account on data and model parameters). This includes variations of production and transportation costs, technology availability and efficiency, as well as the availability of certain transport routes and reference demand parameters. As a result, we obtain key variables (energy production and consumption, CO_2 emissions, infrastructure investment) that match the setting of the storylines.

Multimod reflects the complex, non-linear and interrelated reality of energy infrastructure. The model covers multiple periods of planning and system operations. Here, the model proceeds in ten-year steps from 2015 to 2055. The world is disaggregated into nodes which represent geographic entities (30 distinct nodes in this study, as illustrated by Fig. 2). These nodes are home to the different actors along the energy value chain (Fig. 3), i.e. 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, 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 (ship, pipeline, rail, street, power line). 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.

3. Results and discussion

3.1. Overview

Our narratives represent four rather extreme yet plausible developments of the medium term (i.e. the next decade) and long term (beyond 2030 and towards 2055). They are:

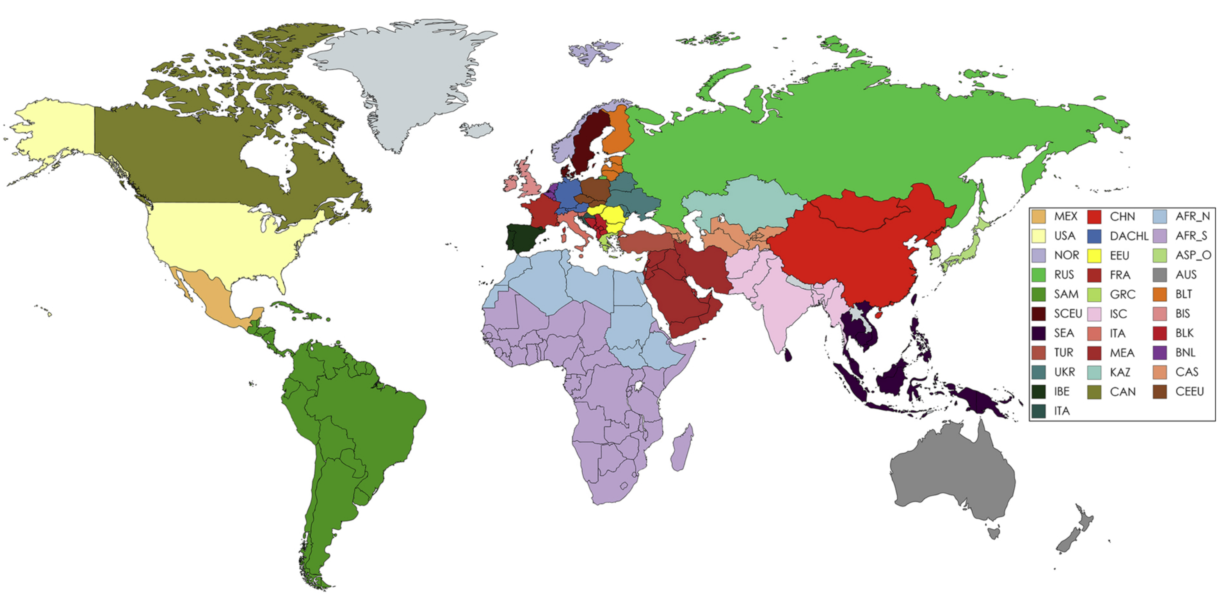

Fig. 3. Illustration of the value chain in Multimod.

Table 1
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 reduction	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 2
Drivers in each scenario and their level of influence.

	Business as usual	Survival of the Fittest	Green Cooperation	ClimateTech
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

- **Business as Usual** (reference case): NDCs agreed in the Paris agreement are mostly met, but a prolongation of geopolitical tensions trumps the possibility of a more ambitious trajectory. As climate change effects increase, decarbonisation efforts are scaled up in the 2030s. However, distributional concerns, a lack of cooperation, and the absence of an integral social transition cause a failure to make the necessary U-turn in the energy system by that time. Towards 2055, climate disasters start to escalate, and global degrowth looms.
- **Survival of the Fittest** (worst case): A wave of isolationism erodes the global world order and depresses the international economy. Energy security starts to dominate agendas, and most nations rely on their (fossil) endowments. Without multilateral agreements, climate issues disappear from most agendas. Informal agendas and regional champions govern this world, whose energy consumption doubles over the coming decades. Towards 2055, near-apocalyptic climate catastrophes destroy much of human civilisation, and only the richest nations can afford the adaptation measures required to survive.
- **Green Cooperation** (best case): Swayed by a new generation of leaders, global reconciliation revives the idea of global governance. Increased stability enables international policy to focus on the long run and regard decarbonisation and poverty allocation as a dual objective. In a multilateral move, focus is placed on the facilitation of investment in both clean technologies and international development banks. This scenario succeeds in decarbonising most of the economy, as citizens eventually live green modernity and join a holistic transition.
- **ClimateTech** (surprise scenario): News about sudden advances in several energy and climate technologies creates a situation of euphoria, in which climate change is considered 'solved' and decarbonisation in the present is off the agenda. With their deployment in the 2030s, it becomes clear that none of these is a white knight able to solve the energy and climate problem once and for all. In a race between emissions and engineering, this scenario manages to prevent significant climate catastrophes but still lacks a vital plan for the long run.

A detailed account of each narrative (i.e. the scenario descriptions as well as their quantitative outcomes in terms of primary energy production, final energy consumption, and the electricity mix) is given in Appendix A.

Table 1 shows the megatrends and key assumptions that are valid for all narratives alike and were defined by the workshop participants. Table 2 shows the combination of drivers that define each scenario. Fig. 4 illustrates the timelines and main events in the four narratives.

3.2. Numerical comparison

The comparative assessment of emissions, energy service consumption, and electricity generation (Fig. 5) 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

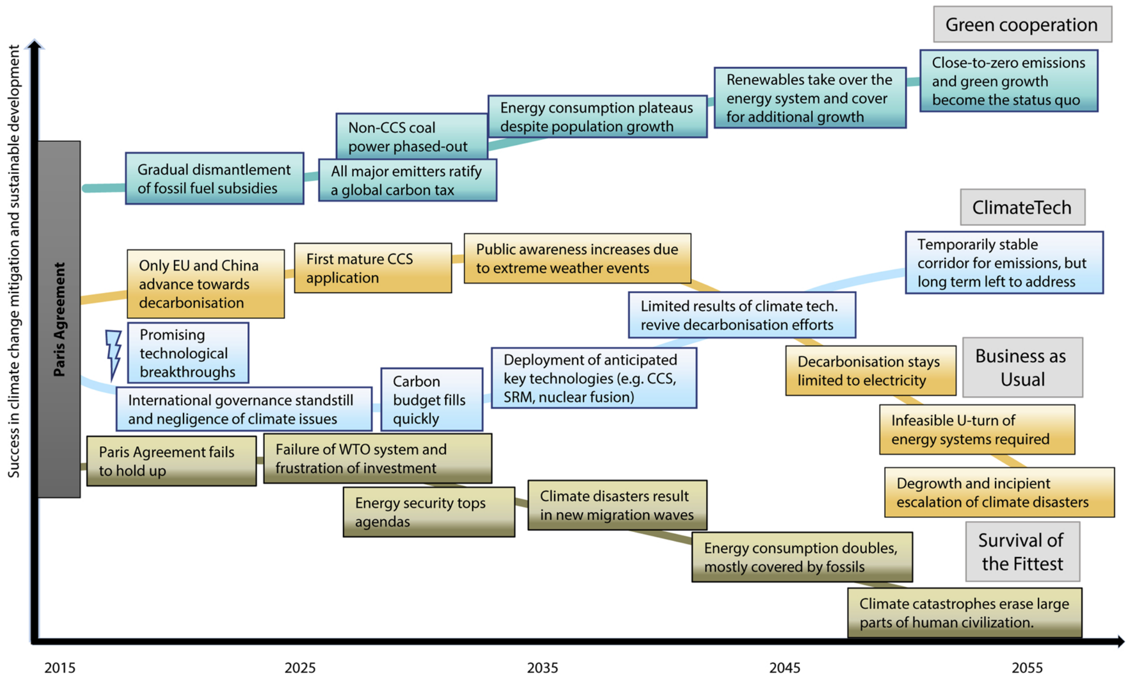

Fig. 4. Illustration of the four narratives and their main events.

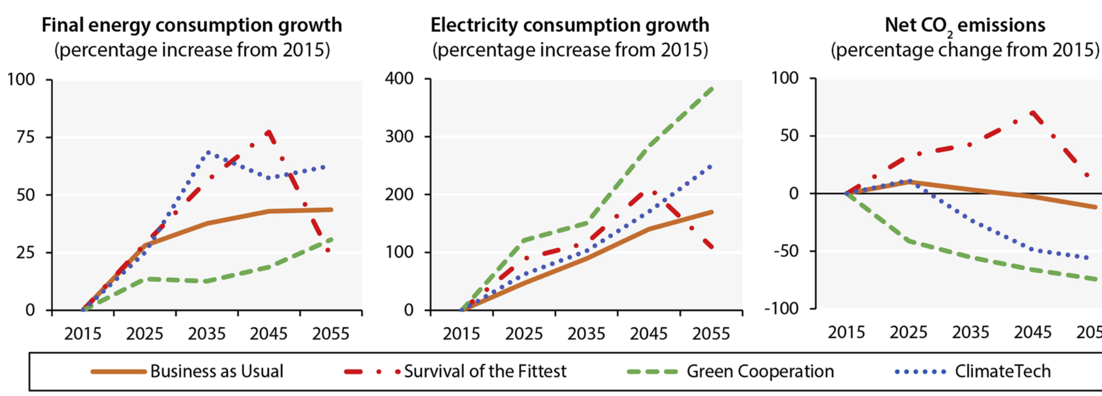

Fig. 5. Final energy consumption (left), electricity consumption (middle), and CO_2 net emissions (right) as percentage changes from 2015 values compared between the scenarios.

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.

Renewables take over massive shares of the electricity mix in all scenarios, but to varying extents (Fig. 6). 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%).[5] Therefore, and similar to the conclusions on energy consumption, the share of renewables can be a

[5] 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.

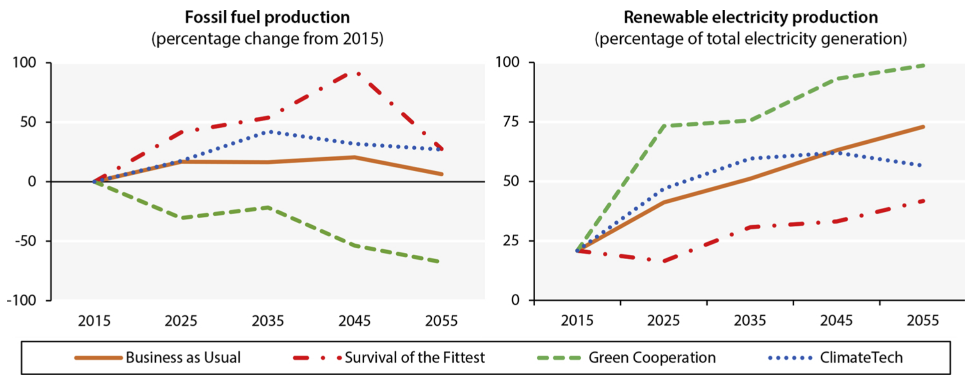

Fig. 6. Fossil fuel production (left, as percent of 2015 values) and renewable electricity generation (right, as percent of total electricity) compared between the scenarios.

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 (Fig. 6) 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.

3.3. 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" [40,p. 135]. Indicators are unique and detectable manifestations for each narrative and can thereby serve as transparent early-warning signals for observers. We chose indicator categories in the dimensions of the STEMPLE+ framework (Table 3). Additionally, Fig. 7 displays several quantitative indicators.

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.

4. Conclusions

Our study presents four alternative narratives for the global energy future and provides an understanding of the interactions and interdependencies between policy, society, energy, climate, and technology. Besides their extensive storyline descriptions, we provide model-based metrics for energy production and consumption as well as the development of the power mix and of CO_2 emissions.

Moreover, several policy conclusions can be derived from the narratives. First, the dangers from a rise in isolationism are twofold: Effective climate policies (and the multilateral agreements that typically define them) require strong international cooperation. Increased isolationism will shrink the space of feasible action and erode the legitimacy of international climate bodies. However, decarbonisation efforts will also depend on encouraging investments in critical technologies, which will often happen through multinational collaboration, but will also require the right signals from policy makers. Private actors will only undertake such investments if the cost and risks associated with them are sufficiently low, and even non-tariff barriers to trade, capital, and technology can do significant harm. Hence, a polycentric world without multilateral support for mitigation will be unlikely to prevent climate change.

Secondly, the integration of economic and energy-related objectives and incentives (such as poverty alleviation, infrastructure modernisation, and private investment) is crucial. Continued population growth is the proverbial "elephant in the room", and the political economy of climate change forces a very active role on the main global actors and economies when it comes to technology transfer and creating incentives, but also geopolitical reconciliation. In this regard, our best-case narrative suggests that multinational cooperation and a holistic (societal) transformation can turn growth green. Mechanisms should be installed that include development banks and novel finance systems which push both public and private investment in the right direction.

Thirdly, the narratives underline the relevance of public opinion and societal transitions: Extreme climate events are most likely to raise awareness of climate issues and sway public opinion towards decarbonisation. However, unless it is universal, this bottom-up trend can still be outweighed by conflicting interests on other levels of society. In the best case, however, society is eventually *living* green modernity – something that decision-makers can influence by investments and policies – following a holistic and integral societal transformation.

In reference to the STEMPLE+ framework, which was used to generate the scenario drivers, military and political factors were identified as two especially governing factors for a successful transition. However, the analysis also highlighted the central importance of other dimensions, which may prove more effective for (national) policy making. Governments can impact the social perception of climate targets, and environmental concerns can substitute formal climate policies (e.g. via the reduction of car emissions in cities). Other examples of effective policies identified in the scenarios are the stronger involvement of decarbonisation and poverty alleviation (e.g. when designing international aid and cooperation programmes) as well as technology transfers and multinational research ventures in clean technologies. For policy makers, this shows that the complexity of the drivers of climate policy and emissions – which may seem discouraging at first sight – actually provides the advantage of offering a large variety of tuning parameters for policy making.

Furthermore, the analysis guides the monitoring of climate change mitigation. Especially our worst-case narrative proves that two prominent benchmarks–share of renewables and electrification of the economy – may be misleading pointers, as also noted by [48]. Instead, we propose a set of indicators to track which narratives may arise.

Our holistic approach demonstrates how the advantages of a qualitative approach in including the complex interactions and non-linear dynamics of global policy, society, and energy can be combined with

Table 3
Indicators for all four scenarios by STEMPLE+ 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 (Fig. 7, panels I-L).	Increased innovations in fossil technologies (extraction, combustion, chemical use) (Fig. 7, 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 (Fig. 7 panel K)	Energy innovations are limited to clean technologies (Fig. 7 panels I-K)	High rate of innovation in various technologies (Fig. 7 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 (Fig. 7 panels D, G)	No coal phase-out (Fig. 7 panels D, G)	Global coal phase-out in the 2020s (Fig. 7 panels D, G),	(Coal) CCS plants substituting conventional power plants
Continued sophistication and diversification of the energy mix with dirty and clean sources (Fig. 7 panels F, G)	Fossil fuel production is nearly doubled by 2040 (Fig. 6)	Quick switch away from fossil fuels to renewables, especially in power (Fig. 6, Fig. 7 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 (Fig. 5, Fig. 7 panel H).	GHG emissions rapidly escalate from 2025 onwards (Fig. 5, Fig. 7 panel H).	GHG emissions growth is stopped in the early 2020s and falls afterwards (Fig. 5, Fig. 7 panel H)	Moderate decrease of emissions, focus on negative emission technologies (Fig. 5, Fig. 7 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	
Plus (here: 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)

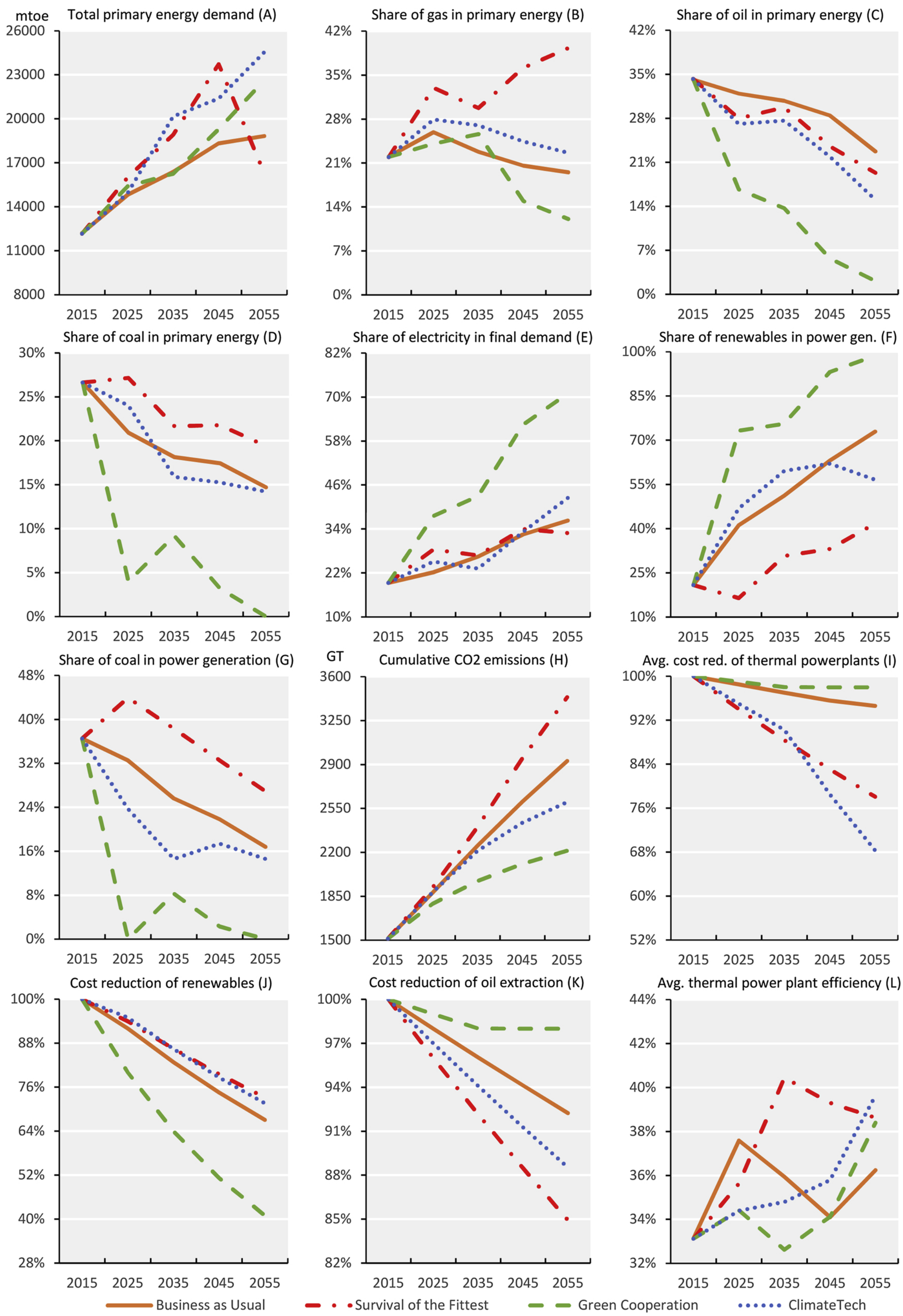

Fig. 7. Quantitative indicators for the four narratives.

the consistency and tangibility of a quantitative model. However, while advocating for a better representation of geopolitical and societal factors in energy systems modelling and scenarios, we realise that our study may in some respect fall short of its own ambitions. The level of heterogeneity among the expert group, the little assessment of unknown unknowns, and the appropriateness of the time horizon may be debated and potentially enhanced, just as the translation mechanism into numerical parameters leaves room for future improvement.

Future applications of our method should also aim at more continuous involvement from workshop participants, e.g. in a follow-up workshop or via a wiki. In general, we are aware that participatory methods are hard to validate [42], which is why the scientific reproducibility and generality of this study is not absolute. On a more technical note, not unlike other scenarios, the narratives are contingent on the eventual technical developments that are assumed (e.g. CCS technology, suitable electricity storage, efficient renewables). Energy scenarios tend to be sensitive with respect to such assumptions [49], and the scientific discourse on whether these developments will eventually happen is still active [50,51]. Moreover, a seemingly small (but conceptually crucial) inconsistency: While the qualitative analysis has a deliberate focus on habitual and lifestyle-derived behaviour (see [38]), the quantitative analysis still assumes (mostly) rational behaviour. Therefore, our analysis should be understood as a further step on the path to incorporating social and political variables in energy modelling, rather than the final goal.

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Appendix A. The Four Narratives

A.1 Business as Usual

A.1.1 The Paris promise: between targets and ambitions in the 20s

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.

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 (Fig. A1). 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.

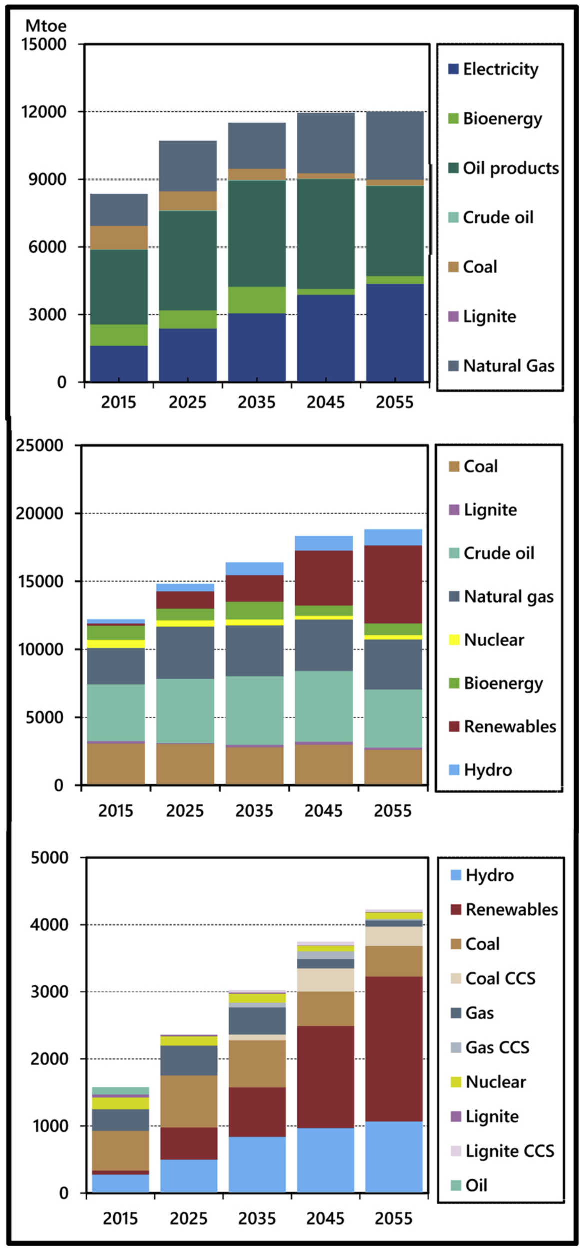

Fig. A1. Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Business as Usual.

A.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 reinvigoration 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.

A.2 Survival of the Fittest

A.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.

A.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.

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 (Fig. A2). 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

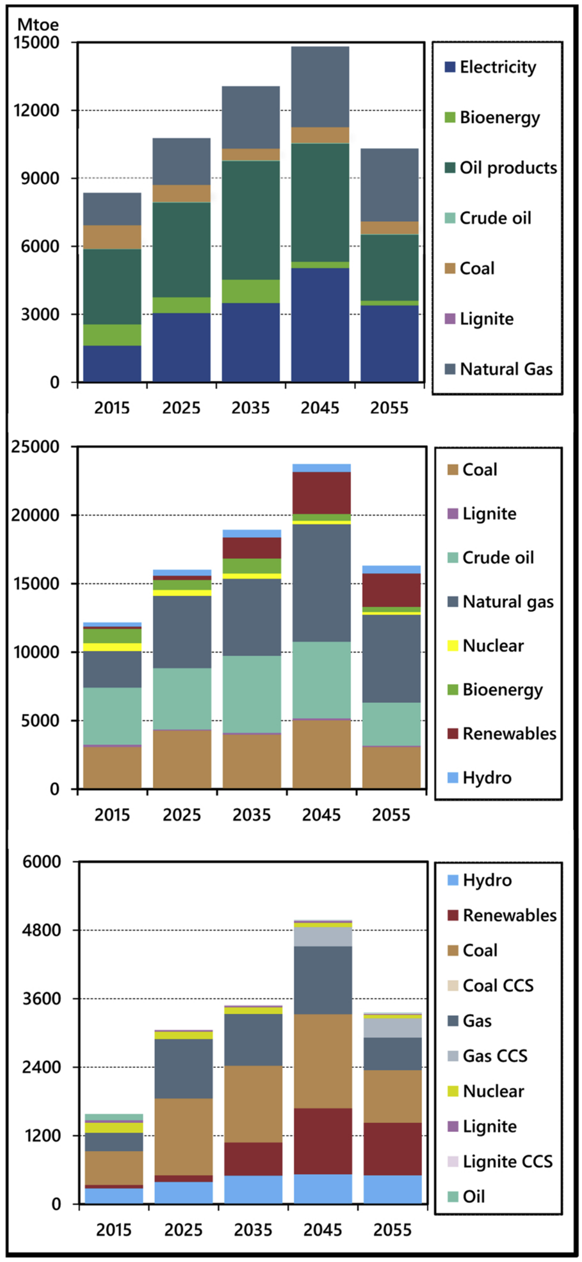

Fig. A2. Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Survival of the Fittest.

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.

A.3 Green cooperation

A.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.

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 (Fig. A3). 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.

A.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

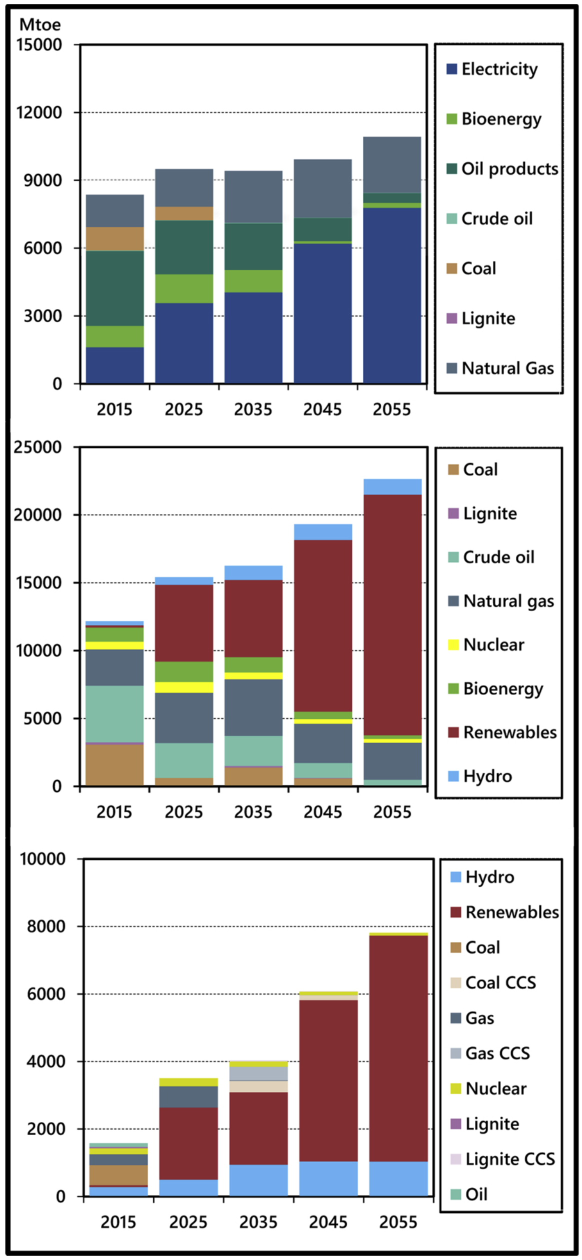

Fig. A3. Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in Green Cooperation.

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.

A.4 ClimateTech

A.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

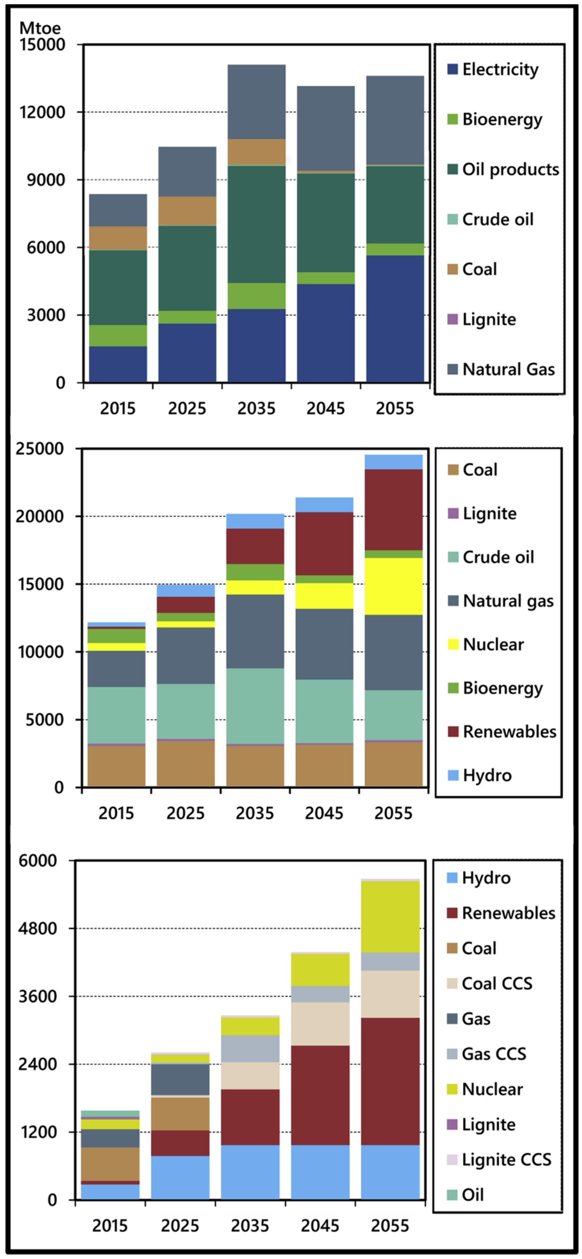

Fig. A4. Global results for final energy consumption (top), primary energy production (middle), and electricity generation by source in ClimateTech.

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 (Fig. A4). 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.

A.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.

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 (Fig. A4) 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.

Appendix B. Multimod: Model Setup

Multimod is an energy and resource market model that reflects the complex, non-linear and interrelated reality of energy infrastructure. We refer to [35] for a detailed description of the model, its purpose, and its relation to other energy models. The model represents the entire supply chain of different energy carriers (both fossil and renewable) in a specially disaggregated framework, as illustrated by Fig. 3.

Similar to other complementarity models and market games, Multimod defines a supply chain of market actors who engage in the production, trading, transformation, transport, and consumption of energy carriers and services. 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

[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.

Table A1
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 $\sum_h dur_h = 1$)	$e \in E_l^L$	Service or production capacity
$\exp_{(\cdot)}^{(\cdot)}$	Capacity expansion limit	$inv_{(\cdot)}^{(\cdot)}$	Unit cost of capacity expansion
$trf_{(\cdot)}^{(\cdot)}$	Unit cost for service provision	$dep_{(\cdot)}^{(\cdot)}$	Infrastructure depreciation rate
$loss_{(\cdot)}^{(\cdot)}$	Relative losses though service usage	$ems_{(\cdot)}^{(\cdot)}$	Unit emissions
$cost_{yhsne}^P(\cdot)$	Production cost function	hor_{sne}^P	Production horizon (reserves)
lin_{ysne}^P	Linear term of the production cost function ($lin^P \geq 0$)	$transf_{yncef}^C$	Transformation rate by technology c at node n from input e to output f
qud_{ysne}^P	Quadratic term of the production cost function $(e, f) \in E_c^C$	shr_{ynce}^C	Minimum share of (input) fuel e by transformation technology c
$cour_{ysnd}^S$	Cournot market power parameter	$quota_{(\cdot)}^{(\cdot)}$	Quota for nodal/regional/global emissions
avl_{yhsne}^P	Availability factor of production capacity	eff_{ynde}^D	Efficiency of demand satisfaction of sector d by fuel e at node n
$e \in E_c^{C-}$	Inverse demand curve of sector d	$eucl_{yhnde}^D$	Linear end use cost parameter
int_{yhnd}^D	Intercept of inverse demand curve for fuel e at node n	$eucc_{yhnde}^D$	constant end use cost parameter
slp_{yhnd}^D	Slope of inverse demand curve for fuel e at node n	$shr_{ynl}^{(\cdot)}$	Minimum share of sector fuel mix constraint l (in energy services)
δ_y	Discount factor		
Variables			
$q_{(\cdot)}^{(\cdot)}$	Quantity produced/sold/interacting with service	$p_{(\cdot)}^{(\cdot)}$	Market-clearing price of fuel or service
$f_{(\cdot)}^{(\cdot)}$	Flow of energy or emissions	$z_{(\cdot)}^{(\cdot)}$	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	$h \in H_{vo}^V$	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		

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.

The remainder of this section outlines the model's equations (partitioned by the different actors) as well as a brief note on the central updates and changes with respect to the version of the model in [35]. Table A1 summarises the model's notation.

Suppliers in each node maximise their profits (1) from the production and sales of fuels, considering their costs for production (2), transportation, transformation, and storage. Their behaviour is restricted by production capacity (3), storage balance (4), production capacity investment limits (5), reserve limits (6), and the nodal mass balance constraint (7). Noticeably, they are the only Multimod agent that can exercise market power à la Cournot, i.e. they may not act as price-takers but charge a mark-up on their marginal costs and choose their supply strategically.

$$\max_{\substack{q^P, q^A, q^C, \\ q^{O-}, q^{O+}, q^D, \\ z^P}} \sum_{\substack{y \in Y, h \in H, \\ n \in N. e \in E}} \delta_y dur_h \left[\begin{array}{l} \sum_{d \in D} \left[\begin{array}{c} cour_{ysnd}^S \Pi_{yhnde}^D(\cdot) \\ +(1 - cour_{ysnd}^S) p_{yhsnde}^D \end{array} \right] q_{yhsnde}^D \\ -cost_{yhsne}^P(\cdot) - \sum_{a \in A_{ne}^+} p_{yha}^A q_{yhsa}^A - \sum_{c \in C} p_{yhnce}^C q_{yhsnce}^C \\ - \sum_{o \in O_e^E} (p_{yhno}^{O-} q_{yhsno}^{O-} + p_{yhno}^{O+} q_{yhsno}^{O+}) \\ - \sum_{g \in G} p_{yng}^G ems_{ysneg}^P q_{yhsne}^P - inv_{ysne}^P z_{ysne}^P \end{array} \right] \tag{1}$$

s.t.

$$cost_{yhsne}^P(\cdot) = lin_{ysne}^P q_{yhsne}^P + qud_{ysne}^P (q_{yhsne}^P)^2 \tag{2}$$

$$q^{P}_{yhsne} \le avl^{P}_{yhsne}\left(cap^{P}_{ysne} + \sum_{y`<y} dep^{P}_{y`ysne} z^{P}_{y`sne}\right) \tag{3}$$

$$\sum_{h\in H^{V}_{vo}} dur_h q^{O+}_{yhsno} = \sum_{h\in H^{V}_{vo}} dur_h (1 - loss^{O-}_{o}) q^{O-}_{yhsno} \tag{4}$$

$$z^{P}_{ysne} \le exp^{P}_{ysne} \tag{5}$$

$$\sum_{y\in Y, h\in H} dur_h q^{P}_{yhsne} \le hor^{P}_{sne} \tag{6}$$

$$\begin{aligned}(1 - loss^{P}_{sne}) q^{P}_{yhsne} &- \sum_{d\in D} q^{D}_{yhsnde} \\ &+ \sum_{c\in C, f\in E^{C-}_{c}} transf^{C}_{yncfe} q^{C}_{yhsncf} - \sum_{c\in C} q^{C}_{yhsnce} + \sum_{a\in A^{+}_{ne}} (1 - loss^{A}_{a}) q^{A}_{yhsa} \\ &- \sum_{a\in A^{-}_{yhsa}} q^{A}_{yhsa} + \sum_{o\in O^{E}_{e}} (q^{O+}_{yhsno} - q^{O-}_{yhsno}) = 0\end{aligned} \tag{7}$$

Transportation agents ('arc operators') operate, by assumptions, a single arc each, i.e. a specific way and mode of transportation between two nodes. They maximise their profits (8) in a competitive market, given capacity restrictions (9), capacity expansion limits (10), and a market-clearing condition (11).

$$\max_{f^{A}, z^{A}} \sum_{y\in Y, h\in H} \delta_y dur_h \left((p^{A}_{yha} - trf^{A}_{ya}) f^{A}_{yha} - \sum_{g\in G} p^{G}_{yng} ems^{A}_{yag} f^{A}_{yha} - inv^{A}_{ya} z^{A}_{ya} \right) \tag{8}$$

s.t

$$f^{A}_{yha} \le cap^{A}_{ya} + \sum_{y`<y} dep^{A}_{y`ya} z^{A}_{y`a} \tag{9}$$

$$z^{A}_{ya} \le exp^{A}_{ya} \tag{10}$$

$$\sum_{s\in S} q^{A}_{yhsa} = f^{A}_{yha} \tag{11}$$

Transformation operators – owners of power plants and refineries–convert primary into secondary energy and are, by assumption, unique in their corresponding nodes (e.g. there is only one refinery operator in China). They maximise their profits (12), given capacity restrictions (13), (policy-enforced) minimum shares of certain input fuels (14), capacity expansion limits (15), and a market-clearing condition (16).

$$\max_{f^{C}, z^{C}} \sum_{\substack{y\in Y, h\in H,\\ e\in E^{C-}_{c}}} \delta_y dur_h \left((p^{C}_{yhnce} - trf^{C}_{ync}) f^{C}_{yhnce} - \sum_{g\in G} p^{G}_{yng} ems^{C}_{yceg} f^{C}_{yhnce} - inv^{C}_{ync} z^{C}_{ync} \right) \tag{12}$$

s.t

$$\sum_{(e,f)\in E^{C}_{c}} transf^{C}_{yncef} f^{C}_{yhnce} \le cap^{C}_{ync} + \sum_{y`<y} dep^{C}_{y`ync} z^{C}_{y`nc} \tag{13}$$

$$shr^{C}_{ynce} \sum_{(e`,f)\in E^{C}_{c}} transf^{C}_{ynce`f} f^{C}_{yhnce`} \le \sum_{f\in E^{C+}_{c}} transf^{C}_{yncef} f^{C}_{yhnce} \tag{14}$$

$$z^{C}_{ync} \le exp^{C}_{ync} \tag{15}$$

$$\sum_{s\in S} q^{C}_{yhsnce} = f^{C}_{yhnce} \tag{16}$$

Storage operators allow certain energy carriers to be transferred between seasons. The agents maximise their profits (17), given restrictions of the cumulative energy injections (18) as well as restrictions of the period-wise intake (19) and outtake (20), the corresponding three capacity expansions (21), (22), (23), and market-clearing constraints for energy in- and outtake (24), (25).

$$\max_{\substack{f^{O-}, f^{O+}\\ z^{O}, z^{O-}, z^{O+}}} \sum_{y\in Y, h\in H} \delta_y dur_h \left[\begin{array}{c} (p^{O-}_{yhno} - trf^{O-}_{yno}) f^{O-}_{yhno} + p^{O+}_{yhno} f^{O+}_{yhno} \\ - \sum_{g\in G} p^{G}_{yng} ems^{O-}_{yog} f^{O-}_{yhno} - inv^{O}_{yno} z^{O}_{yno} \\ - inv^{O-}_{yno} z^{O-}_{yno} - inv^{O+}_{yno} z^{O+}_{yno} \end{array} \right] \tag{17}$$

s.t

$$\sum_{h\in H^{V}_{vo}} dur_h f^{O-}_{yhno} \le cap^{O}_{yno} + \sum_{y`<y} dep^{O}_{y`yno} z^{O}_{y`no} \tag{18}$$

$$f^{O-}_{yhno} \le cap^{O-}_{yno} + \sum_{y\text{`}<y} dep^{O-}_{y\text{`}yno} z^{O-}_{y\text{`}no} \tag{19}$$

$$f^{O+}_{yhno} \le cap^{O+}_{yno} + \sum_{y\text{`}<y} dep^{O+}_{y\text{`}yno} z^{O+}_{y\text{`}no} \tag{20}$$

$$z^{O}_{yno} \le exp^{O}_{yno}; \quad z^{O-}_{yno} \le exp^{O-}_{yno}; \quad z^{O+}_{yno} \le exp^{O+}_{yno} \tag{21}$$

$$\sum_{s\in S} q^{O-}_{yhsno} = f^{O-}_{yhno}; \quad \sum_{s\in S} q^{O+}_{yhsno} = f^{O+}_{yhno} \tag{22}$$

Emission authorities auction emission permits in a profit-maximising[7] way (26) based on national (27), regional (28), or global (29) greenhouse gas quotas. (30) is the global market clearing condition, including emissions from production, consumption, and all energy services.

$$\max_{f^C} \sum_{\substack{y\in Y,n\in N\\ g\in G}} \delta_y \left(p^G_{yng} - tax^{glob}_{yg} - \sum_{r\in R_n} tax^{reg}_{yrg} - tax^{nod}_{yng} \right) f^G_{yng} \tag{26}$$

s.t

$$\sum_{n\in N} f^G_{yng} \le quota^{glob}_{yg} + \sum_{n\in N} z^G_{yng} \tag{27}$$

$$\sum_{n\in N_r} f^G_{yng} \le quota^{reg}_{yrg} + \sum_{n\in N_r} z^G_{yng} \tag{28}$$

$$f^G_{yng} \le quota^{nod}_{yng} + z^G_{yng} \tag{29}$$

$$\sum_{h\in H,e\in E} dur_h \left(\begin{array}{c} \sum_{s\in S} ems^P_{ysneg} q^P_{yhsne} + \sum_{s\in S,d\in D} ems^D_{ydeg} q^D_{yhsnde} \\ + \sum_{a\in A^+_{ne}} ems^A_{yag} f^A_{yha} \\ + \sum_{c\in C} ems^C_{yceg} f^C_{yhnce} + \sum_{o\in O} ems^{O-}_{yog} f^{O-}_{yhno} \end{array} \right) = f^G_{yng} \tag{30}$$

Consumers that represent the different demand sectors in each node are utility-maximising agents gaining utility from the consumption of energy and weighing it against emission, end-use, and fuel costs. The result of utility maximisation manifests in the demand function (31). The end-use costs are automatically calibrated by auxiliary algorithms of Multimod and mimic endogenous fuel substitution, as elaborated in the appendix of [35].

$$p^D_{yhnde} = eff^D_{ynde} \left[int^D_{yhnd} - slp^D_{yhnd} \left(\sum_{s\in S,f\in E} eff^D_{yndf} q^D_{yhsndf} \right) \right] - eucc^D_{yhnde} - eucc^D_{yhnde} \left(\sum_{s\in S} q^D_{yhsnde} \right) - \sum_{g\in G} p^G_{yng} ems^D_{ydeg} \tag{31}$$

In contrast to the model outlined in [35], we augmented the model in three ways. First, to improve the tractability and numerical behaviour of the model, we removed the logarithmic term of the production cost function and reduced it to a quadratic function. Secondly, we added investments to negative emission technologies z^G_{yng} as a choice variable that enters emission constraints.[8] Lastly, and most importantly, we reformulated the model – originally a mixed complementarity problem (MCP) – into a convex quadratic optimisation problem.

To the best of our knowledge, this represents the first major application of the method described by [37]. The original MCP is given by the Karush–Kuhn–Tucker conditions of the problems derived from (1) to (31), i.e. the set of first-order conditions to the Lagrangians of all agents. Given the size of our dataset, however, this MCP requires more than three days to solve on a modern computer, which makes the calibration of the model nearly infeasible. Therefore, we convexified the model into a quadratically constrained program (QCP).[9] The QCP's objective function is given as the multivariable antiderivative of the entire set of the MCP's stationarity conditions. This antiderivative (32) can be understood as the scalar potential to the vector field that is defined by the first-order derivatives of each agent's objective functions, which can be shown to exist in this case due to the linearity of (inverse) demand and the convexity of the feasible area.

Hence, the final model for this study is given by the maximisation (32) under the restrictions (2)–(7), (9)–(11), (13)–(16), (18)–(25), and (27)–(31). The model is implemented in the algebraic modelling language GAMS and solved using the commercial solver CPLEX.

[7] Although these authorities are public entities without the objective of maximising profits, it is formally easier to introduce them as profit maximisers too. Given the First Theorem of Welfare Economics, the solution of a perfectly competitive market with profit-maximising agents equals the welfare-optimal allocation, which is why these two perspectives do not differ in terms of model results.

[8] We only make use of this feature in the ClimateTech scenario, which features exogenously fixed investment costs and investment limits. In all other scenarios, this option is ruled out.

[9] A sketch of the proof for the equivalence of the MCP and the QCP version can be found in [52].

$$\max_{\substack{q^A,q^C,q^D,q^P,q^{On}\\ z^A,z^C,z^O,z^{On},z^{Op}\\ eucC^D,eucL^D}} \left\{ \sum_{y,h} dur_h \delta_y \left(\begin{array}{c} \left[\sum_{s,e} (eff^D q^D_{y,h,s,n,d,e})\right] \\ \sum_{n,d} \left(\begin{array}{c} \left[int^D - \frac{1}{2} slp^D_{y,h,n,d} \sum_{s,e} (eff^D q^D_{y,h,s,n,d,e}) \right] \\ - \left[\sum_{s,e} (q^D_{y,h,s,n,d,e}) \right] \\ \left[eucC^D_{y,h,n,d,e} + eucL^D_{y,h,n,d,e} \sum_{s,e} (q^D_{y,h,s,n,d,e}) \right] \end{array} \right) \\ - \sum_{s,n,e} [lin^P_{y,s,n,e} q^P_{y,h,s,n,e} + quad^P_{y,s,n,e} (q^P_{y,h,s,n,e})^2] \\ - \sum_{s,a,e} (trf^A_{y,a,e} q^A_{y,h,s,a,e}) \\ - \sum_{s,n,c,e} (trf^C_{y,n,c} q^C_{y,h,s,n,c,e}) \\ - \sum_{s,n,c,e} (trf^{O-}_{y,n,o} q^{O-}_{y,h,s,n,o}) \\ - \sum_{s,n,e} (inv^P_{y,s,n,e} z^P_{y,s,n,e}) \\ - \sum_{a} (inv^A_{y,a} z^A_{y,a}) \\ - \sum_{n,c} (inv^C_{y,n,c} z^C_{y,n,c}) \\ - \sum_{n,o} (inv^O_{y,n,o} z^O_{y,n,o} + inv^{O-}_{y,n,o} z^{O-}_{y,n,o} + inv^{O+}_{y,n,o} z^{O+}_{y,n,o}) \\ - \frac{1}{2} \sum_{s,n,d,e} cour_{y,s,n,d} \left[\begin{array}{l} slp^D_{y,h,n,d} \left(\sum_{e} (eff^D_{y,n,d,e} q^D_{y,h,s,n,d,e}) \right)^2 \\ + eucl^D_{y,h,n,d,e} (q^D_{y,h,n,d,e})^2 \end{array} \right] \end{array} \right) \right\} \tag{32}$$

Appendix C. Multimod: Input data

We use a dataset named *30 nodes plus*, which is an extended and updated version of [35]'s dataset, to which we refer for a general and more comprehensive overview regarding model structure and data sources.

The dataset covers natural gas, coal,[10] lignite, and crude oil on the fossil fuel side as well as hydro, biofuels[11] and other renewables (solar/wind/geothermal), and nuclear energy on the upstream level. Demand sectors can use certain primary fuels directly, or they can be transformed into processed energy carriers (electricity from all fuels and oil products from crude oil). Also, transportation is possible via multiple pre-defined means of transportation (ship, pipeline, rail, street, powerline), depending on fuel and node. Natural gas can also be liquefied to and regasified from LNG. Market power – modelled via conjectural variation in asymmetric competition in quantities under perfect foresight – is assumed for a limited number of oil and gas producers (OPEC members, Qatar, Russia). Emission data is specified for different fuels and actions (i.e. the model accounts for emissions at each point of the value chain). An overview of the most important sources for input data is given in Table A2. The dataset makes extensive use of the DIW Berlin sector-level models and databases.

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[12] 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 [53]. Regarding future periods (i.e. 2025, 2035, 2045, 2055), we derive baseline demand values from the numerical results of [60][13] 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.

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 Cooperation). Of course, climate policies vary widely between the scenarios; for reasons of smoothness of calibration, they were modelled as emission caps in all scenarios.[14] Another set of parameters fitted to the storyline's centres around technological

[10] Coal refers to the sum of hard coal and lignite consumption and the quantity-weighted average, respectively, in line with IEA and BP reports.

[11] Biofuels are defined according to [53] and cover both primitive biomass as well as processed biofuels.

[12] See footnote 6.

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

[14] 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.

Table A2
Main sources for sectoral input data [35,55–59,61–70].

	Production costs	Production capacities	Transportation, & processing	Reserves	Emissions
Coal	[55]				[35, 61]
Gas	[62, 63]				
Oil	[56, 64]	[56, 65]	[35, 66]	[66]	
CCS	[57, 67, 68]				
Renewables	[35, 61, 69]				
Power	[58, 59]	[35, 58, 70]	[35, 58, 61]	[35]	

Table A3
Main sources and assumptions for the narratives p.d.: per decade.

	Business as Usual (BaU)	Survival of the Fittest	Green Cooperation	ClimateTech
	Base year demand: [53] Base reference demand trajectory: [60]			
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
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

development and its consequences. All scenarios feature cost declines and efficiency increases, but their extent and focus differ. While the full extent of the calibration cannot be exhibited in this paper, Table A3 illustrates some of the key differences.

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