



Reframing incentives for climate policy action

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A key aim of climate policy is to progressively substitute renewables and energy efficiency for fossil fuel use. The associated rapid depreciation and replacement of fossil-fuel-related physical and natural capital entail a profound reorganization of industry value chains, international trade and geopolitics. Here we present evidence confirming that the transformation of energy systems is well under way, and we explore the economic and strategic implications of the emerging energy geography. We show specifically that, given the economic implications of the ongoing energy transformation, the framing of climate policy as economically detrimental to those pursuing it is a poor description of strategic incentives. Instead, a new climate policy incentives configuration emerges in which fossil fuel importers are better off decarbonizing, competitive fossil fuel exporters are better off flooding markets and uncompetitive fossil fuel producers—rather than benefitting from ‘free-riding’—suffer from their exposure to stranded assets and lack of investment in decarbonization technologies.

The adoption of the Paris Agreement in 2015 set a worldwide objective of keeping the global average temperature well below 2°C above pre-industrial times, with efforts to achieve 1.5°C (ref. ¹), and called for clearer scientific evidence of the impacts of a 1.5°C pathway². New energy and climate scenarios have been developed to provide such evidence^{2–6}. Net-zero emissions targets have since been adopted for 2050, notably in the European Union, the United Kingdom, Japan and South Korea, and for 2060 in China, which together imply substantial reductions in global fossil fuel use and large markets for low-carbon technology. Reducing emissions requires increased investment in low-carbon technology, with much debated macroeconomic implications^{7–10}. Large quantities of fossil fuel reserves and resources are likely to become ‘unburnable’ or stranded if countries around the world implement climate policies effectively^{11–13}. The transition is already underway, and some stranding will happen, irrespective of any new climate policies, in the present trajectory of the energy system, with critical distributional macroeconomic impacts worldwide¹⁰. Although concerns over peak oil supply have shaped foreign policy for decades, the main macroeconomic and geopolitical challenges may, in fact, result from peaking oil (and other fossil-fuel) demand^{14–18}.

Climate action has traditionally been framed as economically detrimental to those who pursue it. From this perspective, climate action taken by a country is plagued by ‘free-riding’ by others not taking it, who nevertheless benefit from global mitigation, without the economic burden of environmental regulation^{19–22}. However, this motive is not supported by the evidence^{23,24}. More fundamentally, the nature of strategic incentives is misrepresented by this framing: incentives may now be more about industrial strategy, job creation and trade success^{25–27}. The costs of generating solar and wind energy, which depend on location, have already or will soon reach parity with the lowest-cost traditional fossil alternatives^{15,28,29}, and investment in low-carbon technologies is generating substantial new employment^{30–32}.

The notion that a country should benefit from free-riding on other countries’ climate policies can also be challenged. Incremental

decarbonization, increasing energy efficiency and the economic impacts of COVID-19 have led oil and gas demand and prices to decline substantially. This has affected the viability of extraction in less competitive regions¹⁵, despite new fossil fuel subsidies in recovery packages³³, although the recovery has been rapid and generated substantial market uncertainty. Fossil fuel exporters can be economically impacted by the climate policy decisions of other countries through a lower global demand and lower prices, and abandoning climate policies to boost domestic demand or maintain high prices is not sufficient to compensate for declining exports¹⁰.

In this article, we question the traditional framing of climate policy and explore the emergence of a new incentives configuration. We find that positive payoffs may arise for fossil energy importers who reduce imports, whereas negative payoffs arise for energy exporters who lose exports, both being far larger than the actual costs of addressing climate change.

Geopolitical context

The transition to a low-carbon economy has raised major questions of geopolitics in the international relations literature^{16–18,34–36}. Here we adopt Vakulchuk’s definition of ‘geopolitics’, as the connection between geography, resources, space and the power of states³⁶. It has become increasingly clear, with the pace at which renewables are growing, that traditionally fossil-fuel-dominated energy geopolitics must be revisited. With the prospects of renewable energies capturing markets previously dominated by fossil fuels, energy commodity exporters, in some cases affected by the resource curse³⁷, lose export markets. Concurrently, importers improve their trade balances^{16,17}. Revenue losses could lead to political instability in fossil-fuel-exporting economies and, although robust evidence indicates that climate change will increase conflict at all scales³⁸, it is unclear whether the transition will increase or reduce conflict overall^{16,35,36}.

Bazilian, Goldthau and co-workers^{34,39} describe four scenarios of geopolitical evolution, based on whether successful climate action is taken and on how geopolitical rivalries in fossil fuels and

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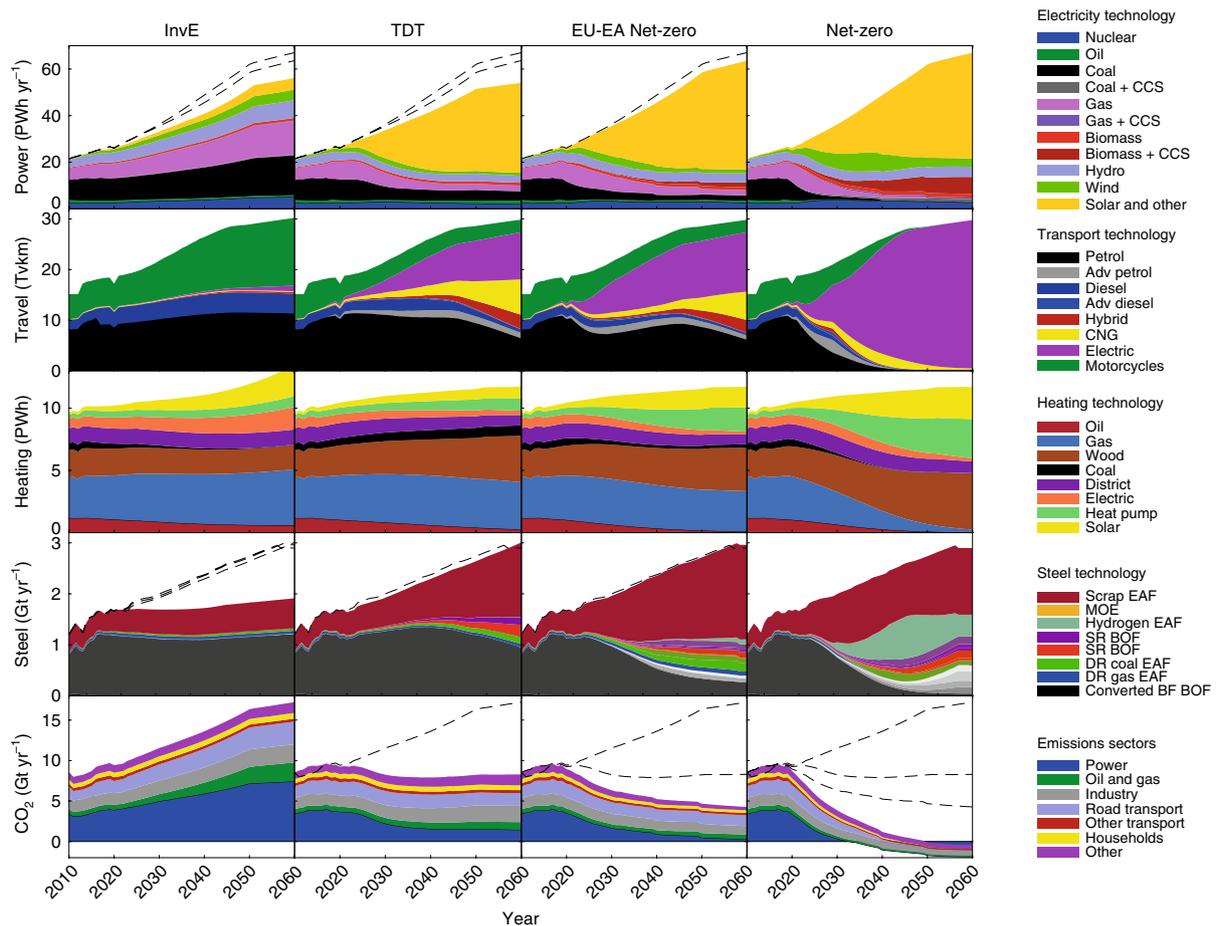


Fig. 1 | Diffusion of technology and evolution of energy use and emissions in key sectors. The evolution of 88 key power generation and final energy use technologies and emissions in four scenarios. Contributions are aggregated for clarity. Dashed lines indicate totals from other panels in the same rows, as guides to the eye for comparison. Adv, advanced; BF, blast furnace; BOF, basic oxygen furnace; CCS, carbon capture and storage; DR, direct reduction; EAF, electric arc furnace; MOE, molten oxide electrolysis; SR, smelt reduction.

renewables are addressed. They call for short- to mid-term quantitative scenario creation that could describe the geopolitical dynamics and narrow down the possibilities. A key question is whether low-carbon-technology development is globally cooperative or fragmented, and whether the emerging renewable energy geopolitics comes to replace fossil energy geopolitics^{18,40}.

Most nations possess sizeable technical potentials for one or more types of renewable energy sources, which reduces the likelihood of any state gaining important control over future energy supplies⁴¹. However, the production of renewables technology is increasingly concentrated in a few regions, which include China, Europe and the United States, and generate new types of geopolitical rivalry^{17,18}. Concerns over access to critical materials to manufacture renewables technology have been raised⁴¹ and, although debated, remain a concern for policymakers. Lastly, the possibility of new resource-curse situations linked to renewables has also been raised¹⁸.

Scholarship in geopolitics thus paints a much more complex picture than the standard framing of climate action as an environmentally necessary but economically costly step. Despite this, the prevailing framing^{22,23,42} underpins important debates, such as those on ‘carbon leakage’ (the relocation of carbon-intensive industries to countries with no or limited climate policy), the historical ‘free-riding’ of developed nations and the right to emit of developing nations. Hypotheses over geopolitics urgently need to be better supported by quantitative modelling evidence to help narrow down the possibilities.

Global scenarios

Understanding quantitatively the economic impacts of the ongoing low-carbon transition and their geopolitical implications requires modelling tools suitable for projecting sociotechnical evolution. Here we used the E3ME-FTT-GENIE integrated framework (E3ME, energy–economy–environment macro econometric; FTT, future technology transformation; GENIE, grid enabled integrated Earth)¹⁰ of disaggregated energy, economy and environment models based on the observed technology evolution dynamics and calibrated on the most recent time series available (Methods). Loosely consistent with Goldthau and co-workers^{34,39}, we created four scenarios from 2022 to 2070, which depict how future energy production, use, trade and income could either underpin expectations or actually materialize. We projected changes in output, investment and employment in 43 sectors and 61 regions of industrial activity, coupled with bilateral trade relationships between regions and input–output relationships between sectors. We simulated endogenous yearly average oil and gas prices and production over 43,000 active oil and gas assets worldwide. We then used a simple game theory framework to identify possible geopolitical incentives.

Technology diffusion trajectory: We simulated the current trajectory of technology and the economy, based on recently observed trends in technology, energy markets and macroeconomics, and explored the direction of technology evolution irrespective of new climate policies. This generates a median global warming of 2.6°C.

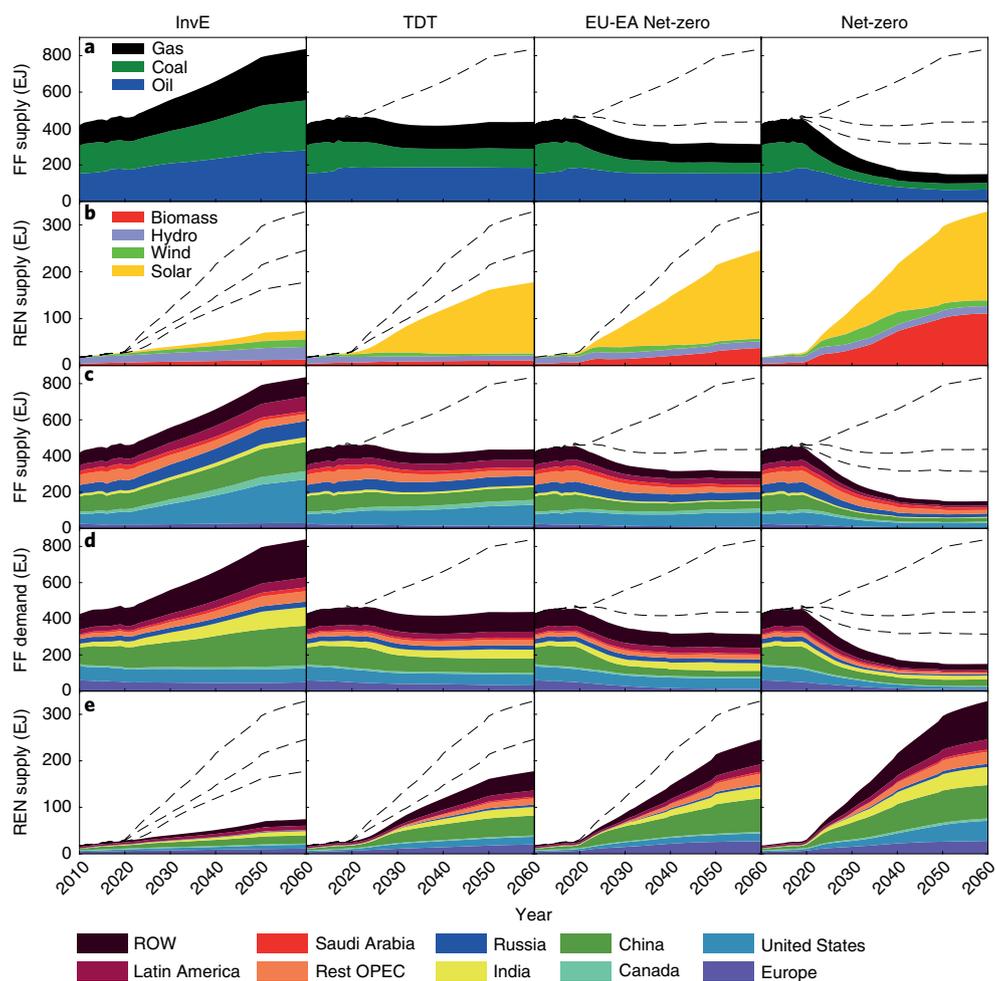


Fig. 2 | The evolving geography of energy demand and supply. **a–e**, The geography of energy supply by fossil fuel (FF) (**a**), supply of renewable electricity by source (REN) (**b**), fossil energy supply in six aggregate regions (**c**), fossil energy demand in six aggregate regions (**d**) and supply of renewable electricity in six aggregate regions (**e**). In **c–e**, the colours in the legend for the regions follow the same order as that in the panels. ROW, rest of world.

Net-zero CO₂ globally in 2050: We added new detailed climate policies by either increasing the stringency of what already exists or by implementing policies that may be reasonably expected in each regional context. The United Kingdom, European Union, China, Japan and South Korea reach net-zero emissions independently in 2050. Moderate amounts of negative emissions are used to offset residual emissions in industry. This achieves a median warming of 1.5 °C.

Net-zero in Europe and East Asia: We used the same policies to achieve net-zero emissions for Europe and East Asia (China in 2060, and Japan, the European Union and South Korea in 2050), but assume technology diffusion trajectory (TDT) policies elsewhere. This achieves a median warming of 2.0 °C.

Investment expectations: We replaced our energy technology evolution model by exogenous final energy demand data from the International Energy Agency (IEA) World Energy Outlook 2019 current policies scenario⁴³, in which energy markets grow over the simulation period, to reflect the expectations of delayed or abandoned decarbonization by a major subset of investors in energy systems. This generates warming of 3.5 °C.

Changes in energy systems

Figure 1 shows the evolution of technology globally for electricity generation, passenger road transport, household heating and steelmaking, as modelled using the FTT model components, and covers

58% of the global final energy carrier use, and 66% of global CO₂ emissions. Global fuel combustion and industrial emissions in all sectors are also shown.

We observe that the investment expectation (InvE) baseline sees coal and natural gas use dominate power generation, and petrol and diesel use in road transport translate into a steady growth of oil demand, whereas technology remains relatively unchanged for heating and steelmaking and other parts of the economy. Note that the InvE scenario projection is not likely to be realized as it features substantially lower than already-observed growth rates in solar, wind, electric vehicles (EVs) and heat pumps (Supplementary Note 1).

In stark contrast, the TDT scenario projects a relatively rapid continued growth, at the same rates as observed in the data, of some low-carbon technologies (solar, wind, hybrids and EVs, heat pumps and solar heaters), whereas others continue their existing moderate growth (biomass, geothermal, hydroelectricity and compressed natural gas (CNG) vehicles). Some technologies have already been in decline for some time, such as coal-based electricity and diesel cars (United Kingdom, European Union and United States), coal fireplaces and oil boilers in houses, and some inefficient coal-based steelmaking technologies (most countries).

Through a positive feedback of learning-by-doing and diffusion dynamics (Extended Data Fig. 1), solar photovoltaics (PV) becomes the lowest-cost energy generation technology by 2025–2030 in all but the InvE scenario, depending on regions and solar

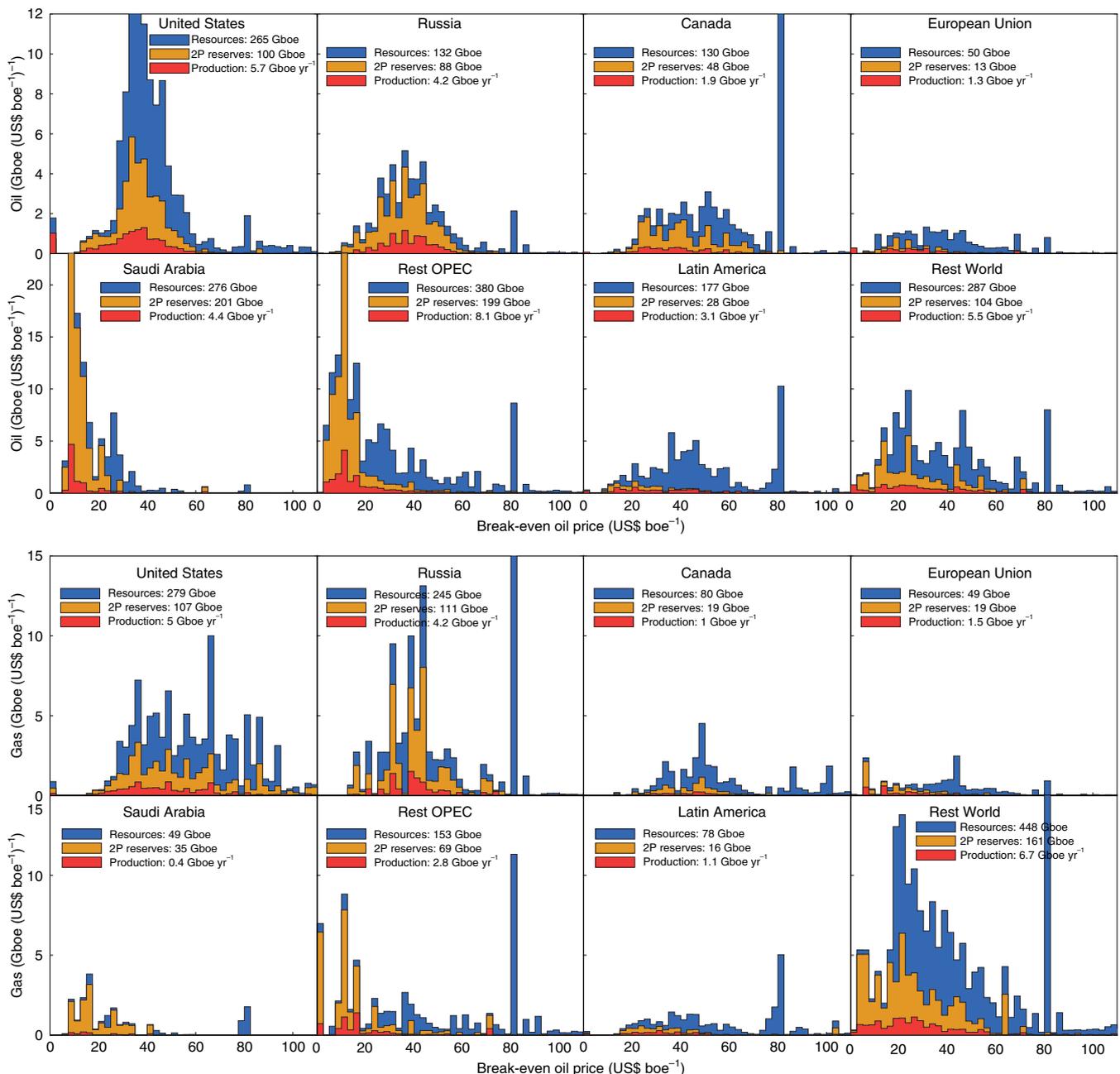


Fig. 3 | World oil and gas reserves and resources. Oil and gas world resources, reserves and production distributed along their break-even oil and gas prices, prices at which they are profitable to extract, processed by the authors using Rystad 2020 data⁴⁶. Production bar heights are scaled up by a factor of five to be visible in the graphs. Vertical axes have units of energy quantities per unit cost range, such that their integral between two limits yields energy quantities. Legends indicate totals. Note that the region 'Rest of OPEC' excludes Saudi Arabia and 'Rest World' aggregates all countries globally that are not included in other panels, for visual clarity. 2P, proven reserves + probable reserves.

irradiation. EVs display a similar type of winner-takes-all phenomenon, although at a later period. Heating technologies evolve as the carbon intensity of households gradually declines. The trajectory of technology in the TDT scenario, as observed in recent data, suggests that primary energy consumed in the next three decades is substantially lower than that suggested by InvE, as the relatively wasteful and costly thermal conversion of primary fossil fuels into electricity, heat or usable work stops growing even though the whole energy system continues to grow. In the Paris-compliant net-zero CO₂ globally in 2050 (Net-zero) scenario, technology transforms at a comparatively faster pace to reach global carbon neutrality, whereas in the European Union–East Asia (EU-EA) Net-zero sce-

nario, low-carbon technology deployment in regions with net-zero targets accelerates the cost reductions for all regions, which induces faster adoption even in regions without climate policies.

We comprehensively modelled the global demand for all energy carriers in all sectors and regions (Fig. 2 (sectoral details are given in Extended Data Fig. 2, and regional details in Extended Data Figs. 3 and 4; see Supplementary Dataset)). We observe a peaking in the use of fossil fuels and nuclear by 2030 and a concurrent rise of renewables in all but the InvE scenario (Fig. 2a,b). PV takes most of the market, followed by biomass, which serves as a negative emissions conduit, and wind, which in our scenarios is gradually outcompeted by PV. The growth of hydro is limited by the number of undammed

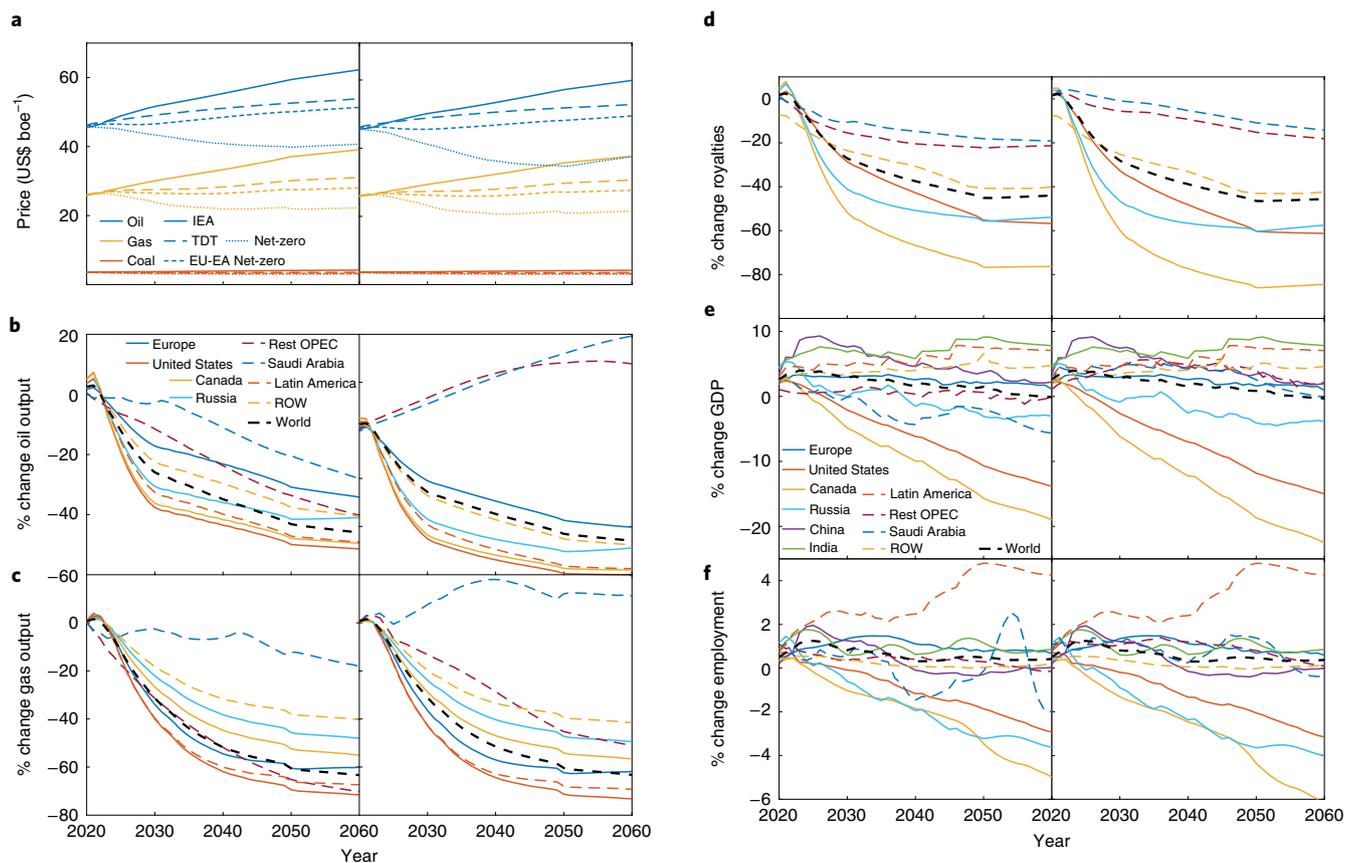


Fig. 4 | Evolution of key energy and macroeconomic variables. **a–c**, Absolute price changes for all scenarios (**a**), and production losses in oil (**b**) and gas (**c**) markets for the EU-EA Net-zero QU (left panels) and SO (right panels) scenarios, expressed as percentage change from the IEA scenario. **d–e**, Changes in government revenues from oil and gas activities through royalties (**d**), and changes in GDP (**e**) and employment (**f**) for the EU-EA Net-zero QU (left panels) and SO (right panels) scenarios, all expressed as percentage change from the IEA scenario. Saudi Arabia is separated from the rest of OPEC for clarity, ROW covers regions and countries not otherwise included and ‘World’ refers to changes at the global level. Government revenues are assumed as deficit-neutral for clarity of the analysis (Supplementary Note 3).

rivers that can be dammed, and other renewables have lower potentials or lack competitiveness (geothermal and ocean-related systems). Cost trajectories are dictated by the interaction between diffusion and learning-by-doing.

Figure 2c–e shows the evolving geography of the global supply and demand of primary fossil energy and renewables. As fossil energy is widely traded internationally but renewable energy is primarily consumed in local electricity grids (Supplementary Note 2), the geographies of demand and supply differ substantially for fossil fuels, but they are essentially identical for renewables. The observed rapid diffusion of renewables substantially decreases the value of regional energy trade balances, without replacement by new equivalent sources of trade. Although renewable technical potentials are mostly dependent on the landmass of nations, fossil fuel production and decline are concentrated in a subset of geologically suited regions⁴⁴.

Distributional impacts and geopolitics

International fossil fuel trade relationships form a key source of economic power in the current geopolitical order^{16,17}. The demise of fossil fuel markets is therefore unlikely to proceed without important changes in economic and political power, and it is critical to explore the various ways in which this could play out^{34,39}. For that, it is necessary to first understand what comparative market power each producer region wields and, second, what macroeconomic and fiscal implications market strategies can have⁴⁵.

We show in Fig. 3 the cost distribution of global oil and gas resources according to the Rystad^{46,47} database, which comprehensively documents over 43,000 active oil and gas assets, and covers most existing resources worldwide (Methods and Supplementary Dataset), aggregated here in eight key regions. In the TDT scenario, our model projects cumulative global oil and gas use up to 2050 of 890 and 630 Gbbl, respectively (480 and 370 Gbbl, respectively, in the Net-zero scenario). Saudi Arabia and other Organization of the Petroleum Exporting Countries (OPEC) together possess over 650 and 202 Gbbl of resources of oil and gas, respectively, characterized predominantly by substantially lower costs of production (below US\$20 per barrel in many cases) compared those of the resources left in the United States, Canada and Russia, which occur at substantially higher production costs (between US\$20 and US\$80 per barrel). This suggests that, under the expectation of limited future oil and gas demand, OPEC countries have a strong rational incentive, together or independently, to capture most future oil and gas demand by maintaining or increasing their production and thereby pricing out other participants from fossil fuel markets⁴⁸.

We defined two scenario variants that represent two opposite OPEC courses of action that delimit a spectrum⁴⁹. At one end of the spectrum, in a scenario of oil and gas assets fire sale (denoted SO for ‘sell-off’), OPEC ramps its production reserve ratio up to a sufficiently high level to gradually acquire a large fraction of global demand as it peaks and declines, effectively offshoring what would otherwise be production losses¹⁶. At the other extreme, in a scenario

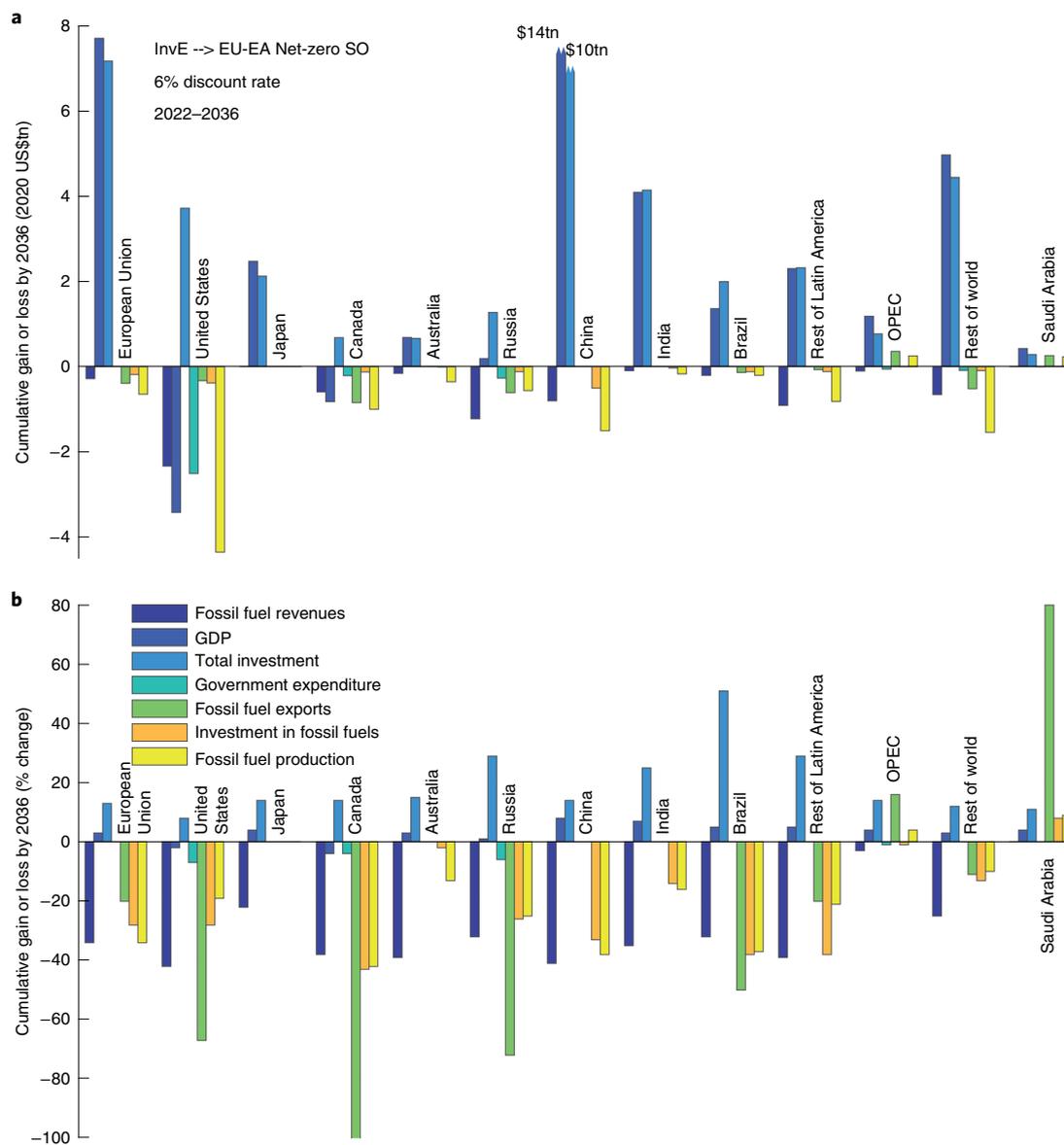


Fig. 5 | Cumulated macroeconomic gains and losses by country. a, b, Changes in the value of fossil fuel assets, GDP, investment and fossil fuel production across chosen economies for both the EU-EA Net-Zero QU and SO scenarios, relative to the InvE scenario, expressed in absolute terms (**a**) and as percentage change (**b**). Gains are positive and losses negative. Values are cumulated over 15 years, between 2022 and 2036, using a 6% discount rate. Note that stranded fossil fuel assets are stocks of financial value, whereas GDP and investment are cumulated economic flows, and thus are not to be compared or added. A cumulation to 2050 is available in Extended Data Fig. 5. tn, trillion.

of strict quotas (denoted QU for ‘quotas’), OPEC limits production to maintain a constant share of the peaking and declining global demand, which maintains its traditional role in stabilizing markets¹⁴. Figure 4a shows changes in prices for all the scenarios, and Fig. 4b,c changes in quantities for the EU-EA Net-zero scenario, which originates from the current technological trajectories and the existing net-zero pledges, relative to the expectations benchmark in InvE. We observe that, whereas in the QU EU-EA Net-zero scenario the production losses are more evenly distributed between nations, in the SO EU-EA Net-zero scenario, the United States, Canada, South America and, to a lesser extent, Russia⁵⁰ are gradually excluded from oil and gas production as it concentrates towards OPEC countries (Methods).

The prices of fossil fuels were estimated in E3ME-FTT by identifying the marginal cost of the resource production that matches demand at every time point, which for oil and gas is based on the

Rystad data. Depending on production decisions, long-term oil prices could remain at values as low as US\$35bbl⁻¹ for extended periods as the expected economic viability of higher cost resources (such as tar sands, oil shales, arctic and deep offshore) deteriorates permanently.

Changes in oil and gas prices, combined with slumps in production, may therefore have disruptive structural effects on high-cost fossil fuel producers, such as the United States, Canada, Russia and South America. Meanwhile, shedding expensive imports benefits gross domestic product (GDP) and employment in large importer regions, such as the European Union, China and India, as money not spent on expensive energy imports is spent domestically, and output is boosted by major low-carbon investment programmes. Figure 4d–f shows this using percentage changes in government royalties, GDP and total employment between the EU-EA Net-zero and the InvE scenarios. These transformations arise from changes

Table 1 | GDP payoff matrices

Importers versus OPEC		OPEC			
		QU		SO	
		Importers	OPEC	Importers	OPEC
Importers	EU-EA Net-zero	26,889	243	26,521	1,182
	TDT	8,367	-40	8,171	410
OPEC versus HCEs		HCEs			
		EU-EA Net-zero		Net-zero	
		HCE	OPEC	HCE	OPEC
OPEC	QU	-2,590	243	-4,595	1,551
	SO	-4,042	1,182	-6,350	2,748

GDP is measured in US\$2020 billion (cumulated between 2022 and 2036, discounted by 6%; positive values are GDP increases with respect to the InvE scenario). Cells in italics indicate probable outcomes. The game has a Nash equilibrium in the EU-EA Net-zero SO scenario combination.

in fossil and energy production sectors, their dependent supply chains and other recipients of spending income in unrelated sectors, which include government royalties. Losses of jobs and output in producer countries are, in general, not overcompensated by the job and output creation effect of renewables deployment, whereas in importer countries, net gains are observed. Supply-chain effects amplify the output changes that originate from the energy sector (manufacturing, construction and services). For clarity of analysis, we assume no compensatory effect from any deficit spending (Supplementary Note 3).

Economic changes implied by the new net-zero pledges (the EU-EA Net-zero scenario against InvE) are given in Fig. 5, which shows output, exports, investment and lost fossil fuel production discounted by 6% and cumulated over the next 15 years (see Extended Data Fig. 5, Supplementary Tables 1 and 2 and Supplementary Dataset for comparison variants). Stranded fossil fuel assets of between US\$7 trillion and US\$11 trillion arise. These findings largely corroborate earlier geopolitical scenario analysis^{17,39}.

Using a simple two-by-two game theory framework applied to importers, OPEC and high-cost producer countries (Table 1, Extended Data Fig. 6 and Supplementary Note 4), we find that if strategic climate and energy policy decisions were taken solely on the basis of the GDP or employment outcomes, and that these were known in advance to policymakers, the EU-EA Net-zero SO would be a stable Nash equilibrium. The decision by importers to decarbonize is a dominant strategy, as is that of OPEC producers to flood markets. High-cost producers are left with the decision whether to decarbonize or not. Their fossil energy industry falls victim to low-cost competition, but the economic benefits of low-carbon investment do not necessarily compensate for the high losses of output in high-carbon industries.

Discussion

A new incentives configuration, beyond the standard framing of climate policy as environmentally necessary but economically costly, emerges with the new energy geopolitics. Whether and how fast fossil energy markets peak and decline is primarily decided by the major energy importers (China, India, Japan and the European Union). These have an economic incentive to decarbonize and their decisions impact producers in general. The magnitude of the re-organization of high-value oil and gas markets depends strongly on choices of energy output made by OPEC countries, a dimension of agency that other producers do not possess. With the impact of the transition on their fiscal position, GDP and jobs of the transition can be largely overcompensated by their output strategy and a compelling narrative emerges in which OPEC countries choose

to protect their national interests, fiscal position and geopolitical power at the expense of economic, financial and political stability in the high-cost producers that their strategy affects (the United States, Canada and Russia). Meanwhile, a lack of commitment or withdrawal from climate policy in high-cost producer countries does not maintain sufficient domestic demand to overcompensate export losses, and the balance of power remains in the hands of major importers. As low-carbon transitions are under way in the United Kingdom, the European Union, China and other nations, as evidenced in technology data, export losses for high-cost exporters (HCEs) are likely to be permanent. In its Net-zero scenario, the IEA projects an increase of OPEC oil market share from 37 to 52% in 2050⁴⁵ (66% in our analysis), with comparable implications for energy markets and geopolitics. Our findings broadly support the qualitative scenarios^{34,39} and regional political dynamics and drives¹⁷ proposed in recent geopolitics literature, and provide a crucial quantitative dimension.

The new energy geopolitics has further deep socio-economic implications also beyond the standard framing of climate policy. First, in line with the literature on great waves^{51,52} and the Just Transition^{53,54}, the creative destruction effect of the low-carbon transition underway is likely to generate localized issues of post-industrial decline in the United States, Russia, Canada, Brazil and other oil producers. This suggests that comprehensive plans for regional redevelopment are probably needed, along with economic diversification towards new technology sectors, which include low-carbon technology exports²⁵⁻²⁷. Second, if economic diversification and divestment away from fossil fuels is not quickly addressed in those countries, the low-carbon transition could lead to a period of global financial and political instability^{16,35}, due to the combination of deep structural change, widespread financial loss and reorganization in financial and market power worldwide. Addressing economic diversification away from fossil fuels is complex but necessary to protect economies from the volatility characteristic of the end of technological eras.

Methods

Most integrated assessment models currently used to assess climate policy and socio-economic scenarios are based on whole-system or utility optimization algorithms, although some are based on optimal growth⁵⁵. Integrated assessment models have helped set the global climate agenda by identifying desirable energy system configurations. However, they are unsuitable for studying trends in energy system dynamics as historical dependences are neglected, whereas systems optimization assumes an empirically unsubstantiated degree of system coordination^{55,56}.

Here we used the non-optimization integrated assessment model E3ME-FTT-GENIE^{10,57} framework based on observed technology evolution dynamics and behaviour measured in economic and technology time series. It covers global macroeconomic dynamics (E3ME), S-shaped energy technological change dynamics (FTT)⁵⁸⁻⁶⁰, fossil fuel and renewables energy markets^{44,61}, and the carbon cycle and climate system (GENIE)⁶. We projected economic change, energy demand, energy prices and regional energy production.

The E3ME-FTT-GENIE integrated framework is described below. The full set of equations that underpin the framework is given and explained in Mercure et al.⁵⁷. Assumptions for all the scenarios are also given.

E3ME. The E3ME model is a highly disaggregated multisectoral and multiregional, demand-led macroeconomic and dynamic input-output model of the global economy. It simulates the demand, supply and trade of final goods, intermediate goods and services globally. It is disaggregated along harmonized data classifications worldwide for 43 consumption categories, 70 (43) sectors of industry within (outside of) the EU member states and the United Kingdom, 61 countries and regions, which includes all EU member states and the G20 nations, that cover the globe, 23 types of users of fuels and 12 types of fuels. The model features 15 econometric regressions calibrated on data between 1970 and 2010, and simulates on yearly time steps onwards up to 2070. The model is demand-led, which means that the demand for final goods and services is first estimated, and the supply of intermediate goods that lead to that supply is determined using input-output tables and bilateral trade relationships between all the regions.

The model features a positive difference between potential supply capacity and actual supply (the output gap), as well as involuntary unemployment of the labour force. This implies that when economic activity fluctuates, short-term

non-equilibrium changes in the employment of labour and capital can arise and, notably, unemployed resources can become employed. The model follows the theoretical basis of demand-led post-Keynesian and Schumpeterian (evolutionary) economics^{8,62} in which investment determines output, rather than output determining investment and capital accumulation, as is done in general equilibrium models. This implies that purchasing power to finance investment is created by banks on the basis of the creditworthiness of investors and investment opportunities, and repaid over the long term. The model therefore possesses an implicit representation of banking and financial markets in which the allocation of financial resources is not restricted by crowding out from other competing activities, as the creation of money in the form of loans can accelerate during periods of optimism, and decline in periods of depression^{8,62}. For this reason, E3ME is the ideal model to study the business cycle dynamically, as it does not assume money neutrality and is path dependent.

The closed set of regressions includes estimating, as dependent variables, household consumption (by construction equal to supply), investment, labour participation, employment, hours worked, wages, prices (domestic and imports), imports and the expansion of industrial productive capacity. Endogenous growth is generated by the inclusion of technology progress factors in several equations, which represent sectoral productivity growth as the economy accumulates scale, knowledge and knowhow with cumulative investment⁵⁷. Final energy demand and the energy sector as a whole is treated in detail similarly, but separately in physical energy quantities.

FTT. E3ME estimates energy demand and related investment for all the sectors and fuel users of the global economy with the exception of the four most carbon-intensive sectors (power, transport, heat and steel), for which technological change is modelled with a substantially higher definition using the FTT family of models. FTT is a bottom-up representation of technological change that reproduces and projects the diffusion of individual technologies calibrated on recent trends. FTT:Power⁵⁸ represents the market competition of 24 power technologies, which include nuclear, coal- oil- and gas-based fuel combustion (with CCS options), PV and concentrated solar power, onshore and offshore wind, hydro, tidal, geothermal and wave technologies. FTT:Transport^{59,63} represents the diffusion of petrol, diesel, hybrid, CNG and EVs and motorcycles in three engine size classes, with 25 technology options. FTT:Heat⁶⁰ looks at the diffusion of oil, coal, wood and gas combustion in households as well as resistive electric heating, electric heat pumps and solar heaters in 13 technology options. Lastly, FTT:Steel represents all the existing steel-making routes based on coal, gas, hydrogen and electricity in 25 types of chains of production. Technologies not represented in FTT currently have very low market shares, which necessarily implies, in a diffusion framework, that their diffusion to such levels, which would invalidate the present scenarios, is highly unlikely within the policy horizon of 2050 (for example, nuclear fusion and hydrogen mobility).

FTT is a general framework for modelling technology ecosystems that is in many ways similar to modelling natural ecosystems, based on the replicator dynamics equation⁶⁴. The replicator equation (or Lotka–Volterra system) is an ubiquitous relationship that emerges in many systems and features nonlinear population dynamics, such as in chemical reactions or ecosystem populations^{64,65}. It is related to discrete choice models and multinomial logits through adding a term in the standard utility model to represent agent interactions (for example, technology availability limited by existing industry sizes and social influence), which gives it the distinctive S-shaped diffusion profile⁶⁵.

The direction of diffusion in FTT is influenced by the economic and policy context on the basis of suitable sector-specific representations of decision-making, by comparing the break-even (levelized) cost of using the various technology options in a discrete choice model weighted by the ubiquity of those technology options. The various levelized costs include a parameter that represents the comparative non-pecuniary costs and advantages of using each technology. This parameter is used to calibrate the direction of diffusion to match what is observed in recent trends of diffusion, notably important for PV, wind, EVs and heat pumps (see Mercure et al.⁵⁹).

A key recent innovation in FTT:Power is a detailed representation of the intermittency of renewables through the introduction of a classification of generators along six load bands, following the method of Ueckerdt et al.⁶⁶, with the addition of an allocation of production time slots to available generators according to intermittency and flexibility constraints. This ensures that the levels of grid flexibility to allow the introduction of large amounts of renewables are respected, which maintains model results within a range deemed to represent a stable electricity grid. Intermittency, optimal intermittent renewable curtailment and energy storage parameters are estimated by Ueckerdt et al.⁶⁶ based on solar and wind data and optimization modelling results. The result in FTT is that the main obstacle for solar and wind penetrating grids is the rate at which the required flexibility can be accommodated. The addition of this electricity market model has implied, in comparison with earlier work¹⁰ based on cruder and more restrictive stability assumptions, that renewables can penetrate the grid more rapidly and effectively.

GENIE. GENIE, an intermediate complexity Earth system model, simulates the global climate carbon cycle to give the future climate state driven by CO₂

emissions, land-use change and non-CO₂ climate forcing agents. It comprises the GOLDSTEIN (global ocean linear drag salt and temperature equation integrator) three-dimensional frictional geostrophic ocean model coupled to a two-dimensional energy moisture balance atmosphere, a thermodynamic–dynamic sea-ice model, the BIOGEM ocean biogeochemistry model, the SEDGEM sediment module and the ENTSML (efficient numerical terrestrial scheme with managed land) dynamic model of terrestrial carbon storage and land use change. GENIE has the resolution of 10° × 5° on average with 16 depth levels in the ocean and has here been applied in the configuration of Holden and co-workers^{57,68} (see references therein).

The probabilistic projections were achieved through an ensemble of simulations for each emissions scenario using an 86-member set⁶⁹ that varies 28 model parameters to produce an estimate of the full parameter uncertainties. Each ensemble member simulation was continued from an AD 850–2005 historical transient spin-up. Post-2005 CO₂ emissions are provided by E3ME, and scaled by 9.9/*X* to match the actual emissions in 2019⁷⁰ (where *X* = 9.3 GtC is the E3ME 2019 emissions) to correct for missing processes in E3ME. The emissions trajectories were then extrapolated to 2100 (InvE, TDT and EU-EA Net-zero scenarios) or until they reached net zero (Net-zero scenario). The Net-zero scenario reaches zero emissions during the E3ME simulation in 2050. Trace gas radiative forcing and land-use-change maps and land use emissions are taken from Representative Concentration Pathway (RCP) 2.6 (EU-EA Net-zero and Net-zero scenarios) and RCP 6.0 (InvE and TDT scenarios). GENIE results for exceedance likelihoods for climate thresholds and median peak warming for each scenario are given in Supplementary Table 3.

The GENIE ensemble has been validated⁶⁹ through comparing the results of 86-member ensemble simulations for the RCP scenarios with CIMIP5 (coupled model intercomparison project phase 5) and EMIC (Earth system model of intermediate complexity) ensembles.

The energy market model using Rystad data. The geographical allocation of oil and gas production was estimated by integrating to the model data from the substantial Rystad Ucube⁶⁶ dataset in the form of break-even cost distributions (as in Fig. 3, aggregated into 61 regions). The Rystad dataset documents over 43,000 existing and potential oil and gas production sites worldwide, which cover the large majority of current global production and existing reserves and resources. It provides each site's break-even oil and gas prices, reserves, resources and production rates. However, the Rystad projected rates of asset production and depletion⁴⁷ were not used in our model, which does not rely on Rystad assumptions.

The energy market model⁶¹ assumes that each site has a likelihood of being in producing mode that is functionally dependent on the difference between the prevailing marginal cost of production and its own break-even cost. The marginal cost is determined by searching, iteratively with the whole of E3ME, for the value at which the supplies matches the E3ME demand, which is itself dependent on energy carrier prices. Dynamic changes in marginal costs are interpreted as driving dynamic changes in energy commodity prices.

The regional production to reserve ratios are exogenous parameters that represent producer decisions. The initial values were obtained from the data to reproduce current regional production according to the reserve and resources database. Future changes in production to reserve ratios for each region were determined according to the chosen rules for the QU and SO scenarios. Changes are only imposed to production to reserve ratios of OPEC countries, to either achieve a production quota that is proportional to global output (QU scenario, and thereby reduce production to reserve ratios accordingly) or attempt to maintain constant absolute production as global demand peaks and declines (SO scenario, and thereby increase production to reserve ratios). Only oil and gas output in OPEC are thus affected by these parameter changes, which affects the allocation of the overall markets.

Renewables are limited through resource costs by technical potentials determined in earlier work⁴⁴.

Scenarios and choices of regional decarbonization policies. *TDT.* All policies are implicit through the economic, energy and technology diffusion data, with the exception of an assumed explicit carbon price for the EU-ETS region and other carbon markets that cover the projection period, which covers all industrial, but not consumer, mobility, household or agriculture, emission sources, following current policy. Regulations are applied in some regions, such as on coal generation in Europe, which cannot increase due to the Large Combustion plant directive. Hydro, comparatively resource limited, is regulated in many regions to avoid large expansions that could otherwise be politically sensitive.

Net-zero. To the implicit policies of the TDT are added explicit policies as follows, with the exception of the carbon price, which is replaced by more stringent values. Emissions reach net zero independently in the United Kingdom, the European Union, South Korea and Japan by 2050, and China by 2060, following current legally binding targets, as well as in the rest of the world as a whole.

Power generation.

- Feed-in tariffs for onshore and offshore wind generation, but solar PV does not benefit from additional support policies beyond what is already in place.

- Subsidies on capital costs for all other renewables (geothermal, concentrated solar power, biomass, wave and tidal) with the exception of hydro and solar PV.
- Hydro is regulated directly in most regions to limit expansion, given that in most parts of the world the number of floodable sites is limited and flooding new sites faces substantial resistance from local residents.
- Coal generation is regulated such that no new plants not fitted with CCS can be built, but existing plants can run to the end of their lifetimes. However, all remaining coal plants are shut down in 2050.
- Public procurement is assumed to take place to install CCS on coal, gas and biomass plants in many developed and middle-income countries where this does not already exist, notably in the United States, Canada, China and India.
- The use of BECCS (bioenergy with carbon capture and storage) is supported by existing policies and the introduction of further public procurement policies to publicly fund the building of BECCS plants in all countries endowed with solid biomass resources.

Road transport. Policy portfolios were designed tailored to five major economies characterized by different vehicle markets (United Kingdom, United States, China, India and Japan), according to the policies already in place and the composition of local vehicle markets. Policies in other countries were designed by using proxies to the most similar of the five markets above. Portfolios include combinations of the following:

- Regulations on the use of inefficient petrol and diesel vehicles, with increasing efficiency targets over time.
- Capital cost subsidies on EVs.
- Taxes on petrol and diesel and/or on the purchase price of high-carbon vehicles.
- Public procurement programmes for supporting the diffusion of EVs.
- Yearly vehicle taxes linked to emissions.

Household heating.

- Taxes on household use of fuels for heating (coal, oil and gas).
- Capital cost subsidies for heat pumps and solar water heaters.
- Public procurement policies to increase the market share of the heat pump industry.
- Regulations on the sale of new coal, oil and inefficient gas boilers.

Steelmaking.

- Regulations on the construction of new inefficient coal-based steel plants.
- Capital cost subsidies for new lower carbon plants such as biomass and hydrogen-based iron ore reduction and smelting, and to fit CCS to existing high-carbon plants.
- Subsidies on the consumption of low-carbon energy carriers.
- Public procurement to build new low-carbon steel plants to develop markets in which they do not exist.

Cross-sectoral policies.

- The energy efficiencies of non-FTT sectors are assumed to change in line with the IEA⁷¹, with corresponding investments in the respective sectors.
- A carbon price is applied to all industrial fuel users with the exception of road transport, household heating, agriculture and fishing, which are covered by other sector-specific fuel taxes and are not expected to participate in emissions trading schemes. The carbon price is exogenous and increases in the European Union from its 2020 value, in nominal euros, until €1955 tC⁻¹ in 2033 and remains there thereafter. Deflating these values using E3ME's endogenous price levels into 2020 US dollars (as E3ME operates in nominal euros) and converting to CO₂, these carbon prices are equivalent to between US\$300 and 500 tCO₂⁻¹ in 2033, decreasing thereafter following different country inflation rates to US\$250–350 tCO₂⁻¹ in 2050 and US\$150–200 tCO₂⁻¹ in 2070.

EU-EA Net-zero. The Net-zero scenario was designed by creating a cross between the TDT and the Net-zero scenario in which the European Union, United Kingdom, Japan, South Korea and China adopt the Net-zero policies as defined above and achieve their respective targets, whereas every other country follows the TDT. Note that technology spillovers (for example, learning) in the model imply that this scenario is not a simple linear combination of the parent scenarios, because low-carbon technology adoption in countries without net-zero policies is higher than that in the TDT.

SO and QU scenario variants. These scenarios were generated by varying the exogenous production ratio to the reserve ratio of OPEC countries including Saudi Arabia (given that OPEC is disaggregated between Saudi Arabia, OPEC countries in Africa and the rest of OPEC), assuming that only OPEC has the freedom and incentive to do so. Production in the model is proportional to existing reserves in each producing region, and the proportionality factor is determined

by the data such that production data are consistent with reserve data. The production-to-reserve ratios in the three OPEC regions are modified by applying the values that achieve either production quotas that remain proportional to global oil and gas outputs (QU scenario) or constant in absolute value (SO scenario). In the central scenarios, production-to-reserve ratios are maintained constant.

SO scenarios could be defined for other regions, notably the United States and Russia; however, we consider these unlikely to materialize without SO responses from OPEC, which, due to its higher competitiveness according to the Rystad data, always wins price wars in the model. Thus, such SO scenarios for regions other than OPEC add little information to what is already shown here. In reality, SO strategies could be plagued by refining capacity bottlenecks or strategic stockpiling behaviour. We assume that refining and fuel transport capacity remains undisturbed (for example, by regional conflict) and that current capacity outlives peak demand. This is reasonable given the existing capacity and the fact that demand growth declines. We furthermore assume that incentives to stockpile drastically decline in situations of peak demand, as overproduction is likely, which reduces opportunities for arbitrage. Trade tariffs on oil and gas could be imposed to protect domestic industries, notably in the United States, which decouples them from global markets, but are not modelled here.

InvE scenario. This scenario involves no other assumptions than policies present in the TDT and replacing all FTT outputs (energy end use and energy sector investment) with exogenous data consistent with the IEA's World Energy Outlook 2019 current policies scenario⁴³. This scenario, qualitatively similar to that of RCP8.5⁷², sees growth in all fossil fuel markets, and was chosen over the newer IEA's World Energy Outlook 2020 scenarios, which are qualitatively different¹⁵. The InvE scenario cannot be reached under any realistic set of assumptions in E3ME-FTT projections, as it would violate the model premise of near-term continuity in observed technology diffusion trajectories. This scenario was chosen as a proxy for recent past expectations for the future of fossil energy markets, of investors who may still entertain beliefs of indefinite growth in future fossil fuel markets. As it is not possible to determine which investors entertain which expectations, the realism of the InvE scenario as a proxy for expectations cannot be assessed; therefore, it is used only to develop a what-if comparative narrative.

Data availability

The data needed to replicate and interpret the study are included in a supplementary data file with this article. Additional data from the various models used in this study for variables not included in the supplementary data file can be obtained from the authors upon reasonable request. Original data from Rystad and the IEA are licensed by these owners, but the datasets derived by the authors from these datasets and used in the study are included in the supplementary data file.

Code availability

The computer code and algorithm needed to replicate the study for the E3ME-FTT model is licensed and not publicly available, but can be obtained from the authors upon reasonable request.

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Author contributions

J.-F.M. designed, coordinated and performed the research, with contributions from G.S., P.S., P.B.H. and H.P. J.-F.M. wrote the article with support from N.R.E., G.S., J.E.V., H.P., P.S., P.B.H. and N.V. J.-F.M. and P.V. ran the E3ME-FTT simulations, with support from U.C. and H.P. J.-F.M. and P.S. developed the updated FTT:Power and the fossil resource depletion model, and integrated the Rystad dataset into the framework. A.L. developed the updated FTT:Transport model, its data and the policy assumptions. P.S. and J.-F.M. developed and applied the game theory model. N.V. ran the GENIE simulations with support from P.B.H. J.E.V. contributed geopolitical expertise. N.R.E. coordinated the overall FRANTIC NERC project.

Competing interests

The authors declare no competing interests.

Additional information

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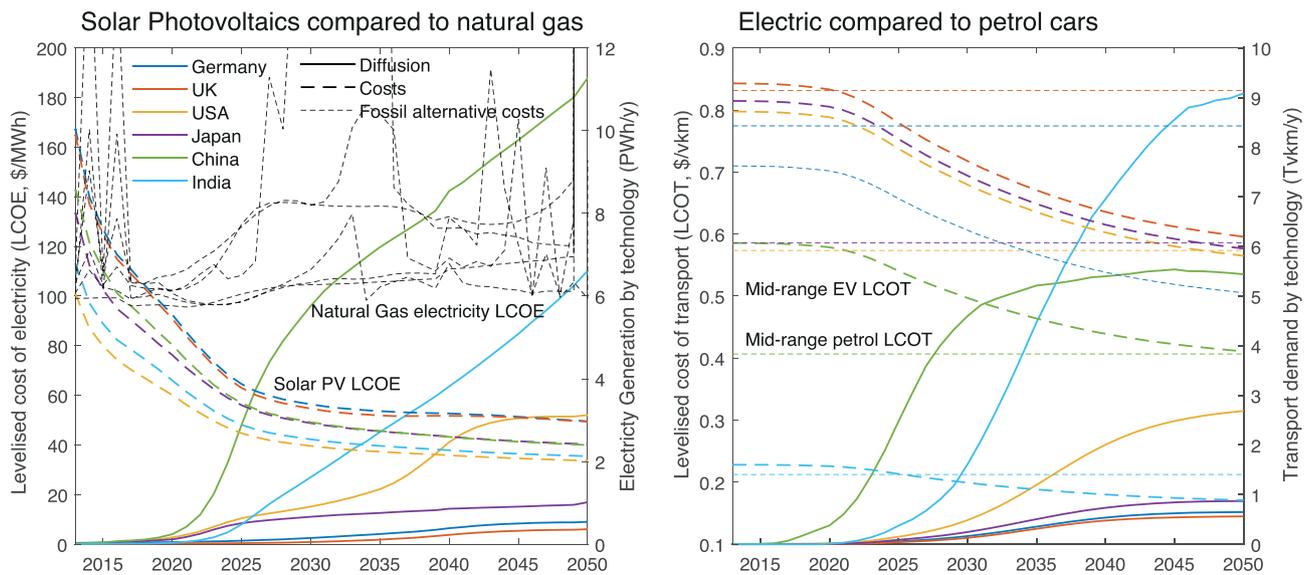
Correspondence and requests for materials should be addressed to J.-F. Mercure.

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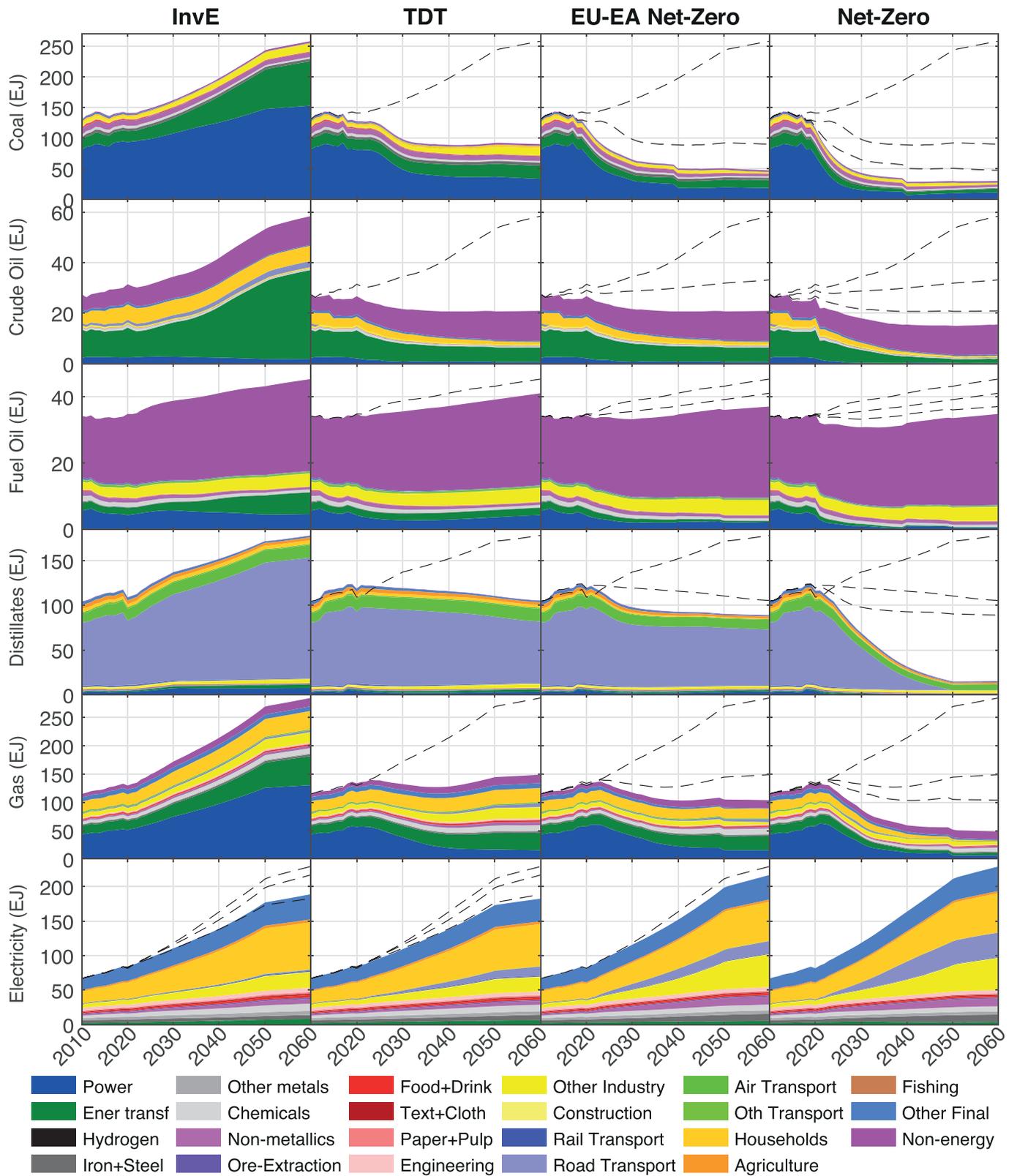
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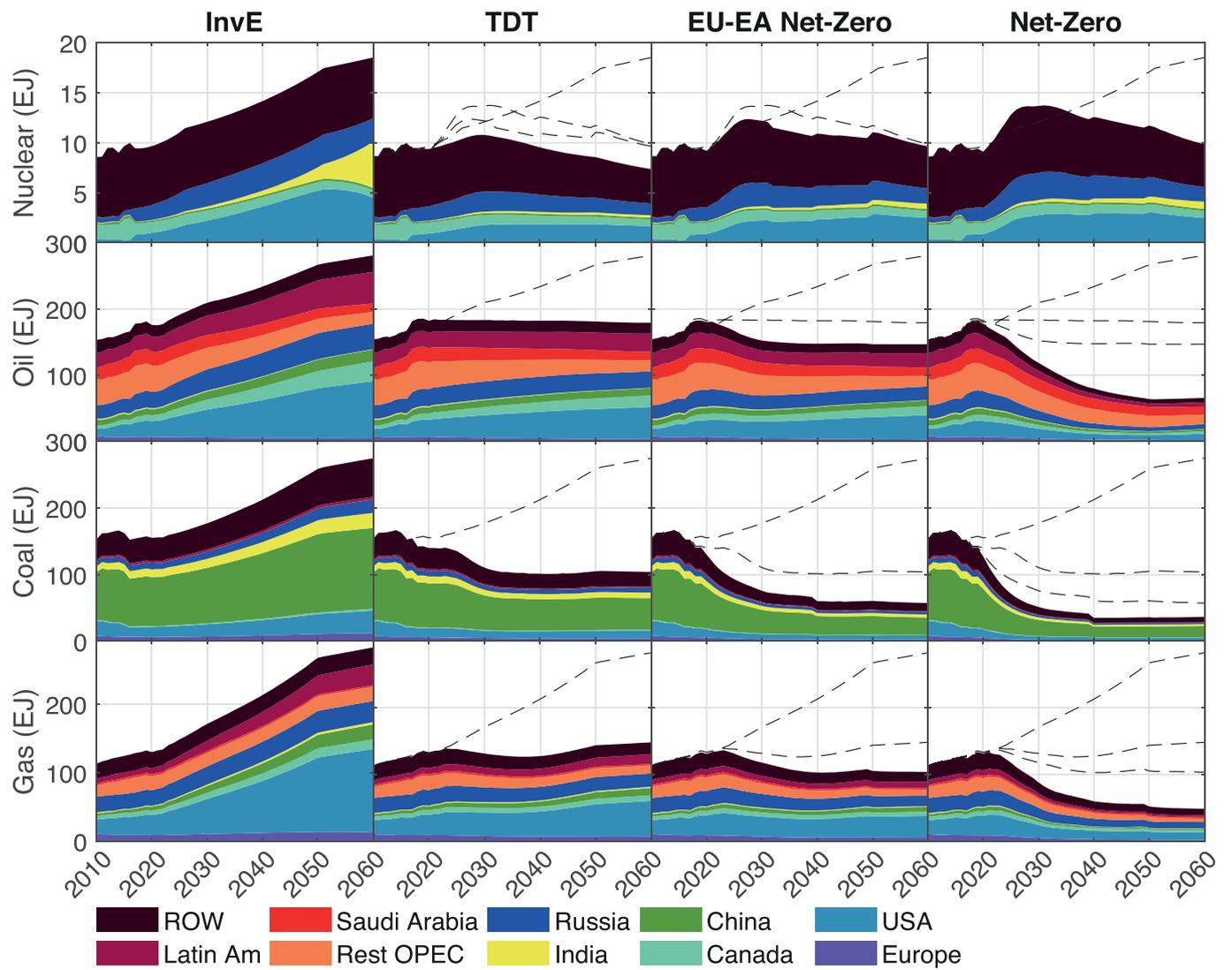
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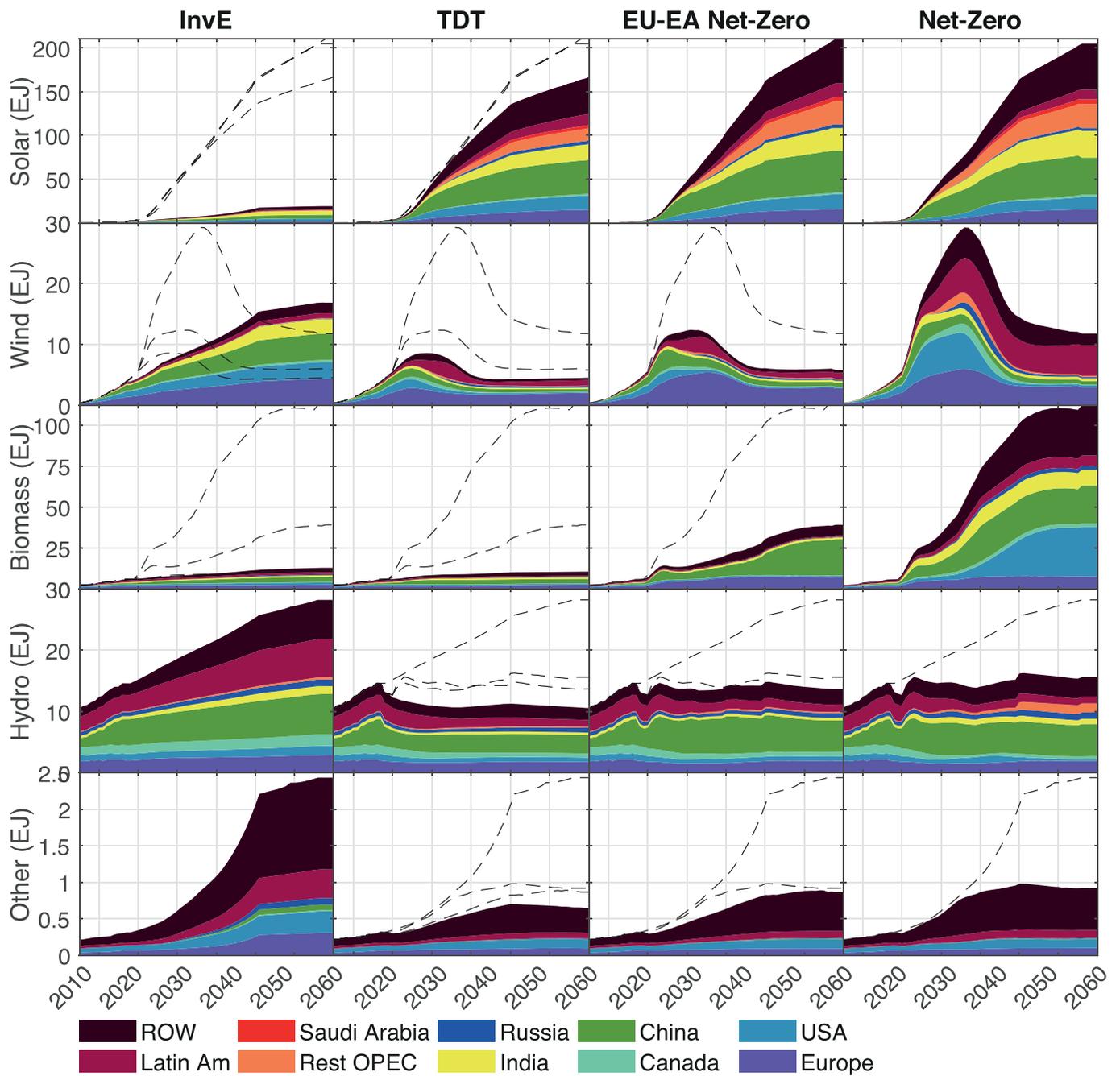
Extended Data Fig. 1 | Technology dynamics for solar photovoltaic and electric vehicles. The dashed and dotted lines, associated with the left-hand side vertical axes, show technological costs for chosen regions given in the legend. The dashed lines show PV and EV levelised costs (the break-even service costs for one unit of electricity or transport), while the dotted lines show the levelised costs of the best fossil alternative, gas turbines and petrol vehicles (for vehicles, the mid-range class was used). The solid lines, associated with the right-hand side vertical axes, show the diffusion of solar PV and EVs. The dynamics show that costs going down incentivise more technology uptake, which generates cost reductions, in a positive reinforcing cycle. Fossil technologies are mature, without substantial learning, their cost dominated by resource costs. In the case of gas turbine costs, the fluctuations are related to variations in capacity factors (or load hours) that vary according to how the plants are used to balance the electricity grid.



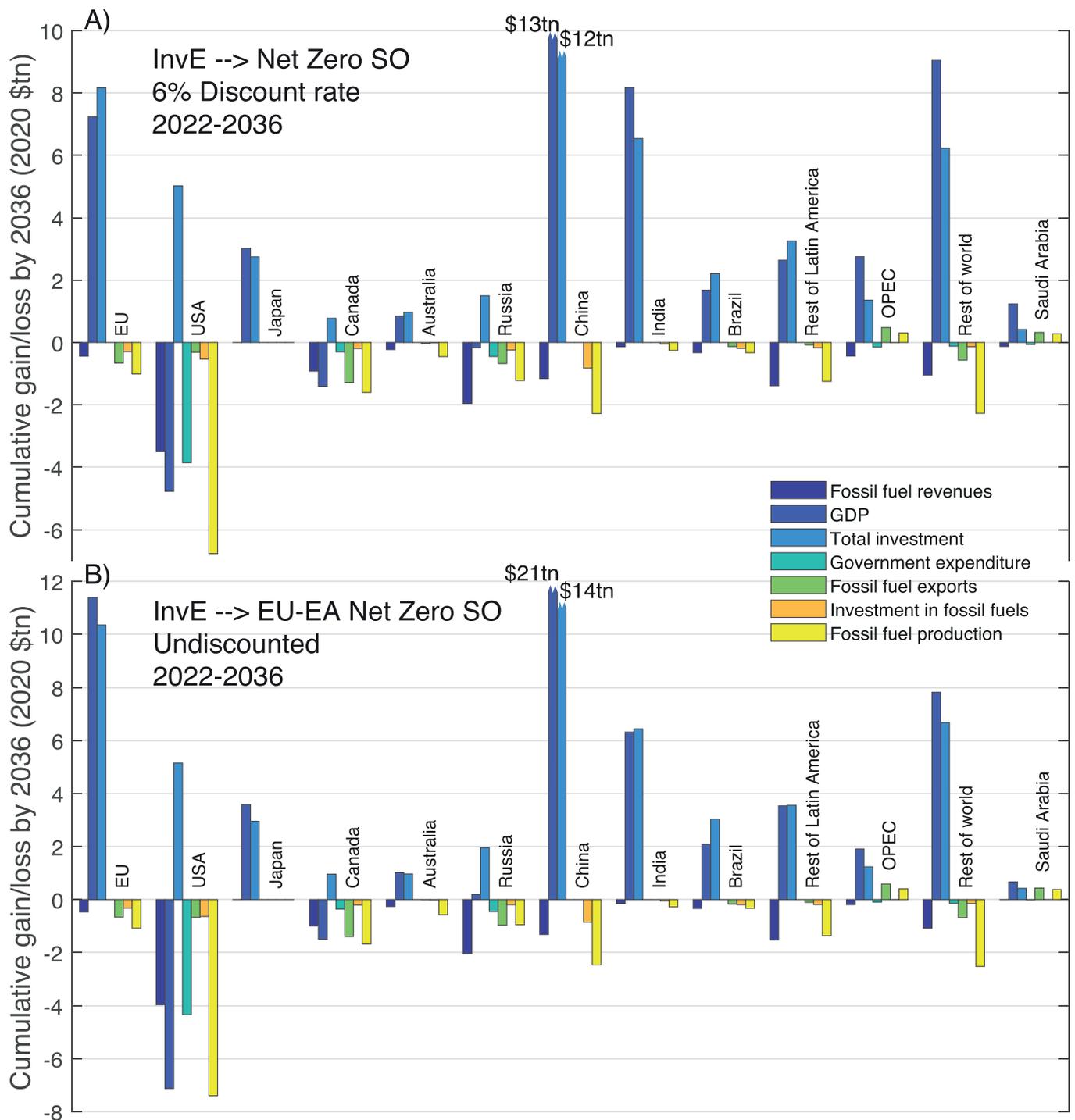
Extended Data Fig. 2 | Projections for all scenarios of all major energy vectors in the economy. Dashed lines are guide to the eyes indicating totals of other scenarios in the same quantity.



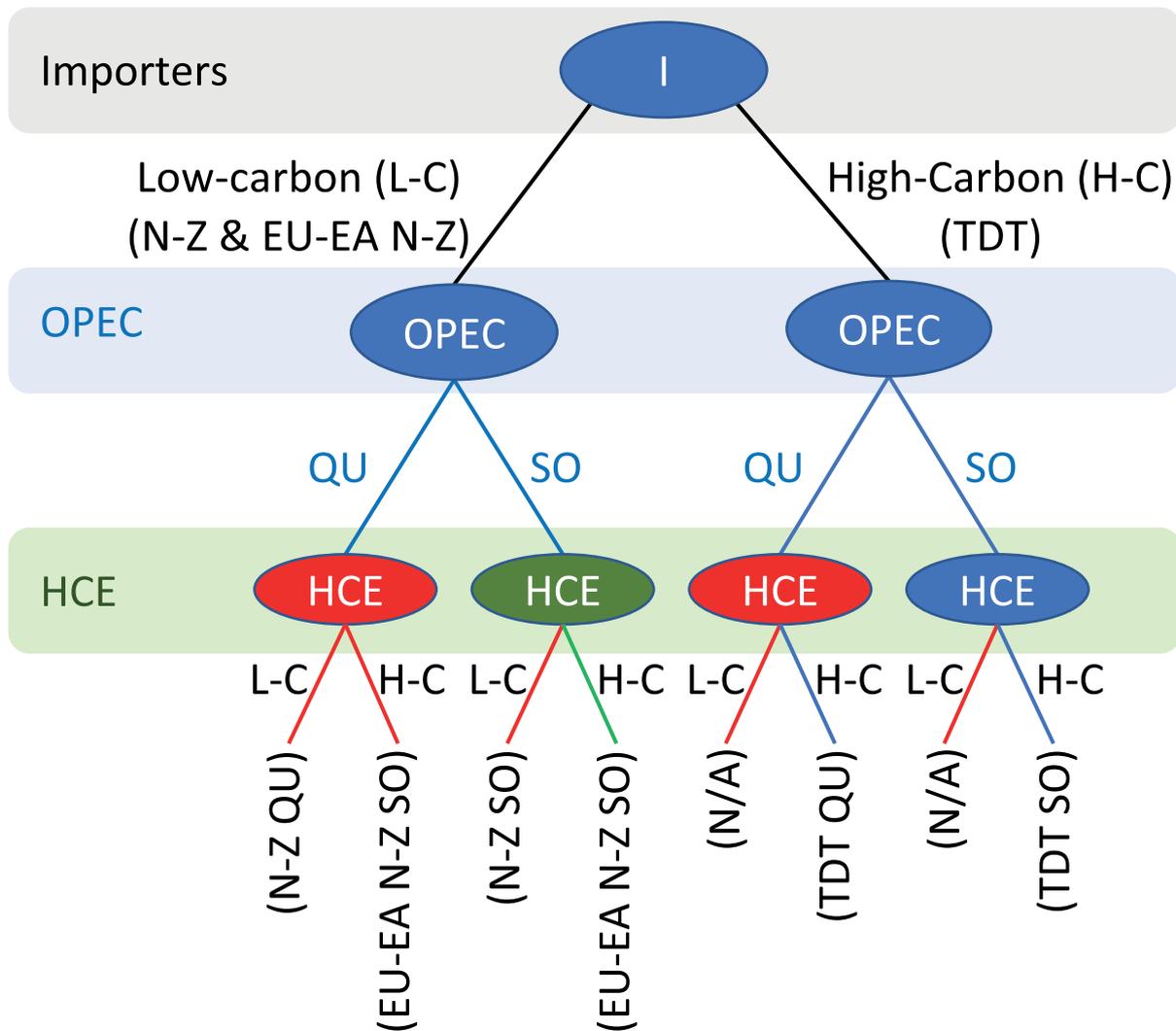
Extended Data Fig. 3 | Projections for all scenarios of non-renewable energy use by region. Dashed lines are guide to the eyes indicating totals of other scenarios in the same quantity.



Extended Data Fig. 4 | Projections for all scenarios of renewable energy use by region. Dashed lines are guide to the eyes indicating totals of other scenarios in the same quantity.



Extended Data Fig. 5 | Cumulated gains and losses in the value of fossil fuel assets, GDP, investment and fossil fuel production across chosen economies. (a) for the Net-zero SO scenario, relative to the InvE scenario, expressed in absolute, and (b) for the EU-EA Net-zero SO scenario relative to the InvE undiscounted. Gains are positive and losses negative. Values are cumulated over 15 years, between 2022 and 2036, using a 6% discount rate.



Extended Data Fig. 6 | Structure of the game and possible scenario outcomes. Importers can decide between a high or low-carbon energy system. OPEC can decide between observing quotas or flooding fossil fuel markets. High-Cost Exporters (HCE) can choose between high or low-carbon energy systems. The combinations of decisions leading to overall scenarios are shown at the bottom. N/A are infeasible scenarios, where HCE deciding unilaterally to decarbonise is ruled out by existing low-carbon policy in importer countries.