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Reframing incentives for climate policy action

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Abstract

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 will entail a profound reorganisation 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 where fossil fuel importers are better off decarbonising, 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 decarbonisation technologies.

Main Text

Introduction

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,[1] calling for clearer scientific evidence of the impacts of a 1.5°C pathway.[2] 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 EU, the UK, 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 worldwide.[10] While 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 pursuing 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, depending on location, have already or will soon reach parity with the lowest-cost traditional fossil alternatives,[15,28,29] while 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 decarbonisation, 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 regions,[15] despite new fossil fuel subsidies in recovery packages,[33] although the recovery has been rapid, generating substantial market uncertainty. Fossil fuel exporters can be economically impacted by climate policy decisions of other countries through 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 exports.[10]

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 reducing imports while negative payoffs arise for energy exporters losing 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 states.[36] 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 curse,[37] 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 scales,[38] it is unclear whether the transition will increase or reduce conflict overall.[16,35,36]

Bazilian and Goldthau et al.[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 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, reducing the likelihood of any state gaining significant control over future energy supplies.[41] However, the production of renewables technology is increasingly concentrated in a few regions, including China, Europe and the United States, generating new types of geopolitical rivalry.[17,18] Concerns over access to critical materials for manufacturing renewables technology have been raised[41], and although debated, remain a concern for policy-makers. Lastly, the possibility of new resource curse situations linked to renewables has also been also raised.[18]

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 possibilities

Global scenarios

Understanding quantitatively the economic impacts of the ongoing low-carbon transition and their geopolitical implications requires modelling tools suitable for projecting socio-technical evolution. Here we use the E3ME-FTT-GENIE integrated framework[10] of disaggregated energy, economy and environment models based on observed technology evolution dynamics and calibrated on the most recent time series available (Methods). Loosely consistent with Goldthau,[34,39] we create four scenarios from 2022 to 2070 depicting how future energy production, use, trade and income could either underpin expectations or actually materialise. We project changes in output, investment and employment in 43 sectors and 61 regions of industrial activity, coupled by bilateral trade relationships between regions and input-output relationships between sectors. We simulate endogenous yearly average oil and gas prices and production over 43,000 active oil and gas assets worldwide. We then use a simple game theory framework to identify possible geopolitical incentives.

Technology Diffusion Trajectory (TDT) – We simulate the current trajectory of technology and the economy, based on recently observed trends in technology, energy markets and macroeconomics, exploring the direction of technology evolution irrespective of new climate policies. This generates a median global warming of 2.6°C.

Net-zero CO_2 globally in 2050 (Net-zero) – We add 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 UK, EU, 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 (EU-EA Net-zero) – We use the same policies to achieve net-zero emissions for Europe and East Asia (China in 2060, Japan, the EU and South Korea in 2050) but assume TDT policies elsewhere. This achieves a median warming of 2.0°C.

Investment Expectations (InvE) – We replace our energy technology evolution model by exogenous final energy demand data from the IEA's World Energy Outlook 2019 current policies scenario,[43] in which energy markets grow over the simulation period, to reflect expectations of delayed or abandoned decarbonisation 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 components, covering 58% of 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 InvE baseline sees coal and natural gas use dominate power generation, petrol and diesel use in road transport translate into a steady growth of oil demand, while 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 realised as it features substantially lower than already-observed growth rates in solar, wind, electric vehicles and heat pumps (Suppl. 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 electric vehicles, heat pumps, solar heaters) while others continue their existing moderate growth (biomass, geothermal, hydroelectricity, CNG vehicles). Some technologies have already been in decline for some time, such as coal-based electricity and diesel cars (UK, EU, US), 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 (Ext. 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 irradiation. Electric vehicles 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 what InvE suggests, 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 scenario, technology transforms at a comparatively faster pace to reach global carbon neutrality, while in the

EU-EA Net-zero scenario, low-carbon technology deployment in regions with net-zero targets accelerates cost reductions for all regions, inducing faster adoption even in regions without climate policies.

We comprehensively model the global demand for all energy carriers in all sectors and regions (Figure 2; sectoral details are given in Ext. Data Fig. 2, regional details in Ext. Data Fig. 3-4; see Suppl. Dataset). We observe a peaking in the use of fossil fuels and nuclear by 2030 and 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 rivers that can be dammed, while 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,d,e shows the evolving geography of the global supply and demand of primary fossil energy and renewables. Since fossil energy is widely traded internationally but renewable energy is primarily consumed in local electricity grids (Suppl. Note 2), the geographies of demand and supply differ substantially for fossil fuels while 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. While renewable technical potentials are mostly dependent on the landmass of nations, fossil fuel production and decline are concentrated in a subset of geologically suited regions.[44]

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 have.[45]

We show in Figure 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 covering most existing resources worldwide (Methods and Suppl. 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 in the Net-zero scenario). Saudi Arabia and other OPEC countries together possess over 650 and 202 Gbbl of resources of oil and gas, characterised predominantly by substantially lower costs of production (below $20 per barrel in many cases), compared to the resources left in the US, Canada and Russia, occurring at substantially higher production costs (between $20 and $80 per barrel). This suggests that, under the expectation of limited future oil and gas demand, OPEC countries would have a strong rational incentive, together or independently, to capture most future oil and gas demand by maintaining or increasing their production thereby pricing out other participants from fossil fuel markets.[48]

We define two scenario variants that represent two opposite OPEC courses of action delimiting a spectrum.[49] At one end of the spectrum, in a scenario of oil and gas asset fire-sale (denoted SO for 'sell-off'), OPEC ramps its production to 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 losses.[16] At the other extreme, in a scenario of strict quotas (denoted QU for 'quotas'), OPEC limits production to maintain a constant share of the peaking and declining global demand, keeping its traditional role in stabilising markets.[14] Figure 4a shows changes in prices for all scenarios, and Figure 4b,c changes in quantities for the EU-EA Net-zero scenario originating from 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 US, Canada, South America, and to a lesser extent Russia,[50] are gradually excluded from oil and gas production as it concentrates towards OPEC countries (Methods).

The prices of fossil fuels are 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 \$35/bbl 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 US, Canada, Russia and South America. Meanwhile shedding expensive imports benefits GDP and employment in large importer regions such as the EU, China and India, as money not spent on expensive energy imports is spent domestically, while output is boosted by major low-carbon investment programmes. Figure 4d,e,f shows this using percent changes in government royalties, GDP and total employment between the Net-zero and the InvE scenarios. These transformations arise from changes in fossil and energy production sectors, their dependent supply chains and other recipients of spending income in unrelated sectors, including 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, while in importer countries, net gains are observed. Supply chain effects amplify output changes that originate from the energy sector (manufacturing, construction, services). For clarity of analysis, we assume no compensatory effect from any deficit spending (Suppl. Note 3).

Economic changes implied by the new net-zero pledges (the EU-EA Net-zero scenario against InvE) are given in Figure 5, showing output, exports, investment and lost fossil fuel production discounted by 6% and cumulated over the next 15 years (see Ext. Data Fig. 5, Suppl. Tables 1-2 and Suppl. Dataset for comparison variants). Stranded fossil fuel assets arise of between \$7-11tn. 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, Suppl. Note 4, Ext. Data Fig. 6), 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 policy-makers, the EU-EA Net-Zero SO would be a stable Nash equilibrium. The decision by importers to decarbonise is a dominant strategy, as is that of OPEC producers to flood markets. High-cost producers are left with the decision whether to decarbonise or not. Their fossil energy industry falls victim to low-cost competition, while the economic benefits of low-carbon investment do not necessarily compensate for 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, the EU). These have an economic incentive to decarbonise and their decisions impact producers in general. The magnitude of the re-organisation 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. Since the impact of the transition on their fiscal position, GDP and jobs of the transition can be largely overcompensated by their output strategy, 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 US, 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, the balance of power remaining in the hands of major importers. Since low-carbon transitions are under way in the UK, the EU, China and other nations, as evidenced in technology data, export losses for high-cost exporters 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 2050[45] (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 drives[17] proposed in recent geopolitics literature, providing a crucial quantitative dimension.

The new energy geopolitics has further deep socio-economic implications also beyond the standard framing of climate policy. Firstly, 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 localised issues of post-industrial decline in the US, Russia, Canada, Brazil and other oil producers. This suggests that comprehensive plans for regional redevelopment are likely needed along with economic diversification towards new technology sectors, including low-carbon technology exports.[25–27] Secondly, 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 re-organisation 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 (IAMs) currently used for assessing climate policy and socio-economic scenarios are based on whole system or utility optimisation algorithms, while some are based on optimal growth[55]. IAMs have helped set the global climate agenda by identifying desirable energy system configurations. However, they are unsuitable for studying trends in energy system dynamics, since historical dependences are neglected, while systems optimisation assumes an empirically unsubstantiated degree of system coordination.[55,56]

Here we use the non-optimisation IAM 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 project economic change, energy demand, energy prices and regional energy production.

The E3ME-FTT-GENIE integrated framework is described below. The full set of equations underpinning the framework is given and explained in [[57]]. Assumptions for all scenarios are also given.

E3ME

The Energy-Economy-Environment Macro Econometric model (E3ME) is a highly disaggregated multi-sectoral and multi-regional, demand-led macroeconometric 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 harmonised data classifications worldwide for 43 consumption categories, 70 (43) sectors of industry within (outside of) the EU member states and the UK, 61 countries and regions including all EU member states and G20 nations covering 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 leading to that supply is determined using input-output tables and bilateral trade relationships between all 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 done in general equilibrium models. This implies that purchasing power to finance investment is created by banks on the basis of the credit-worthiness 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 that 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 investment.[57] 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 in all sectors and fuel users of the global economy with the exception of the four most carbon-intensive sectors (power, transport, heat, steel), for which technological change is modelled with substantially higher definition using the Future Technology Transformations (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:Power[58] represents the market competition of 24 power technologies including nuclear, coal/oil/gas-based fuel combustion (with carbon capture and storage (CCS) options), photovoltaic and concentrated solar (PV/CSP), onshore/offshore wind, hydro, tidal, geothermal and wave technologies. FTT:Transport[59,63] represents the diffusion of petrol, diesel, hybrid, compressed natural gas and electric vehicles and motorcycles in 3 engine size classes, with 25 technology options. FTT:Heat[60] 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 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 that would invalidate the present scenarios is highly unlikely within the policy horizon of 2050 (e.g. nuclear fusion, 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 equation.[64] The replicator equation (or Lotka-Volterra system) is an ubiquitous relationship that emerges in many systems featuring non-linear 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 representing agent interactions (e.g. technology availability limited by existing industry sizes, social influence) that gives it the distinctive S-shaped diffusion profile.[65]

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 representing 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 [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 6 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 level of grid flexibility to allow the introduction of large amounts of renewables are respected, maintaining 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 based on solar and wind data and optimisation 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 to earlier work[10] 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 CO_2 emissions, land-use change and non-CO_2 climate forcing agents. It comprises the GOLDSTEIN (global ocean linear drag salt and temperature equation integrator) 3-D frictional geostrophic ocean model coupled to a 2-D energy moisture balance atmosphere, a thermodynamic-dynamic sea-ice model, the BIOGEM ocean biogeochemistry model, 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° x 5° on average with 16 depth levels in the ocean and has here been applied in the configuration of [67,68] (see references therein).

The probabilistic projections are achieved through an ensemble of simulations for each emissions scenario using an 86-member set[69] that varies 28 model parameters in order to produce an estimate of the full parameter uncertainties. Each ensemble member simulation is continued from an AD 850 to 2005 historical transient spin-up. Post-2005 CO_2 emissions are provided by E3ME, scaled by 9.9/X to match actual emissions in 2019[70] (where X=9.3 GtC is E3ME 2019 emissions), to correct for missing processes in E3ME. The emissions trajectories are then extrapolated to 2100 (InvE , TDT and EU-EA Net Zero scenarios) or until they reach 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 Suppl Table 3.

The GENIE ensemble has been validated[69] 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 is estimated by integrating to the model data from the substantial Rystad Ucube[46] dataset in the form of breakeven cost distributions (as in Figure 3, aggregated into 61 regions). The Rystad dataset documents over 43,000 existing and potential oil and gas production sites worldwide, covering the large majority of current global production and existing reserves and resources. It provides each site's breakeven oil and gas prices, reserves, resources and production rates. However, Rystad projected rates of asset production and depletion[47] are not used in our model, which does not rely on Rystad assumptions.

The energy market model[61] 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 breakeven 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 representing producer decisions. Initial values are 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 regions are determined according to chosen rules for the QU and SO scenarios. Changes are only imposed to production to reserve ratios of OPEC countries, in order to either achieve a production quota that is proportional to global output (QU scenario, thereby reducing production to reserve ratios accordingly), or attempting to maintain constant absolute production while global demand is peaking and declining (SO scenario, thereby increasing 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 work.[44]

Scenarios and choices of regional decarbonisation 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 covering the projection period, covering all industrial but not consumer, mobility, household nor 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 UK, the EU, 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, solar CSP, 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 US, Canada, China and India.
- The use of BECCS 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 by solid biomass resources.

Road transport:

Policy portfolios were designed tailored to five major economies characterised by different vehicle markets (UK, US, China, India, and Japan), according to what policies are 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 programs for supporting the diffusion of EVs.
- Yearly vehicle taxes linked to emissions

Household heating:

- Taxes on household use of fuels for heating (coal, oil, 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 on 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 in order to develop markets where they do not exist.

Cross-sectoral policies

- Energy efficiency: the energy efficiency of non-FTT sectors are assumed to change in line with the IEA[71], with corresponding investments in the respective sectors.
- Carbon price: 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 EU from its 2020 value, in nominal EUR, until €1955/tC in 2033 and remains there thereafter. Deflating these values using E3ME's endogenous price levels into 2020USD (since E3ME operates in nominal EUR) and converting to CO_2, these carbon prices are equivalent to between \$300-500/tCO_2 in 2033, going down thereafter following different country inflation rates to \$250-350/tCO_2 in 2050 and \$150-200/tCO_2 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 EU, UK, Japan, South Korea and China adopt the Net-Zero policies as defined above and achieve their respective targets, while every other country follows the TDT. Note that technology spillovers (e.g. learning) in the model imply that this scenario is not a simple linear combination of the parent scenarios, since low-carbon technology adoption in countries without net-zero policies is higher than in the TDT.

SO and QU scenario variants – These scenarios were generated by varying the exogenous production ratio to 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, the proportionality factor being determined by the data such that production data is 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 US and Russia; however, we consider those unlikely to materialise without SO response from OPEC, which, due to its higher competitiveness according to Rystad data, in the model, always wins price wars. 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 undisrupted (e.g. by regional conflict), and that current capacity outlives peak demand. This is reasonable given existing capacity, and the fact that demand growth declines. We furthermore assume that incentives for stockpiling drastically decline in situations of peak demand, as overproduction is likely, reducing opportunities for arbitrage. Trade tariffs on oil and gas could be imposed to protect domestic industries, notably in the US, decoupling 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 WEO 2019 current policies scenario. This scenario, qualitatively similar to RCP8.5,[72] sees growth in all fossil fuel markets, and was chosen over the newer IEA's WEO 2020 scenarios which are qualitatively different. 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. Since 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.

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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 to 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.

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.

Tables

Table 1 | GDP payoffs matrices

Importers vs OPEC		OPEC			
		QU		SO	
		Importers	**OPEC**	**Importers**	**OPEC**
Importers	**EU-EA-NZ**	26889	243	***26521***	***1182***
	TDT	8367	-40	8171	410

OPEC vs High-Cost exporters		High-cost exporters (HCE)			
		EU-EA Net-Zero		Net-Zero	
		HCE	**OPEC**	**HCE**	**OPEC**
OPEC	**QU**	-2590	243	-4595	1551
	SO	***-4042***	***1182***	-6350	2748

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

Figure captions (main text figures)

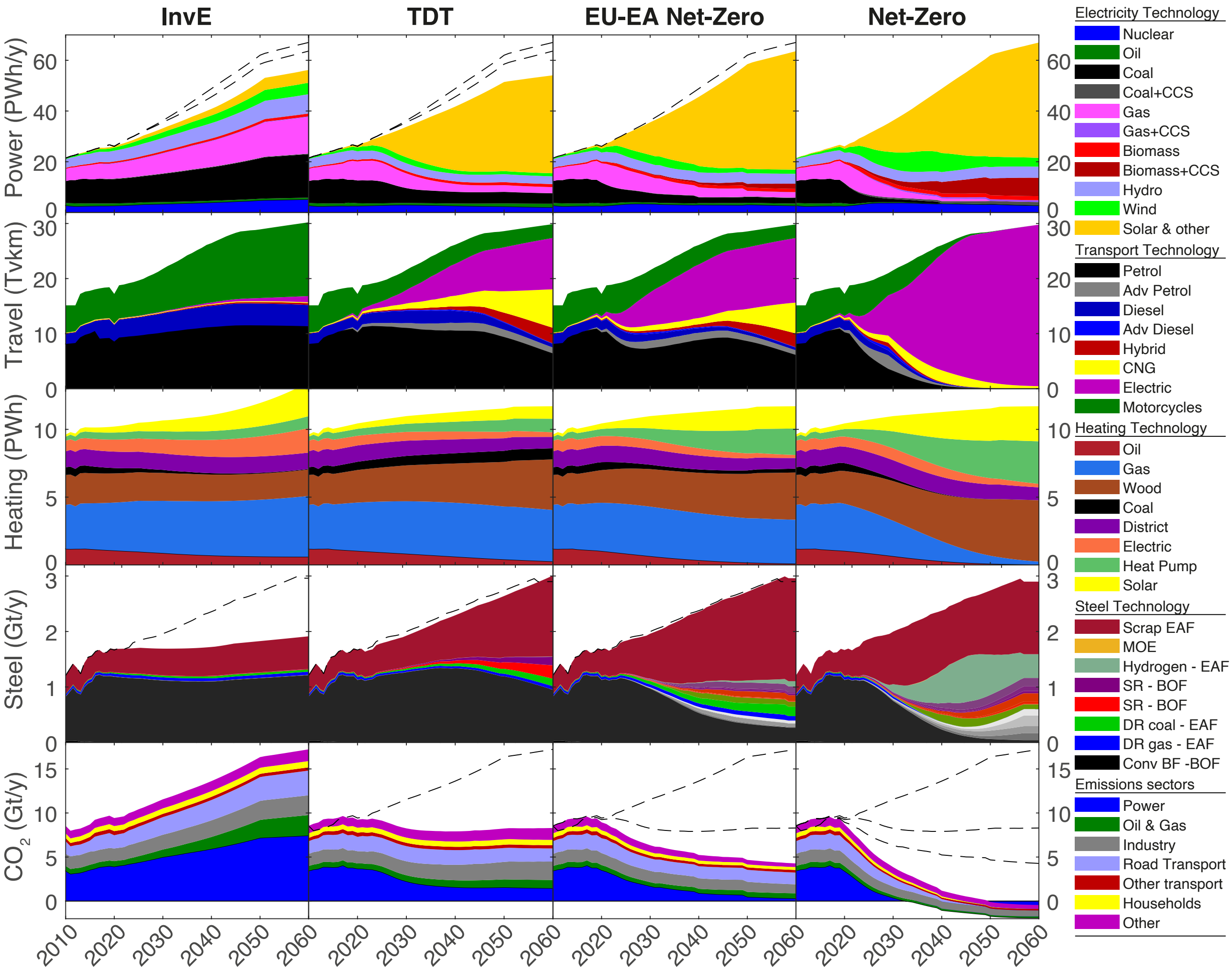

Fig. 1 | Diffusion of technology and evolution of energy use and emissions in key sectors. The evolution of 88 key power generation and final energy use technologies and emissions in four scenarios. Contributions are aggregated for clarity. CCS stands for Carbon Capture and Storage, CNG for Compressed Natural Gas, EAF for Electric Arc Furnace, MOE for Molten Oxide Electrolysis, SR for Smelt Reduction, BOF for Basic Oxygen Furnace, DR for Direct Reduction, BF for Blast Furnace.

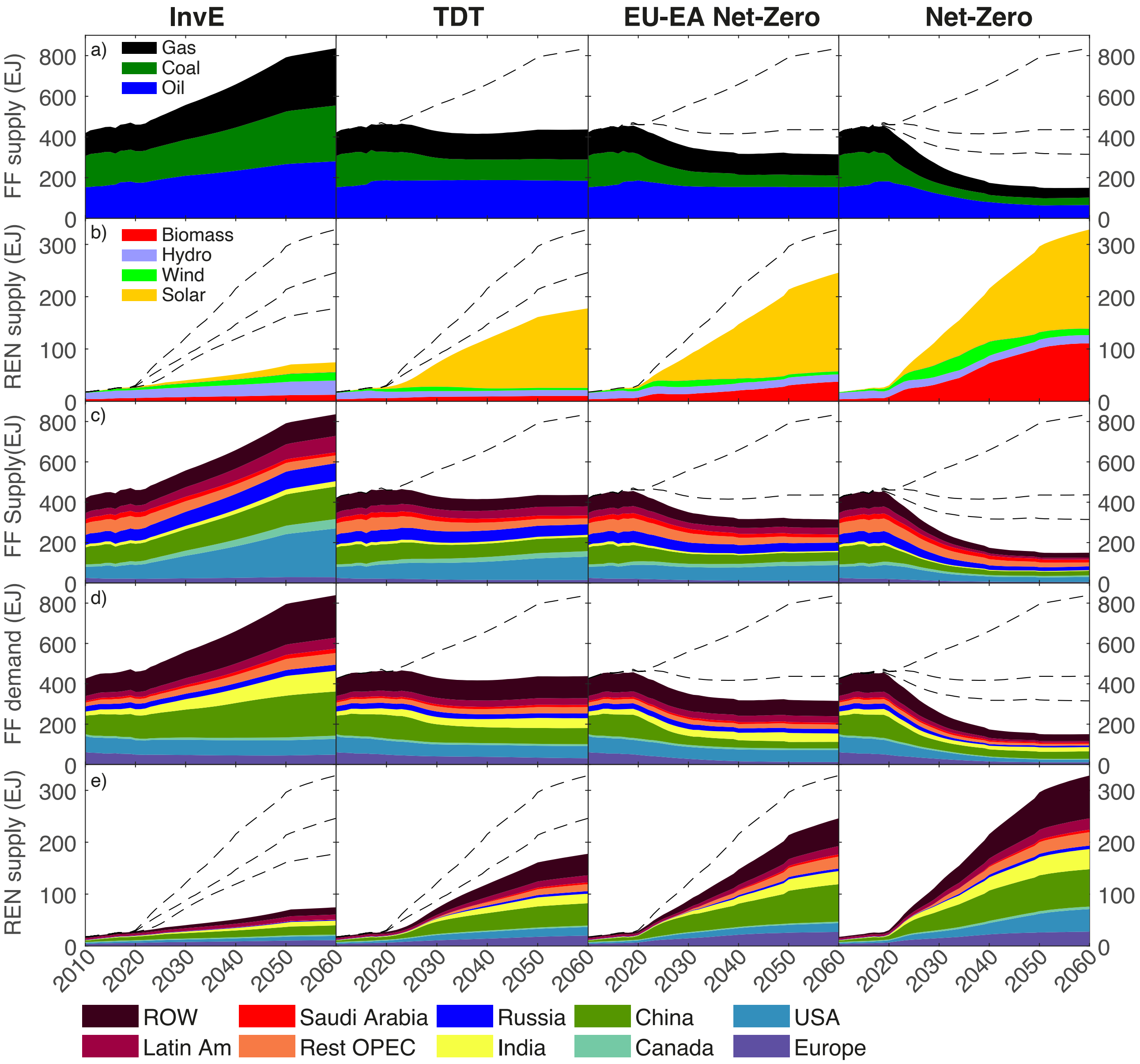

Fig. 2 | The evolving geography of energy demand and supply. The geography of (a) fossil energy supply by fuel, (b) supply of renewable electricity by source, (c) fossil energy supply in 6 aggregate regions, (d) fossil energy demand in six aggregate regions, (e) supply of renewable electricity in six aggregate regions. Colours in the legend for regions follow the same order as in the panels.

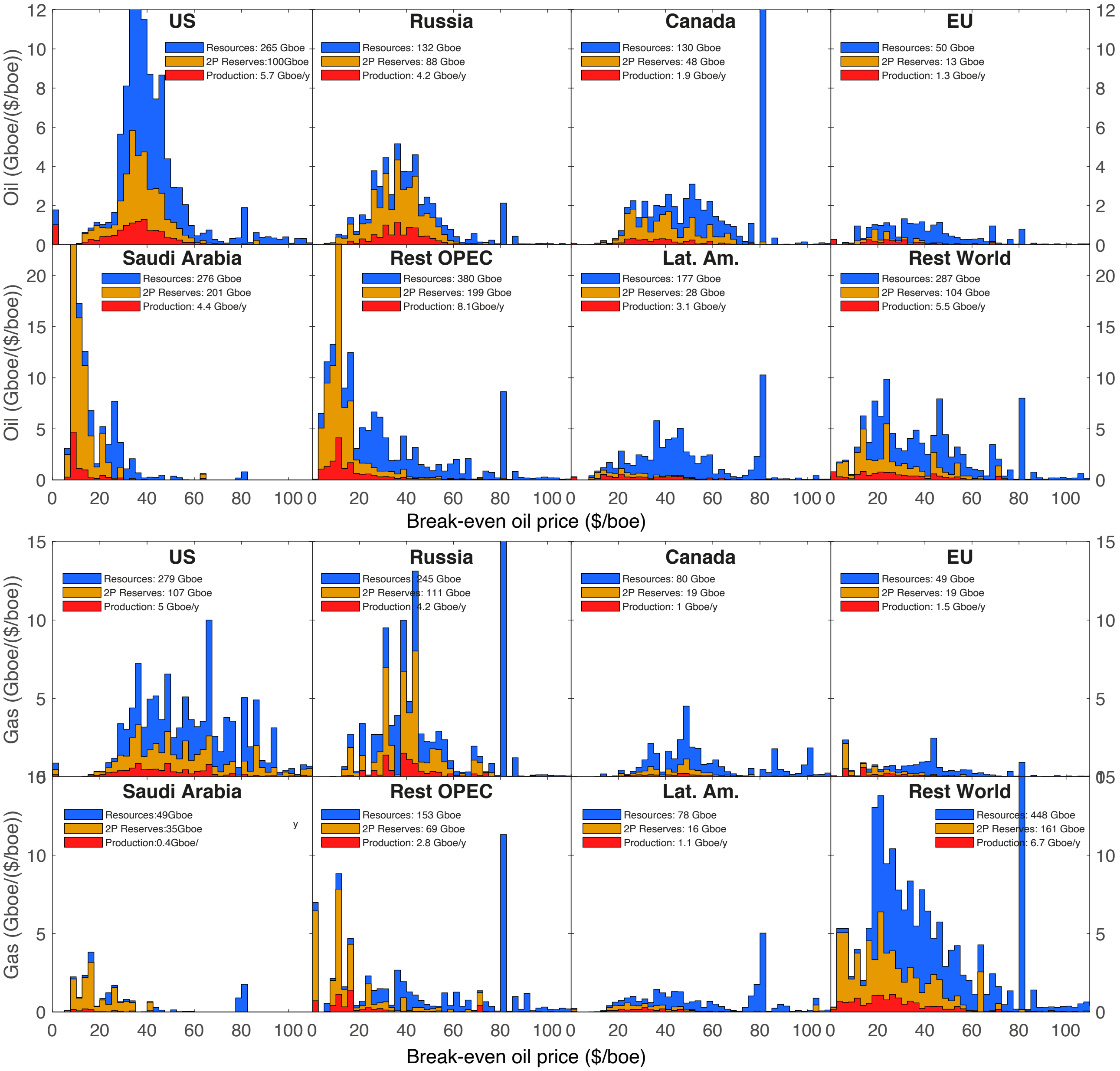

Fig. 3 | World oil and gas reserves and resources. Oil and gas world resources, reserves and production distributed along their breakeven oil and gas prices, prices at which they are profitable to extract, processed by the authors using Rystad (2020). Production bar heights were scaled up by a factor of 5 in order 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 while 'Rest World' aggregates all countries globally that are not included in other panels, for visual clarity.

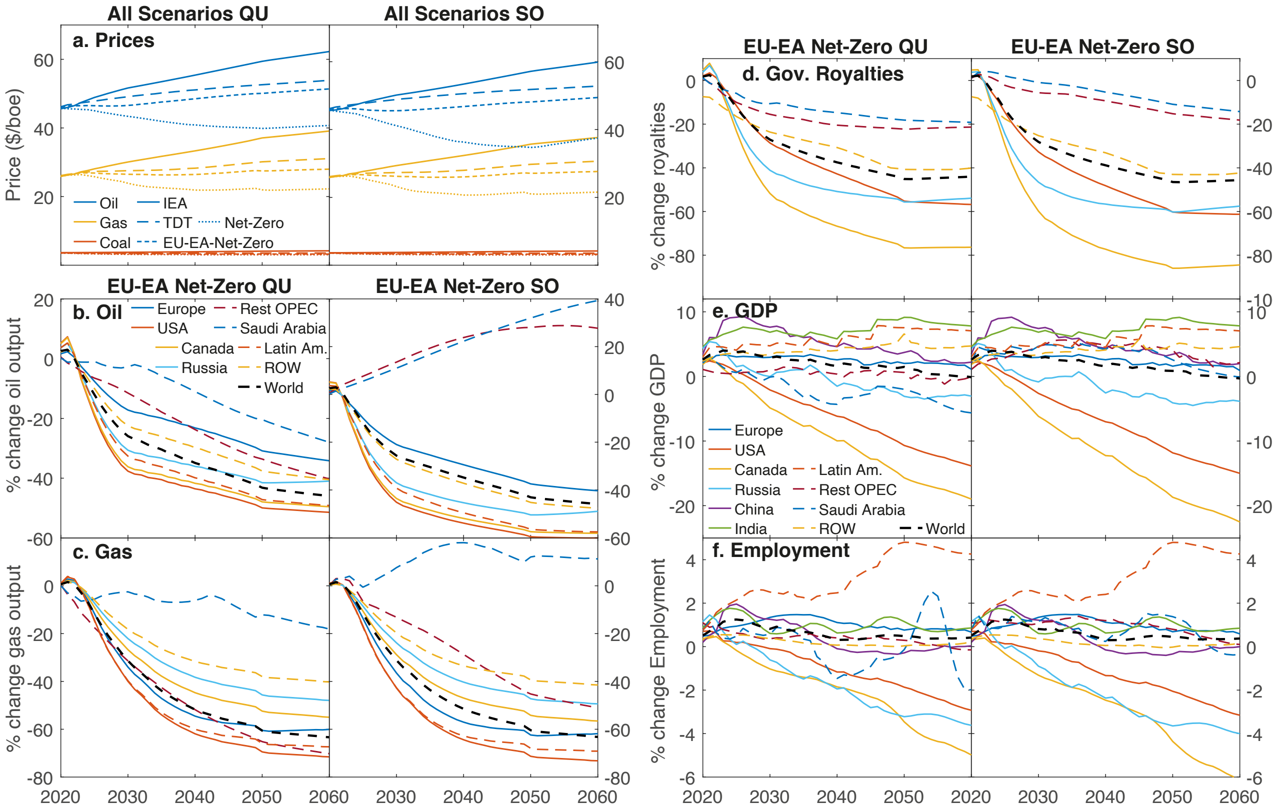

Fig. 4 | Evolution of key energy and macroeconomic variables. (Left panels) Absolute price changes, production losses in oil and gas markets in the 'Quotas' (QU) and 'Sell-off' (SO) scenarios, expressed as a % change from the IEA scenario. (Right panels) Changes in government revenues from oil and gas activities through royalties, changes in GDP and employment, all expressed as % changes from the IEA scenario. Saudi Arabia is separated from the rest of OPEC for clarity, 'ROW' stands for Rest of the World for regions and countries not otherwise included, while 'World' refers to changes at the global level. Government revenues are assumed deficit-neutral for clarity of analysis (Suppl. Note 3).

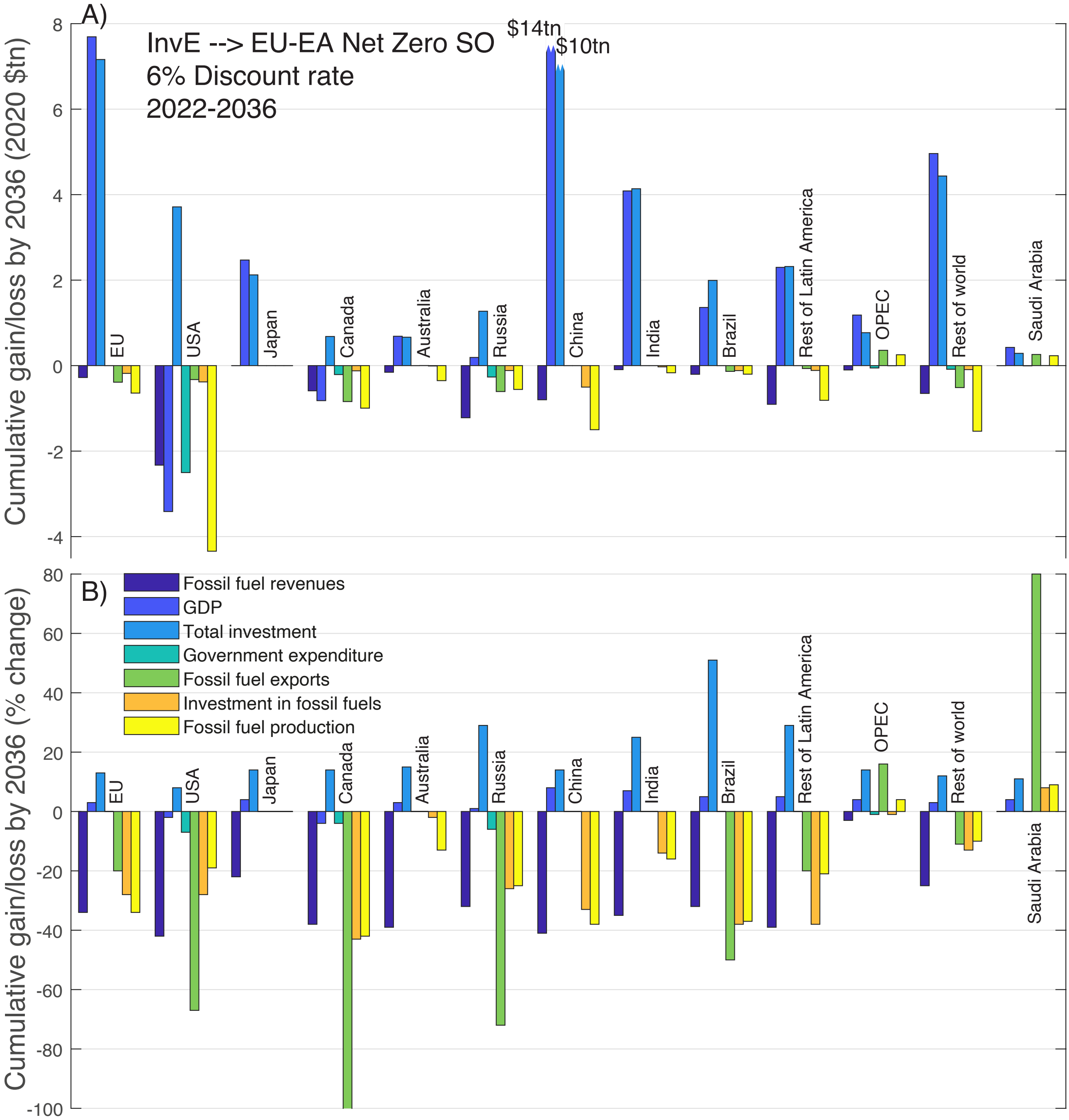

Fig. 5 | Cumulated macroeconomic gains and losses by country. Changes in the value of fossil fuel assets, GDP, investment and fossil fuel production across chosen economies, for both QU and SO scenarios, relative to the IEA scenario, expressed in absolute (a) and as percent change (b). Gains are positive 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, while GDP and investment are cumulated economic flows, and thus are not to be compared or added. A cumulation to 2050 is available in Ext. Data Fig. 5.

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Reframing incentives for climate policy action

Supplementary Information

Suppl. Note 1:

The data on observations of technological trends is an integral part of our database parameterising the FTT model, in which historical trends of technological diffusion are carefully documented. Notably, power generation data are obtained from the IEA and augmented by data gathered from other sources where gaps exist (IRENA, renewables associations, government websites). Data on cars were obtained by merging numbers from Marklines with data obtained from a large number of manufacturer websites for most regions featured in E3ME-FTT.[59,63] Data on heating systems and steelmaking were obtained from similar combinations of resources.[60] Technological data for power generation and transport were updated recently up to 2018 or 2019 for this modelling exercise, while heat technology data dates from 2016. Time series cover at least 5 years in each case. Trends in diffusion of electric vehicles, heat pumps and solar PV are readily observable and different in each region.

COVID-19 is however changing the picture further, by altering energy use behaviour. However, while energy use has changed drastically during the pandemic,[73] the evidence remains insufficient to make reliable predictions regarding which way COVID-related changes in fossil energy use will evolve. Evidence suggests that current reductions in demand may be temporary as the drivers of fossil energy use have not yet changed substantially due to the illiquidity of industrial and end-use capital.[74]

Suppl. Note 2:

Before the COVID crisis, OPEC members collectively produced 19% (34% of oil, 17% of gas) but consumed 9% of global primary energy, accounting for 0.73% of their combined national employment and 19% of their industrial output. The US (Russia, Canada), with a recent surge in oil and gas production, contributed 15% (14%, 5%) of global energy, while they also consumed 15% (6%, 2%). This corresponds to 0.13% (0.72%, 0.62%) of regional employment and 8% (8%,7%) of industrial output situated in oil, gas and coal-related activities.

With changes in output and oil and gas prices, a multiplier effect arises as intermediate and final output directly and indirectly related to fossil fuel production, transportation and refining are affected. The US has only recently become a net exporter of oil and gas, following the shale revolution, but it also plays an important role in the global oil refining industry, importing crude and exporting manufactured fuels. Thus changes in oil and gas prices affect the US at various points in its intermediate and final production and exports. These data are obtained from our E3ME economic database. Economic data in E3ME originate from a combination of IEA data, national accounts, World Bank data, Comtrade, OECD, Rystad and national datasets.

Suppl. Note 3.

At the onset of recessions, financial crises and exogenous economic shocks (e.g. COVID-19), government spending generally automatically increases on the basis of deficit and an expansion of the national debt to cover expenses such as unemployment benefits, poverty relief and various types of support to individuals and ailing businesses. Including such mitigation measures would be extremely complicated and would unnecessarily obscure the analysis presented in this work. Notably, the impacts of the new energy geography would to some degree have to be measured on the back of the expansion of the deficit and national debt instead of GDP and employment. Furthermore, it is not possible to determine the levels of credit-worthiness that various nations would be perceived to have and the lending terms that they would be facing in domestic and international credit markets, nor the exact size of sovereign wealth funds where they exist (e.g. Saudi Arabia, Norway). Thus, while the employment impacts of loss of economic activity in fossil fuel sectors and dependent industries could likely be substantially mitigated by deficit spending in fossil producer regions (e.g. Canada, US, Russia, OPEC), thus making the absolute economic impacts presented here unrealistic, we must stress that deficit spending decisions are inherently political, and that the results presented are contingent on an assumption of government budget neutrality, for the sake of clarity.

Suppl Note 4:

We take the InvE scenario as a reference, and use estimated GDP losses against InvE for each E3ME region as the criteria upon which political decisions are taken in the climate policy game (GDP is also a reasonable proxy for employment in the present context, thus using employment generates the same results). We cluster nations within three broad groups facing similar economic incentives from low-carbon transition dynamics, and assume collective decisions in each group, namely the Importers (here the EU, China, Japan, South Korea), the High-Cost Exporters (here mainly the US, Canada, Russia) and the Low-Cost Exporters (OPEC).

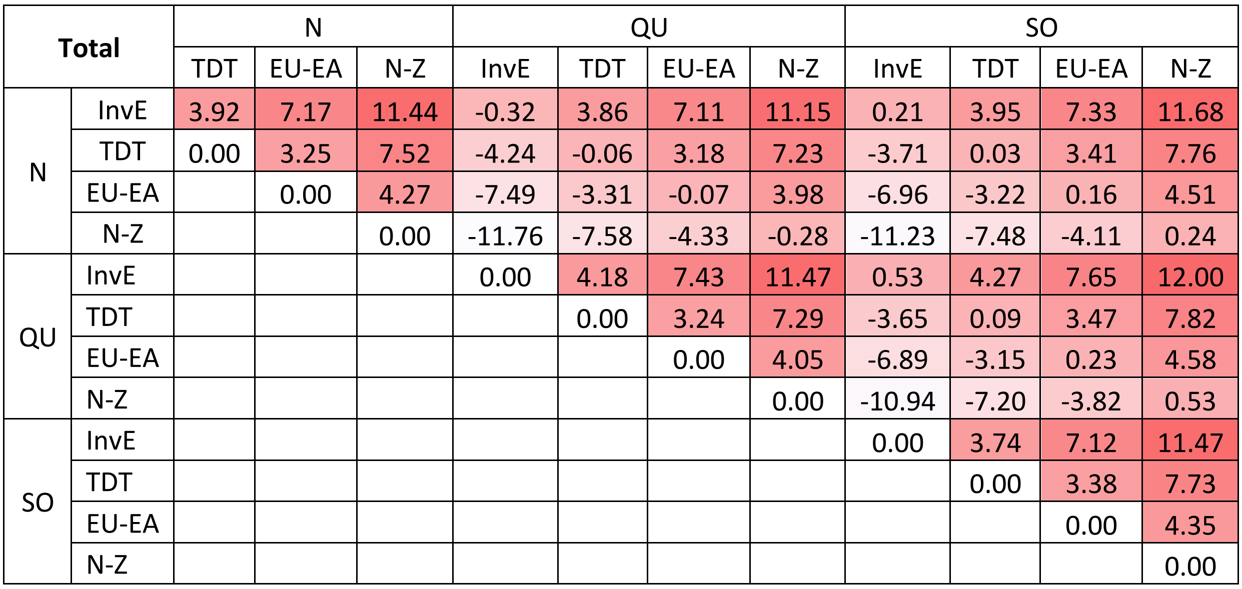
Taking the triplet of scenarios TDT, EU-EA Net-Zero and Net-zero, we describe the incentives faced by Importers whether or not to decarbonise, by OPEC to either ramp-up production of fossil fuels (SO) or implement strict quotas (QU), and High-Cost Exporters (HCE) whether or not to follow importers in decarbonising. We assume that it is not possible for Importers to force HCE to decarbonise against their will, nor for HCE to impose onto Importers to cancel their net-zero plans, and therefore not one group can unilaterally decide the overall scenario.

We use a simple two-by-two game theory framework in two stages. This is illustrated in Suppl. Fig. 6. A decision is made by Importers whether to decarbonise or not, which is linked to a decision by OPEC whether to observe quotas (QU) or flood markets (SO). Given this, the High-Cost Exporters decide whether to decarbonise or not. This can be summarised in two simple two-by-two payoff matrices between Importers, High-Cost Exporters and Low-Cost Exporters, given in Table 1.

In the Importers vs OPEC game, Importers have an incentive to decarbonise, while OPEC have an incentive to flood markets with oil and gas. Both strategies are dominant. This leaves HCE to decide, given the decisions of Importers and OPEC, whether or not to follow Importers in decarbonising, since in decarbonising, they can in principle generate activity in the low-carbon sectors despite that they lose out in the high carbon sectors. However, we find that in the OPEC vs HCE game, HCE do not decarbonise, and this is dominant. The interpretation therefore is that EU-EA Net-Zero SO is a Nash equilibrium.

This analysis is descriptive and its purpose is to explain the strategic incentives of nations under short term economic expectations. This Nash equilibrium should not be interpreted in a normative sense (i.e. as a prescription), since it is ultimately in the advantage of every nation to take steps to avoid damages from climate change, which are not studied here, and to further diversify their economies towards new successful industries.

In an earlier report[10] we stated that if the World decarbonises, the US is better off decarbonising as well, in terms of GDP, as otherwise it becomes an importer of oil and gas while it forgoes low-carbon investment benefits. This result remains true, however it critically depends on how many other countries do decarbonise, and here in the EU-EA Net-Zero, some fossil fuels remain in use, maintaining some level of activity in US production and fuel transformation, whereas in the Net-Zero scenario US fossil fuel-related activity shuts down entirely. In other words, if none of the High-Cost Exporters decarbonise, they all have an incentive to maintain that status quo. However, if the whole world decarbonises, each High-Cost Exporter has an incentive to decarbonise as well.



Total		N			QU				SO			
		TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z
N	InvE	3.92	7.17	11.44	-0.32	3.86	7.11	11.15	0.21	3.95	7.33	11.68
	TDT	0.00	3.25	7.52	-4.24	-0.06	3.18	7.23	-3.71	0.03	3.41	7.76
	EU-EA		0.00	4.27	-7.49	-3.31	-0.07	3.98	-6.96	-3.22	0.16	4.51
	N-Z			0.00	-11.76	-7.58	-4.33	-0.28	-11.23	-7.48	-4.11	0.24
QU	InvE				0.00	4.18	7.43	11.47	0.53	4.27	7.65	12.00
	TDT					0.00	3.24	7.29	-3.65	0.09	3.47	7.82
	EU-EA						0.00	4.05	-6.89	-3.15	0.23	4.58
	N-Z							0.00	-10.94	-7.20	-3.82	0.53
SO	InvE								0.00	3.74	7.12	11.47
	TDT									0.00	3.38	7.73
	EU-EA										0.00	4.35
	N-Z											0.00

Suppl. Table 1 | Total global loss of fossil fuel revenues. Cumulated between 2022 and 2036 discounted by 6% for all possible pairs of scenarios, assuming that investors expect either of the vertical left-hand side scenarios, and that either of the horizontal top scenarios are realised.

Oil		N			QU				SO			
		TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z
N	InvE	1.83	4.21	7.10	-0.24	1.79	4.17	6.83	0.15	1.85	4.35	7.28
	TDT	0.00	2.38	5.27	-2.07	-0.03	2.34	5.00	-1.68	0.02	2.53	5.46
	EU-EA		0.00	2.89	-4.45	-2.42	-0.04	2.62	-4.06	-2.36	0.14	3.07
	N-Z			0.00	-7.34	-5.31	-2.93	-0.27	-6.95	-5.25	-2.74	0.19
QU	InvE				0.00	2.04	4.41	7.07	0.39	2.10	4.60	7.53
	TDT					0.00	2.37	5.03	-1.64	0.06	2.56	5.49
	EU-EA						0.00	2.66	-4.02	-2.31	0.19	3.12
	N-Z							0.00	-6.68	-4.98	-2.47	0.46
SO	InvE								0.00	1.70	4.20	7.13
	TDT									0.00	2.50	5.43
	EU-EA										0.00	2.93
	N-Z											0.00

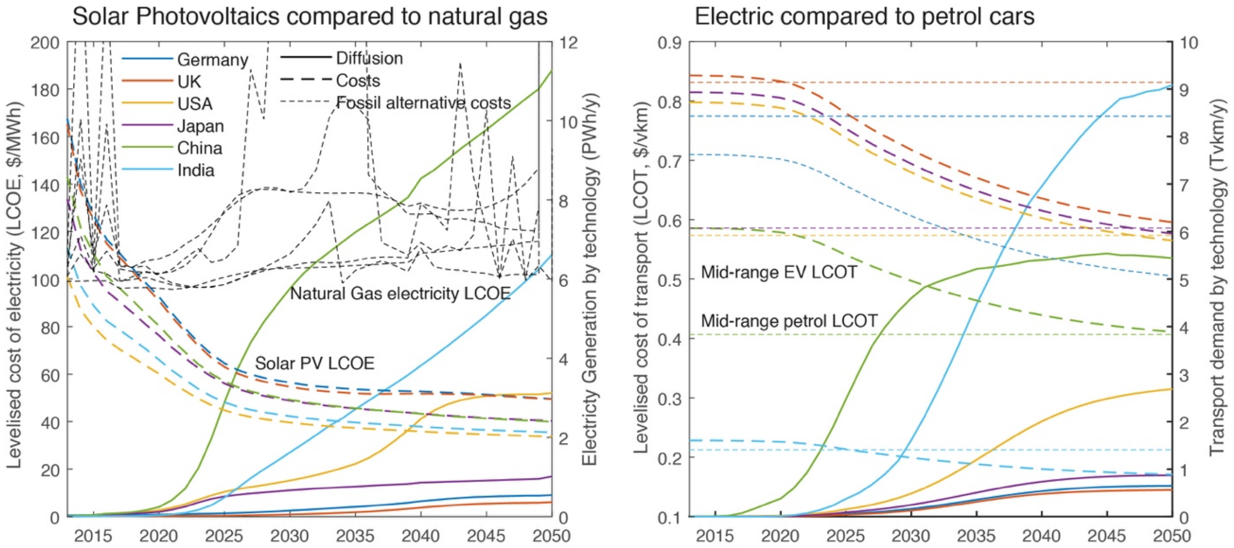
Coal		N			QU				SO			
		TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z
N	InvE	0.18	0.30	0.37	0.00	0.18	0.30	0.37	0.00	0.18	0.30	0.37
	TDT	0.00	0.12	0.19	-0.18	0.00	0.12	0.19	-0.18	0.00	0.12	0.19
	EU-EA		0.00	0.07	-0.30	-0.12	0.00	0.07	-0.30	-0.12	0.00	0.07
	N-Z			0.00	-0.37	-0.19	-0.07	0.00	-0.37	-0.19	-0.07	0.00
QU	InvE				0.00	0.18	0.30	0.37	0.00	0.18	0.30	0.37
	TDT					0.00	0.12	0.19	-0.18	0.00	0.12	0.19
	EU-EA						0.00	0.07	-0.30	-0.12	0.00	0.07
	N-Z							0.00	-0.37	-0.19	-0.07	0.00
SO	InvE								0.00	0.18	0.30	0.37
	TDT									0.00	0.12	0.19
	EU-EA										0.00	0.07
	N-Z											0.00

Gas		N			QU				SO			
		TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z	InvE	TDT	EU-EA	N-Z
N	InvE	1.74	2.37	3.61	-0.08	1.72	2.34	3.59	0.07	1.75	2.38	3.67
	TDT	0.00	0.62	1.87	-1.82	-0.03	0.60	1.85	-1.68	0.01	0.64	1.92
	EU-EA		0.00	1.24	-2.44	-0.65	-0.02	1.23	-2.30	-0.62	0.02	1.30
	N-Z			0.00	-3.69	-1.89	-1.26	-0.01	-3.54	-1.86	-1.23	0.06
QU	InvE				0.00	1.79	2.42	3.67	0.14	1.83	2.46	3.74
	TDT					0.00	0.63	1.88	-1.65	0.03	0.67	1.95
	EU-EA						0.00	1.25	-2.28	-0.60	0.04	1.32
	N-Z							0.00	-3.53	-1.85	-1.21	0.07
SO	InvE								0.00	1.68	2.32	3.60
	TDT									0.00	0.64	1.92
	EU-EA										0.00	1.28
	N-Z											0.00

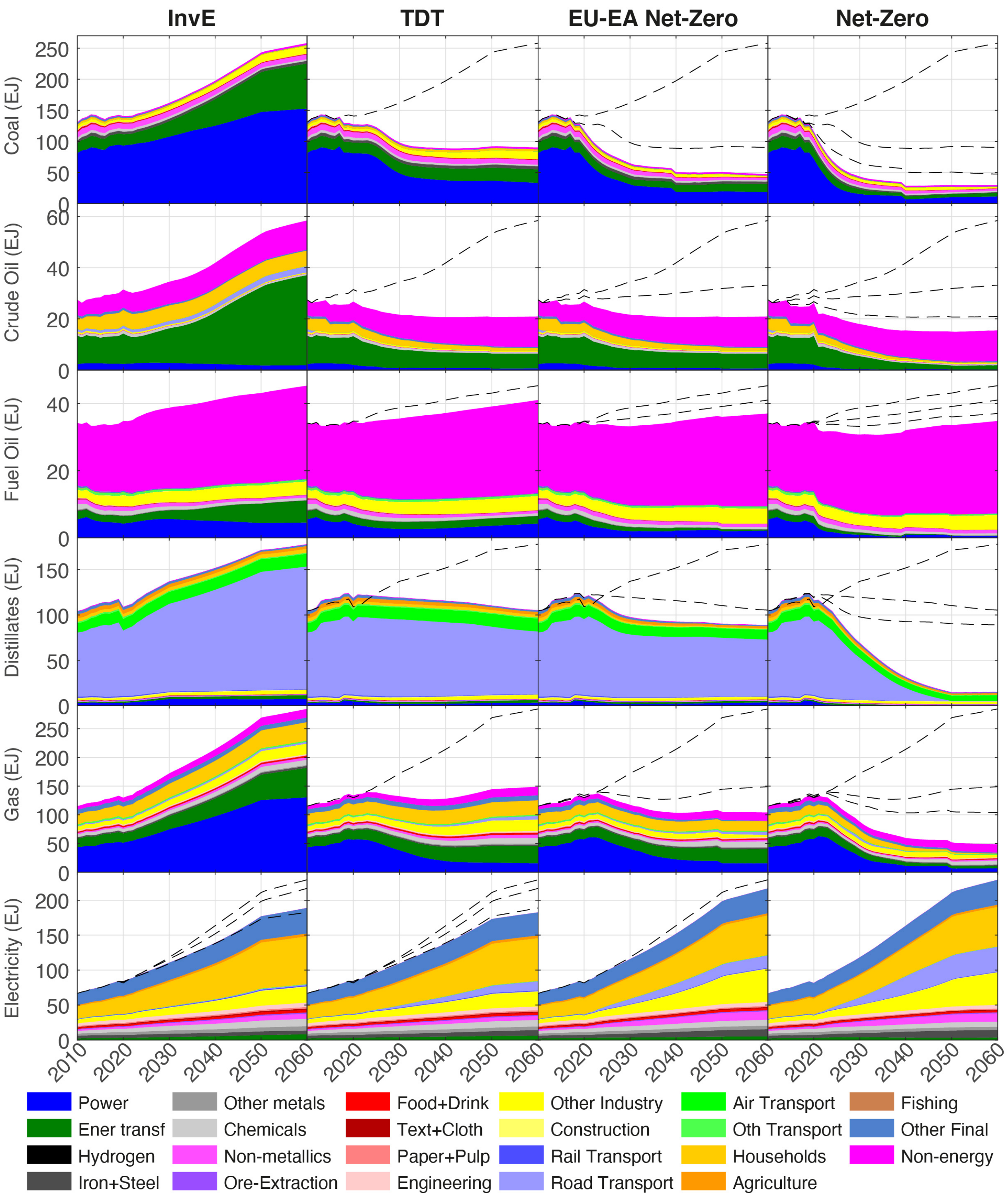
Suppl. Table 2 | Global loss of fossil fuel revenues by fuel type. Cumulated between 2022 and 2036 discounted by 6% for all possible pairs of scenarios, assuming that investors expect either of the vertical left-hand side scenarios, and that either of the horizontal top scenarios are realised.

Scenarios	Probability of warming not exceeding X°C (%)				Median of the peak warming (°C)
	4 °C	3 °C	2 °C	1.5 °C	
IEA	80.2	8.1	0	0	3.49
TDT	98.8	77.9	1.2	0	2.63
EU-EA Net-Zero	100	98.8	47.7	1.2	2.02
Net-zero	100	100	94.2	52.3	1.49

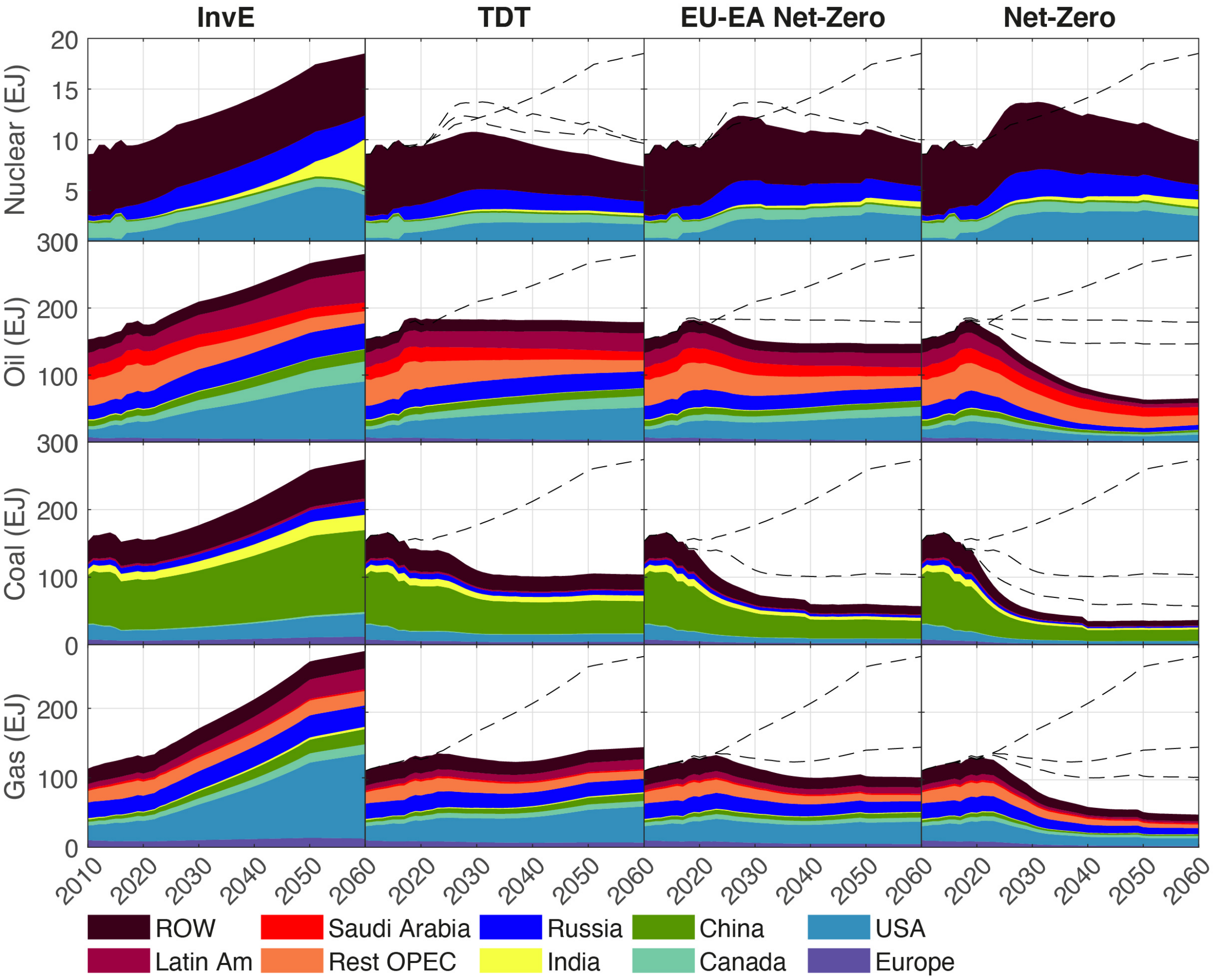
Suppl. Table 3 | Likelihoods of exceeding various climate thresholds and median peak warming. Calculated for each E3ME-FTT scenario using the climate model GENIE.



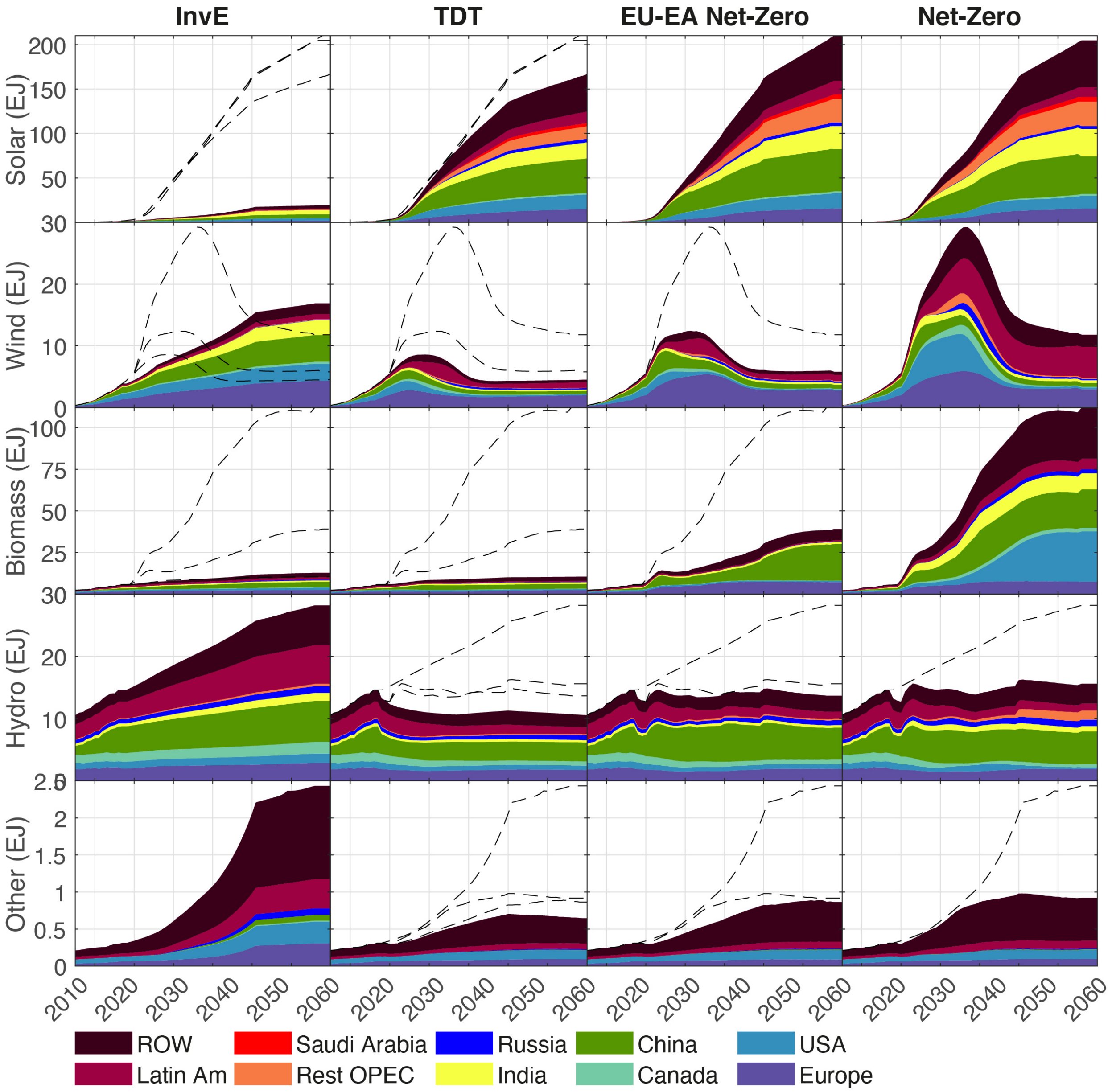
Ext. Data Fig. 1 | Technology dynamics for solar photovoltaic and electric vehicles. The dashed and dotted lines, associated with the left-hand side vertical axes, show technological costs for chosen regions given in the legend. The dashed lines show PV and EV levelised costs (the break-even service 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.



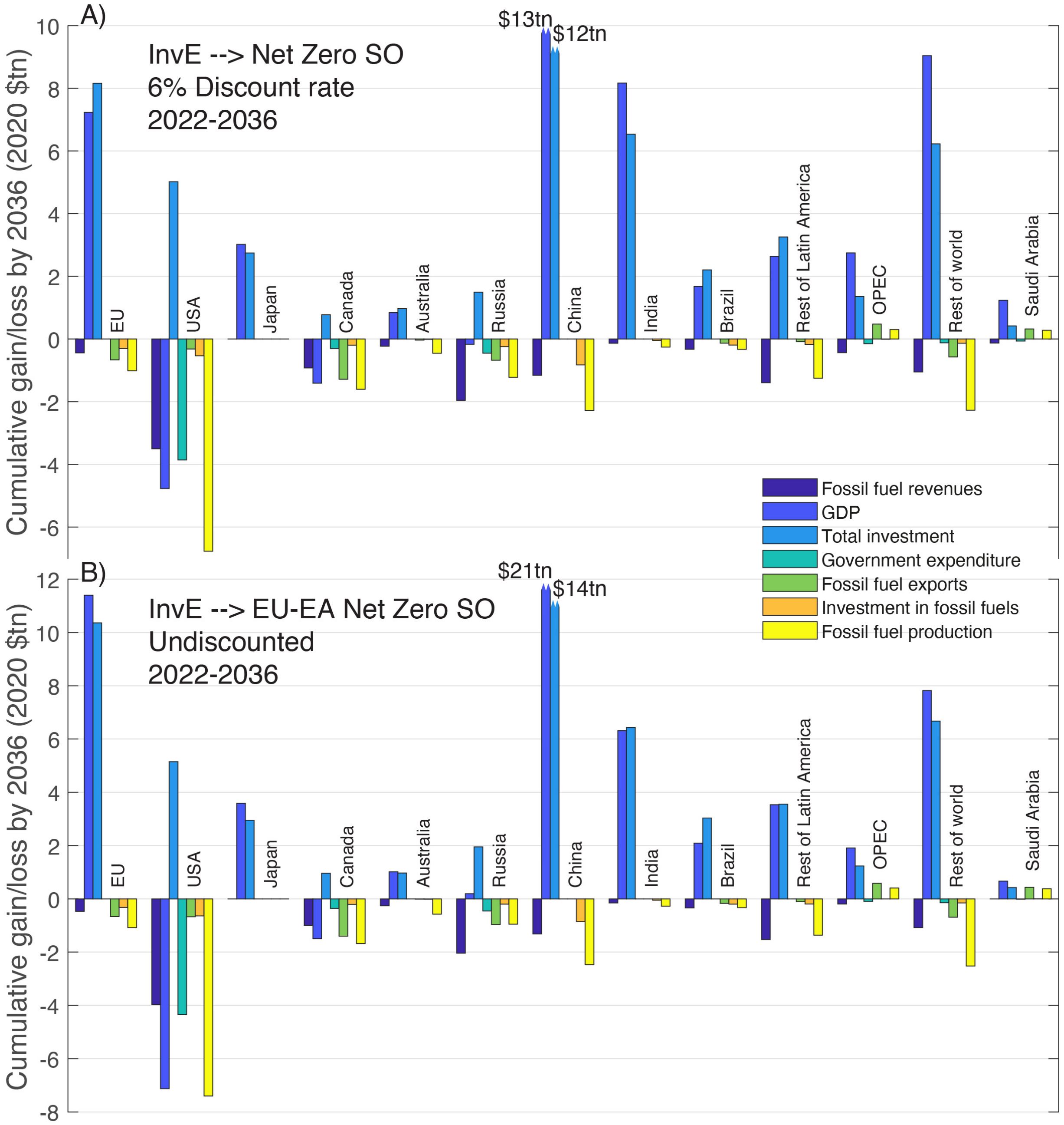
Ext. Data Fig. 2 | Projections for all scenarios of all major energy vectors in the economy. Dashed lines are guide to the eyes indicating totals of other scenarios in the same quantity.



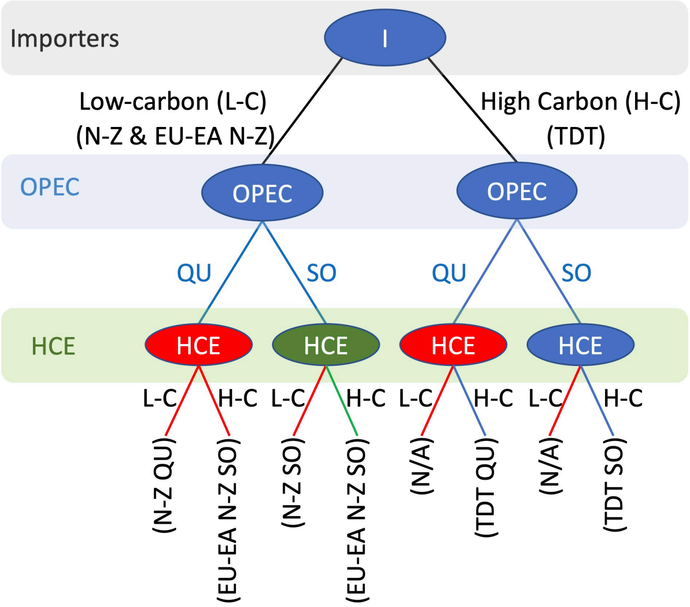
Ext. Data Fig. 3 | Projections for all scenarios of non-renewable energy use by region.



Ext. Data Fig. 4 | Projections for all scenarios of renewable energy use by region.



Ext. 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.



Ext. 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.

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