Reframing the climate policy game

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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 may 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 a prisoner's dilemma is a poor description of strategic incentives. Instead, a new climate policy game emerges in which 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.

Introduction

The adoption of the Paris Agreement in 2015 set a global 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 as part of the effort to shed light on this question.[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' (stranded) if countries around the world effectively implement climate policies.[11–13] The transition may already be underway, and some stranding may even 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.[14,15]

Climate policy has traditionally been understood as a 'Prisoner's Dilemma' (PD) game, where the objective of curbing emissions of CO2 is plagued by 'free-riding' by those not doing so, but who nevertheless benefit from global mitigation, without the economic burden of environmental regulation.[16–19] However, this motive is not supported by the evidence.[20,21] But furthermore, the nature of the incentives driving the game may currently be changing: the game may have become about industrial strategy, job creation and success of trade, which is not a simple PD problem. 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,[15,22] while investment in low-carbon technologies is generating substantial new employment.[23–25]

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 prices to decline substantially, affecting the viability of extraction in less competitive regions.[15] 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 make up for losses of exports.[10]

In this article, we ask if the PD game remains an accurate representation of reality, and if not, what the climate policy game has become. Indeed, 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. A key task for the policy-making and finance communities is to accurately anticipate what the new energy geography will be, and to predict its macroeconomic and geopolitical implications.

Method and scenarios

Understanding the ongoing low-carbon transition and its geopolitical implications requires suitable tools. Most integrated assessment models (IAMs) currently used for assessing climate policy and socio-economic scenarios are based on whole system/utility optimisation algorithms[26]. 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.[26,27] By contrast, non-optimisation IAMs, calibrated on time series and driven by system dynamics, can more accurately project energy system transformations.

Here we use the E3ME-FTT-GENIE integrated framework[10,28] of highly disaggregated energy, economy and environment models based on observed technology evolution dynamics and calibrated on the most recent time series available (Methods). Our model covers global macroeconomic dynamics (E3ME), S-shaped energy technological change dynamics (FTT),[29–31] fossil fuel and renewables energy markets,[32,33] and the carbon cycle and climate system (GENIE).[6] The framework explores these coupled dynamics in 61 regions covering the globe, 43 sectors of industrial activity with particular focus and detail on the four sectors of highest fossil energy use, representing 88 technologies in power generation, transport, heat and steelmaking (FTT). [29–31] We project changes in output, investment and employment in all sectors and 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 using a resource depletion simulation calibrated with a dataset that details 120,000 oil and gas production assets worldwide (Methods). We use a simple game theory framework to identify likely geopolitical motives.

We define four scenarios, from now to 2070, of technology, energy use and economic evolution in 61 regions, on the basis of current policies, developments already under way, and evidence-based expectations regarding future climate policies (Methods).

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 with the effects of past and current policies represented implicitly through the data. We interpret the TDT scenario as a realistic representation of business as usual, i.e. not contingent on the adoption of new climate policies such as may be needed to achieve climate targets. It is consistent with a median global average temperature warming of 2.6°C (Methods).

Net-zero CO_2 globally in 2050 (Net-zero) – We add new climate policies (e.g. technology subsidies, feed-in tariffs, fuel taxes, public procurement, and an increasing exogenous carbon price, see Methods) by either increasing the stringency of what already exists in reach region, or by implementing policies that may be reasonably expected in each regional context, based on two indications, the regional technological compositions and an extrapolation of policies adopted in other regions with similar contexts. The UK, EU, China, Japan and South Korea reach net-zero emissions independently in 2050. Moderate amounts of negative emissions from biomass power generation linked to carbon capture and storage (BECCS) are used to offset residual emissions in other industrial sectors. This scenario 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, Japan, South Korea) but assume TDT policies for all other nations. This represents a second baseline in which TDT is augmented to include new net-zero targets adopted by major economies. This scenario achieves a median warming of 2.0°C.

Investment Expectations (InvE) – We switch off our energy technology evolution model (FTT) and replace its variables by prescribing exogenously all final energy demand from data, in which energy markets grow over the simulation period, to reflect expectations of relatively slow or delayed decarbonisation by a major subset of investors in energy systems. We use data from the IEA's World Energy Outlook 2019 current policies scenario,[34] run the macroeconomic model (E3ME) alone but determine fossil fuel prices using our fossil fuel resource depletion model consistent with the demand. This scenario is consistent with a median warming of 3.5°C, and is similar to standard baselines (e.g. RCP 8.5[35]) used widely.

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. In the InvE scenario, the technology composition is derived from the IEA scenario data. 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, 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 (Suppl. Fig. 1), solar photovoltaics (PV) becomes the lowest cost technology soon after 2025-2030 in all but the InvE scenario, depending on regions and solar irradiation. Electric vehicles display a similar type of winner-take-all phenomenon, although at a later period. Lastly, 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 the absolute value of 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 in 61 regions, shown in Figure 2 (sectoral details are given in Suppl. Fig. 2, regional details in Suppl. Fig. 3-4; see Suppl. Dataset 1). 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 area of nations, fossil fuel production and decline are concentrated in a subset of geologically suited regions.[32]

Distributional impacts and geopolitics

International fossil fuel trade forms a key source of economic power in the current geopolitical order. 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. 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.

We show in Figure 3 the cost distribution of global oil and gas resources according to the Rystad[36] database, which comprehensively documents over 120,000 oil and gas assets covering most existing resources worldwide (Methods and Suppl. Dataset 2), 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 should they wish to do so, under the expectation of limited future oil and gas demand, OPEC countries could together or independently decide to flood markets to price out other participants from fossil fuel markets by maintaining or increasing their levels of production.

We define two scenario variants that represent two opposite OPEC courses of action. 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. 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 of stabilising markets.[14] Figure 4a shows changes in 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, 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 in the case of oil and gas, uses a depletion algorithm based on the Rystad data. Depending on decisions made, long-term oil prices could remain at values as low as $35/bbl for long periods as the expected economic viability of higher cost resources (such as tar sands, oil shales, arctic and deep offshore) deteriorates.

Changes in oil and gas prices, combined with slumps in production, may therefore have disruptive structural effects on high-cost fossil fuel exporters 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 exporter 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 Suppl. Fig. 5, Suppl. Tables 1-2 and Suppl. Dataset 3 for comparison variants).

Lastly, we find, using in a simple two-by-two game theory framework (Table 1, Suppl. Note 4, Suppl. Fig. 6) that if one assumed that 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 by policy-makers, the EU-EA Net-Zero SO would be a stable Nash equilibrium. Here, the decision by importers to decarbonise is a dominant strategy, as is that of OPEC to flood markets.

Discussion

A new geopolitical game, other than the PD, emerges with the new energy geography. Whether and how fast fossil energy markets peak and decline is primarily decided by the major energy importers (China, India, Japan, the EU), who have an economic incentive to decarbonise, decisions that inflict economic damage on producers in general. Meanwhile, the magnitude of the re-organisation of high value oil and gas market changes depends strongly on choices of energy output made by OPEC countries, a dimension of agency that other producers do not possess. Since the impact on their fiscal position, GDP and jobs of the transition can be largely overcompensated by their output strategy, a compelling narrative emerges in which low-cost exporters (OPEC) 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.

The new energy geography has deep socio-economic and geopolitical implications, and changes game theoretical interpretations of political dynamics. First, in line with the great waves literature[37,38] and the Just Transition movement, the creative destruction effect of the low-carbon transition underway is likely to generate localised issues of post-industrial decline, particularly in the US, Russia, Canada. This suggests that comprehensive plans for regional redevelopment are likely needed along with economic diversification towards new technology sectors including catching up in the race towards low-carbon technology exports. 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, 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

The E3ME-FTT-GENIE integrated framework is described below. The full set of equations underpinning the framework is given and explained in [[28]]. 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[8,39] 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.[8,39] 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, demand (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.[28] 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[29] 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[30,40] 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[41] 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.[42] 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.[42,43] 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.[43]

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 [30]).

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.,[44] 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 10º x 5º on average with 16 depth levels in the ocean and has here been applied in the configuration of [45,46] (see references therein).

The probabilistic projections are achieved through an ensemble of simulations for each emissions scenario using an 86-member set[47] 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[48] (where X=9.3 GtC is E3ME 2019 emissions), to correct for missing processes in E3ME. The emissions trajectories are then extrapolated to 2100 (IEA and TDT scenarios) or until they reach net-zero (2C 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 (net-zero and 2C scenarios) and RCP 6.0 (IEA and TDT scenarios). GENIE results for exceedance likelihoods for climate thresholds and median peak warming for each scenario are given in Table 1.

The GENIE ensemble has been validated[47] 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[36] dataset in the form of breakeven cost distributions (as in Figure 3, aggregated into 61 regions). The Rystad dataset documents over 120,000 oil and gas production sites worldwide, which covers 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.

The energy market model[33] 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.[32]

The formation of scenarios and choices of regional decarbonisation policy portfolios

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 not solar PV.
- 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
- 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[49], 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, 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.

Declarations

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Author contributions

J.-F.M. designed and coordinated 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. 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.

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Tables

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

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

Table 1: GDP payoffs matrices measured in $2020bn (cumulated between 2022 and 2036, discounted by 6%; positive values are GDP increases with respect to the InvE scenario). Red cells indicate probable outcomes. The game has a Nash equilibrium in the EU-EA Net-Zero SO scenario combination.