# Macroeconomic impact of stranded fossil-fuel assets

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Several major economies rely heavily on fossil-fuel production and exports, yet current low-carbon technology diffusion, energy efficiency and climate policy may be substantially reducing global demand for fossil fuels.[1-4] This trend is inconsistent with observed investment in new fossil-fuel ventures[1,2], which could become stranded as a result. Here we use an integrated global economy-environment simulation model to study the macroeconomic impact of stranded fossil-fuel assets (SFFA). Our analysis suggests that part of the SFFA would occur as a result of an already ongoing technological trajectory, irrespective of whether new climate policies are adopted or not; the loss would be amplified if new climate policies to reach the 2°C target are adopted and/or if low-cost producers (some OPEC countries) maintain their level of production ('sell-out') despite declining demand; the magnitude of the loss from SFFA may amount to a discounted global wealth loss of $1-4tn; and there are clear distributional impacts, with winners (e.g. net importers such as China or the EU) and losers (e.g. Russia, the US or Canada, which could see their fossil-fuel industries nearly shut down), although the two effects would largely offset each other at the level of aggregate global GDP.

The Paris Agreement aims to limit the increase in global average temperature to 'well below 2°C above pre-industrial levels'[5]. This requires that a fraction of existing reserves of fossil fuels and production capacity remain unused, hence becoming stranded fossil-fuel assets (SFFA)[6-10]. Where investors

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assume that these reserves will be commercialised, the stocks of listed fossil-fuel companies may be over-valued. This gives rise to a 'carbon bubble', which has been emphasised or downplayed by reference to the credibility of climate policy[8,9,11-14]. Here, we show that climate policy is not the only driver of stranding. Stranding results from an ongoing technological transition, which remains robust even if major fossil-fuel producers (e.g. US) refrain from adopting climate mitigation policies. Such refusal would only aggravate the macroeconomic impact on producers because of their increased exposure to stranding as global demand decreases, potentially amplified by a likely asset sell-out by lower-cost fossil-fuel producers and new climate policies. For importing countries, a scenario that leads to stranding has moderate positive effects on GDP and employment levels. Our conclusions support the existence of a carbon bubble which, if not deflated early, could lead to a discounted global wealth loss of between $1-4tn, a loss comparable to the 2007 financial crisis. Further economic damage from a potential bubble burst could be avoided by decarbonising early.

The existence of a carbon bubble has been questioned on grounds of credibility or timing of climate policies[11,12]. That would explain investors' relative confidence in fossil-fuel stocks[11,12] and the projected increase in fossil-fuel prices until 2040[2]. Yet, there is evidence that climate mitigation policies may intensify in the future. A report covering 99 countries concludes that over 75% of global emissions are subject to an economy-wide emissions-reduction or climate policy scheme[15]. Moreover, the ratification of the Paris Agreement and its reaffirmation at COP-22 have added momentum to climate action despite the position of the new US administration[16]. Furthermore, low fossil-fuel prices may reflect the intention of producer countries to 'sell-out' their assets, i.e. to maintain or increase their level of production despite declining demand for fossil-fuel assets.[17] But that is not all.

Irrespective of whether new climate policies are adopted or not, global demand growth for fossil fuels is already slowing down in the current technological transition[1,2]. The question then is whether under the current pace of low-carbon technology diffusion, fossil-fuel assets are bound to become stranded due to the trajectories in renewable energy deployment, transport fuel efficiency and transport electrification. Indeed, the technological transition currently underway has major implications for the value of fossil fuels, due to investment and policy decisions made in the past. Faced with SFFA of potentially massive proportions, the financial sector's response to the low-carbon transition will largely determine whether the carbon bubble burst will prompt a 2008-like crisis[11,12,14,18].

We use a simulation-based integrated energy-economy-carbon-cycle-climate model, E3ME-FTT-GENIE (see Methods and see Suppl. Table 1) to calculate the macroeconomic implications of future SFFA. Integrated assessment models (IAMs) generally rely on general equilibrium methods and systems optimisation[25-27]. Such models struggle to represent the effects of imperfect information and foresight for real-world agents and investors. By contrast, a dynamic simulation-based model relying on empirical data on socio-economic and technology diffusion trajectories can better serve this purpose (see Suppl. Note 1). In this method, investments in new technology and the interactional effects of changing social preferences generate 'momentum' for technology diffusion that can be quantitatively estimated for specific policy sets. Our model, E3ME-FTT-GENIE, is currently the only such simulation-based IAM that couples the macroeconomy, energy and the environment covering the entire global energy and transport systems with detailed sectoral and geographical resolution[19,28,29].

We study and compare three main scenarios (see Table 1 and Methods for scenario details): fuel use from the International Energy Agency (IEA) 'new policies scenario', which we call **'IEA expectations'** (IEA) to reflect the influence of the IEA's projections on the formation of investor and policy-maker expectations as to future demand (see Fig 1a,b for electricity generation and transport); our own E3ME-FTT **'Technology Diffusion Trajectory'** (TDT) projection with energy demand derived from our technology diffusion modelling in the power[21], road transport[23], buildings and other sectors under the ongoing technological trajectory (Fig 1c,d); and a projection, which we call **'2°C'** scenario, under a chosen set of policies that achieve 75% probability of remaining below 2°C (Fig 1e,f, see Suppl. Fig. 1 for climate modelling), while keeping the use of bioenergy below 95 EJ/y and thereby limiting excessive land-use change[30]. Only the TDT and 2°C scenarios rely on FTT technology diffusion modelling.

Unlike the 'IEA expectations' scenario, our 'Technology Diffusion Trajectory' scenario captures technology diffusion phenomena by relying on historical data and projecting it into the future.

Significantly, historical data implicitly includes the effects of past policies and investment decisions. On that basis, the ‘Technology Diffusion Trajectory’ scenario reflects higher energy efficiency and leads to lower demand. Liquid fossil-fuel use in transport peaks in both our ‘Technology Diffusion Trajectory’ and the ‘2°C’ scenarios before 2050 (Fig 1, Fig. 2a, for sectoral fuel use and emissions, see Suppl. Fig. 2). Solar energy partially displaces the use of coal and natural gas for power generation. Based on recent diffusion data (see Methods and Suppl. Table 1), our model suggests that a low-carbon transition is already underway in both sectors. Our sensitivity analysis (Suppl. Note 2 and Suppl. Table 3) confirms that these results are robust and driven by historical data rather than by exogenous modelling assumptions.

Significantly, the lower demand for fossil fuels leads to substantial SFFA, whether 2°C policies are adopted or not (Fig. 2a). For individual countries, the effects vary depending on regional marginal costs of fossil-fuel production, with concentration of production in OPEC countries where costs are lower (Fig 2b). Regions with higher marginal costs experience a steep decline in production (e.g. Russia), or lose almost their entire oil and gas industry (e.g. Canada, US).

The magnitude of the loss depends on a variety of factors. Our analysis suggests that the behaviour of low-cost producers and/or the adoption of 2°C policies can lead to an amplification of the loss (see Table 1 and Supp. Table 2). The magnitude of the loss may indeed be amplified if low-cost producers decide to increase their production relative to reserves ratio to outplay other asset owners and minimise their losses (‘selling out’, a detailed definition is given in the Methods and Suppl. Note 3) (Fig 2c,d). Slowing or peaking demand leads to fossil-fuel prices peaking (without sell-out) or immediately declining (with sell-out). In the ‘2°C’ scenario, fossil-fuel markets substantially shrink and the prices fall abruptly between 2020-2030, a potentially disastrous scenario with substantial wealth losses to asset owners (investors, companies) but not to consumer countries. This result highlights the important strategic implications of decarbonisation for the EU, China and India (consumers) as compared to the US, Canada or Russia (producers).

At the global level, it is possible to quantify the potential loss in value of fossil-fuel assets (see Suppl. Notes 4). If we assume that investment in fossil fuels in the present day continues based on: questioning commitments to policy; the return expectations derived from the 'IEA expectations' projection; and the assets' rigid lifespan with expected returns until 2035. And then if, contrary to investors' expectations, policies to achieve the 2°C target are adopted, and low-cost producers sell-out their assets, then approximately \$12tn (in 2016 USD, which amounts to \$4tn present value when discounted with a 10% corporate rate) of financial value could vanish off their balance sheets globally in the form of stranded assets (see Supp. Table 2). This is over 15% of global GDP in 2016 (\$75tn). This quantification arises from pairing the 'IEA expectations' scenario with the '2°C' scenario with 'sell-out'. If instead of the 'IEA expectations', we pair our own baseline (the 'Technology Diffusion Trajectory' scenario) with the '2°C' scenario under the sell-out assumption, the total value loss from SFFA is approximately \$9tn (in 2016 USD) (\$3tn with 10% discount rate) (see Supp. Table 2). Our quantification is broadly consistent with recent financial exposure estimates calculated at a regional and country level for the EU and the US[14] (detailed explanation in Suppl. Note 4). Note that a 10% discount rate represents an investment horizon of about 10-15 years, and that fossil-fuel ventures have lifetimes ranging between 2 (shale oil) and 50 (pipelines) years (oil wells: 15-30 years; oil tankers: 20-30 years; coal mines: > 50 years). For reference, the subprime mortgage market value loss that took place following the 2007-8 financial crisis was around \$0.25tn, leading to global stock market capitalisation decline of about \$25tn[18].

Regarding the impact of SFFA on GDP and employment, Figure 2e,f shows the change in GDP and employment between our 'Technology Diffusion Trajectory' without sell-out and '2°C' scenarios, with sell-out, for several major economies/groups. The low-carbon transition generates a modest GDP and employment increase in regions with limited exposure to fossil-fuel production (e.g. Germany and most EU countries, and Japan). This is due to a reduction of the trade imbalance arising from fossil-fuel imports, and higher employment arising from new investment in low-carbon technologies. The improvement occurs despite the general increase of energy prices and hence costs for energy-intensive industries[28,29]. Meanwhile, fossil-fuel exporters experience a steep decline in their output and employment, due to the near shutdown of their fossil-fuel industry. These patterns emerge alongside a <1% overall impact of the transition on global GDP (<1% GDP change), indicating that impacts are primarily distributional, with clear winners (e.g. the EU and China) and losers (e.g. US and Canada, but also Russia and OPEC countries).

In both the ‘Technology Diffusion Trajectory’ and ‘2°C’ scenarios, a substantial fraction of the global fossil-fuel industry eventually becomes stranded. In reality, these impacts should be felt in two independent ways (see Suppl. Note 4): through wealth losses and value of fossil-fuel companies and their shareholders, and through macroeconomic change (GDP and employment losses in the fossil-fuel industry, structural change) leaving winners and losers. Figure 3a compares cumulative GDP changes with the cumulative 2016 value of SFFA between the present and 2035. Due to different country-reliance on the fossil-fuel industry, impacts have different magnitudes and directions (see Suppl. Note 5).

Reducing fossil-fuel demand generates an overall positive effect for the EU and China and a negative one for Canada and the US. Figure 3b,c shows, however, that since impacts on the Canadian and US economies primarily depend on decisions taken in the rest of the World, the US is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them. This is due to the way global fossil-fuel prices are formed. If the rest of the world reduces fossil-fuel consumption and there is a sell-out, then lower fuel prices will make much US production non-viable, regardless of its own policy, meaning that its assets become stranded. If the US promotes a fossil fuel-intensive economy, then the situation becomes worse, as it ends up importing this fuel from low-cost producers in the Middle East, while it forgoes the benefits of investment in low-carbon technology (for other countries, see Suppl. Fig. 3, Suppl. Table 8 and Suppl. Note 5).

Importantly, the macroeconomic impacts of SFFA on producer countries are primarily determined by climate mitigation decisions taken by the sum of consuming countries (e.g. China or the EU), and thus a single country, however large, cannot alter this trajectory on its own. Also, critically, this finding contradicts the conventional assumption that global climate action is accurately described by the prisoner’s dilemma game, which would allow a country to free-ride. But an exposed country can mitigate the impact of stranding by divesting from fossil fuels, as an insurance policy against what the rest of the world does. What remains to be known, however, is the degree to which SFFAs impose a risk to regional and global financial stability.

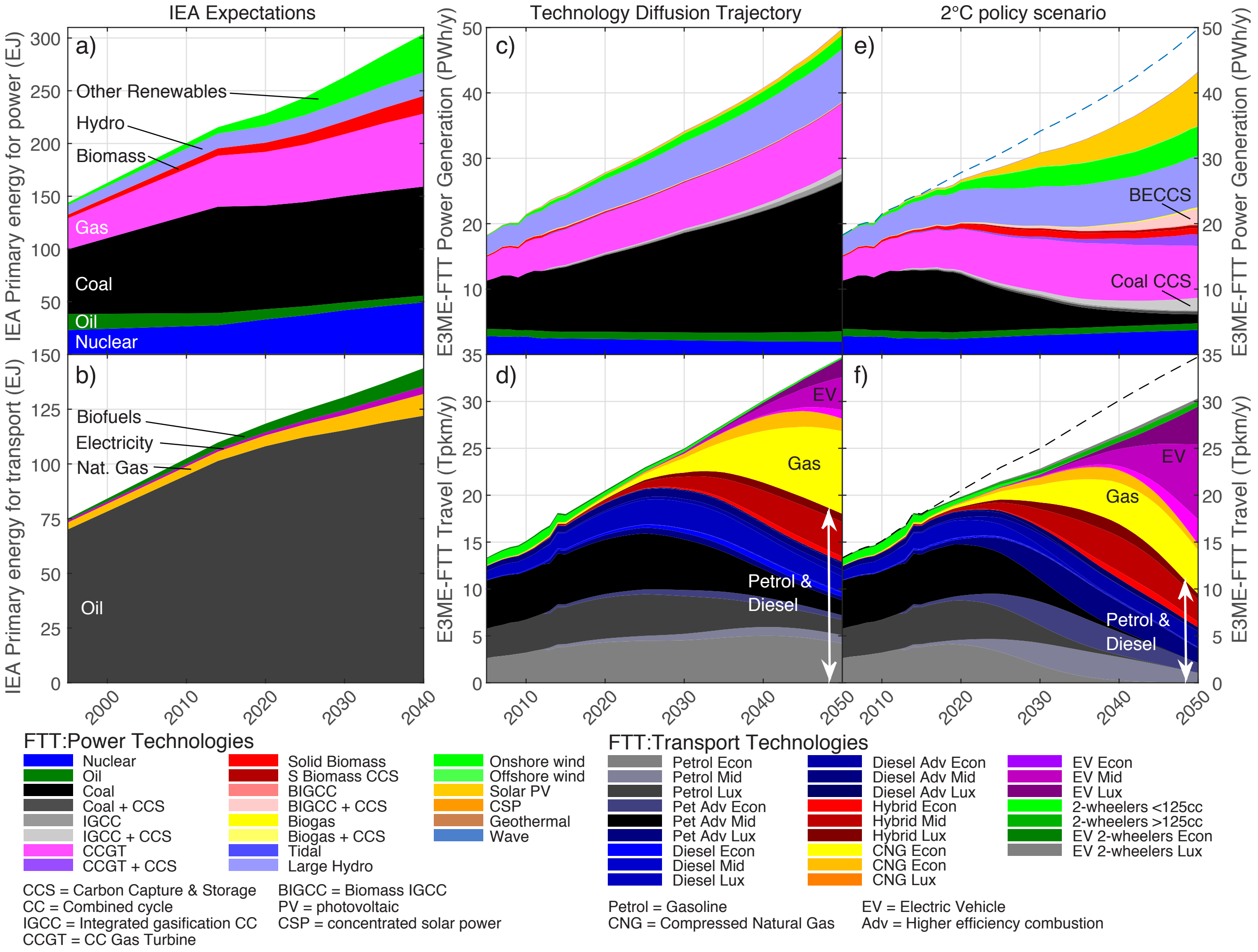

**Figure 1 | Projections of future energy use for power generation and transport. a-b**) Global IEA fuel demand in the ‘IEA expectations’ scenario. c-f) Technology composition in electricity generation (**c,e**) and road transport (**d,f**) in our ‘Technology Diffusion Trajectory’ (**c-d**) and ‘2°C’ scenarios (**e-f**). IEA fuel demand is taken from [2]. Dashed lines refer to our ‘Technology Diffusion Trajectory’ scenario for comparison.

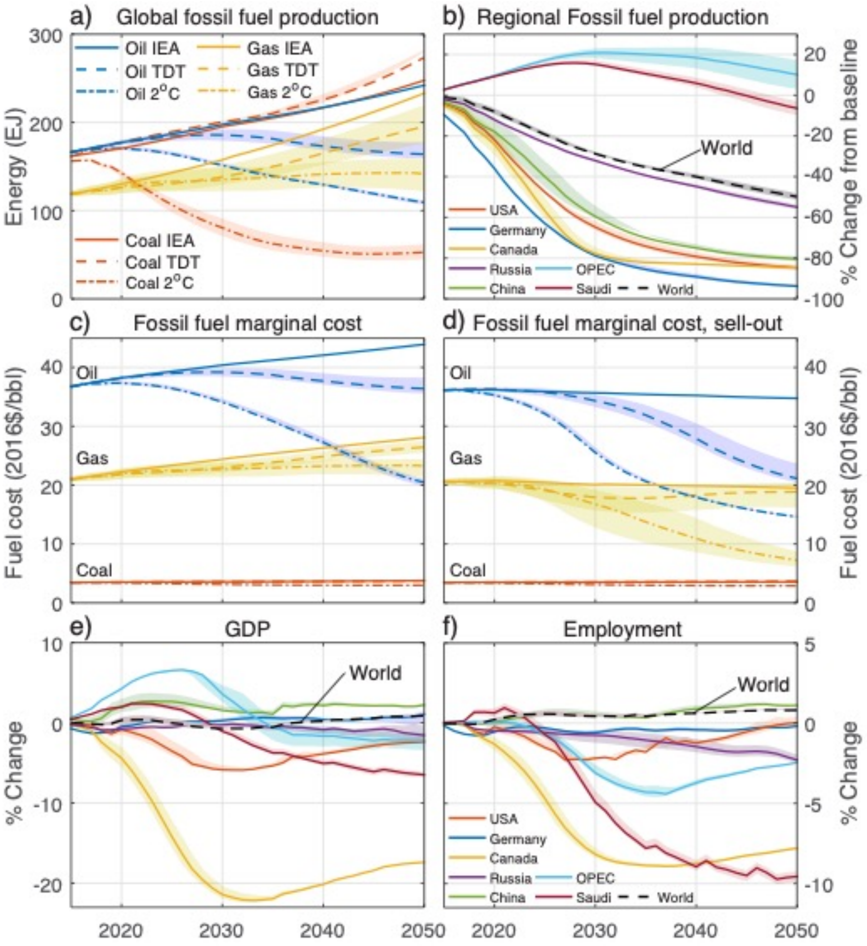

**Figure 2 | Change in fossil-fuel asset value and production across countries, and in macroeconomic indicators. a)** Global production of fossil fuels, for the 'IEA expectations' (IEA) scenario, our 'Technology Diffusion Trajectory' scenario (TDT), and our '2°C' policies scenario. **b)** Change in total fossil-fuel production, between the '2°C policies' and our 'Technology Diffusion Trajectory' scenarios. **c-d)** Marginal costs of fossil fuels in the same three scenarios, without sell-out **(c)** and with sell-out **(d)**. **e-f)** Changes in GDP and employment between the '2°C policies' sell-out scenario and our 'Technology Diffusion Trajectory' scenario without sell-out (negative means a loss). The width of traces represents maximum uncertainty generated by varying technology parameters (see Suppl. Table 3). OPEC excludes Saudi Arabia for higher detail. Macro impacts for Canada feature higher levels of economic uncertainty (not shown), as such high impacts could be mitigated in reality by various policies such as deficit spending by the government; however, we exclude studying deficit spending here for simplicity of interpretation (we assume balanced budgets).

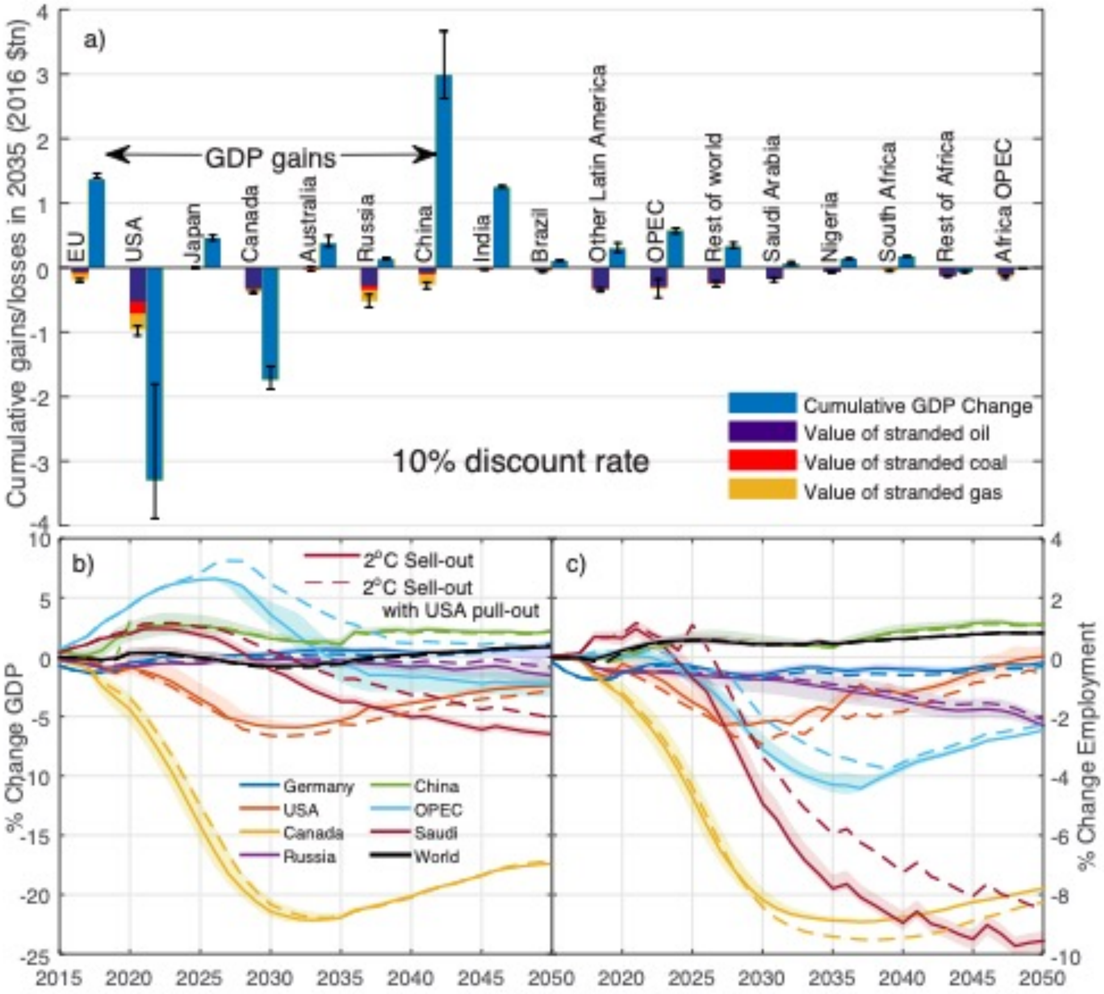

**Figure 3 | SFFA losses and impacts across countries. a**) Discounted cumulated fossil-fuel value loss to 2035 for oil, gas and coal, and GDP changes up to 2035, between the 2°C sell-out scenario and the 'IEA expectations' scenario (see Suppl. Table 2 and Suppl. Fig. 4 for other scenarios and aggregation methods). Negative bars indicate losses. Error bars represent maximum uncertainty on total SFFA generated by varying technology parameters (see Suppl Table 3, Suppl. Table 4 provides a breakdown for individual fuels). **b**) Percent change in GDP between the 2°C sell-out scenario and our 'Technology Diffusion Trajectory' non-sell-out scenario (solid lines), and between the 2°C sell-out scenario with a US' withdrawal from climate policy and the same (dashed lines). **c**) Same for labour force employment change.

## Table 1 | Scenarios and models

| Sector | | | Power generation | Road Transport | Household heating | Other transport | Industry | Rest |
|---|---|---|---|---|---|---|---|---|
| Model | | | FTT | FTT | FTT | E3ME | E3ME | E3ME |
| Scenario | IEA expectations | | Energy sector not modelled, replaced by fuel use data taken from IEA | | | | | |
| | Technology Diffusion Trajectory | No sell-out | CO$_2$P, FiT, Reg | Implicit in data | Implicit in data | Implicit in data | Implicit in data | Implicit in data |
| | | Sell-out | Same, with exogenous assumptions over fossil fuel production (prod./reserve ratio) | | | | | |
| | 2°C | No sell-out | CO$_2$P, Sub, FiT, Reg, K-S | FT, RT, BioM, Reg, K-S | FT, Sub | CO$_2$P, Reg | CO$_2$P, Reg | CO$_2$P, Reg |
| | | Sell-out | Same, with exogenous assumptions over fossil fuel production (prod./reserve ratio) | | | | | |

Abbreviations: CO$_2$P = Carbon Price, FiT = Feed-in Tariff, Sub = Capital cost subsidies, RT = registration carbon tax, Reg = Regulations, K-S = Kick-start program

Notes: Policy details available in the Methods. For carbon prices, sell-out assumptions and a sell-out sensitivity analysis, see Suppl. Figs. 5-6. For key model characteristics, see Methods, Suppl. Table 1 and Suppl. Note 1. For sensitivity analyses on key technology parameters, see Suppl. Note 2, Suppl. Tables 3-4 and Suppl. Fig. 8. Suppl. Table 5 and Suppl. Fig. 7-11 compare our scenarios to others in the literature. Suppl. Table 6 compares GENIE outputs with other models. For fossil fuel prices see Suppl Table 7. For sectoral impacts, see Suppl. Note 5 and Suppl. Table 8. The 'IEA expectations' scenario corresponds to the World Energy Outlook's 'New Policies Scenario' [2]. Detailed policies can be obtained from the Suppl. Data.

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## Author contributions

JFM designed and coordinated the research. JFM, JV, NRE, HP and IS wrote the article. JFM, HP and UC ran simulations. UC and HP managed E3ME. JFM and AL developed FTT:Transport. JFM and PS developed FTT:Power and the resource depletion model. FK and JFM developed FTT:Heat. PH and NRE ran GENIE simulations and provided scientific support on climate change. JV contributed geopolitical expertise.

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Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to JFM (J.Mercure@science.ru.nl).

## Methods

### Detailed scenario definitions

'*IEA Expectations':* In this scenario, we replace our energy model (FTT and E3ME estimations) by exogenous fuel use data from the IEA's 'new policies' scenario[31]. We derive macroeconomic variables from the evolution of a fixed energy system (FTT is turned off). We use our fossil-fuel resource depletion model in order to estimate changes in the marginal cost of production of fossil fuels. This enables us to calculate fossil-fuel asset values. Given that this scenario *does not* make use of our technology projections with FTT*,* we use this scenario with the interpretation that it represents the expectations of investors, who do not fully realise the state of change of technology, in particular electric vehicles and renewables that, as we argue in the text, is taking place.

'*Technology Diffusion Trajectory*': In this scenario, we use the three FTT diffusion models and our own E3ME energy sector model (see Suppl. Table 1) to estimate changes in fuel use due to the diffusion of new technologies. This is the baseline of the E3ME-FTT-GENIE model, which differs substantially from the IEA's. We interpret this scenario as that which, we argue, is likely to be realised instead of the 'IEA expectations', according to the current technological trajectory observed in historical data that parameterise our models, if no climate policies are adopted. Policies are not specified explicitly, but instead, are implicitly taken into consideration through the data.

'*2°C*': In this scenario, we choose a set of policies that achieves 75% chance of not exceeding 2°C of peak warming, according to the GENIE model, itself validated with respect to CMIP5 models (see Suppl. Fig 1). We estimate the diffusion of new low-carbon technologies and evolution of the energy sector under these policies using E3ME-FTT. Policies (e.g. subsidies, taxes, regulations) are specified explicitly.

'*Sell-out*' *versions of all scenarios:* In both the 'Technology Diffusion Trajectory' and the '2°C' scenarios, the issue of the sell-out of fossil fuel resources by low-cost producers is a real but not inevitable possibility. We therefore present both 'sell-out' and 'non-sell-out' versions for each scenario. The 'sell-out' is defined by increasing production to reserve ratios of producer countries, which concentrates production to OPEC and other low-cost production areas. Meanwhile, in the 'non-sell-out' scenarios, these ratios are constant, as they have been until recently[22]. These assumptions are exogenous (see Suppl. Note 3). SFFAs are given for all combinations in Suppl. Table 2.

## Policy assumptions for achieving a 2°C target

The set of policies that we use to reach the Paris targets constitutes one of many possible sets that could theoretically reach the targets. They achieve emissions reductions consistent with a 75% probability of reaching the 2°C target, and include the following:

*Multiple sectors*: $CO_2$ pricing is used to incentivise technological change across sectors in E3ME-FTT. One price/tax is defined exogenously, in nominal USD, at every year for every country, shown in Suppl. Figure 5A. This policy applies to power generation and all heavy industry sectors (oil & gas, metals, cement, paper, etc). It is not applied to households nor to road transport.

*Electricity generation*: Combinations of policies are used to efficiently decarbonise electricity generation, following earlier work[21]. These involve $CO_2$ pricing (above) to incentivise technological change away from fossil-fuel generators, subsidies to some renewables (biomass, geothermal, CCS) and nuclear to level the playing field, feed-in tariffs for wind and solar-based technologies, and regulations to phase out the use of coal-based generators (none newly built). In some countries (foremost USA, China, India), a kick-start program for CCS and bioenergy with CCS is implemented to accelerate its uptake. All new policies are introduced in or after 2020.

*Road transport*: Combinations of policies are used to incentivise the adoption of vehicles with lower emissions, following earlier work[23]. This includes (1) fuel efficiency regulations for new liquid fuel vehicles; (2) a phase-out of older models with lower efficiency; (3) kick-start procurement programmes for electric vehicles where they are not available (by public authorities or private institutions, e.g. municipality vehicles and taxis); (4) a tax starting at 50$/(gCO2/km) (2012 values) to incentivise vehicle choice; (5) a fuel tax (increasing from 0.10$ per litre of fuel in 2018 to 1.00$, in 2050, 2012 prices) to curb the total amount of driving; (6) biofuel mandates that increase between current values to between 10% and 30% (40% in Brazil) in 2050, different for every country, extrapolating IEA projections[32].

*Industrial sectors*: Fuel efficiency policy and regulations are used, requiring firms to invest in more recent, higher efficiency production capital and processes, beyond what is delivered by the carbon price. These measures are publicly funded, following the IEA's 450ppm scenario assumptions[32]. Further regulations are used that ban newly built coal-based processes (e.g. boilers) in all sectors.

*Buildings*: For households, we assume a tax on the residential use of fossil fuels (starting at 60\$/t$CO_2$ in 2020, linearly increasing by 6\$/t$CO_2$ per year, 2016 prices), and subsidies on modern renewable heating technologies (starting at -25% in 2020, gradual phase-out after 2030). Commercial buildings increase energy efficiency rates, following the assumptions in the IEA's 450ppm scenario[32].

## The Simulation-based Integrated Assessment model

E3ME-FTT-GENIE is an integrated assessment simulation model that comprises a model of the global economy and energy sector (E3ME), three subcomponents for modelling technological change with higher detail than E3ME (the FTT family), a global model of fossil-fuel supply, and an integrated model of the carbon cycle and climate system (GENIE). E3ME, FTT and the fossil supply model are hard-linked in the same computer simulation, while GENIE is run separately, connected to the former group by soft-coupling (transferring data). A peer-reviewed description of the model with fully detailed equations is available with open access[19]; key model codes and datasets can be obtained upon request to the authors.

## The E3ME model

E3ME is a highly disaggregated demand-led global macroeconometric model[20,33-35] based on Post-Keynesian foundations[29,35,36], which implies a non-equilibrium simulation framework (see Suppl. Table 1). It assumes that commercial banks lend according to bank reserves, which are created on-demand by the central bank[36-38]. This means that increased demand for technologies and intermediate products in the process of decarbonisation is financed (at least in part) by bank loans, and spare production capacity in the economy, as well as existing unemployment, lead to possible output boosts during major building periods and slumps during debt repayment periods[29]. In the jargon of the field, while Computable General Equilibrium (CGE) models normally 'crowd-out' finance (additional investment in a given asset class implies a compensating reduction in investment in other asset classes), E3ME assumes a full availability of finance through credit creation by banks (additional investment in one sector does not require cancelling investment elsewhere, see [29] for a discussion). Note that E3ME does not feature an explicit representation of the sectoral detail of the financial sector (it is not stock-flow consistent) or model financial contagion; however, it features endogenous money through its investment equations, which is necessary and sufficient for this paper.

E3ME has 43 sectors of production, 22 users of fuels, 12 fuels, and 59 regions. It uses a chosen set of 28 econometric relationships (incl. employment, trade, prices, investment, household consumption, energy demand) regressed over a corresponding high dimension dataset covering the past 45 years, and extrapolates these econometric relationships self-consistently up to 2050. E3ME includes endogenous technological change in the form of technology progress indicators in each industrial sector and fuel user, providing the source of endogenous growth. It is not an equilibrium model; it is path dependent and demand-led in the Keynesian sense. E3ME has been used in numerous policy analyses and impact assessments, for the European Commission and elsewhere internationally (for example, see [39-41]). Recent discussions of the implications on results of the choice of an economic model for assessing the impacts of energy and climate policies are given in [29,35]. Previously, such debates have often concerned simpler types of IAMs (e.g. DICE)[42-44], while newer debates are emerging that address issues of framing and philosophy of science[45,46]. Recent empirical studies appear to find no evidence for crowding-out in the finance of innovation, from the perspective of access to finance[47,48]. E3ME has been validated against historical data by reproducing history between 1972 and 2006, based on the normal regression parameters[49].

### The FTT model

Technology diffusion is not well described by time series econometrics, as it involves non-linear diffusion dynamics (S-shaped diffusion[50]). To improve our resolution of technological change in the fossil-fuel intensive sectors of electricity and transport, we use the Future Technology Transformations (FTT) family of sectoral evolutionary bottom-up models of technological change dynamically integrated to E3ME[19,21,23,51]. FTT projects existing low-carbon technology diffusion trajectories based on observationally determined preferences of heterogenous consumers and investors using a diffusion algorithm.

FTT models market share exchanges between competing technologies in the power, road transport and household heating sectors based on technology 'fitness' to consumer/investor preferences. Agents have probabilistically distributed preferences calibrated on cross-sectional market datasets[23,51,52]. Choices are evaluated using chains of binary logits, weighted by their market share. The diffusion patterns of technologies are functions of their own market share and those of others, which reproduces standard observed S-shaped diffusion profiles (a so-called evolutionary replicator dynamics equation, or Lotka-Volterra competition equation[53-55]). FTT does not use optimisation algorithms and it is a time-step path-dependent simulation model (see Suppl. Table 1).

It is crucial to note that FTT projects the evolution of technology in the future by extending the current technological trajectory with a diffusion algorithm calibrated on recent history. The key property of FTT, strong path-dependence (or strong auto-correlation in time), typically found in technology transitions,[50,56,57] is given to the model by two features. (1) Technologies with larger market shares have a proportionally greater propensity to increase their market share, until they reach market domination. This is a key stylised feature of the diffusion of innovations[50,57,58]. (2) Continuity of the technological trajectory at the transition year from historical data to the projection (2013 ± 3-5 years) is obtained by empirically determining cost factors (denoted $\boldsymbol{\gamma}$, see below and Suppl. Fig. 8**)**. Since the diffusion of innovations typically evolves continuously, there should not be a change of trajectory at the transition from history to projection. By ensuring that this is so, we obtain a baseline trajectory in which some new low-carbon technologies (e.g. Hybrid and Electric Vehicles, solar PV) already diffuse to non-negligible or substantial market shares, and some traditional vehicle types decline (e.g. small motorcycles in China). This baseline (the ‘Technology Diffusion Trajectory’ scenario) includes current policies implicitly in the data, i.e. they are not specified explicitly. The introduction of additional policy, in later years, results in further gradual changes to the technological trajectory, typically after 2025, differences that become further from the baseline along the simulation time span. Sensitivity analysis (Suppl. Table 3) shows that these trajectories are robust under substantial changes of all relevant technological parameters.

The $\gamma$ factors are determined in the following way. Historical databases were carefully constructed by the authors by combining various data sources (transport and household heating, see Suppl. Table 1) or taken from IEA statistics (power generation). The $\gamma$ values are added to the respective levelised cost that is compared among options by hypothetical (heterogenous) agents in the model.[23,52] One and only one set of $\gamma$ values ensures that the first 3-5 years of projected diffusion features the same trajectory (time-derivative of market shares) as the last 3-5 years of historical data from the starting date of the various simulations (2012 for transport, 2013 for power, 2015 for heat, see Suppl. Fig. 8 for an example). This is the sole purpose of $\gamma$. The interpretation of $\gamma$ is a sum of all pecuniary or non-pecuniary cost factors not explicitly defined in the model, which includes agent preferences and existing incentives from current policy frameworks, as well as implicit valuations of non-pecuniary factors such as (for vehicles) engine power, comfort, status, etc. While the heterogeneity of agents is explicitly specified in FTT cost data and handled by the model (through empirical cost distributions, see for example [[52]]), $\gamma$ are constant scalar values (i.e. not distributed or time-dependent). As is the case for any parameter determined with historical data, the further we model in the future, the less reliable the $\gamma$ are but, just as with regression parameters, they do represent our best current knowledge as inferred from history.

## The fossil-fuel supply model

The supply of oil, coal and gas, in primary form, is modelled using a dynamical resource depletion algorithm[22]. It is equivalent in function and theory to that recently used by McGlade & Ekins[6]. Cost distributions of non-renewable resources are used, based on an extensive survey of global fossil reserves and resources[22]. The algorithm is then used to evaluate how resources are depleted, and how their marginal cost changes as the demand changes (i.e. which is the most costly extraction venture, given extraction rates for all other extraction sites in production, supplying demand). As reserves are consumed and/or demand increases, fossil resources previously considered uneconomic, come online, requesting price increases. Meanwhile, when demand slumps, the most costly extraction ventures are first to shut down production (e.g. deep offshore, oil sands). The data are disaggregated geographically following the E3ME regional classification.

The model assumes that the marginal cost sets the price, thus excluding effects on the price by events such as armed conflicts, processing bottlenecks (e.g. refineries coming online and offline) and time delays associated to new projects coming online. While fossil-fuel price changes may not always immediately follow changes in the marginal cost in reality, differences are cyclical (due to the ability of firms to cross-subsidise and produce at a loss for a limited time) and the long-term trend is robust. Taxes and duties on fuels, which differ in every region of the world, are not included in Fig. 2 of the main paper, nor in the calculation of SFFA. E3ME includes end-user fuel prices from the IEA database, including taxes. The source for energy price data is the IEA. In the scenarios we do not explicitly include the phase-out of fossil fuel subsidies but the carbon price, when applied to fuels, effectively turns the subsidies into taxes. It is noted that some of the largest fuel subsidies are in countries that are energy exporters and that reducing or removing the subsidies would help support public budgets (although it increases pressure on households). End-user prices are updated during the simulation to reflect changes in fossil-fuel marginal costs from the fossil fuel supply model; however end-user prices are not used in the calculation of SFFA. Behavioural assumptions over production decisions have important impacts in this sub-model, described further below.

### The GENIE model

GENIE is a global climate-carbon cycle model, applied in the configuration of [24], comprising the GOLDSTEIN 3-D ocean coupled to a 2-D energy-moisture balance atmosphere, with models of sea ice, the ENTSML terrestrial carbon storage and land-use change (LUC), BIOGEM ocean biogeochemistry, weathering and SEDGEM sediment modules[59-62]. Resolution is 10°×5° on average with 16 depth levels in the ocean. To provide probabilistic projections, we perform ensembles of simulations using an 86-member set that varies 28 model parameters and is constrained to give plausible post-industrial climate and $CO_2$ concentrations[63]. Simulations are continued from 850 to 2005 AD historical transients[64]. Post-2005 $CO_2$ emissions are from E3ME, scaled by 9.82/8.62, to match estimated total emissions[65], accounting for sources not represented in E3ME, and extrapolated to zero at 2079. For the 2C scenario, non-CO2 trace gas radiative forcing and LUC maps are taken from RCP2.6[66]. For the purposes of validation, the GENIE ensemble has been forced with the RCP scenarios and these simulations are compared with the CMIP5 and AR5 EMIC ensembles in Suppl. Table 6.

In the 2°C scenario, median peak warming relative to 2005 is 1.00°C, with 10% and 90% percentiles of 0.74°C and 1.45°C. Corresponding values for peak $CO_2$ concentration are 457, 437 and 479 ppm. Total warming from 1850–1900 to 2003–2012 is estimated as 0.78±0.06°C[67], giving median peak warming relative to preindustrial levels of 1.78°C. Ensemble distributions of warming and $CO_2$ are plotted in Suppl. Figure 1. Oscillations are associated with reorganizations of ocean circulation or snow-albedo feedbacks rendered visible by the lack of chaotic variability in the simplified atmosphere.

It could be questioned why such a detailed climate model is needed in this analysis. One key aspect of our analysis is the quantification of additional SFFA that arise due to climate policy. For this quantification to be meaningful, it is also necessary to quantify the climate and carbon cycle uncertainties that are associated with these policies (here a 75% probability of avoiding 2°C warming). Rapid decarbonisation pathways lie outside of the RCP framework, so that our physically based climate-carbon cycle model is a more appropriate and robust tool than e.g. an emulator under extrapolation.

## Data availability statement

The data that support the findings of this study are available from Cambridge Econometrics, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Cambridge Econometrics.

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# Macroeconomic impact of stranded fossil-fuel assets
# Supplementary notes, figures and tables online

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## Suppl. Note 1 | Differences between E3ME-FTT-GENIE and other models

Since it is a simulation model, and because the economic model is demand-led based on Post-Keynesian theory, E3ME-FTT-GENIE produces results that contrast with those from other detailed sectoral IAMs applied to climate change issues[1,2]. This is due to the model's non-equilibrium formalism, which represents finance and money creation[3,4], while equilibrium models used in most of the climate change literature do not represent money or banking. Including money and banking is important, because the financial system generates booms and recessions, such as that which took place in 2008. In demand-led models, production is not determined directly by the quantity of production capital available, but by the demand for products, and thus capital and labour can become stranded in particular situations.

Although E3ME is a sectoral model consistent with Post-Keynesian theory, it does not feature a detailed stock-flow model of finance or a model of financial contagion. Such features would be useful but are not crucial for the present study, which focuses on sectoral impacts, not financial stability. Stock-flow consistent Post-Keynesian models connected to climate modules exist[5,6]; however, none to date have the sectoral detail required in the present study. Meanwhile, attempts are being made to add the financial sector to equilibrium models, notably with the model GEM-E3-FIT (see [3]).

In conventional equilibrium models, capital resources are equal to total saving year on year. If capital resources are used to fund low-carbon technology, this requires either higher savings or results in the same quantity of capital resources being taken away from other productive sectors of the economy; both of these automatically lead to the GDP losses associated with climate mitigation action. This leads economists to frame climate mitigation as a prisoner's dilemma involving free-riders. Conversely, in the same models, if a sector loses output due to economic change (e.g. the fossil-fuel sector), the capital from this sector becomes free and immediately re-allocated to other sectors instead of being lost, compensating GDP even though the affected countries suffer the shutdown of a sector, the loss of machinery and rises in unemployment. We argue that in reality, the capital is not re-used for other purposes, but instead it is written off. Therefore, we argue, the assumption of capital re-allocation in these models artificially reduces the distributional impacts of climate mitigation, a problem that has mostly escaped attention, while it exclusively leads to GDP loss when climate policy is adopted. Equilibrium models also often assume full employment of the working age population, which has a similar effect.

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In non-equilibrium models such as E3ME-FTT-GENIE, neither of these two equilibrium-enforced effects take place. This is due to the fact that investment decisions are not directly constrained by saving decisions, as the balance is accounted for by changes in aggregate debt (borrowing or debt repayment), consistent with modern accounts of the monetary and financial systems[7-9]. This implies that in E3ME-FTT-GENIE, while there is no free-rider problem that arises with climate mitigation (climate action can lead to increases in investment, GDP and employment, without prior rises in saving), distributional impacts across sectors and regions are more pronounced (capital and labour can be stranded), in comparison to models that do not represent money, finance or details of the labour market.

We acknowledge work that has been done in other models concerning joining up top-down macroeconomic modelling to bottom-up technology modelling. Notably, many models were improved in this respect in the 2006 project entitled ‘Endogenous Technological Change And The Economics Of Atmospheric Stabilisation’,[10] and in 2010, ‘The Economics Of Low Stabilization’.[2] More recently, other model comparisons have been carried out[11-13]. While highly valuable, these representations are, however, not sufficiently sophisticated to generate the type of insights presented in this paper.

### Differences between E3ME-FTT-GENIE and the IEA’s World Energy Model

We compare E3ME-FTT results with those of the IEA ‘World Energy Outlook’ (WEO) featured in Figure 1 of the main text, attempting to explain the differences. The IEA uses its flagship ‘World Energy Model’ (WEM) to create WEO forecasts[14]. Two key differences between that and E3ME-FTT are important to mention: (1) WEM does not model S-shaped non-linear technology diffusion, but uses multinomial logits instead, implying a standard representative agent with complete information, and (2) WEM uses exogenous GDP growth assumptions, on which energy demand projections rely. Since numerical assumptions in WEM are not given by the IEA for us to compare against ours, we base our explanation of outcome differences on model structure. We note that the energy component of E3ME-FTT is based on the same IEA energy balances data.

Point (1) implies that WEM models technology diffusion solely based on cost considerations, and is thus analogous to a standard cost-optimisation model without behavioural information. For instance, in its sub-component Momo for road transport, the diffusion of light-duty vehicles by technology type is not non-linear (as in self-reinforcing S-shaped diffusion) but instead technology choice relies linearly on cost data. This implies that changes in the state of diffusion only happen when relative prices change: if relative technology costs do not change over time, an active evolving policy is necessary (e.g. an increasing carbon price). Thus without policy, no diffusion takes place by construction, while in FTT, on-going diffusion processes exist even without policy, which are accelerated by climate policy.

Point (2) implies that since its total production is fixed, sectoral production in WEM can only respond to price changes but not to demand changes, as demand for energy end-use services is modelled based on these exogenous GDP growth assumptions. However, price changes themselves will also be partly fixed by the resulting relatively rigid sectoral output. Therefore, energy demand changes originate almost exclusively from technological change, not from the economy. For instance, when the demand in WEM for fossil fuels declines, but intermediate demand for equipment and products for investment in the fossil-fuel and heavy industry sectors does not change, this artificially mitigates intermediate demand reductions for energy substantially, which would be observed if sectoral output was modelled endogenously. This is a substantial source of SFFA in the present work, as sectoral output is fully endogenous, providing a more complete representation of the sources of change in energy demand.

These two points result in energy demand projections in the WEO to be partly determined exogenously through fixed GDP assumptions, partly through insufficiently sophisticated representations of technology diffusion. Although it responds to climate policy through price signals, total energy demand growth in the WEO is independent from many important endogenous factors such that SFFA cannot be observed in WEM.

## Suppl. Note 2 | Sensitivity analysis for the technological trajectory

Sensitivity analyses were carried out to test the stability and robustness of scenarios with substantial changes to key technology parameters. The exercise was carried out for power generation and road transport, which together contribute 41% of current fuel use. Results are shown in Suppl. Tables 3 and 4. The parameters chosen are those that we expect will generate the largest changes to SFFA values. Changes are in percent for costs, and in added percentage points for rates. The parameters tested for power generation are (i) the capital costs of renewables (REN, ±20%), (ii) learning rates (±5 percentage points) and (iii) industry discount rates (±5 percentage points). For transport, the parameters are (iv) the prices of electric vehicles (EV, ±20%), (v) non-pecuniary costs (±20%), (vi) learning rates (±5 percentage points), (vii) consumer discount rates (±10 percentage points) and (viii) the fuel efficiency of new fossil fuel vehicles (±20%). We report the resulting changes, in % change over the same scenario without variation (i.e. $(\Delta S_2 - \Delta S_1)/\Delta S_2$), on the shares of renewables, of photovoltaic (PV), of EVs, of advanced efficiency combustion vehicles including hybrids (ADV) and conventional fossil fuel vehicles (FF), as well as changes in the value of fossil fuel assets for each fuel type and global GDP, discounted by 10% and cumulated to 2050.

The justification for these variations is as follows: (i) 20% is the maximum systematic error on mean capital costs we consider possible at one STD (the model, with its distributed cost formulation, already considers that around 30-40% of non-systematic cost variations exist, depending on the technology). (ii) power sector learning rates used range between 1% and 17%,[15] with a mean of 6%; variations cannot be more than 5-6 percentage points. (iii) Real world power sector discount rates are usually between 5% and 10%, depending on institutions[16,17]; systematic variations cannot exceed 5 percentage points. (iv) 20% is the maximum systematic errors on mean capital costs we consider possible at one STD (the model assumes distributed prices with STDs of 50%-80% of the mean for cars; EVs have lower price variations of 30% due to a lower number of models available). (v) Variations on non-pecuniary costs are reflections of systematic error on vehicle costs, and thus the same argument as (iv) applies. (vi) learning rates used are between 1% and 10% with mean of 5%; variations cannot exceed 5 percentage points. (vii) the consumer discount rate is 15%. In the literature, they span from 5% to 40% depending on the study design and assumptions[18,19]; thus at most 10 percentage points variations are possible. (viii) We use manufacturer fuel economy values, which are based on a standard driving cycle, adjusted to match total IEA fuel use for road transport. The driving cycle may not accurately represent driver behaviour leading to underestimation of around 30% in fuel use. We consider at most 20% systematic error possible at 1 STD.

We do not carry out directly sensitivities on fossil-fuel prices for the reason that these are not exogenous but endogenous variables in the model (there are no fossil-fuel price assumptions in E3ME-FTT); instead, fossil-fuel prices uncertainties can be caused by other exogenous assumptions such as the assumed reserve to production ratios chosen by producer countries. The sell-out itself is a process that results from such choices. SI Fig. 6 shows the impact of changing these values by 50%; this leads to changes on fossil-fuel prices of the order of 1% (coal), 5% (oil) 50% (gas). Fossil-fuel price variations could be caused by other factors such as armed conflict and other unexpected supply bottlenecks; however, we make the explicit assumption that this does not happen for simplicity of interpretation. Policy sources of uncertainty on SFFA are covered by SI Table 2. Fossil fuel prices are reported in Suppl. Table 7.

We do not allow varying the availability of technologies in the FTT models, for the following reason. FTT technologies are all, without exception, currently sold in markets (as evidenced by our historical data). Changing their availability would represent questioning reality if we remove them, while substantially increasing their future uptake beyond what can be achieved by modelling policy violates our diffusion modelling premise.

We observe that changes in our sensitivity analysis are relatively small in all cases. While changes in the technological shares can be of up to 16% ('2°C' scenario) and 60% ('Technology Diffusion Trajectory'), this generates changes to fossil fuel asset values of at most 11%. In terms of technology shares, we observe that the 'Technology Diffusion Trajectory' scenario is more prone to change, for changes in technology parameters, than the ‘2°C’ scenario, and this is explained by the fact that policy constrains more strongly outcomes in the ‘2°C’ scenario.

The largest impacts on fossil fuel asset values observed take place with changes of industry discount rates in power generation, which prompts substitution between coal and gas (thus exchanging coal and gas SFFAs) and, since gas has a higher price per energy content, impacts on asset values do not cancel out. Non-pecuniary (perceived) costs also affect oil asset values, as well as the fuel efficiency of combustion vehicles.

We combine the impacts using a root mean square. The interpretation for this is that if the uncertainty over technological parameters corresponded to the variations introduced here were independent and normally distributed, the resulting error propagation would be calculated in this way. If all such variations took place simultaneously, at most 15% uncertainty would be generated on fossil fuel asset values for each scenario. Since uncertainty could take place in both scenarios simultaneously, and that we calculate SFFAs using differences, at most 21% uncertainty would be generated. Although we do not know the real uncertainty over these parameters, experience with data tells us that these variations are reasonable. We conclude that for the policy scenarios considered, uncertainty on asset values is less than 21%, and therefore these scenarios are robust against variations of technology parameters. To estimate the maximum and minimum plausible variations in SFFA under combined variations of input parameters we performed two additional runs, which we used to generate the uncertainty bounds of Figures 2-3 of the main text. To achieve this, we used all parameter variations that generate increases in SFFA under the assumptions in Suppl. Table 3 in one model run, and all parameter variations that lead to lower SFFA in another, which we used as upper and lower uncertainty bounds.

It must be noted that our model is a diffusion model. In other models, if the model design involves searching the configuration space for the lowest cost configurations, and points in modelled time are not strongly dependent on past values, small changes in capital costs, discount rates or learning rates can generate relatively large differences in optimal technology configuration. This can be interpreted as modelling agents with perfect information and infinite access to technology. This is not what we do, which explains the relatively modest sensitivities obtained.

Here, the starting diffusion trajectory is constrained by the trajectory observed in recent historical data. The data constrain what near future configurations can be, which thus cannot radically change even for relatively large changes in parameters. Diffusion has, by definition, strong path-dependence and momentum in time and, by 2035, outcomes cannot be radically different from the present.

Similarly, altering the set of available technologies does not make much difference in FTT, for the following reason. Altering the ‘menu’ involves introducing new technologies (as stated above, we do not consider removing FTT technologies), with small market shares. Hypothetical new technologies with small shares take longer than until 2035 to diffuse to any significant degree, even if they possessed extremely attractive features (e.g. low cost) or policy support, only due to diffusion dynamics (unless a substantial public procurement program was assumed). In other words, 2035 is most likely too early for any new technology not modelled in FTT to radically change the landscape. This is a well known feature of the diffusion process, which, due to path-dependence, is rigid and contingent on history. This is supported by a whole body of literature on technological transitions[20-24]. Thus, the range of technological developments that one can observe in a diffusion model is more restricted than in models with weaker path-dependence.

## Suppl. Note 3 | Assumptions of fossil asset owner behaviour

The representation of fossil asset owner behaviour in the fossil resource depletion algorithm[25] comes in the form of a rate of depletion expressed as a production to reserve ratio (in $y^{-1}$, see Suppl. Figure 5 B), a parameter defined for each year in each fossil-fuel producing E3ME region (see below). Fossil commodity prices are taken as global, while production and consumption are assumed to interact within a global pool. In each cost range, production is proportional to the local depletion rate times the amount of reserves remaining in that range, and the sum across all cost ranges determines total production in each region, while global production is equal to global demand. The marginal cost that matches global supply to global demand is searched for through iteration of the equations at each E3ME-FTT time step.

Following the standard definition, reserves are fossil fuels in the ground considered economic to extract, while resources cover all known fossil-fuel deposits, thus not necessarily economic. Economic viability is largely determined by comparing extraction costs to commodity prices. In situations of increasing or constant demand, as reserves are gradually consumed, prompting commodity prices to increase, the model assumes that quantities of nearly competitive resources are re-classified as reserves; their extraction begins, and their marginal cost sets the price. When demand declines, it is possible that some high-cost reserves are taken out of production and re-classified as resources, allowing a downward commodity price movement. Reserves in each cost range are extracted at the same rate regionally defined. The starting rate is empirically defined based on historical data[25], representing a combination of asset owner choices and technical rates of extraction. If lower cost producers increase their quota, they force higher cost producers to reduce theirs.  Thus, if producers in regions operating predominantly in low-cost ranges (e.g. OPEC) so desire, they can increase their production to reserve ratio to undercut producers with higher costs in order to grab market share, i.e. extract their reserves faster in relation to the rate at which the price allows them to re-classify resources as reserves, effectively selling out their low-cost reserves instead of speculating on future prices. This could happen if low-cost producers begin to expect that future sales may be limited, in contrast to their past behaviour in which they expected sales to last indefinitely and reserved part of their product to sell at higher future prices[26].

Here, in the 'non-sell-out' scenarios, we assume constant production to reserve ratios, using those determined in earlier work[25] (their inverse equates to 44, 62 and 122 years for oil, gas and coal). A particular set of deviations of these parameters is what we call 'sell-out' scenarios, where we assume increasing ratios for low-cost producer countries (in particular Saudi Arabia and other OPEC countries), as shown in Suppl. Figure 5B. The particular values used were chosen such that production concentrates substantially towards OPEC (we assume that this is the purpose of decisions made in OPEC countries in order not to decrease their fossil-fuel income); a wide range of such values leads to similar outcomes, as shown in Suppl. Fig 6; reducing by 50% our chosen deviations in production to reserve ratios in all countries impact total cumulated SFFA and GDP by 8% (oil), <0.1% (coal), 29% (gas), 14% (total) and 15% (GDP).

## Suppl. Note 4 | Contrasting wealth loss and output loss

Wealth losses (stocks of value of assets on firms' or individuals' balance sheets) are not the same as output losses (flows of value added, e.g. GDP loss). When a bubble bursts, assets suddenly lose their value. These losses appear on the balance sheets of firms, but do not necessarily imply loss of output for the economy. However, a common reaction of financial institutions is to substantially cut lending when they face substantially altered balance sheets[9,27]. This restricts investment, which leads to output loss in the real economy, in comparison to a scenario where banks continue lending. The cumulative impact of the latter effect can be much larger than the initial wealth loss, as was observed during the 2008 subprime mortgage crisis, since constraints on lending are likely to spill over to activities outside the sector in which the crisis originated[27].

Meanwhile, output loss can take place without any such financial effects, simply due to structural change in the economy, such as with the fossil-fuel extraction sector shutting down due to insufficient demand.

We distinguish two effects here: (1) disruptions to the finance of other non-fossil-fuel related activities (the fossil-fuel bubble bursting), caused by panic on financial markets resulting from the impact of a sudden loss of fossil-fuel wealth on balance sheets, and (2) the real economy impacts of significantly down-sizing the fossil-fuel sector.

In (1), losses to output due to restrictions of lending by financial institutions could be large or small, depending on whether the bubble is deflated calmly (early diversification of investment) or bursts suddenly, and whether warnings are heeded and investment in fossil-fuel assets is avoided as much as possible. A sudden burst could lead to worldwide loss of output outside the fossil-fuel sector, as happened recently with the financial crisis. *We do not quantify this effect in this study* because there is no widely accepted way to quantitatively predict these phenomena at this scale, as the true dynamics of these financial contagion effects at the global scale are not fully known.

In (2), structural change leads to loss of output in fossil-fuel producer countries and gains to fossil-fuel importer countries, with worldwide changes in GDP that roughly cancel out to below 1% change (i.e. distributional effects). *These effects are included since they can be modelled in detail in E3ME-FTT*. A dramatic bubble burst (1) would aggravate (2) into a financial crisis and recession. The consequence is that our projections of the degree of loss represent a minimum, which could be intensified, depending on the degree of financial disruption and the pace of financial contagion.

**Wealth losses for different scenarios and investment horizons**

Wealth losses in scenarios of stranded fossil-fuel assets originate from the process of investments being made based on expectations of higher returns than turn out to occur subsequently. Here, we consider various scenarios combining different asset owner behaviour and decarbonisation policy. The results are given in Suppl. Table 2, which shows, as rows, the scenarios expected by investors, and as columns, the scenarios that turn out to be realised. These values are consistent with recent exposure estimates[28] (see below), the latter now starting to be taken into consideration by banks in their decisions[29].

The interpretation is as follows. We take a scenario in which we assume an investment horizon year of 2035, and assume that investment is made in the present or near future, expecting return until the horizon date, based on subjective price projections by investors. We assume that investment costs are sunk, and return depends on whether the ventures turn out to be profitable. If the price and quantity sold turn out different than the projection, the wealth loss is the expected demand times the expected price minus the realised demand times the realised price over the simulation time span until the horizon year. Assets changing hands between the present and the horizon year make little difference to the outcomes; once someone has invested in fossil-fuel capital (e.g. pipelines, tankers, oil extraction equipment, drilling), subsequently selling the venture does not change the total value of the loss (although it may change who makes the loss). The key assumption is that the quantity of fossil-fuel assets expected to be burned is locked in once bets are placed and, if demand turns out less than committed supply, assets become stranded and the value invested is lost.

For example, we assume that investors take 2035 as a horizon and invest all capital needed for fossil-fuel production up to this date in the present, expecting returns based on demand and prices given in IEA projections[30]. They subsequently find, over later years, that the Paris Agreement is becoming fully implemented worldwide, that OPEC countries refuse to reduce their production substantially, and that therefore prices and demand are significantly lower than expected when investment decisions were initially made. Resources initially invested in extraction equipment (e.g. Arctic, deep offshore, tar sands) is lost since the assets expected to be extracted from the ground will never be burned (and new pipelines, tankers etc are never used). Companies may go bankrupt if their cashflows decline significantly, as they may default on bank loans, even if their production continues and is sold at low prices.

Different investment horizons yield different results, but do not generate additional insights. Instead, one may wish to consider SFFA values discounted at different rates (Suppl. Table 2) to represent the investment horizon on the basis that investors take bets on expected future discounted income. Since knowing what investors think is not possible, we provide a number of possible investor expectation scenarios, against the same set of realised scenarios, in matrix form. For example, if one considers that the selling-out by OPEC members is already committed and taken into account by investors, one may assume the ‘IEA expectations’ or ‘Technology Diffusion Trajectory’ scenario with sell-out, and contrast it against a ‘2°C’ sell-out scenario, and observe the SFFA losses that arise then. In most scenarios, SFFA losses are comparable or larger than the initial 2007-8 sub-prime mortgage crisis loss[27]. The magnitude and direction of cumulated global GDP loss is highly dependent on the way remaining fossil-fuel production is distributed across the globe.

Our results are consistent, in a loose sense, with recent estimates of financial exposure for the EU and the USA. Battiston et al.[28] estimate around $1.7tn of value at risk when considering the fossil-fuel sector only. In our work, for the EU and the USA combined, we obtain $1.2tn (discounted) and $3.3tn (undiscounted) of total SFFA. The comparison can only be made loosely, since the values do not have the exact same meaning; while we calculate loss of income on sales of fossil fuels, Battiston et al. calculate the sum of the value at risk of assets of listed companies (loans, equity, etc). We do not know what investors expect as return, while the asset value plus return should in many cases be higher than the values they report. Nevertheless, we consider our values to be in the correct range, when considering their results.

Our results, however, are not quite consistent with Dietz et al.[31] Since the methodology and interpretation of the results differ substantially, they should not be compared. Dietz et al. use exogenous GDP growth as a proxy for climate Value at Risk, using Nordhaus' model DICE[32], and no real representation of the energy system, but they include climate damages as a probability distribution. In DICE, GDP decreases by assumption proportionally to abatement measures and damages[32]. In this formulation, investment devoted to abatement is by definition unproductive, and impacts on GDP of stringent climate policy can, by construction, only be negative (see the 'crowding out' issue discussed above). In contrast, while E3ME does not include climate damages, and therefore has no representation of 'fat-tailed' extreme events distributions, it provides a detailed sectoral account of abatement, investment, trade, and the impacts of these on output (for instance, positive employment impacts of building and deploying renewables). Since the quantity of money is endogenous, resources invested in mitigation do not require cancelling out resources invested in other parts of the economy (i.e. aggregate debt growth can increase GDP). Therefore, the overall impact on GDP of stringent climate policy can be positive in some countries and negative in others, by substantial amounts that in the case described here, cancel out to less than 1% in aggregate. To some degree, our results are driven by changes in trade, such that some regions' losses come alongside other regions' gains (as total exports equals total imports globally). The analyses are thus not really comparable.

## Suppl. Note 5 | Impacts of investment and fossil-fuel prices on the macroeconomy

Fossil energy commodities are accounted for in E3ME's national accounting system, while energy prices are updated every year as they change. Declines in exports for producing regions lead in the model to reduced activity in the oil and gas or mining sectors and other sectors in their supply chains (through input-output tables), which can generate unemployment, and generally reduce regional GDP. Changes in fossil-fuel or electricity prices influence competitiveness but also investment in every sector, particularly energy intensive ones. Sectoral and regional details are given in Suppl. Table 8. More detailed data can be forwarded by the authors on request.

Selling carbon permits/allowances can generate significant income for the public sector. We take the assumption that this income is re-used by government for reducing income taxes. This contributes significantly to boosting industrial competitiveness. Governments cannot indefinitely accumulate this income, and thus will eventually spend it by funding new programmes. Changing the way in which it is spent does not change the results significantly[33]. It is possible, however, that some governments use this income to reduce deficits or repay debt; we assume here that this doesn't happen, as this subject is outside of the scope of our study. In our model, this would lead to a reduction of GDP that is independent from the effects presented here.

E3ME is demand-led, and therefore resources invested in one project do not require cancelling out resources invested in other parts of the macro-economy, as is the case in other models[3]. Thus investment-intensive scenarios tend to increase GDP and employment in the short term as activity grows in construction and other sectors related through input-output tables. This explains the emergence of growth related to building low-carbon infrastructure and equipment. The response of governments to falling economic activity due to loss of fossil fuel production would, in many cases, most likely involve deficit spending to mitigate large impacts on GDP and employment, notably in the USA and Canada. Here, we assume balanced government budgets instead and thus do not allow for this possibility, for clarity of the paper. In short, we do not allow changes in public debt, but we do allow changes in private debt.

Regional macroeconomic losses do not strongly depend on where fossil-fuel industry headquarters or shareholders are situated (often in Europe, e.g. Shell and BP), but rather, on where the activities of these companies take place (the Middle-East, Africa, Canada, etc), since this is where most of the investment takes place. Wealth losses by fossil-fuel firms and price falls affect their ability to (1) retain profit and (2) leverage banking and equity finance, both of which affect their ability to invest in new projects. These effects could have financial implications sensitive to the location of firms' headquarters but, as discussed above, we do not model losses in wealth (and their impacts on leveraging ability) but concentrate on losses in output. When new projects are cancelled, it is predominantly at the extraction location that the loss of employment and wage spending takes place and therefore here we neglect effects related to the geographical location of shareholders and firm headquarters.

### Modelling fossil fuel markets and trade

Following the broader structure of the E3ME model, trade in fossil fuels is modelled using a demand-driven approach. First, econometrically estimated regional final demand is aggregated to the global level, and then the necessary global supply to meet this demand is allocated across regions according to their production costs, following the dynamics of our fossil-fuel supply model, where the marginal cost that matches global supply is sought, generating endogenous prices. We do not estimate trade on a bilateral basis (as we do for other products) since fossil fuels are commoditised products which violates the Armington assumption of differentiated production that underpins the modelling of trade in other sectors.[34] It is instead assumed that the available supplies are matched to demands in an efficient manner with transportation costs minimised.

E3ME includes end-user fuel prices including taxes, and these values are updated to reflect changes in fossil-fuel marginal costs from the fossil-fuel supply model; however end-user prices are not used in the calculation of SFFA. Fossil-fuel commodity prices used in the calculation of SFFA are obtained by adjusting calculated marginal costs for 2016 to the 2016 oil price (obtained from Bloomberg), and this scaling factor is maintained for subsequent years.

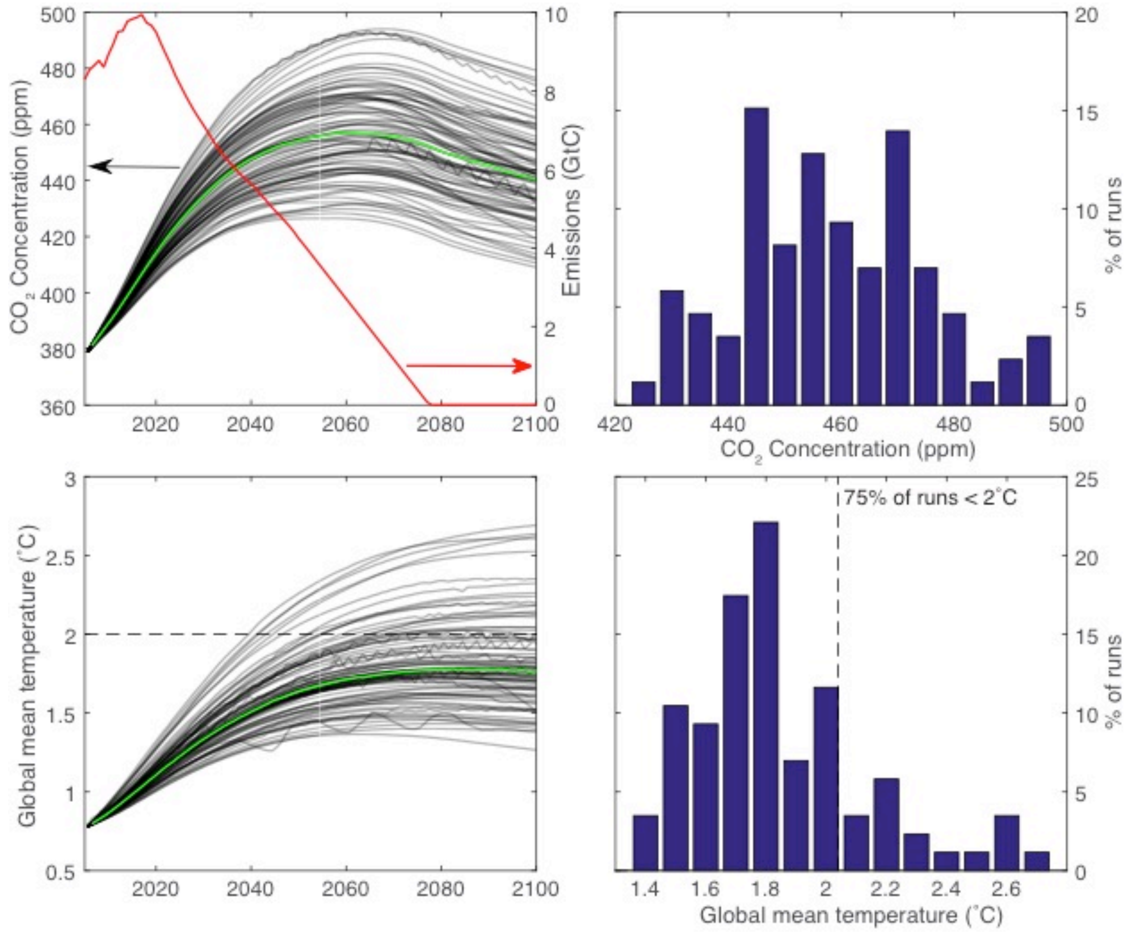
### Sectoral economic impacts

Suppl. Table 8 provides sectoral and regional breakdowns of GDP and employment figures. The largest negative economic impacts occur in countries that are expensive producers of fossil fuels (e.g. Canada and the US). In these countries, even a small permanent drop in fuel prices can leave some fossil-fuel assets stranded, which has several important consequences for their national economies. First there is the direct effect of reduced production in the energy sector itself, with secondary effects from the loss of high-paid jobs and reductions in energy-sector investment activity. The loss of tax receipts (e.g. royalties) can be just as important, however, as these revenues are often used to fund public services and social programmes. The modelling assumes that government budgets are balanced so a loss of tax receipts implies a reduction in spending. Countries such as Canada therefore see reduced fuel exports, reductions in energy-sector investment, falling government expenditure and multiplier-based effects on household expenditure.

## Supplementary Figures and Tables

### Suppl. Table 1 | Methods summary

| Model | Data and key mechanisms | | Refs |
|---|---|---|---|
| Fossil fuel module | Main algorithm | $\Delta n(C,t) = \nu\, n(C,t) f(P-C)$, $C$ =cost, $n(C,t)$ = cost distribution<br>Find price *P* such that $\int \Delta \mathrm{n}(\mathrm{C},\mathrm{t})\mathrm{dC} = Demand(P)$ $\nu$ = production to reserve ratio | [25] |
| | Data sources | WEC, BGR, IEA, ETSAP, BP and other reports | [25,35] |
| FTT | Main algorithm | Diffusion: $\Delta S_i = \sum_j S_i S_j \left[A_{ij}F_{ij} - A_{ji}F_{ji}\right]\Delta t$, $S_i$ = Market share of option *i*<br>$A_{ij}$ = Building and turnover rates<br>Binary logit: $F_{ij} = \left[1 + \exp\left(\frac{C_i+\gamma_i-C_j-\gamma_j}{\sigma_{ij}}\right)\right]^{-1}$, $\sigma_{ij}$ = Agent heterogeneity<br>$\gamma_i$ = Non-pecuniary costs | [36-40] |
| | Data sources | FTT:Power: IEA Energy Balances, IEA technology costs | [16,17] |
| | | FTT:Transport: Eurostat, manufacturer websites, Marklines | [41] |
| | | FTT:Heat: ODYSSEE, IEA, Agencies, academic papers | [37,42] |
| E3ME | Main algorithm | Linear co-integration econometric equations, with error-correction method | [43] |
| | | [1] Demand = f(income, prices, interest rates, inflation, pop. age structure)<br>[2] Investment = f(output, prices, wages, interest rates, spare capacity)<br>[3] Bilateral trade = f(prices, tech. progress)<br>[4] Prices = f(costs, import prices, tech. progress)<br>[5] Employment = f(output, wages, tech. progress, working hours)<br>[6] Prod. capacity = f(expected growth, tech. progress, population)<br>[7] Energy demand = f(output, prices, investment, R&D) | [4,33, 44-48] |
| | Data sources | Eurostat, OECD, Prodcom, World Bank, IEA, National statistics offices | |
| GENIE | Main algorithm | Atmospheric temperature field: 2D Energy-moisture balance dependent on net radiative forcing $R(t)$<br>$T_A(x,t) = f_1(T_O(x,t), I(x,t), C_A(t), C_L(x,t), R(t))$, | [49] |
| | | Ocean temperature field: 3D Frictional-geostrophic ocean<br>$T_O(x,t) = f_2(T_A(x,t), I(x,t), R(t))$, | [49] |
| | | Atmospheric carbon timeseries, depends on emissions timeseries $E(t)$<br>$C_A(t) = f_3(T_O(x,t), I(x,t), C_O(x,t), C_L(x,t), E(t))$, | [50] |
| | | Land carbon cycle: ENTS, depends on land-use change time series $L(t)$<br>$C_L(x,t) = f_4(T_A(x,t), C_A(x,t), L(t))$, | [51,52] |
| | | Ocean carbon cycle: BIOGEM<br>$C_O(x,t) = f_5(T_O(x,t), I(x,t), C_A(x,t))$, | [50,53] |
| | | Sea-ice state<br>$I(x,t) = f_6(T_O(x,t), T_A(x,t))$. | [49] |
| | Data sources | Data - validation against CMIP5 modelling output (see Suppl. Table 6) | |

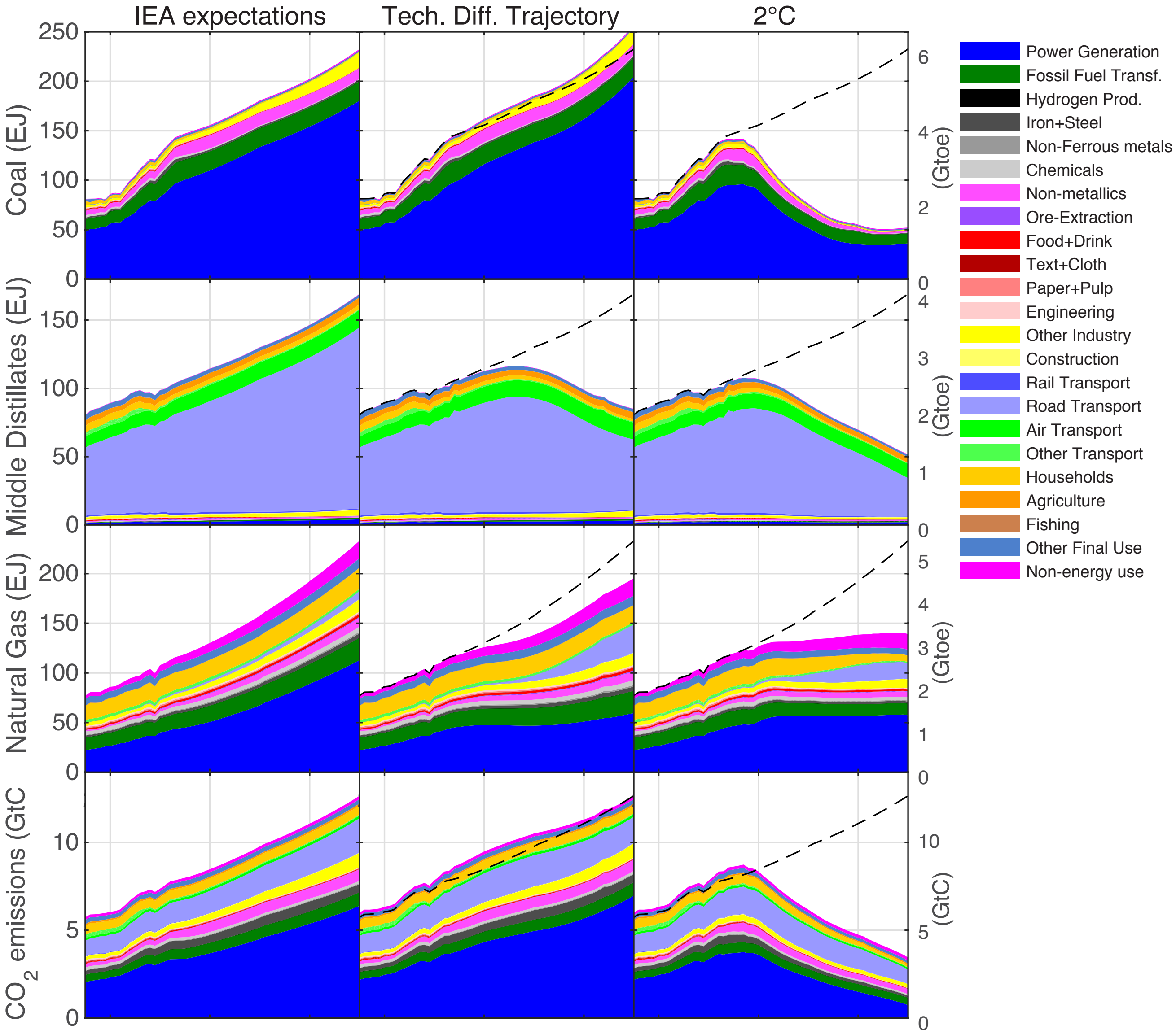


**Suppl. Figure 1 | Climate impacts of the 2°C policies scenario**. Concentrations (top panels). Global average temperature change (bottom panels). The bottom row shows model variations indicating 75% probability of not exceeding 2°C. Green lines indicate ensemble medians.

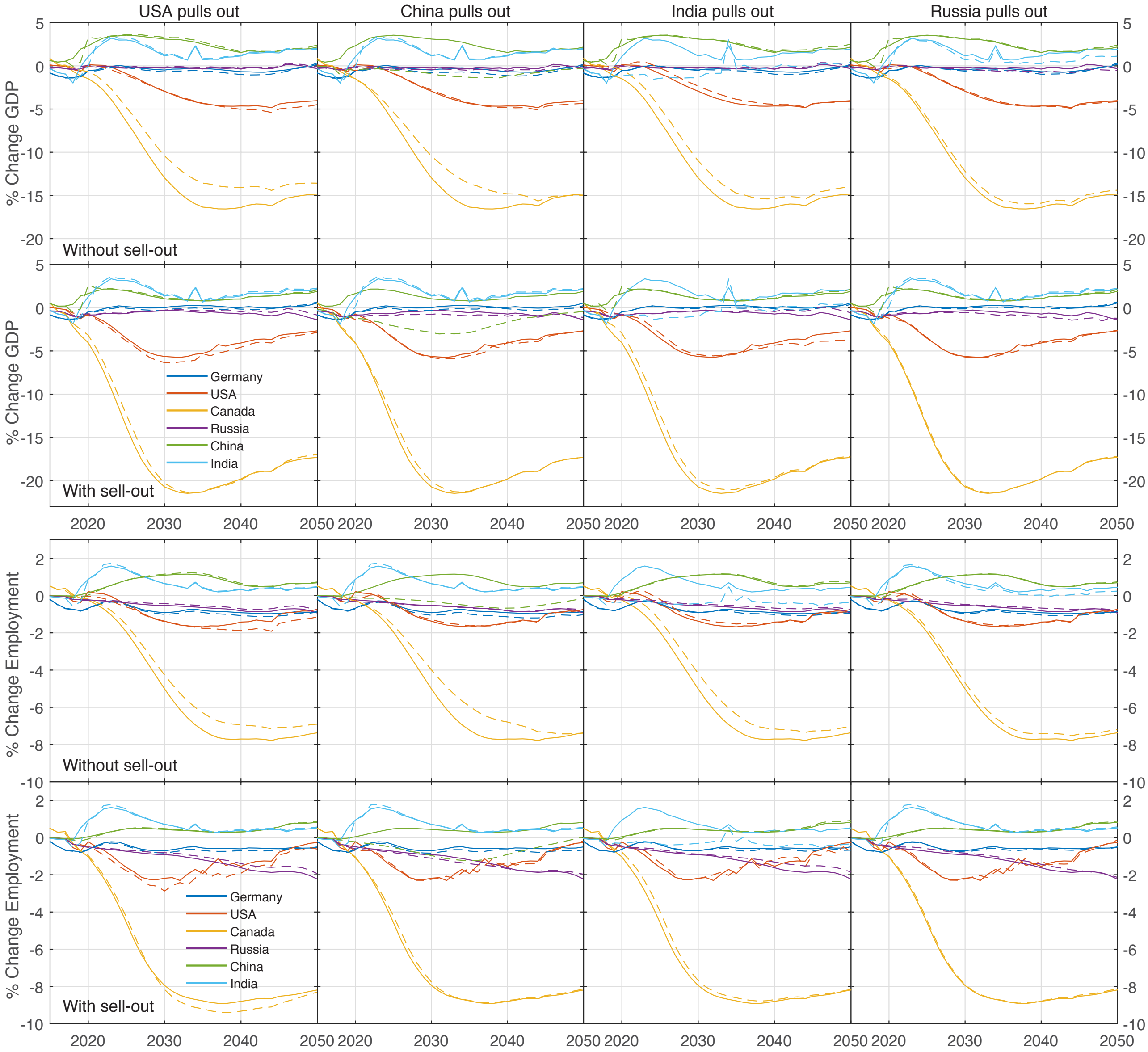
**Suppl. Table 2 | Possible 2035 cumulative global total values of stranded fossil-fuel assets** by fuel type and GDP changes, in trillions of 2016 USD ($tn), for relevant pairs of scenarios.

| | | IEA Sell-out | | | TDT | | | TDT Sell-out | | | 2°C | | | 2°C Sell-out | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0% | 5% | 10% | 0% | 5% | 10% | 0% | 5% | 10% | 0% | 5% | 10% | 0% | 5% | 10% |
| IEA | Coal | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 | 0.0 | -0.1 | -0.1 | 0.0 | 1.0 | 0.6 | 0.3 | 1.0 | 0.6 | 0.3 |
| | Oil | 2.2 | 1.3 | 0.8 | 1.4 | 0.7 | 0.4 | 3.3 | 1.8 | 1.1 | 5.7 | 3.1 | 1.8 | 8.2 | 4.5 | 2.7 |
| | Gas | 1.5 | 0.9 | 0.5 | 1.4 | 0.8 | 0.5 | 2.8 | 1.6 | 1.0 | 1.6 | 0.9 | 0.5 | 3.2 | 1.8 | 1.1 |
| | Tot | 3.7 | 2.2 | 1.4 | 2.7 | 1.5 | 0.8 | 5.9 | 3.3 | 2.0 | 8.3 | 4.5 | 2.7 | 12.4 | 6.9 | 4.1 |
| | GDP | 24 | 13 | 7.7 | -13 | -8.3 | -5.9 | 6.8 | 2.4 | 0.4 | -17 | -11 | -8.3 | -7.8 | -6.0 | -4.8 |
| IEA Sell-out | Coal | | | | -0.1 | -0.1 | 0.0 | -0.1 | -0.1 | -0.1 | 0.9 | 0.5 | 0.3 | 0.9 | 0.5 | 0.3 |
| | Oil | | | | -0.8 | -0.6 | -0.5 | 1.1 | 0.5 | 0.2 | 3.6 | 1.8 | 1.0 | 6.0 | 3.3 | 1.9 |
| | Gas | | | | -0.1 | -0.1 | 0.0 | 1.2 | 0.7 | 0.4 | 0.1 | 0.0 | 0.0 | 1.7 | 0.9 | 0.5 |
| | Tot | | | | -1.0 | -0.7 | -0.6 | 2.2 | 1.1 | 0.6 | 4.6 | 2.4 | 1.3 | 8.7 | 4.7 | 2.7 |
| | GDP | | | | -37 | -21 | -14 | -17 | -11 | -7.3 | -41 | -25 | -16.0 | -32 | -19 | -13 |
| TDT | Coal | | | | | | | 0.0 | 0.0 | 0.0 | 1.0 | 0.6 | 0.4 | 1.0 | 0.6 | 0.4 |
| | Oil | | | | | | | 1.9 | 1.1 | 0.7 | 4.4 | 2.4 | 1.5 | 6.8 | 3.8 | 2.3 |
| | Gas | | | | | | | 1.3 | 0.8 | 0.5 | 0.2 | 0.1 | 0.0 | 1.8 | 1.0 | 0.6 |
| | Tot | | | | | | | 3.2 | 1.9 | 1.2 | 5.6 | 3.1 | 1.8 | 9.7 | 5.4 | 3.3 |
| | GDP | | | | | | | 20 | 11 | 6.2 | -3.9 | -3.1 | -2.4 | 5.0 | 2.3 | 1.1 |
| TDT Sell-out | Coal | | | | | | | | | | 1.1 | 0.6 | 0.4 | 1.1 | 0.6 | 0.4 |
| | Oil | | | | | | | | | | 2.5 | 1.3 | 0.8 | 4.9 | 2.7 | 1.6 |
| | Gas | | | | | | | | | | -1.2 | -0.7 | -0.5 | 0.5 | 0.2 | 0.1 |
| | Tot | | | | | | | | | | 2.4 | 1.2 | 0.7 | 6.5 | 3.6 | 2.1 |
| | GDP | | | | | | | | | | -24 | -14 | -8.6 | -15 | -8.3 | -5.1 |
| 2°C | Coal | | | | | | | | | | | | | 0.0 | 0.0 | 0.0 |
| | Oil | | | | | | | | | | | | | 2.5 | 1.4 | 0.9 |
| | Gas | | | | | | | | | | | | | 1.6 | 0.9 | 0.6 |
| | Tot | | | | | | | | | | | | | 4.1 | 2.3 | 1.4 |
| | GDP | | | | | | | | | | | | | 8.9 | 5.4 | 3.5 |

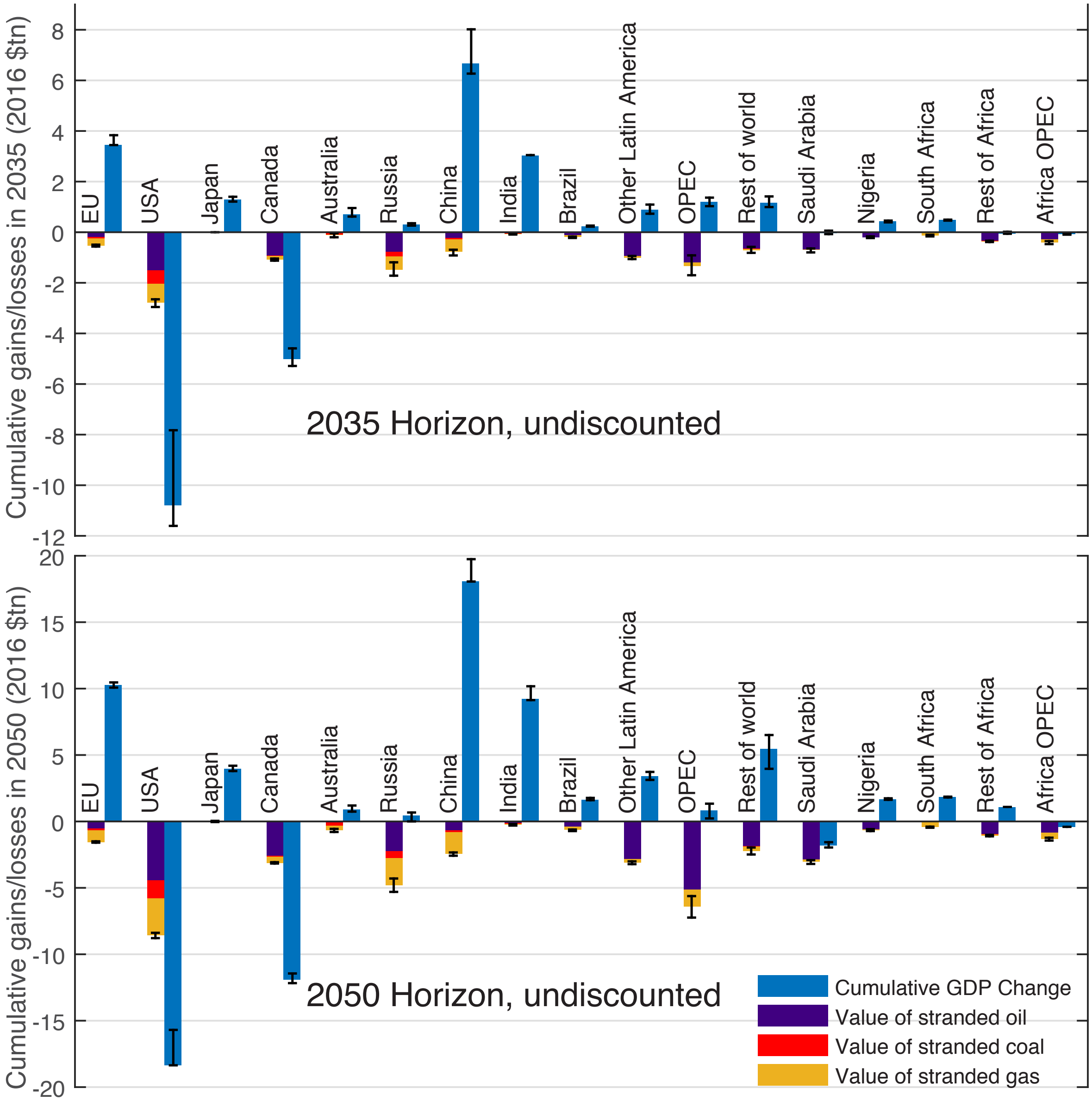
Notes: Numbers relate to loss incurred due to investors investing based on expectations of one scenario (rows) and facing another in reality afterwards (columns). Negative values refer to gains. Values are cumulated between 2016 and 2035, expressed in constant 2016 USD discounted with 0% (undiscounted), 5% and 10% rates. TDT refers to the 'Technology Diffusion Trajectory' E3ME-FTT scenario, IEA to the 'IEA expectations' scenario, while 2°C refers to our '2°C' scenario, based on E3ME-FTT, that achieves emissions reductions consistent with 75% probability of not exceeding 2°C of global warming. Colouring is a guide to the eye to indicate scenarios that have highest amounts of stranded assets (in red). The black boxes identify the three carbon bubble scenarios discussed in the main text.



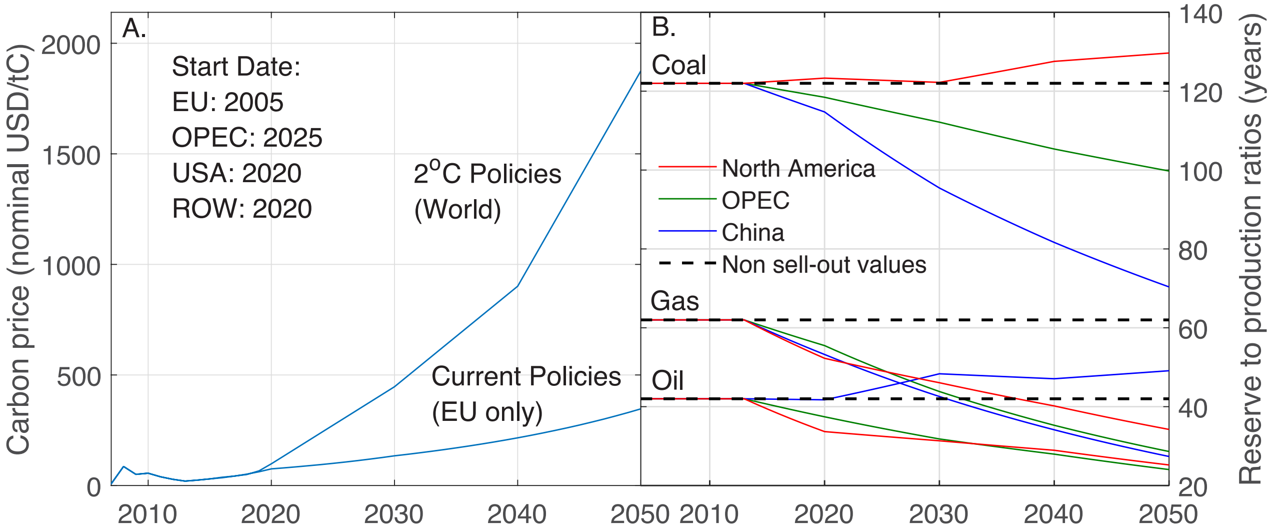
**Suppl. Figure 2 | Global demand for fossil fuels.** Coal, middle distillates (petrol and diesel) and natural gas by E3ME fuel user, followed by global fuel combustion and industrial emissions. These are given for a baseline involving fuel demand from the IEA (9) (first column), fuel demand fully endogenously determined by E3ME-FTT under the 'Technology Diffusion Trajectory' (second column), and an E3ME-FTT scenario with global emissions consistent with a 75% chance of not exceeding 2°C of warming (third column). Dashed lines refer to the 'IEA expectations' scenario for comparison.



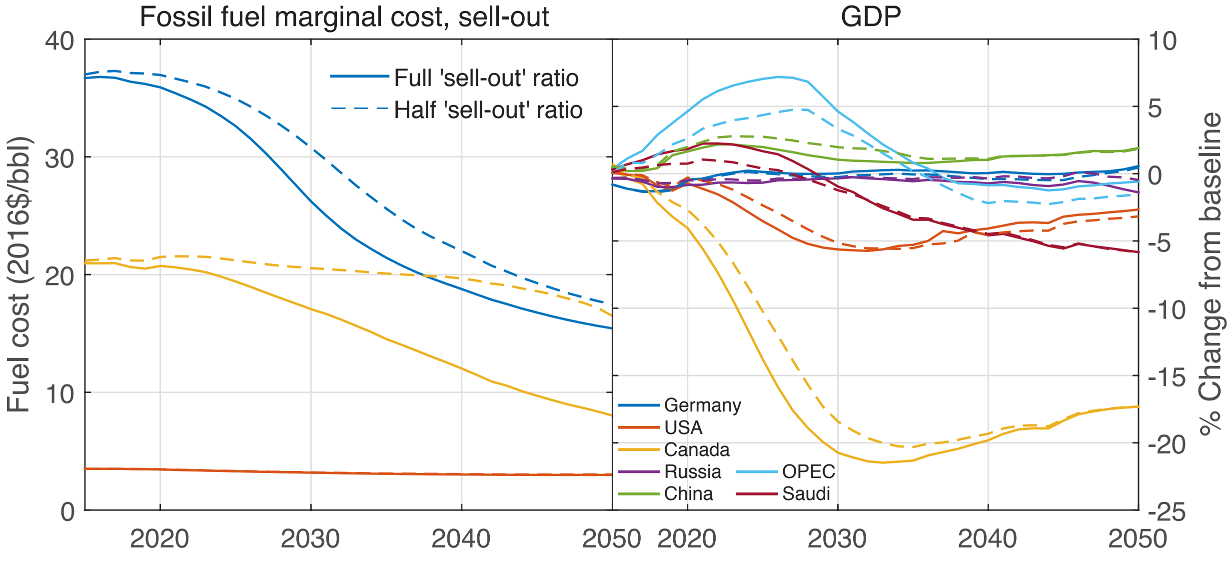
**Suppl. Figure 3 | Macroeconomic impacts of regional withdrawals from the Paris Agreement.** GDP (top 8 panels) and employment (bottom 8 panels), for the normal non-sell-out case (top rows) and the sell-out case (bottom rows). The solid lines refer to the 2°C policies scenario compared to the Technology Diffusion Trajectory baseline with all countries respecting the Paris Agreement, while the dashed lines refer to equivalent withdrawal scenarios.



**Suppl. Figure 4 | Cumulative gains/losses for different horizons.** Undiscounted cumulated SFFA losses and changes in GDP up to 2035 (top) and 2050 (bottom) between the '2°C' sell-out scenario and the 'IEA expectations' scenario. Error bars represent maximum uncertainty generated by varying technology parameters (see SI Tables 3-4).



**Suppl. Figure 5 | Carbon price and production/reserve assumptions.** A) Carbon price assumptions for each scenario, in nominal terms (including inflation). In our 'Technology Diffusion Trajectory' scenario, the carbon price only applies to the EU. In the 'policies for '2°C' scenario, all countries adopt a form of carbon pricing or taxing. A single price globally was used with different implementation dates indicated. In real terms, this carbon price means different values in different regions (due to different inflation rates), of the order of 200USD/t$CO_2$. B) Assumptions for the selling-out behaviour of fossil-fuel producers, expressed in reserve to production ratios (i.e. years left of reserves at current production), without sell-out (dashed lines) and with sell-out (coloured lines), chosen as values that lead to production concentration in the Middle-East (other countries not shown). Here, OPEC includes Saudi Arabia.



**Suppl. Figure 6 | Effect of production to reserve ratio.** A) Sensitivity test on fuel prices by halving the value of the deviation of the sell-out production to reserve ratio parameter given in Fig S5 B (dashed lines) in comparison to the 'policies for 2°C' sell-out scenario. B) Impact on GDP in this sensitivity test. OPEC excludes Saudi Arabia for higher detail. Impacts on total cumulated SFFA and GDP values are of less than 15%.

**Suppl. Table 3 | Sensitivity analysis on technology parameters**.

| | Sensitivity parameters | | % Change technology shares | | | | | % Change discounted SFFA & GDP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FTT Baseline | Var | REN | PV | EV | ADV | FF | Oil | Gas | Coal | Tot | GDP |
| Power Generation | REN capital costs | +20% | -7.85 | -15.5 | 0.00 | 0.00 | 0.00 | -0.04 | 0.21 | 1.87 | 0.15 | -0.01 |
| | REN capital costs | -20% | 6.90 | 9.16 | 0.00 | 0.00 | 0.00 | 0.04 | -0.04 | -1.95 | -0.11 | 0.01 |
| | REN learning | +5pp | 5.44 | 16.8 | 0.00 | 0.00 | 0.00 | 0.03 | 0.01 | -0.85 | -0.03 | 0.00 |
| | REN learning | -5pp | -6.47 | -27.1 | 0.00 | 0.00 | 0.00 | -0.05 | 0.05 | 0.79 | 0.03 | -0.01 |
| | Discount rate | +5pp | -2.86 | 58.7 | 0.00 | 0.00 | 0.00 | 0.37 | 11.2 | -3.80 | 3.22 | 0.38 |
| | Discount rate | -5pp | 14.3 | -16.2 | 0.00 | 0.00 | 0.00 | -0.12 | -9.08 | -0.11 | -2.70 | -0.19 |
| Road Transport | Perceived costs | +20% | 0.12 | 0.31 | -5.47 | 0.66 | 1.11 | 2.24 | -0.10 | 0.01 | 1.43 | 0.06 |
| | Perceived costs | -20% | 4.25 | -13.0 | -33.1 | -2.94 | 18.5 | -2.52 | 0.44 | 0.16 | -1.50 | 0.44 |
| | Learning rates | +5pp | -0.03 | -0.10 | 3.49 | 3.53 | -7.41 | -0.90 | 0.63 | 0.04 | -0.40 | -0.01 |
| | Learning rates | -5pp | -0.03 | -0.15 | -10.1 | -2.93 | 9.10 | 1.13 | -0.36 | 0.24 | 0.64 | 0.11 |
| | Discount rate | +10pp | -0.02 | 0.00 | 6.94 | 0.04 | -2.90 | -0.80 | 0.10 | 0.01 | -0.49 | -0.01 |
| | Discount rate | -10pp | 0.06 | 0.16 | -8.98 | 0.16 | 3.39 | 0.90 | -0.09 | 0.00 | 0.55 | 0.02 |
| | EV costs | +20% | -0.08 | -0.59 | -9.49 | 1.74 | 0.93 | 0.11 | -0.03 | -0.03 | 0.06 | -0.01 |
| | EV costs | -20% | 0.04 | 0.55 | 8.44 | -1.56 | -0.80 | -0.10 | 0.03 | 0.03 | -0.05 | 0.01 |
| | ADV Fuel Efficiency | +20% | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | ADV Fuel Efficiency | -20% | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Combined model run upper | | -18.19 | 5.96 | -20.92 | -7.18 | 27.10 | 3.67 | 12.13 | -0.49 | 5.74 | 0.54 |
| | Combined model run lower | | 19.19 | -10.34 | 0.09 | 11.48 | -26.95 | -3.20 | -8.69 | -1.49 | -4.60 | -0.29 |
| | Root mean square | | 20.3 | 72.3 | 39.1 | 5.97 | 22.4 | 3.89 | 14.4 | 4.83 | 4.80 | 0.64 |
| | 2°C scenario | Var | REN | PV | EV | ADV | FF | Oil | Gas | Coal | Tot | GDP |
| Power Generation | REN capital costs | +20% | -0.07 | 4.88 | 0.00 | 0.00 | 0.00 | 0.00 | 1.41 | -1.56 | 0.41 | 0.00 |
| | REN capital costs | -20% | -0.06 | -6.19 | 0.00 | 0.00 | 0.00 | 0.00 | -1.29 | 1.81 | -0.35 | 0.00 |
| | REN learning | +5pp | 0.18 | -5.75 | 0.00 | 0.00 | 0.00 | 0.03 | -0.89 | 1.57 | -0.21 | 0.03 |
| | REN learning | -5pp | -0.43 | 4.30 | 0.00 | 0.00 | 0.00 | -0.02 | 0.76 | -1.24 | 0.19 | -0.02 |
| | Discount rate | +5pp | -3.03 | 7.60 | 0.00 | 0.00 | 0.00 | 0.22 | 10.5 | -6.38 | 3.35 | 0.22 |
| | Discount rate | -5pp | 3.84 | -10.4 | 0.00 | 0.00 | 0.00 | -0.02 | -10.8 | 5.24 | -3.36 | -0.02 |
| Road Transport | Perceived costs | +20% | 0.01 | -0.23 | -2.35 | 1.07 | 9.30 | 1.91 | 0.26 | -0.01 | 1.28 | 0.00 |
| | Perceived costs | -20% | -0.27 | -4.17 | 12.1 | -8.00 | -16.2 | -3.21 | 0.05 | 0.04 | -1.99 | 0.11 |
| | Learning rates | +5pp | -0.01 | 0.10 | 1.37 | -0.02 | -6.71 | 0.08 | 0.02 | 0.00 | 0.06 | 0.00 |
| | Learning rates | -5pp | -0.12 | -0.19 | 4.53 | -7.98 | 7.14 | -0.36 | -0.17 | 0.02 | -0.28 | 0.01 |
| | Discount rate | +10pp | -0.20 | -0.23 | 12.9 | -12.1 | -3.75 | -1.03 | -0.21 | 0.04 | -0.71 | 0.01 |
| | Discount rate | -10pp | 0.10 | 0.31 | -11.8 | 9.89 | 5.34 | 1.07 | 0.18 | -0.03 | 0.73 | -0.01 |
| | EV costs | +20% | 0.02 | 0.05 | -2.46 | 1.13 | 0.09 | 0.07 | -0.02 | 0.00 | 0.00 | 0.00 |
| | EV costs | -20% | -0.01 | -0.03 | 2.85 | -1.24 | -0.14 | -0.06 | 0.02 | 0.01 | -0.03 | 0.00 |
| | ADV Fuel Efficiency | +20% | -0.03 | 0.13 | -0.59 | 0.41 | -4.03 | 3.34 | -0.06 | -0.01 | 2.08 | -0.03 |
| | ADV Fuel Efficiency | -20% | 0.03 | -0.12 | 0.81 | -0.52 | 5.43 | -3.35 | 0.08 | 0.01 | -2.08 | 0.03 |
| | Combined in model run upper | | -3.30 | 11.15 | -12.55 | 8.12 | 18.78 | 2.78 | 12.91 | -5.52 | 5.56 | 0.27 |
| | Combined in model run lower | | 3.54 | -16.73 | 11.67 | -13.68 | 10.33 | -1.34 | -11.0 | 4.82 | -4.08 | -0.10 |
| | Root mean square | | 6.39 | 26.9 | 22.3 | 19.4 | 23.1 | 6.73 | 15.2 | 13.9 | 6.33 | 0.25 |
| | Scenarios combined | | 21.3 | 77.1 | 45.0 | 20.3 | 32.2 | 7.77 | 20.9 | 14.7 | 7.94 | 0.69 |

Abbreviations: REN = shares of renewables + nuclear, PV = shares of solar photovoltaic, EV = shares of electric vehicles, ADV = shares of future higher efficiency combustion vehicles, FF = shares of conventional combustion vehicles (in 2050). SFFA and GDP are discounted and cumulated to 2050. Note that ‘pp’ refers to percentage points. Combined model runs combine parameters above in single model runs with several variations, while root mean squares combine runs with individual variations.

**Suppl. Table 4 | Uncertainty ranges for regional SFFA and GDP changes,** in 2016bn$, based on the sensitivity analysis given in Suppl. Table 3, corresponding to error bars in Fig. 3 and Suppl. Fig. 4. Values in coloured boxes are SFFA values, numbers to the right are matching uncertainty ranges. Columns denoted with '+' and '-' refer to maxima and minima of uncertainty ranges.

**2035 horizon, Discounted 10%**

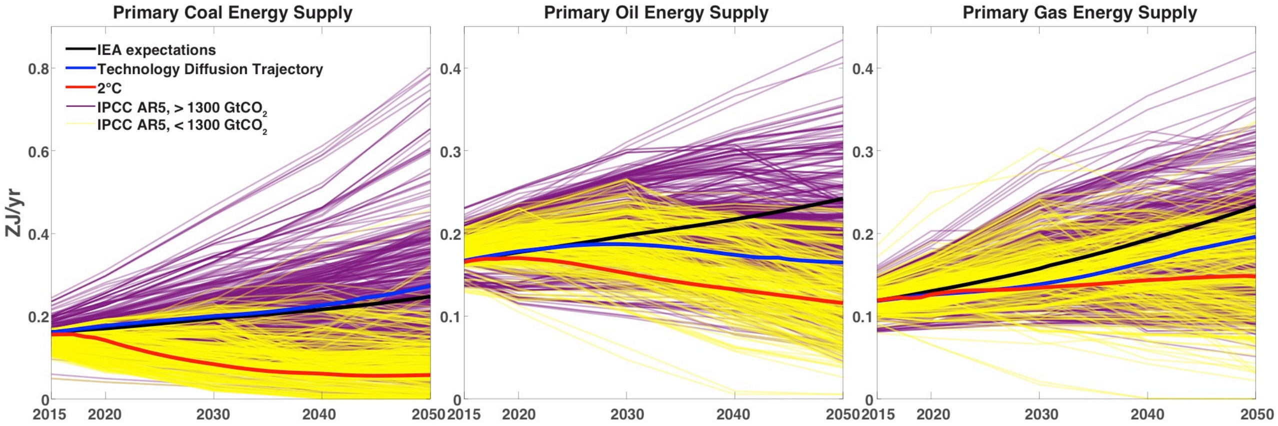
| Country | Oil | Coal | Gas | Total | GDP | Oil + | Oil - | Coal+ | Coal - | Gas + | Gas - | Total+ | Total - | GDP + | GDP - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EU | 68.2 | 19.3 | 103.5 | 190.9 | -1368 | 1.6 | -3.3 | 0.9 | -0.7 | 15.4 | -19.3 | -15.9 | 20.5 | 22.4 | -93.2 |
| USA | 525.7 | 186.6 | 250.5 | 962.7 | 3298 | 18.7 | -34.6 | 15.6 | -13.8 | 56.5 | -83.2 | -61.1 | 91.4 | -1491 | 591.0 |
| Japan | -0.1 | 0.1 | -0.3 | -0.3 | -458.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | -0.1 | -0.1 | 0.1 | 36.4 | -45.9 |
| Canada | 324.6 | 5.2 | 47.0 | 376.8 | 1739.1 | 11.5 | -20.8 | 0.4 | -0.4 | 13.1 | -18.0 | -17.4 | 27.5 | -208.7 | 144.8 |
| Australia | -4.8 | 26.3 | -9.2 | 12.2 | -379.5 | 0.7 | -1.6 | 5.1 | -4.6 | 29.8 | -37.9 | -30.2 | 38.3 | -116.9 | 54.3 |
| Russia | 276.1 | 66.3 | 178.6 | 521.0 | -130.7 | 7.6 | -16.2 | 7.1 | -6.3 | 106.1 | -94.2 | -106.6 | 95.9 | -20.2 | 5.7 |
| China | 81.4 | 18.9 | 167.1 | 267.4 | -2987 | 2.1 | -4.1 | 2.3 | -2.0 | 40.1 | -60.3 | -40.2 | 60.5 | -679.6 | 366.1 |
| India | 11.1 | 6.3 | 7.4 | 24.7 | -1248 | 0.3 | -0.7 | 0.7 | -0.7 | 4.0 | -4.4 | -4.1 | 4.6 | 1.8 | -25.5 |
| Brazil | 37.2 | 0.1 | 23.3 | 60.5 | -103.9 | 2.0 | -4.4 | 0.0 | 0.0 | 5.4 | -8.3 | -5.8 | 9.4 | 8.6 | -10.6 |
| LAM | 327.6 | 0.2 | 16.4 | 344.2 | -299.5 | 12.0 | -24.0 | 0.1 | -0.1 | 19.4 | -18.4 | -22.8 | 30.2 | 60.4 | -83.8 |
| OPEC | 298.3 | 1.3 | 30.6 | 330.3 | -577.3 | 27.0 | -70.3 | 0.1 | -0.1 | 148.4 | -116.1 | -150.8 | 135.7 | -37.8 | 47.0 |
| ROW | 238.7 | 6.2 | 15.1 | 260.1 | -328.5 | 6.2 | -13.2 | 0.8 | -0.7 | 45.4 | -36.9 | -45.8 | 39.2 | -60.0 | 21.7 |
| Saudi | 172.3 | 0.0 | 6.3 | 178.7 | -63.0 | 15.0 | -38.8 | 0.0 | 0.0 | 17.0 | -13.7 | -22.6 | 41.2 | -31.7 | 18.5 |
| Nigeria | 71.8 | 0.1 | 1.4 | 73.2 | -136.3 | 1.9 | -4.8 | 0.0 | 0.0 | 12.3 | -9.6 | -12.5 | 10.7 | 13.8 | -14.4 |
| S Africa | 0.1 | 0.6 | 42.2 | 42.9 | -177.3 | 0.0 | 0.0 | 0.1 | -0.1 | 7.9 | -13.2 | -7.9 | 13.2 | -3.2 | 2.5 |
| R Africa | 123.5 | 1.3 | 7.8 | 132.6 | 73.9 | 3.2 | -6.9 | 0.2 | -0.1 | 9.2 | -8.2 | -9.7 | 10.8 | 5.7 | -27.1 |
| A OPEC | 101.3 | 0.0 | 45.0 | 146.3 | 19.2 | 2.7 | -6.9 | 0.0 | 0.0 | 22.3 | -24.5 | -22.5 | 25.5 | -1.6 | 0.1 |

**2035 Horizon, Undiscounted**

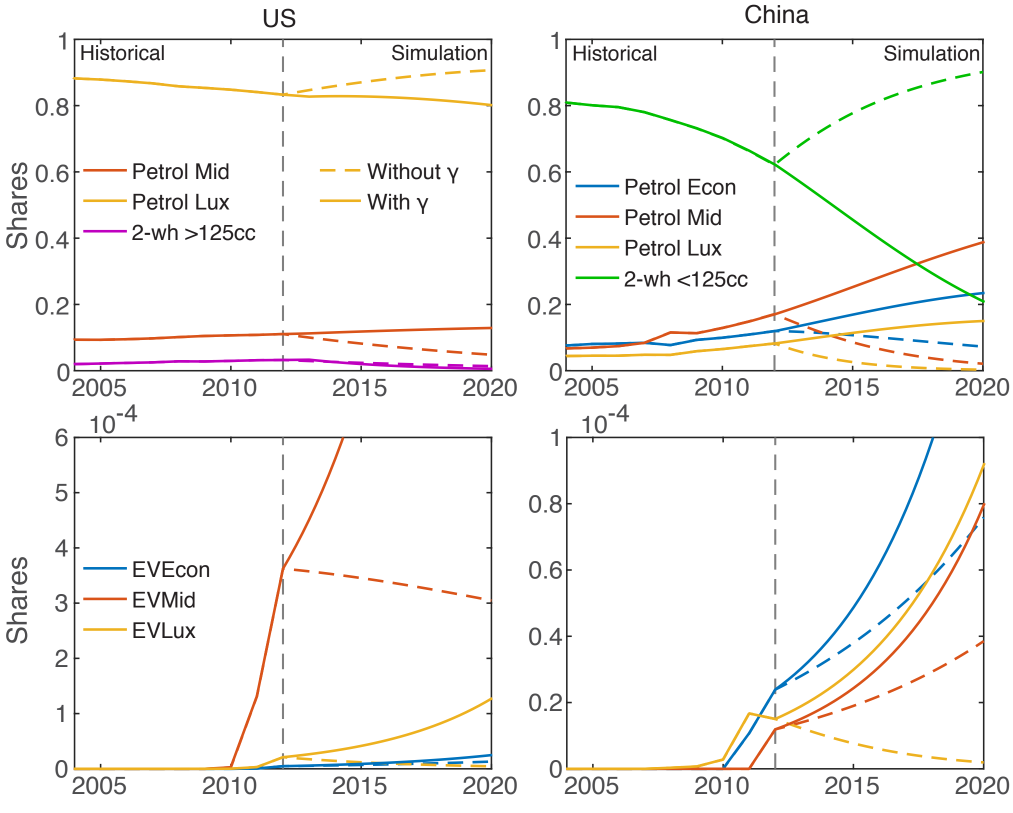
| Country | Oil | Coal | Gas | Total | GDP | Oil + | Oil - | Coal+ | Coal- | Gas + | Gas - | Total+ | Total - | GDP + | GDP - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EU | 191.1 | 50.4 | 284.4 | 525.9 | -3448.4 | 2.4 | -6.3 | 1.9 | -1.8 | 32.6 | -39.4 | -33.3 | 41.5 | 3.9 | -385.2 |
| USA | 1506.4 | 518.3 | 749.3 | 2774.0 | 10800 | 27.4 | -58.0 | 36.1 | -36.1 | 113.9 | -169.1 | -122.6 | 182.4 | -2974 | 806.1 |
| Japan | -0.1 | 0.4 | -0.6 | -0.3 | -1285.5 | 0.0 | 0.0 | 0.1 | -0.1 | 0.2 | -0.2 | -0.2 | 0.2 | 75.7 | -115.2 |
| Canada | 918.7 | 14.4 | 140.6 | 1073.6 | 5016.3 | 16.9 | -34.0 | 1.0 | -1.0 | 27.0 | -37.8 | -31.9 | 50.8 | -425.0 | 269.8 |
| Australia | 1.3 | 84.3 | 29.0 | 114.7 | -705.9 | 1.1 | -3.4 | 12.4 | -12.7 | 67.4 | -84.7 | -68.6 | 85.7 | -249.7 | 87.7 |
| Russia | 771.4 | 187.9 | 518.5 | 1477.8 | -301.2 | 11.5 | -32.9 | 16.8 | -17.1 | 286.7 | -237.6 | -287.5 | 240.5 | -53.1 | 39.8 |
| China | 227.7 | 54.2 | 489.5 | 771.3 | -6668.4 | 3.1 | -7.6 | 5.4 | -5.5 | 77.8 | -125.4 | -78.0 | 125.7 | -1350 | 400.3 |
| India | 33.1 | 17.9 | 23.1 | 74.1 | -3020.3 | 0.5 | -1.6 | 1.8 | -1.8 | 10.0 | -10.4 | -10.1 | 10.6 | 25.5 | -27.7 |
| Brazil | 116.2 | 0.3 | 68.2 | 184.7 | -219.6 | 3.0 | -9.4 | 0.1 | -0.1 | 10.6 | -17.2 | -11.0 | 19.6 | 13.3 | -37.6 |
| LAM | 940.7 | 0.7 | 56.5 | 997.8 | -888.6 | 17.9 | -44.8 | 0.2 | -0.2 | 51.9 | -46.0 | -54.9 | 64.2 | 158.3 | -202.9 |
| OPEC | 1185.2 | 3.7 | 153.2 | 1342.1 | -1205.2 | 42.6 | -170.5 | 0.3 | -0.3 | 424.6 | -315.3 | -426.7 | 358.5 | -161.0 | 176.3 |
| ROW | 649.5 | 17.7 | 43.9 | 711.1 | -1155.7 | 9.3 | -27.1 | 1.8 | -1.9 | 131.2 | -101.0 | -131.5 | 104.6 | -258.5 | 163.1 |
| Saudi | 672.1 | 0.0 | 25.6 | 697.7 | 30.8 | 23.6 | -93.6 | 0.0 | 0.0 | 48.1 | -36.6 | -53.6 | 100.5 | -91.7 | 44.8 |
| Nigeria | 198.4 | 0.2 | 4.0 | 202.6 | -424.9 | 3.0 | -11.1 | 0.0 | 0.0 | 36.2 | -26.8 | -36.3 | 29.0 | 35.5 | -33.2 |
| S Africa | 0.3 | 1.8 | 121.2 | 123.4 | -490.4 | 0.0 | 0.0 | 0.2 | -0.2 | 14.4 | -27.3 | -14.4 | 27.3 | -4.9 | 4.5 |
| R Africa | 336.2 | 3.6 | 22.7 | 362.5 | 46.3 | 4.9 | -14.3 | 0.4 | -0.4 | 25.7 | -21.5 | -26.2 | 25.8 | 12.3 | -63.4 |
| A OPEC | 280.8 | 0.0 | 129.5 | 410.3 | 69.8 | 4.3 | -16.3 | 0.0 | 0.0 | 56.4 | -58.8 | -56.5 | 61.0 | -4.3 | -0.6 |

**2050 horizon, Undiscounted**

| Country | Oil | Coal | Gas | Total | GDP | Oil + | Oil - | Coal+ | Coal- | Gas + | Gas - | Total+ | Total - | GDP + | GDP - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EU | 524.6 | 122.7 | 895.2 | 1542.5 | -10275 | 3.0 | -7.5 | 2.8 | -3.0 | 42.7 | -54.0 | -43.7 | 56.1 | 201.0 | -189.6 |
| USA | 4402.1 | 1375.0 | 2771.0 | 8548.1 | 18359 | 29.7 | -62.3 | 58.4 | -65.6 | 146.7 | -220.1 | -163.4 | 236.1 | -2667 | 1252.5 |
| Japan | 0.3 | 1.1 | -0.6 | 0.8 | -3944.6 | 0.0 | 0.0 | 0.1 | -0.1 | 0.4 | -0.5 | -0.5 | 0.5 | 150.9 | -249.0 |
| Canada | 2580.0 | 38.2 | 489.7 | 3107.9 | 11897 | 17.3 | -34.8 | 1.6 | -1.8 | 35.1 | -50.5 | -39.2 | 61.3 | -452.0 | 275.7 |
| Australia | 61.7 | 255.9 | 344.2 | 661.7 | -893.1 | 1.7 | -4.4 | 22.8 | -26.4 | 97.7 | -130.1 | -101.2 | 132.1 | -305.4 | 153.1 |
| Russia | 2217.7 | 511.1 | 2054.8 | 4783.7 | -445.5 | 15.5 | -40.4 | 29.4 | -33.6 | 487.0 | -517.1 | -488.4 | 519.5 | -226.4 | 300.8 |
| China | 640.7 | 148.3 | 1639.9 | 2428.9 | -18060 | 3.8 | -8.9 | 9.8 | -11.3 | 91.4 | -150.6 | -92.2 | 151.2 | -1683 | 244.9 |
| India | 96.9 | 49.1 | 92.5 | 238.6 | -9210.9 | 0.7 | -2.1 | 3.2 | -3.8 | 16.0 | -19.1 | -16.5 | 19.5 | 77.3 | -964.3 |
| Brazil | 386.4 | 1.0 | 234.6 | 621.9 | -1607.4 | 4.7 | -12.5 | 0.1 | -0.1 | 12.8 | -21.1 | -13.7 | 24.5 | 7.1 | -164.2 |
| LAM | 2812.3 | 2.3 | 285.8 | 3100.3 | -3404.5 | 22.8 | -53.5 | 0.3 | -0.3 | 91.2 | -101.3 | -94.0 | 114.6 | 277.7 | -323.4 |
| OPEC | 5094.9 | 9.9 | 1294.3 | 6399.1 | -806.5 | 84.0 | -245.2 | 0.5 | -0.6 | 774.9 | -802.7 | -779.5 | 839.3 | -529.5 | 581.4 |
| ROW | 1819.6 | 48.0 | 346.5 | 2214.0 | -5455.4 | 13.2 | -34.3 | 3.5 | -4.1 | 252.8 | -271.1 | -253.2 | 273.3 | -1049 | 1493.3 |
| Saudi | 2840.7 | 0.0 | 175.8 | 3016.5 | 1792.9 | 46.1 | -134.1 | 0.0 | 0.0 | 87.2 | -91.1 | -98.7 | 162.1 | -229.3 | 160.2 |
| Nigeria | 580.2 | 0.4 | 69.4 | 650.0 | -1670.6 | 5.3 | -15.4 | 0.0 | 0.0 | 70.6 | -74.8 | -70.8 | 76.4 | 42.6 | -69.7 |
| S Africa | 0.9 | 4.9 | 400.9 | 406.7 | -1838.4 | 0.0 | 0.0 | 0.3 | -0.4 | 14.6 | -29.2 | -14.6 | 29.2 | -25.4 | 31.7 |
| R Africa | 938.7 | 9.7 | 116.2 | 1064.6 | -1048.6 | 6.9 | -18.1 | 0.7 | -0.8 | 48.3 | -53.2 | -48.8 | 56.2 | 43.5 | -44.8 |
| A OPEC | 827.9 | 0.0 | 493.5 | 1321.4 | 408.6 | 7.8 | -22.8 | 0.0 | 0.0 | 96.0 | -115.9 | -96.3 | 118.1 | -6.1 | 0.2 |



**Suppl. Figure 7 | Comparison with IPCC.** This work's fossil energy supply displayed on top of the IPCC AR5 ensembles. Dark purple curves are scenarios of which cumulative emissions are greater than 1300 $GtCO_2$ (355 GtC), while yellow curves are below, where 1300 $GtCO_2$ is considered to approximately match 50% chance of remaining below 2°C.[54] Data obtained from the AR5 scenario database at tntcat.iiasa.ac.at/AR5DB/ .



**Suppl. Figure 8 | Empirical determination of non-pecuniary costs.** Comparison of FTT model outputs, taking private passenger transport as an example, to show the role of the $\gamma$ factors representing non-pecuniary costs. Dashed lines are model outputs with $\gamma = 0$, solid lines are model outputs with $\gamma$ factors minimising the difference in trajectory (slope difference) between historical data (left of the vertical dashed line) and the FTT simulation (right of the vertical dashed line). All technologies in every region were assessed visually by the authors. The $\gamma$ factors are interpreted as all costs not explicitly specified in the FTT formulation. Lux, Mid and Econ refer to engine size or power vehicle class, EV stands for electric vehicles, 2-wh stands for two-wheelers[39]. Other vehicle types in the model are not shown for clarity of presentation.

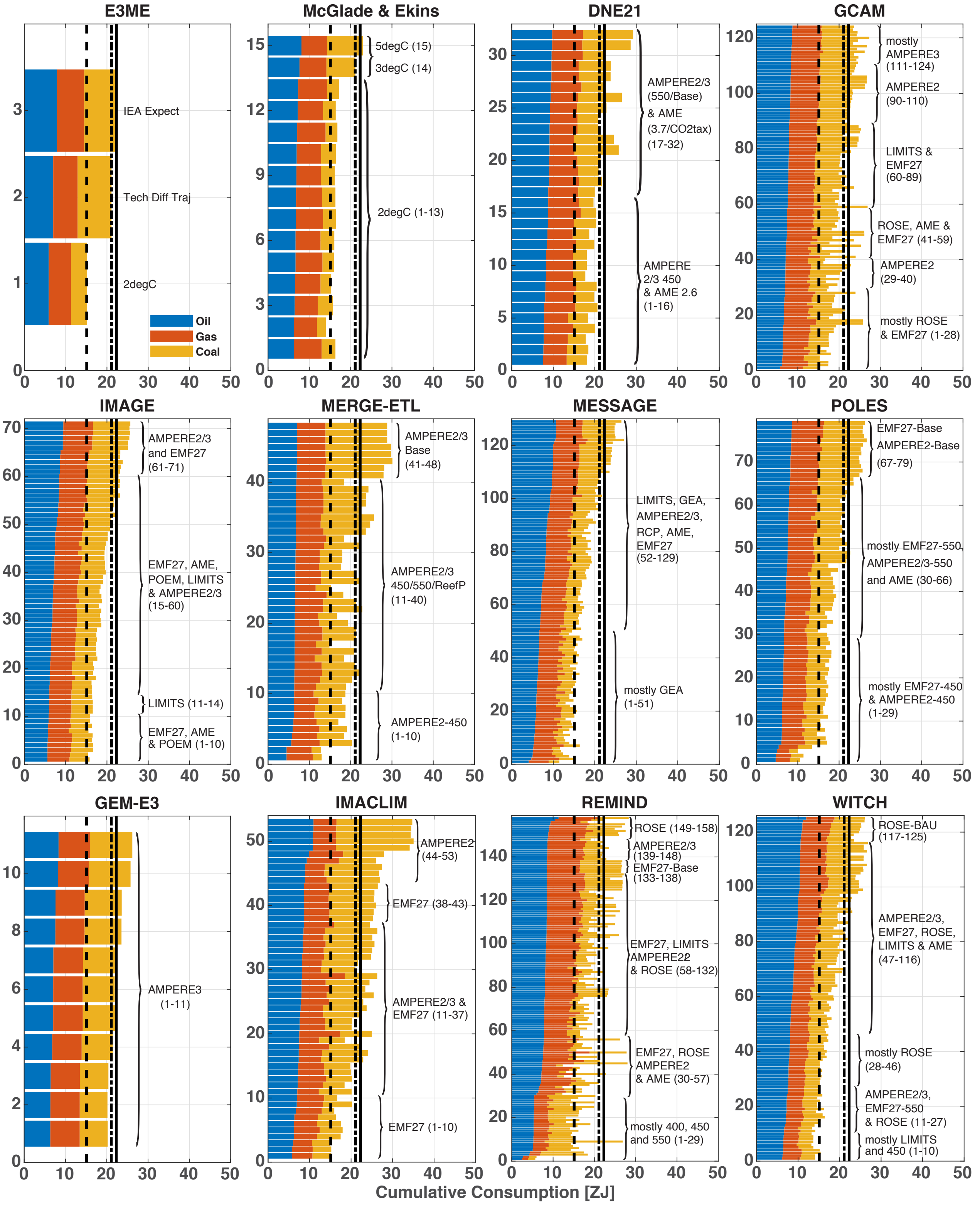
**Suppl. Table 5 | Comparison of the main scenarios presented in this paper with other modelling exercises.** Cumulative production of fossil fuels in the 'IEA expectations', 'Technology Diffusion Trajectory' and '2ºC' scenarios, compared with equivalent values presented in Bauer et al.[13] (top table) and McGlade & Ekins[55] (bottom table). The cumulative revenues from fossil fuels in the same period are compared with the scenarios presented in [13] (middle table). The comparison includes the scenarios presented in McGlade & Ekins[55] using the model TIAM-UCL, and the different models and values presented in Bauer et al.[13]. Note that to be consistent with these sources, revenue values are cumulated and discounted starting from 2011, and therefore are not directly comparable with those in Suppl. Table 2, which are discounted starting in 2017.

**Cumulative production (our paper) and consumption of fossil fuels between 2011-2050 [ZJ]**

| | | Oil | | Natural Gas | | Coal | |
|---|---|---|---|---|---|---|---|
| | | min | max | min | max | min | max |
| This work | 2°C | 5.9 | | 5.4 | | 3.8 | |
| | Tech. Diff. Trajectory | 7.0 | | 5.9 | | 8.2 | |
| | IEA Expectations | 7.9 | | 6.6 | | 7.8 | |
| Bauer et al. [13] | 450-e values | 6.4 | 8.8 | 3.8 | 7.8 | 2.4 | 7.7 |
| | 450-e models | IMAGE | DNE21 | WITCH | REMIND | REMIND | GCAM |
| | 550-e values | 6.5 | 9.7 | 5.0 | 9.1 | 4.4 | 8.6 |
| | 550-e models | MERGE-ETL | MESSAGE | WITCH | REMIND | REMIND | IMACLIM |
| | NoPol Values | 7.0 | 10.8 | 5.5 | 9.2 | 7.8 | 17.8 |
| | NoPol models | MERGE-ETL | IMACLIM | IMACLIM | REMIND | MESSAGE | IMACLIM |
| McGlade & Ekins [55] | 2degC Values | 6.2 | 7.2 | 5.5 | 7.0 | 2.2 | 3.7 |
| | 2degC sub-scenario | OILLOW | DEMHIGH | FFCHIGH | DEMHIGH | NOCCS | FFCHIGH |
| | 3degC | 7.6 | | 6.4 | | 7.1 | |
| | 5degC | 8.1 | | 6.2 | | 8.7 | |

**Cumulative revenues from fossil fuels between 2011-2050 [US$ trillion NPV 2010 discounted at 5%]**

| | | Oil | | Natural Gas | | Coal | |
|---|---|---|---|---|---|---|---|
| | | min | max | min | max | min | max |
| This work | 2°C | 13.8 | | 7.2 | | 1.0 | |
| | Tech. Diff. Trajectory | 16.8 | | 7.7 | | 1.7 | |
| | IEA Expectations | 18.5 | | 8.7 | | 1.6 | |
| Bauer et al. [13] | 450-e values | 14.2 | 68.9 | 8.8 | 41.0 | 2.1 | 9.3 |
| | 450-e models | MESSAGE | DNE21 | GCAM | DNE21 | REMIND | POLES |
| | 550-e values | 16.6 | 73.4 | 8.9 | 41.1 | 3.3 | 11.3 |
| | 550-e models | MESSAGE | DNE21 | GCAM | DNE21 | REMIND | DNE21 |
| | NoPol Values | 18.5 | 74.4 | 9.1 | 39.5 | 5.9 | 20.7 |
| | NoPol models | MESSAGE | DNE21 | GCAM | DNE21 | GCAM | DNE21 |



**Suppl. Figure 9 | Comparison of E3ME-FTT primary fossil-fuel demand to other IAMs,** cumulated over the 2011-2050 period**.** Comparison of E3ME-FTT scenarios of this work to the AR5 ensemble of model results from 11 models, including TIAM-UCL used by McGlade & Ekins[55], showing model results for various model comparison projects and studies (indicated in each panel). The vertical lines are guides to the eye indicating the total fossil fuel demand from the scenarios of this work. Data obtained from the AR5 scenario database at tntcat.iiasa.ac.at/AR5DB/.

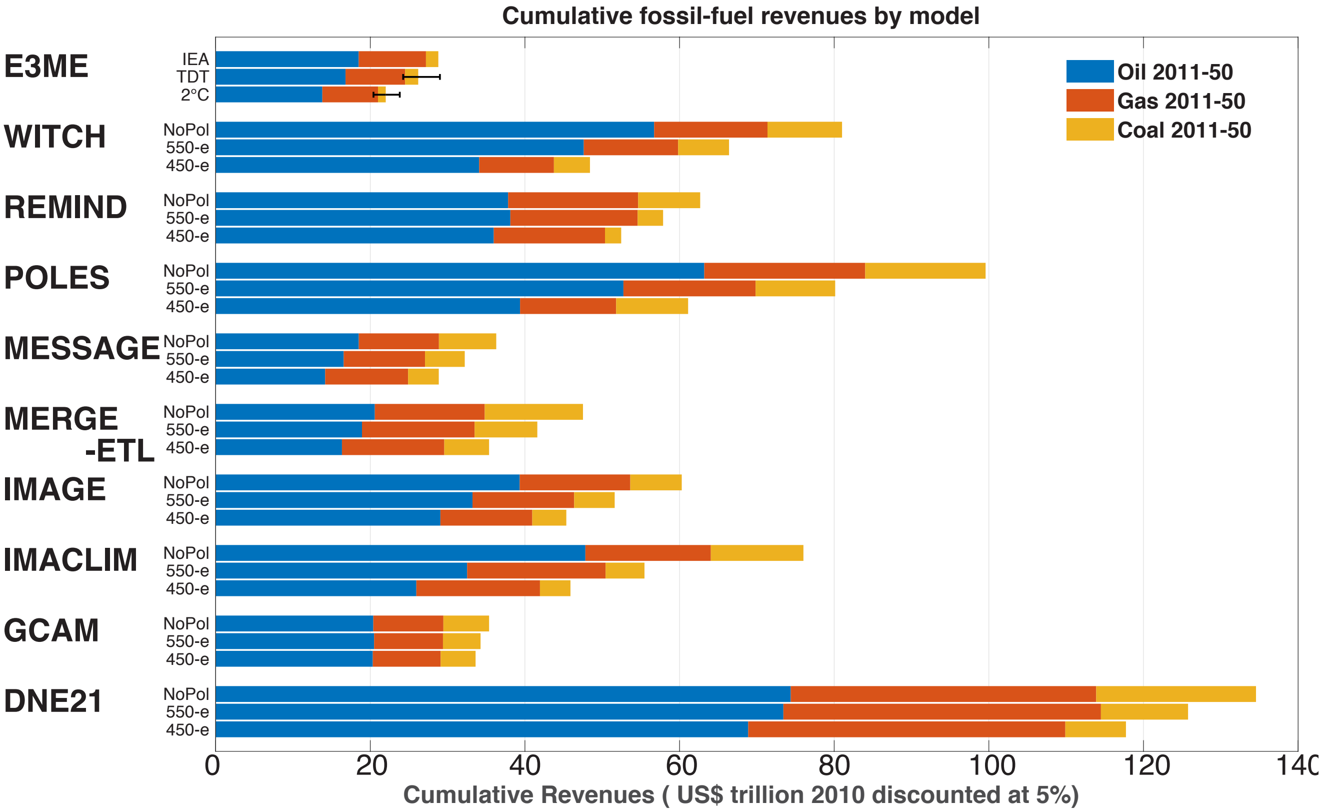
**Suppl. Table 6 | Comparison of GENIE with other models.** GENIE-1 global mean warming (2090-2005) compared to CMIP5[56] and EMIC AR5 inter-comparison[57]. AR5 and CMIP5 warming is 2081-2100 mean relative to the 1985-2005 baseline. Data are ensemble median (5%, 95% confidence) (GENIE-1) and ensemble mean (minimum, maximum) (EMIC AR5 and CMIP5).

| | GENIE-1 | EMIC AR5 | CMIP5 |
|---|---|---|---|
| RCP2.6 | 0.9 (0.6, 1.5) | 1.0 (0.6, 1.4) | 1.0 (0.0, 2.0) |
| RCP4.5 | 1.7 (1.2, 2.6) | 1.7 (0.9, 2.4) | 1.8 (1.0, 2.8) |
| RCP6.0 | 2.2 (1.7, 3.2) | 2.1 (1.1, 2.8) | 2.3 (1.5, 3.2) |
| RCP8.5 | 3.4 (2.7, 4.9) | 3.1 (1.6, 4.1) | 3.7 (2.5, 5.0) |

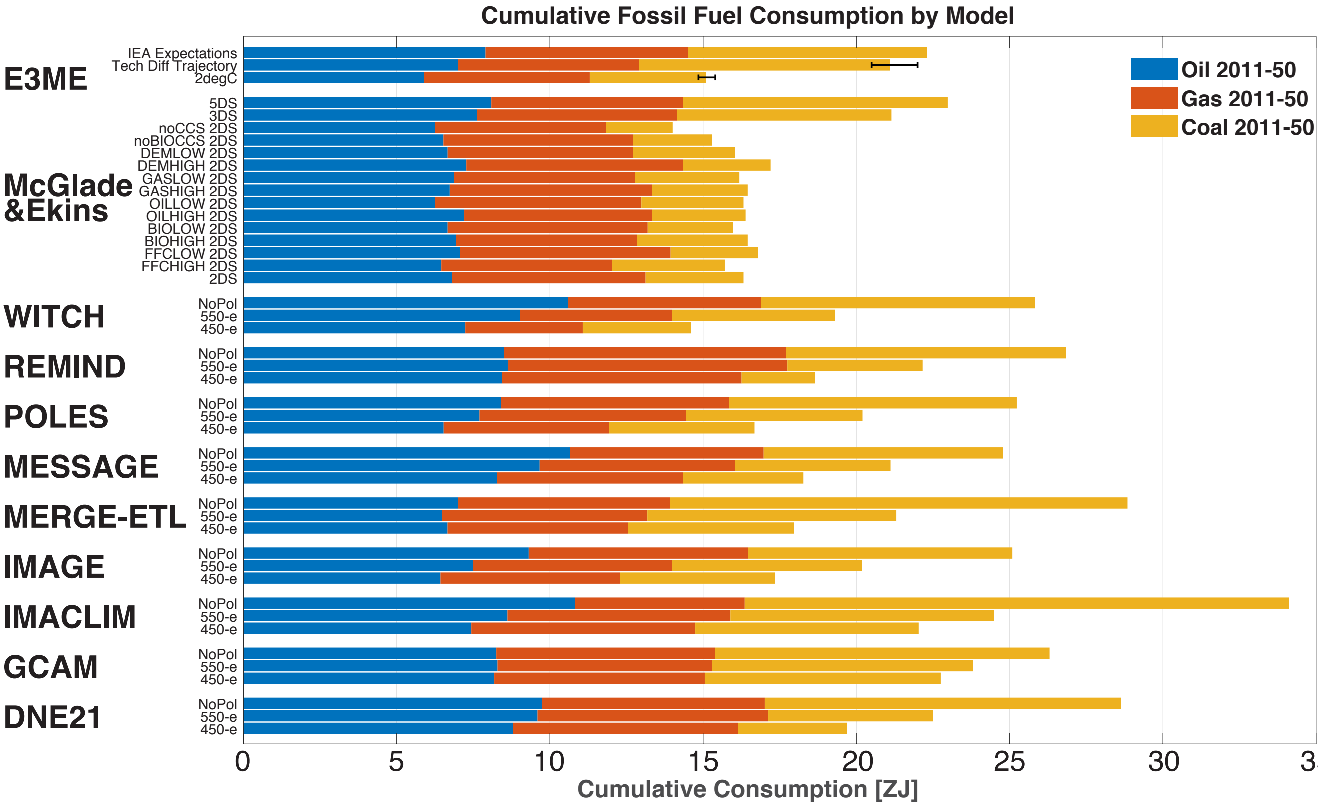
**Suppl. Table 7 | Fossil fuel prices by scenario (2016$/bbl)**

| | **Oil** | | | **Coal** | | | **Gas** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **2016** | **2035** | **2050** | **2016** | **2035** | **2050** | **2016** | **2035** | **2050** |
| IEA | 35.5 | 39.5 | 42.1 | 3.3 | 3.4 | 3.6 | 20.4 | 24.3 | 26.9 |
| IEA SO | 34.7 | 33.9 | 33.3 | 3.3 | 3.4 | 3.4 | 19.7 | 19.2 | 18.7 |
| TDT | 35.5 | 37.1 | 34.9 | 3.3 | 3.5 | 3.6 | 20.3 | 22.9 | 25.3 |
| TDT SO | 34.7 | 30.6 | 20.2 | 3.3 | 3.4 | 3.5 | 19.6 | 17.0 | 18.1 |
| 2°C | 35.5 | 29.6 | 19.6 | 3.3 | 2.9 | 2.9 | 20.4 | 22.0 | 22.3 |
| 2°C SO | 34.6 | 19.8 | 14.0 | 3.3 | 2.9 | 2.8 | 19.7 | 13.2 | 6.9 |
| $\nu_0$ test | 35.0 | 24.1 | 16.4 | 3.3 | 2.9 | 2.8 | 20.0 | 18.9 | 15.5 |
| TDT + | 35.8 | 38.1 | 36.7 | 3.3 | 3.5 | 3.6 | 20.8 | 23.8 | 26.4 |
| TDT - | 35.4 | 36.4 | 34.0 | 3.3 | 3.4 | 3.6 | 19.8 | 22.1 | 24.4 |
| 2°C + | 35.7 | 30.3 | 20.2 | 3.3 | 2.9 | 2.8 | 20.9 | 22.9 | 23.4 |
| 2°C - | 35.4 | 29.4 | 19.0 | 3.3 | 3.0 | 2.9 | 19.9 | 20.6 | 20.4 |
| 2°C SO + | 34.9 | 20.2 | 14.2 | 3.3 | 2.8 | 2.7 | 20.3 | 16.3 | 8.3 |
| 2°C SO - | 34.5 | 19.8 | 13.9 | 3.3 | 2.9 | 2.8 | 19.2 | 9.7 | 5.9 |

Notes: '$\nu_0$ test' stands for the sensitivity test on the reserve to production ratio (Suppl. Fig. 6). '+' and '-' stand for the combined sensitivity tests given in Suppl. Tables 3-4, while 'SO' stands for sell-out scenarios. Prices are obtained by scaling 2016 marginal costs from this model to 2016 fossil fuel prices, and are used to determine SFFA losses.



**Suppl. Figure 10 | Comparison of E3ME-FTT fossil-fuel revenues to other IAMs,** cumulated over the 2011-2050 period**.** Comparison of E3ME-FTT scenarios of this work to those in Bauer et. al.[13] Data obtained from the author.



**Suppl. Figure 11 | Comparison of E3ME-FTT primary fossil-fuel demand to other IAMs,** cumulated over the 2011-2050 period**.** Comparison of E3ME-FTT scenarios of this work and that in Bauer et al.[13] and McGlade & Ekins[55] Data obtained from the author.

**Suppl. Table 8 | Sectoral impacts of SFFAs in chosen regions and sectors**

| | IEA expectations to 2ºC sellout | | | | Tech. Diff. Trajectory to 2ºC sellout | | | |
|---|---|---|---|---|---|---|---|---|
| **Global** | 2035 | | 2050 | | 2035 | | 2050 | |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | 0.7 | 0.6 | 1.2 | 0.4 | 0.5 | 0.5 | 0.7 | 0.4 |
| Extraction sectors | -9.9 | -10.0 | -7.1 | -6.9 | -9.5 | -9.7 | -6.8 | -6.5 |
| Basic manufacturing | -0.6 | 0.9 | 0.8 | 1.1 | -0.3 | 0.8 | 0.9 | 1.0 |
| Advanced manufacturing | -0.2 | 1.7 | 1.3 | 1.2 | -0.2 | 1.7 | 1.1 | 0.9 |
| Utilities | -2.1 | 1.3 | -3.2 | -4.7 | -2.1 | 1.3 | -3.4 | -4.8 |
| Construction | 0.3 | 0.9 | 2.8 | 2.4 | 0.3 | 1.0 | 2.7 | 2.2 |
| Distribution and retail | -0.7 | 0.6 | 1.1 | 1.4 | -0.7 | 0.7 | 0.9 | 1.0 |
| Transport and communications | -0.3 | 1.1 | 2.0 | 1.6 | -1.0 | 0.8 | 0.4 | 0.9 |
| Business services | 0.4 | 0.3 | 1.8 | 0.8 | -0.2 | 0.2 | 0.9 | 0.6 |
| Public services | -1.8 | -1.2 | -1.3 | -0.9 | -1.9 | -1.3 | -1.5 | -1.1 |
| All sectors | -0.5 | 0.4 | 0.9 | 0.7 | -0.7 | 0.3 | 0.5 | 0.5 |

| | IEA expectations to 2ºC sellout | | | | Tech. Diff. Trajectory to 2ºC sellout | | | |
|---|---|---|---|---|---|---|---|---|
| **EU** | 2035 | | 2050 | | 2035 | | 2050 | |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | 2.7 | 0.1 | 8.5 | -0.6 | 2.3 | 0.2 | 4.9 | -0.3 |
| Extraction sectors | -10.1 | -6.0 | -5.7 | -3.0 | -10.0 | -5.5 | -6.2 | -3.4 |
| Basic manufacturing | 0.7 | -0.2 | 1.7 | -0.5 | 0.6 | -0.1 | 1.2 | -0.5 |
| Advanced manufacturing | 0.7 | 0.3 | 2.7 | 1.0 | 0.1 | 0.0 | 1.8 | 0.7 |
| Utilities | 0.7 | 0.1 | 1.1 | 0.1 | 0.6 | 0.2 | 0.8 | 0.2 |
| Construction | 1.2 | 0.2 | 2.8 | 0.5 | 0.8 | 0.1 | 2.3 | 0.4 |
| Distribution and retail | -7.3 | -6.9 | -6.5 | -6.2 | -7.5 | -6.9 | -7.4 | -6.5 |
| Transport and communications | 1.2 | 0.5 | 1.7 | 0.3 | 1.1 | 0.4 | 1.7 | 0.3 |
| Business services | 0.9 | 0.4 | 2.1 | 0.4 | 0.6 | 0.4 | 1.4 | 0.3 |
| Public services | 1.6 | 0.6 | 2.4 | 0.9 | 1.3 | 0.5 | 1.2 | 0.3 |
| All sectors | 0.8 | 0.4 | 1.9 | 0.7 | 0.6 | 0.3 | 1.2 | 0.5 |

| | IEA expectations to 2ºC sellout | | | | Tech. Diff. Trajectory to 2ºC sellout | | | |
|---|---|---|---|---|---|---|---|---|
| **US** | 2035 | | 2050 | | 2035 | | 2050 | |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | -0.3 | 0.0 | 4.7 | 0.0 | -3.3 | 0.0 | -2.7 | 0.0 |
| Extraction sectors | -50.6 | -16.2 | -45.2 | -21.8 | -49.1 | -14.8 | -42.3 | -16.8 |
| Basic manufacturing | -7.0 | -0.5 | -2.1 | 9.7 | -6.6 | -1.1 | -1.6 | 9.3 |
| Advanced manufacturing | -8.6 | 0.7 | 0.1 | 2.9 | -11.5 | 0.7 | -3.6 | 2.7 |
| Utilities | -8.0 | -7.2 | -11.3 | -9.5 | -7.9 | -6.8 | -11.2 | -8.8 |
| Construction | -6.3 | -8.3 | -1.7 | -0.9 | -7.1 | -9.3 | -2.8 | -2.1 |
| Distribution and retail | -5.4 | 0.0 | -0.3 | 0.8 | -6.4 | -0.4 | -1.6 | 0.1 |
| Transport and communications | -3.0 | 0.5 | 0.6 | 2.9 | -4.8 | 0.0 | -2.0 | 2.1 |
| Business services | -1.6 | -1.2 | 1.5 | 0.2 | -3.5 | -1.8 | -1.5 | -0.5 |
| Public services | -3.5 | -2.9 | -2.3 | -2.0 | -3.6 | -2.8 | -2.3 | -1.9 |
| All sectors | -4.6 | -1.7 | -1.0 | 0.0 | -5.7 | -1.9 | -2.5 | -0.3 |

| | IEA expectations to 2ºC sellout | | | | Tech. Diff. Trajectory to 2ºC sellout | | | |
|---|---|---|---|---|---|---|---|---|
| **Canada** | 2035 | | 2050 | | 2035 | | 2050 | |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | -8.5 | 1.2 | 0.9 | -6.3 | -9.3 | 1.5 | -0.7 | -5.8 |
| Extraction sectors | -81.9 | -74.0 | -81.0 | -76.6 | -81.3 | -73.1 | -80.5 | -75.9 |
| Basic manufacturing | -8.1 | -2.7 | -6.4 | -1.2 | -8.0 | -2.9 | -6.0 | -1.6 |
| Advanced manufacturing | -4.8 | -2.8 | -3.4 | -3.0 | -4.6 | -2.6 | -3.2 | -2.7 |
| Utilities | -4.5 | -4.5 | -8.0 | -8.1 | -4.0 | -4.3 | -7.8 | -8.0 |
| Construction | -10.6 | -7.8 | -5.7 | -5.3 | -10.1 | -7.4 | -5.6 | -5.2 |
| Distribution and retail | -17.2 | -9.6 | -14.2 | -8.3 | -16.5 | -9.2 | -14.0 | -8.2 |
| Transport and communications | -13.6 | -6.6 | -13.1 | 0.3 | -13.2 | -6.4 | -13.2 | -0.4 |
| Business services | -15.2 | -5.6 | -13.4 | -6.9 | -14.7 | -5.4 | -13.7 | -6.8 |
| Public services | -20.3 | -20.3 | -19.3 | -19.2 | -19.6 | -19.6 | -18.9 | -18.9 |
| All sectors | -16.1 | -9.4 | -13.6 | -8.3 | -15.6 | -9.1 | -13.4 | -8.2 |

|  | IEA expectations to 2ºC sellout |  |  |  | Tech. Diff. Trajectory to 2ºC sellout |  |  |  |
|---|---|---|---|---|---|---|---|---|
| **China** | 2035 |  | 2050 |  | 2035 |  | 2050 |  |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | 2.0 | 0.1 | 4.5 | 0.2 | 2.0 | 0.1 | 3.6 | 0.2 |
| Extraction sectors | -21.4 | -33.6 | -10.5 | -19.6 | -21.1 | -33.1 | -10.0 | -18.9 |
| Basic manufacturing | 0.5 | 0.7 | 2.0 | 0.5 | 0.7 | 0.8 | 1.4 | 0.4 |
| Advanced manufacturing | 0.1 | -0.2 | 1.4 | 0.8 | 0.8 | 0.1 | 1.4 | 0.6 |
| Utilities | 0.8 | 0.6 | 1.2 | 0.9 | 1.2 | 0.9 | 1.2 | 0.9 |
| Construction | 0.8 | 0.7 | 3.7 | 1.2 | 1.2 | 0.8 | 3.9 | 0.6 |
| Distribution and retail | 1.6 | 2.7 | 5.6 | 5.1 | 2.3 | 3.3 | 5.5 | 4.7 |
| Transport and communications | 1.4 | 1.3 | 5.7 | 3.2 | 1.6 | 1.4 | 4.7 | 2.8 |
| Business services | 1.1 | 0.1 | 2.6 | 0.2 | 1.6 | 0.1 | 2.5 | 0.1 |
| Public services | 0.2 | 0.2 | 0.4 | 0.3 | 0.2 | 0.2 | 0.4 | 0.3 |
| All sectors | 0.3 | 0.3 | 2.2 | 1.0 | 0.6 | 0.4 | 1.9 | 0.9 |

|  | IEA expectations to 2ºC sellout |  |  |  | Tech. Diff. Trajectory to 2ºC sellout |  |  |  |
|---|---|---|---|---|---|---|---|---|
| **India** | 2035 |  | 2050 |  | 2035 |  | 2050 |  |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | 0.9 | 0.4 | 0.5 | -0.8 | 0.8 | 0.2 | 0.0 | -0.7 |
| Extraction sectors | -18.2 | -11.4 | 12.7 | -22.9 | -15.8 | -11.1 | 11.8 | -22.6 |
| Basic manufacturing | -10.5 | 1.0 | -11.6 | 0.6 | -4.5 | 1.1 | -1.0 | 0.7 |
| Advanced manufacturing | -4.0 | 3.1 | 3.9 | 2.1 | -1.9 | 3.2 | 4.5 | 1.6 |
| Utilities | -4.2 | -4.1 | 26.7 | 25.2 | -4.4 | -4.2 | 26.1 | 24.7 |
| Construction | 1.3 | 1.8 | 3.9 | 3.1 | 1.5 | 2.1 | 3.8 | 2.9 |
| Distribution and retail | 0.4 | -0.4 | 15.1 | 3.5 | 0.5 | -0.5 | 5.5 | 1.1 |
| Transport and communications | 4.0 | 3.3 | 5.7 | 3.1 | 2.4 | 2.3 | 1.3 | 0.7 |
| Business services | 0.6 | 0.1 | 3.4 | 0.5 | 0.4 | 0.2 | 1.8 | 0.4 |
| Public services | 0.2 | 0.2 | 0.7 | 0.7 | 0.1 | 0.1 | 0.2 | 0.3 |
| All sectors | -1.1 | 0.6 | 2.1 | 1.0 | -0.2 | 0.5 | 2.1 | 0.5 |

|  | IEA expectations to 2ºC sellout |  |  |  | Tech. Diff. Trajectory to 2ºC sellout |  |  |  |
|---|---|---|---|---|---|---|---|---|
| **Russia** | 2035 |  | 2050 |  | 2035 |  | 2050 |  |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | -0.5 | 1.4 | -1.2 | 1.1 | -0.4 | 1.2 | -1.4 | 0.2 |
| Extraction sectors | -18.4 | -37.2 | -24.2 | -45.0 | -18.1 | -37.0 | -24.0 | -45.0 |
| Basic manufacturing | -1.0 | 0.0 | -1.7 | -0.6 | -1.0 | 0.0 | -1.6 | -0.9 |
| Advanced manufacturing | -1.2 | 0.8 | -1.1 | 0.2 | -0.8 | 0.7 | -0.3 | 0.4 |
| Utilities | -10.4 | -10.9 | -13.5 | -14.4 | -10.3 | -10.8 | -13.6 | -14.5 |
| Construction | 0.1 | -0.3 | 0.7 | 1.3 | 0.5 | 0.1 | 1.1 | 1.0 |
| Distribution and retail | -1.2 | 0.1 | -1.2 | -0.4 | -0.9 | 0.1 | -1.0 | -0.3 |
| Transport and communications | -0.2 | -0.2 | -0.6 | -0.1 | -0.1 | -0.2 | -0.5 | -0.1 |
| Business services | 0.6 | -0.3 | 1.4 | 0.6 | 0.8 | -0.3 | 1.5 | 0.5 |
| Public services | -5.9 | -4.6 | -10.1 | -8.3 | -5.8 | -4.5 | -10.1 | -8.3 |
| All sectors | -2.3 | -1.3 | -2.8 | -2.2 | -2.1 | -1.3 | -2.6 | -2.3 |

|  | IEA expectations to 2ºC sellout |  |  |  | Tech. Diff. Trajectory to 2ºC sellout |  |  |  |
|---|---|---|---|---|---|---|---|---|
| **OPEC** | 2035 |  | 2050 |  | 2035 |  | 2050 |  |
| % change in | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. | Prod. | Empl. |
| Agriculture | -0.6 | -0.2 | -0.9 | -0.1 | -1.2 | -0.2 | -1.7 | -0.1 |
| Extraction sectors | 7.8 | 3.2 | 2.4 | 0.9 | 7.9 | 3.3 | 2.5 | 0.9 |
| Basic manufacturing | -2.2 | 0.4 | -3.3 | 0.8 | -1.7 | 0.1 | -1.8 | 0.2 |
| Advanced manufacturing | 0.0 | 0.1 | 0.1 | 0.2 | -0.9 | -0.1 | -0.8 | -0.1 |
| Utilities | -3.7 | -11.7 | -4.1 | -16.7 | -4.0 | -12.4 | -4.3 | -17.3 |
| Construction | -1.5 | -0.7 | 0.3 | 0.1 | -1.8 | -0.8 | -0.2 | 0.0 |
| Distribution and retail | -2.3 | -0.5 | -4.6 | -0.9 | -1.3 | -0.1 | -3.6 | -0.4 |
| Transport and communications | 0.6 | 0.4 | 0.5 | 0.6 | 0.0 | 0.4 | -0.7 | 0.5 |
| Business services | 0.1 | 0.2 | -0.1 | -0.2 | -0.5 | 0.2 | -1.0 | -0.4 |
| Public services | -15.6 | -17.5 | -13.1 | -10.8 | -15.8 | -17.7 | -13.6 | -11.3 |
| All sectors | -1.7 | -2.5 | -2.3 | -1.6 | -1.9 | -2.5 | -2.7 | -1.7 |

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