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 assume that these reserves will be commercialised, the stocks of listed fossil-fuel companies

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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.

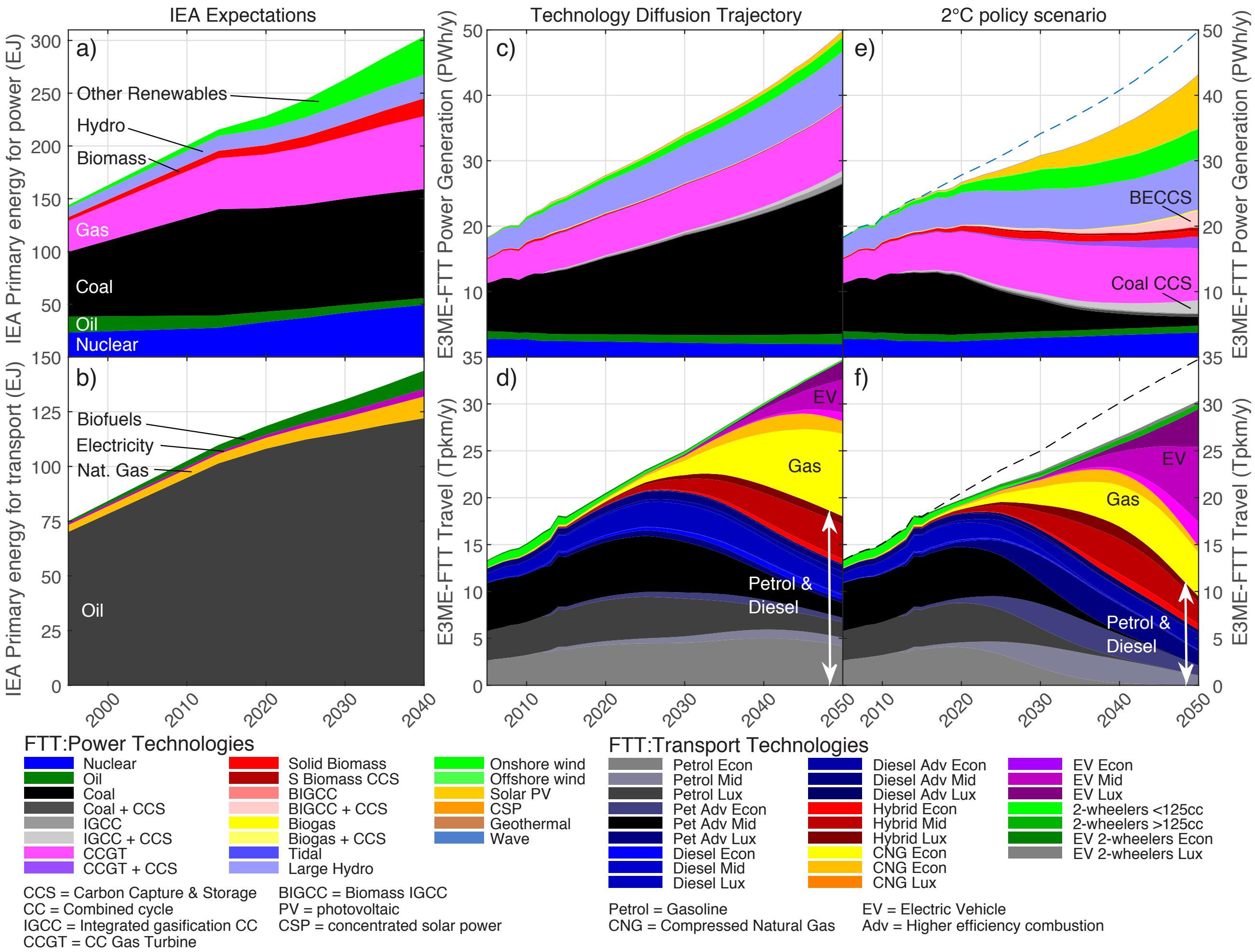

Figure 1 | Projections of future energy use for power generation and transport. a-b) Global IEA fuel demand in the 'IEA expectations' scenario. c-f) Technology composition in electricity generation (**c,e**) and road transport (**d,f**) in our 'Technology Diffusion Trajectory' (**c-d**) and '2°C' scenarios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

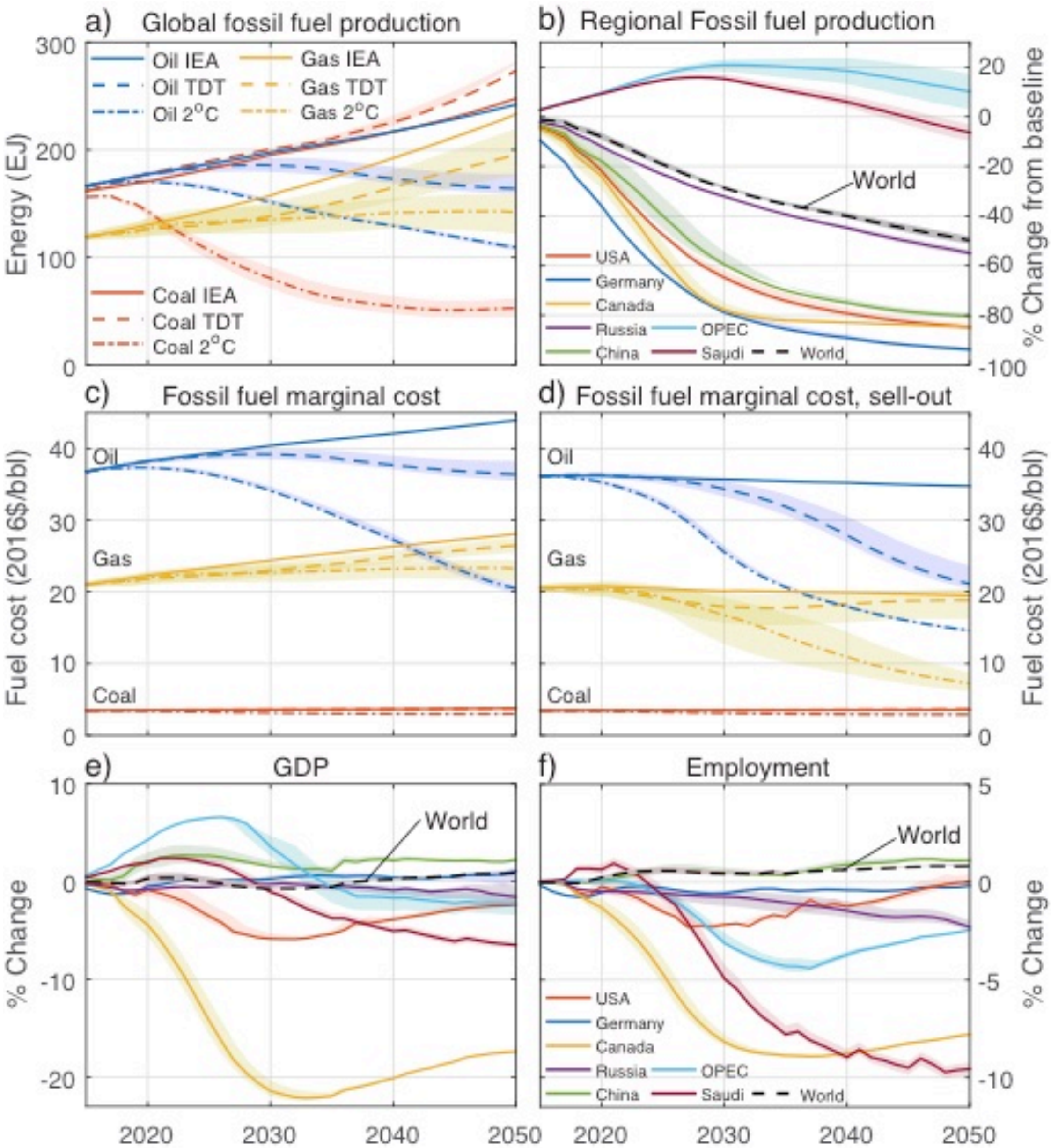

Figure 2 | Change in fossil-fuel asset value and production across countries, and in macroeconomic indicators. a) Global production of fossil fuels, for the 'IEA expectations' (IEA) scenario, our 'Technology Diffusion Trajectory' scenario (TDT), and our '2°C' policies scenario. **b**) Change in total 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).

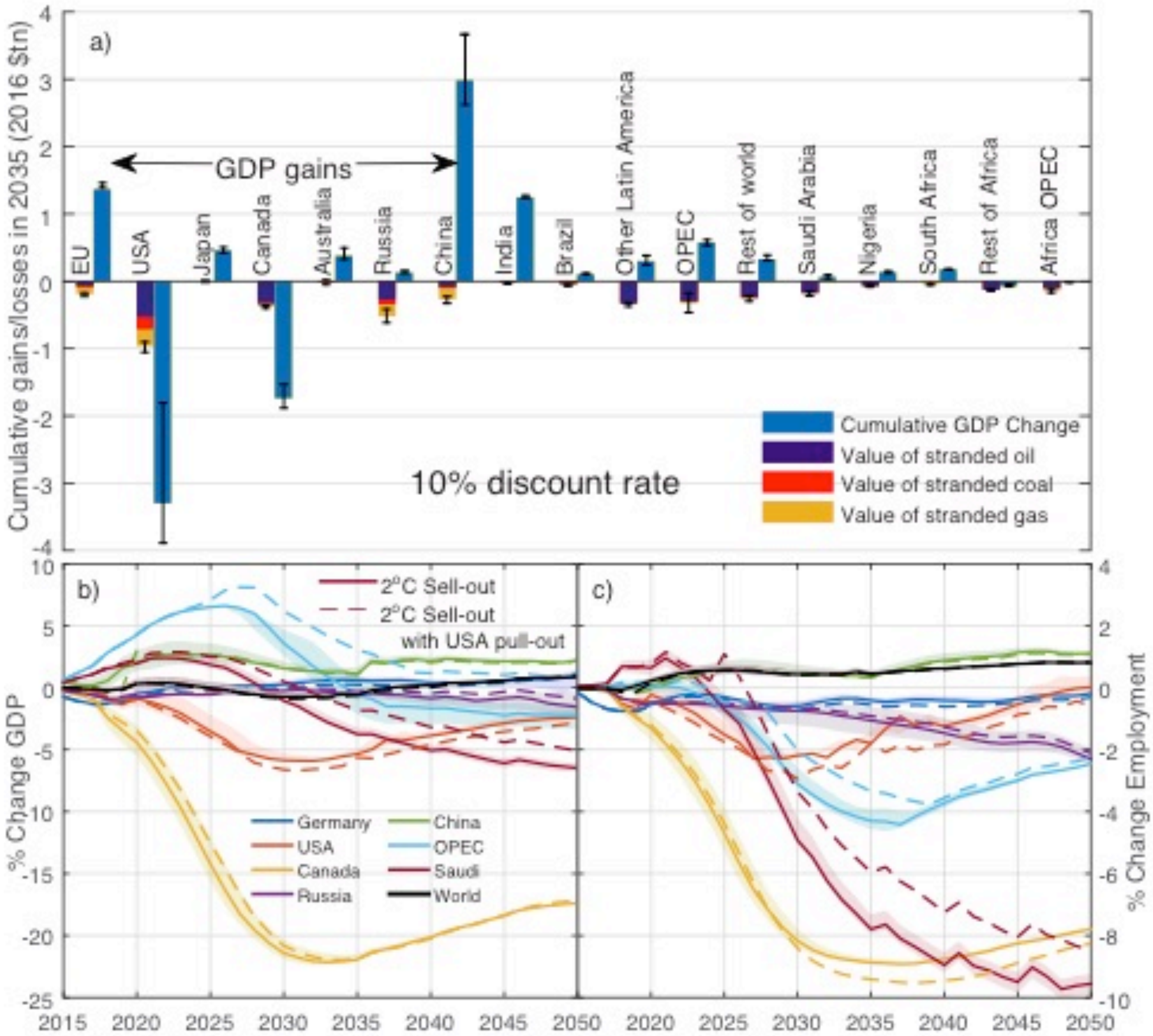

Figure 3 | SFFA losses and impacts across countries. a) Discounted cumulated fossil-fuel value loss to 2035 for oil, gas and coal, and GDP changes up to 2035, between the 2°C sell-out scenario and the 'IEA expectations' scenario (see Suppl. Table 2 and Suppl. Fig. 4 for other scenarios and aggregation 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

<table>
<tr><th colspan="3">Sector</th><th>Power generation</th><th>Road Transport</th><th>Household heating</th><th>Other transport</th><th>Industry</th><th>Rest</th></tr>
<tr><td colspan="3">Model</td><td>FTT</td><td>FTT</td><td>FTT</td><td>E3ME</td><td>E3ME</td><td>E3ME</td></tr>
<tr><td rowspan="5">Scenario</td><td colspan="2">IEA expectations</td><td colspan="6">Energy sector not modelled, replaced by fuel use data taken from IEA</td></tr>
<tr><td rowspan="2">Technology Diffusion Trajectory</td><td>No sell-out</td><td>CO_2P, FiT, Reg</td><td>Implicit in data</td><td>Implicit in data</td><td>Implicit in data</td><td>Implicit in data</td><td>Implicit in data</td></tr>
<tr><td>Sell-out</td><td colspan="6">Same, with exogenous assumptions over fossil fuel production (prod./reserve ratio)</td></tr>
<tr><td rowspan="2">2°C</td><td>No sell-out</td><td>CO_2P, Sub, FiT, Reg, K-S</td><td>FT, RT, BioM, Reg, K-S</td><td>FT, Sub</td><td>CO_2P, Reg</td><td>CO_2P, Reg</td><td>CO_2P, Reg</td></tr>
<tr><td>Sell-out</td><td colspan="6">Same, with exogenous assumptions over fossil fuel production (prod./reserve ratio)</td></tr>
</table>

Abbreviations: CO_2P = 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 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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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\$/tCO_2 in 2020, linearly increasing by 6\$/tCO_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 γ, 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 γ 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 γ 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 γ 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, 2016 for heat, see Suppl. Fig. 8 for an example). This is the sole purpose of γ. The interpretation of γ 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]]), γ 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 γ 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 tursn 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 increase 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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