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Supplementary information

Stranded fossil-fuel assets translate to major losses for investors in advanced economies

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Supplementary Information:
Stranded fossil-fuel assets translate into major losses for investors in advanced economies

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sSupplementary Tables 1-4 referenced in Methods

Supplementary Table 1 | Likelihoods of exceeding various climate thresholds and median peak warming for each E3ME-FTT scenario, using GENIE.

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

Supplementary Table 2 | Concordance of ORBIS company, shareholder, and financial company categories with those used in the paper.

Stage 3: company sector classification	
Classification in paper	NACE Classification
Oil & Gas	510-990, 1900-1920, 2000-2060, 4900-5229
Electricity	3500-3900
Manufacturing (no petrochemicals and other chemicals)	1000-1820, 2100-2120, 2200-2229, 3100-3320, 5800-5829
Finance, insurance, and real estate	6400-6530
Professional Services	6200-6399, 6800-8299
Other	All other NACE codes
Stage 4: ultimate owner classification	
Classification in paper	ORBIS variable “Shareholder type”
Individuals (shareholders)	Employees, managers, directors, One or more named individuals or families, Unnamed private shareholders, aggregated
Unknown	Unknown, 100% minus known shareholdings
Government	“Public authority, state, government"
Financial firms	
Classification in paper	Orbis variable “Type of Entity”
Pensions self-managed	Mutual and pension fund/Nominee/Trust/Trustee
Private equity	Private equity firm, Venture capital
Banks	Bank
Insurance	Insurance company
Other financial firms	Financial company, Hedge fund,

Supplementary Table 3 | Regression coefficients (Equation 1).

Dependent	Explanatory	Intercept, a	Slope, b	SE
ln(E)	ln(A)	-0.772	0.924	0.768
ln(A)	ln(E)	1.320	0.882	0.750
ln(A)	ln(R)	0.793	0.775	1.228
ln(A)	ln(W)	1.428	0.442	1.555

Supplementary Table 4 | Total asset A distributions by company size S.

Variable	small	medium	large	very large
mean ln(A)	0.113	0.961	1.855	4.245
stdev ln(A)	0.485	0.876	1.193	1.955

Supplementary Note 1: E3ME-FTT-GENIE model description

E3ME

The Energy-Economy-Environment Macro Econometric model (E3ME) is a highly disaggregated multi-sectoral and multi-regional, demand-led macroeconometric and dynamic input-output model of the global economy. It simulates the demand, supply, and trade of final goods, intermediate goods, and services globally. It is disaggregated along harmonized data classifications worldwide for 43 consumption categories, 70 (43) sectors of industry within (outside of) the EU member states and the UK, 61 countries and regions including all EU member states and G20 nations covering the globe, 23 types of users of fuels and 12 types of fuels. The model features 28 econometric regressions estimated on data between 1970 and 2018 and simulates on yearly time steps onwards up to 2070. The estimation of parameters using data up to 2018 ensures that more recent data is reflected in the econometric relationships. The base year for input-output tables in E3ME is 2010. Afterward, feedbacks from the energy module are captured in the economic input-output tables to reflect changes in energy input demand by different users. The model is demand-led, which means that the demand for final goods and services is first estimated, and the supply of intermediate goods leading to that supply is determined using input-output tables and bilateral trade relationships between all regions.

The model features a positive difference between potential supply capacity and actual supply (the output gap), as well as involuntary unemployment of the labour force. This implies that when economic activity fluctuates, short-term non-equilibrium changes in the employment of labor and capital can arise, and notably, unemployed resources can become employed. The model follows the theoretical basis of demand-led Post-Keynesian and Schumpeterian (evolutionary) economics[1,2] in which investment determines savings and output, rather than output and savings determining investment and capital accumulation as done in general equilibrium models. This implies that purchasing power to finance investment is created by banks on the basis of the creditworthiness of investors and investment opportunities and repaid over the long term. The model therefore possesses an implicit representation of banking and financial markets, in which the allocation of financial resources is not restricted by crowding-out from other competing activities, as the creation of money in the form of loans can accelerate during periods of optimism, and decline in periods of depression[1,2]. For that reason, E3ME is an appropriate model to study the business cycle dynamically, as it does not assume money neutrality and is path-dependent.

The closed set of regressions includes estimating, as dependent variables, demand (by construction equal to supply), investment, labor participation, employment, hours worked, wages, prices (domestic and imports), imports and the expansion of industrial productive capacity. Endogenous growth is generated by the inclusion of technology progress factors in several equations, which represent sectoral productivity growth as the economy accumulates scale, knowledge and knowhow with cumulative investment[3]. Final energy demand and the energy sector as a whole is treated in detail similarly but separately in physical energy quantities.

It should be noted that most integrated assessment models with sectoral disaggregation (necessary to model the changes in oil and gas demand as a result of change in the economy) currently used to assess climate policy and socio-economic scenarios are based on whole-system or utility optimization algorithms. Unlike E3ME, these computable general equilibrium models are not only supply-led but also imply a greater degree of system coordination as output and demand decisions are determined by simultaneous price adjustments. E3ME (and FTT, see below) are based on observed technology evolution dynamics and behaviour measured in economic and technology time series. We stress, however, that the practical differences between CGE and macroeconometric approaches are small for the purposes of this paper. Both are based on comparable sets of I-O tables, and sectoral patterns tend to be similar when model outputs are directly compared[4,5]. Both project historical energy demand contingent on similar system constraints and policies, especially in the near future of the next 15 years. And both rely on energy supply models that allow least-cost producers to bring their product to market. One difference makes the E3ME results on asset stranding conservative: CGEs assume that the baseline scenario operates with an optimal allocation of resources; therefore, the policy-induced reallocation of resources leads to declines in GDP, while the demand-driven approach in E3ME and no assumption of optimality leads to an increase in GDP, which in turn leads to higher demand for oil and gas relative to the CGE setup and lower stranded assets. Note moreover that E3ME-FTT possesses a level of sectoral and also regional disaggregation more than twice the next most disaggregated model available, which may be the strongest justification for its use. This matters notably when modelling output choices of different oil and gas producers given that few, if any, other models have this regional resolution.

At a model-philosophy level, E3ME is consistent with modeling stranded assets because it is a demand-driven, conditional forecast based on history. Rather than forming expectations about future optimizing behavior, the reliance on historical (up to present) patterns emphasizes limitations to knowledge and to the knowable for the individuals whose behavior is assumed to underpin the aggregate quantities modeled.[6] This modelling approach is consistent with the idea of stranded assets, where expectations about the future are based on past trends (backward-looking) and revised as new information about policy measures and evolving consumer preferences are incorporated. At the extreme end of whole-system-optimization over the entire future by (forward-looking) agents with rational expectations and efficient policy implementation, widespread stranded assets cannot, strictly speaking, occur[7]. However, the relevant CGE comparator models are recursive-dynamic, and therefore not forward-looking but myopic. They are thus compatible with non-forward-looking expectations and stranded assets as well. The difference here is that E3ME emphasizes path-dependence whereas CGEs engage in period-by-period optimization. In sum, the result of using a recursive dynamic CGE model to drive stranded asset losses in this work could be similar to using E3ME; the main difference is the greater sectoral and regional disaggregation to study structural change in the latter[8].

<u>FTT</u>

E3ME estimates energy demand and related investment in all sectors and fuel users of the global economy with the exception of the four most carbon-intensive sectors (power, transport, heat, steel), for which technological change is modelled with substantially higher definition using the Future Technology Transformations (FTT) family of models. FTT is a bottom-up representation of technological change that reproduces and projects the diffusion of individual technologies calibrated on recent trends. FTT:Power[9] represents the market competition of 24 power technologies including nuclear, coal/oil/gas-based fuel combustion (with carbon capture and storage (CCS) options), photovoltaic and concentrated solar (PV/CSP), onshore/offshore wind, hydro, tidal, geothermal and wave technologies. FTT:Transport[10,11] represents the diffusion of petrol, diesel, hybrid, compressed natural gas and electric vehicles and motorcycles in 3 engine size classes, with 25 technology options. FTT:Heat[12] looks at the diffusion of oil, coal, wood and gas combustion in households as well as resistive electric heating, electric heat pumps and solar heaters in 13 technology options. Lastly, FTT:Steel represents all existing steel-making routes based on coal, gas, hydrogen, and electricity in 25 types of chains of production. Technologies not represented in FTT currently have very low market shares, which necessarily implies, in a diffusion framework, that their diffusion to such levels that would invalidate the present scenarios is highly unlikely within the policy horizon of 2050 (e.g., nuclear fusion, hydrogen mobility).

FTT is a general framework for modelling technology ecosystems that is in many ways similar to modelling natural ecosystems, based on the replicator dynamics equation[13]. The replicator equation (or Lotka-Volterra system) is a ubiquitous relationship that emerges in many systems featuring non-linear population dynamics such as in chemical reactions or ecosystem populations[13,14]. It is related to discrete choice models and multinomial logits through adding a term in the standard utility model representing agent interactions (e.g. technology availability limited by existing industry sizes, social influence) that gives it the distinctive S-shaped diffusion profile[14].

The direction of diffusion in FTT is influenced by the economic and policy context on the basis of suitable sector-specific representations of decision-making, by comparing the break-even (levelized) cost of using the various technology options, in a discrete choice model weighted by the ubiquity of those technology options. The various levelized costs include a parameter representing the comparative non-pecuniary costs and advantages of using each technology. This parameter is used to calibrate the direction of diffusion to match what is observed in recent trends of diffusion, notably important for PV, wind, EVs and heat pumps (see Mercure et al.[10]).

A key recent innovation in FTT:Power is a detailed representation of the intermittency of renewables through the introduction of a classification of generators along 6 load bands, following the method of Ueckerdt et al.[15], with the addition of an allocation of production time slots to available generators according to intermittency and flexibility constraints. This ensures that the level of grid flexibility to allow the introduction of large amounts of renewables is respected, maintaining model results within a range deemed to represent a stable electricity grid. Intermittency, optimal intermittent renewable curtailment, and energy storage parameters are estimated by Ueckerdt et al. based on solar and wind data and optimization modelling results. In FTT the main obstacle for solar and wind penetrating grids is the rate at which the required flexibility can be accommodated. The addition of this electricity market model has implied, in comparison to earlier work[16] based on cruder and more restrictive stability assumptions, that renewables can penetrate the grid more rapidly and effectively.

<u>GENIE</u>

GENIE, an intermediate complexity Earth system model, simulates the global climate carbon cycle to give the future climate state driven by CO_2 emissions, land-use change and non-CO_2 climate forcing agents. It comprises the GOLDSTEIN (global ocean linear drag salt and temperature equation integrator) 3-D frictional geostrophic ocean model coupled to a 2-D energy moisture balance atmosphere, a thermodynamic-dynamic sea-ice model, the BIOGEM ocean biogeochemistry model, SEDGEM sediment module, and the ENTSML (efficient numerical terrestrial scheme with managed land) dynamic model of terrestrial carbon storage and land-use change. GENIE has the resolution of 10º x 5º on average with 16 depth levels in the ocean and has here been applied in the configuration of refs[17,18] (see references therein).

The probabilistic projections are achieved through an ensemble of simulations for each emissions scenario using an 86-member set[19] that varies 28 model parameters in order to produce an estimate of the full parameter uncertainties. Each ensemble member simulation is continued from an AD 850 to 2005 historical transient spin-up. Post-2005 CO_2 emissions are provided by E3ME until 2070, scaled by 9.9/X to match actual emissions in 2019[20] (where X=9.3 GtC is E3ME 2019 emissions), to correct for missing processes in E3ME. After 2070, the emissions trajectories are extrapolated to 2100 or until they reach net-zero. The NetZero scenario (details below) reaches zero CO_2 emissions during the E3ME simulation in 2050. Aerosol and non-CO_2 trace gas radiative forcing and land-use-change maps (which drive internal simulated land-use emissions) are taken from Representative Concentration Pathway (RCP) 2.6 (NetZero and EUEA scenarios) and RCP 6.0 (InvE and TDT scenarios). RCP2.6 has little non-CO2 forcing at 2050, with aerosols (-0.41 Wm-2) largely cancelling non-CO2 GHG (0.86 Wm-2). Despite these small residual net GHG emission in 2050 in the NetZero scenario, median peak warming is at 1.49°C and therefore consistent with the Paris agreement. GENIE results for exceedance likelihoods for climate thresholds and median peak warming for each scenario are given in Table S1.

The GENIE ensemble has been validated[19] through comparing the results of 86-member ensemble simulations for the RCP scenarios with CMIP5 (coupled model intercomparison project phase 5) and EMIC (Earth system model of intermediate complexity) ensembles.

Supplementary Note 2: Scenario Descriptions

Summary

E3ME-FTT-GENIE is used to generate 4 different energy demand scenarios: two serve as ‘baselines’ for initial expectations, two serve as ‘policy scenarios’ for realigned expectations. For one of the policy scenarios, EUEA, we further distinguish two oil and gas producer behaviours to supply the demand in the policy scenario.

As baselines, we define two possible starting points for investors’ current expectations towards oil and gas assets, and assume that current oil and gas values reflect these initial expectations. The first baseline follows the IEA’s WEO 2019 current policies scenario, consistent with 3.5ºC median warming, and is called Investor Expectations, *InvE*. As an alternative starting point, we assume the more environmentally benign Technological Diffusion Trajectory, *TDT*, which is based on observed low-carbon deployment trajectories and is consistent with 2.6ºC warming.

To represent revised expectations, the first policy scenario, termed *EUEA*, incorporates the stated policies of the European Union (EU) and East Asia (EA) to reach net-zero greenhouse gas/CO_2 emissions by 2050/2060 respectively, noting that non-CO_2 emissions are exogenous and follow RCP2.6 (Methods). The EUEA scenario has a median warming of 2ºC. The second is a more stringent policy scenario, called *NetZero*, which is consistent with 1.5ºC warming, on the basis of additional policies ensuring net-zero CO_2 emissions by 2050 at the global level. Mitigation is modelled as a combination of policies including sector and fuel-specific regulation, subsidies and carbon pricing (see below for details).

In line with the IEA’s expectations[21], both policy scenarios feature sell-off (SO) behaviour, whereby companies operating at low-cost fields in the Middle East supply a larger and increasing share of the market as the global oil and gas demand peaks and declines and low-cost producers scramble to capture the declining market. To reflect possible geopolitical configurations[22], we also develop an alternative strategy of OPEC producers strictly enforcing declining national quotas to maintain constant market shares (QU). To distinguish supplier behaviour in all policy scenarios, we add the suffixes *SO* and *QU* to each policy scenario (in the baseline scenarios, production levels are proportional to reserves[3]). Scenarios are summarized in Supplementary Table 5, and detailed below and in Mercure et al. (2021)[22].

Supplementary Table 5 | Scenarios used to build expectations realignments.

Scenario label	Type	Description
InvE	Baseline	Investor expectations: 3.5ºC median warming
TDT	Baseline	Technological Diffusion Trajectory: 2.6ºC median warming
EUEA-SO	Policy Scenario	EU and East Asia implement net-zero greenhouse gas/CO_2 emissions by 2050/2060 respectively: 2ºC median warming; OPEC oil and gas producers flood markets in a sell-off (SO)

EUEA-Quota	Policy Scenario	EU and East Asia implement net zero targets: 2ºC median warming; producers maintain current market share by observing quotas (QU)
NetZero-SO	Policy Scenario	The world as a whole reaches net zero CO_2 emissions by 2050: 1.5ºC median warming; producers engage in sell-off (SO) behaviour

Details

TDT (Technology Diffusion Trajectory): All policies are implicit through the economic, energy and technology diffusion data, with the exception of an assumed explicit carbon price for the EU-ETS region and other carbon markets covering the projection period, covering all industrial but not consumer, mobility, household nor agriculture emission sources, following current policy. Regulations are applied in some regions such as on coal generation in Europe, which cannot increase due to the Large Combustion plant directive. Hydro, comparatively resource-limited, is regulated in many regions to avoid large expansions that could otherwise be politically sensitive.

InvE (Investor Expectations): This scenario involves no other assumptions than policies present in the TDT and replacing all FTT outputs (energy end-use and energy sector investment) with exogenous data consistent with the IEA's WEO 2019 current policies scenario. This scenario, qualitatively similar to RCP8.5, sees growth in all fossil fuel markets, and was chosen over the newer IEA's WEO 2020 scenarios which are qualitatively different. The InvE scenario cannot be reached under any realistic set of assumptions in E3ME-FTT projections, as it would violate the model premise of near-term continuity in observed technology diffusion trajectories. This scenario was chosen as a proxy for expectations for the future of fossil energy markets, of investors who still entertain beliefs of indefinite growth in future fossil fuel markets. Since it is not possible to determine which investors entertain which expectations, the realism of the InvE scenario as a proxy for expectations cannot be assessed; it is used only to develop a what-if comparative narrative.

NetZero: This scenario adds explicit policies to the implicit policies of the TDT as follows, with the exception of the carbon price, which is replaced by more stringent values. Emissions reach net-zero independently in the UK, the EU, South Korea, and Japan by 2050, and China by 2060, following current legally binding targets, and sufficiently stringent policies ensure net zero CO_2 emissions by 2050 at the global level.

Power generation:

- Feed-in tariffs for onshore and offshore wind generation, but not solar PV.
- Subsidies on capital costs for all other renewables (geothermal, solar CSP, biomass, wave and tidal) with the exception of hydro and solar PV.
- Hydro is regulated directly in most regions to limit expansion, given that in most parts of the world the number of floodable sites is limited and flooding new sites faces substantial resistance from local residents.
- Coal generation is regulated such that no new plants not fitted with CCS can be built but existing plants can run to the end of their lifetimes. However, all remaining coal plants are shut down in 2050.
- Public procurement is assumed to take place to install CCS on coal, gas, and biomass plants in many high and middle-income countries where this does not already exist, notably in the US, Canada, China, and India.

- The use of BECCS is supported by existing policies and the introduction of further public procurement policies to publicly fund the building of BECCS plants in all countries endowed by solid biomass resources.

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

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

Household heating:

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

Steelmaking:

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

Cross-sectoral policies:

Energy efficiency: the energy efficiency of non-FTT sectors is assumed to change in line with the IEA[23], with corresponding investments in the respective sectors.

Carbon price: applied to all industrial fuel users with the exception of road transport, household heating, agriculture, and fishing, which are covered by other sector-specific fuel taxes and are not expected to participate in emissions trading schemes. Carbon revenues are used mainly to finance energy efficiency investments, with left-overs being split between income tax, VAT, and social security payment reductions. The carbon price is exogenous and increases in the EU from its 2020 value, in nominal EUR, until €1955/tC in 2033 and remains there thereafter. The rest of the world moves to match EU prices, so prices are equalized across the world. Deflating these values using E3ME's endogenous price levels into 2020USD (since E3ME operates in nominal EUR) and converting to CO_2, these carbon prices are equivalent to between \$300-500/tCO_2 in 2033, going down thereafter following different country inflation rates to \$250-350/tCO_2 in 2050 and \$150-200/tCO_2 in 2070.

EUEA: The EUEA scenario was designed by creating a cross between the TDT and the NetZero scenario in which the EU, UK, Japan, South Korea, and China adopt the net-zero policies as defined above and achieve their respective targets, while every other country follows the TDT. Note that technology spillovers (e.g., learning) in the model imply that this scenario is not a simple linear combination of the parent scenarios, since low-carbon technology adoption in countries without net-zero policies is higher than in the TDT.

Sell-off (SO) and quota (QU) behaviour variants: These scenarios are generated by varying the exogenous production to reserve ratio of OPEC countries including Saudi Arabia (given that OPEC is disaggregated between Saudi Arabia, OPEC countries in Africa and the rest of OPEC), assuming that only OPEC has the freedom and incentive to do so. Production in the model is by default proportional to existing reserves in each producing region, the proportionality factor being determined by the data such that production data is consistent with reserve data. The production to reserve ratios in the three OPEC regions are modified by applying the values that achieve either production quotas that remain proportional to global oil and gas outputs (QU scenario) or constant in absolute value (SO scenario).

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

Supplementary Note 3: Choice of Discount Rate

The level of the private discount rate chosen affects the magnitude of the losses and can also have distributive consequences if asset loss time profiles vary across assets. We apply a discount rate of 6% to calculate the net present value of future cash flow from oil and gas fields. Rates in the literature on the oil and gas sector vary widely[24]. Our discount rate of 6% is in the lower part of the spectrum and was chosen based on two factors. The first was feedback from a stakeholder workshop in the process of writing up this project, where participants active in the financial sector argued for setting a relatively low discount rate. Since this paper analyzes financial returns, this feedback influenced our choice of discount rate.[i] The second factor is the prevalence of generally low and falling minimum required rates of return on investment, or hurdle rates, in the energy sector in high income countries where most private losses are recorded. For instance, a recent survey for the UK's Department of Business, Energy and Industrial Strategy found hurdle rates to have declined across energy generation technologies from 2015 to 2018 and to be in the range of 6% to 8% for most technologies[25]. Further, the IEA published a report on financing the clean energy transition in developing countries that noted hurdle rates below 6% in the USA and Germany, but higher in developing countries[26], which can be explained by varying country risk premiums[27]. Ultimately discount rates are set by each

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[i] Discount rates in the oil and gas sector for their own project decision making can be significantly higher, especially for unconventional and offshore projects[51].

organization itself. We believe that 6% reflects a reasonable average from an investor's perspective.[ii]

Sensitivity of global stranded assets to variation in the discount rate is provided in Suppl. Table 6. This table also shows that ultimately the choice of expectations realignment, i.e. combinations of scenarios, is a more important determinant of losses, so uncertainty about losses is dominated by scenarios, not discount rate. Realignments dominating variation in losses is further illustrated for individual companies in Supplementary Fig. 1, where in 9 out of 14 cases company-level losses under the *Severe* realignment with a 10% discount rate are still higher than under the *Medium* realignment with 6% discounting. And 14 out of 14 companies report higher *Medium* losses discounted at 10% than *Benign* losses with 6% discount rate.

Supplementary Table 6 | Equity shock (USD trillions) as a function of discount rate in each scenario.

Scenario	Annual discount rate			
	4%	6%	8%	10%
Medium	1.673	1.410	1.196	1.023
Medium-Quota	2.192	1.859	1.588	1.367
Severe	2.735	2.322	1.987	1.713
Benign	0.531	0.458	0.399	0.349

Supplementary Note 4: Technical insolvency including companies with limited information

When asset losses exceed shareholder equity, a company records negative equity on its balance sheet, impairing some of the collateral backing its debt. Such companies are called 'technically insolvent', but are still operational as long as they have enough cash flow to service their debt[28]. In the main text, we report losses exceeding equity by a total of US$129 billion in 239 companies with total debt of US$361 billion that report comprehensive balance sheet data. This is also the amount of loss of 'creditors' shown in the graphs. The total reported in the main text is arrived at by summing only over companies classified in Orbis as C1 or C2 (consolidated accounts with typically good information on balance sheet quantities) to ensure no overstatement of impaired collateral. However, there are two other categories of firms – firms with limited financial information and with no financial information – that are excluded from this tally but some of whom nevertheless become technically insolvent according to our accounting. At least some of these companies' financial data are missing and their values imputed with the procedure described in the Methods. If we incorporate them the number of technically insolvent firms in the *Medium* realignment rises to 1,483, the impaired collateral to $414 billion and the overall debt in these companies is $408 billion. The fact that total impaired collateral is slightly higher than total debt results from our stochastic imputation of missing data, including debt. To prevent our main results from becoming sensitive to these company-level imputations, we only report impaired collateral for companies with extensive balance sheet data reporting in the main text.

[ii] We also note that our discount rate is close to those used in other detailed process integrated assessment models, e.g. by Krey et al.[52], who use a 5% discount rate to calculate the levelized cost of electricity.

Supplementary Note 5: Limitations of ownership data

Our results concerning redistribution of losses contain a considerable degree of uncertainty about ultimate ownership. On institutional redistribution, the restriction of ownership reporting to investors holding no less than 0.01% of shares leads to a considerable amount of loss at stage 3 accruing to ultimate corporate owners in the oil and gas sector and unknown ultimate owners at stage 4. To account for these losses, we keep the residual shock in the company if shareholding sums to less than 100%. Any shareholder with less than 0.01% of the company's stock is not reported (or sometimes reported without a share but a note that the investment is 'negligible'). Thus, while ExxonMobil had 343,633 registered shareholders at the end of 2020[29], there were only 123 current shareholders reported in the Orbis database at time of download that together held 58.14% of ExxonMobil's stock. Since institutional investors tend to hold the largest portions of shares, it is likely that most missing stocks belong to individual shareholders (about half of all shares are owned by institutional investors). However, with investments of more than US$10 million falling below the threshold of reporting for Orbis for companies such as ExxonMobil, it is likely that several small institutional investors may be found among unreported investors in large companies as well. This means that part of the 'unknown' ultimate owners at Stage 4 is likely to be a placeholder for 'fundholders'.

As concerns geography, much suggests that the redistribution towards high-income, fossil energy importing countries shown in the main text is a lower bound. Because of the limits to shareholder reporting just explained, foreign ownership is likely to be undercounted. This may in particular undercount overall foreign direct investment of rich countries, with rich countries having on average a net positive investment position in developing countries[30]. Similarly, it is likely that the exposure of the financial sector in rich countries is a lower bound. For instance the unidentified creditors in developing countries are likely to include a share of high-income country-based foreign banks, while the reverse is much less likely[31,32]. Moreover, illicit outflows of capital from developing countries, called capital flight, number in the US$ billions per year. One estimate calculates annual capital flight across all sectors of US$60 billion out of sub-Saharan Africa alone.[33,34] To the extent that these outflows are linked to the oil and gas sector and is affected by asset stranding (e.g. in Angola or Nigeria), this would register as an international transfer at Stage 3 (typically to an offshore shell company).

Another uncertainty is introduced when shareholdings are not reported as numbers in Orbis. For instance, one possible data entry of an investor's ownership share simply says "majority owned". To avoid overstating ownership and losses, we conservatively attributed 50.1% of ownership to this investor, yet this may understate some investors' ownership in favor of an unknown ultimate owner. Ownership shares can also exceed 100% in rare cases. This occurs because Orbis records changes to ownership on an ongoing basis but takes up to one year to implement them from when they occur, therefore it can be that an ownership increase has been recorded but the corresponding ownership decrease by another shareholder is only recorded several months later (or vice versa). In the few cases where ownership exceeded 100%, we scaled ownership proportionately to achieve 100% share ownership.

Lastly, there is no information about the geographical distribution of fund ownership. At stage 3, we report funds losses in the headquarters country of the fund manager. For instance, losses to BlackRock's funds are reported in the US. At stage 4, we rely on the sparse information about international distribution of clients of funds in the public domain. We use a variety of sources about clients of funds, such as BlackRock's disclosed regional distribution of its clients and then the distribution of fund ownership within these regions, on which better data exists, to approximate the international ultimate ownership of funds, mostly managed from the US.

Supplementary Note 6: Alternative expectations realignments

Summary

We build four realignments, all assumed to occur in 2022, which are summarized in Supplementary Table 7. The *Medium* realignment, which we analyze in the main text, shifts expectations from *InvE* baseline to the *EUEA-SO* policy scenario. The *Benign* realignment starts from a *TDT* baseline instead. The *Severe* realignment shifts from *InvE* to *NetZero-SO*. As a sensitivity over OPEC supplier behaviour, we also explore the *Medium-Quota* realignment. Here, investors shift expectations from *InvE* to *EUEA-Quota* behaviour, where low-cost producers in OPEC countries restrict their sales to today's market share. Supplementary Table 7 overviews the realignments and makes a rough concordance with the scenarios recently published by the Network for Greening the Financial System (NGFS)[35].

Supplementary Table 7 | Overview of realignments of expectations.

Realignment name	Underlying Scenario combination	Closest NGFS scenario couple
Medium	InvE_EUEA-SO	From *Current policies* to *Below 2ºC*
Benign	TDT_EUEA-SO	From *NDCs* to *Below 2ºC*
Severe	InvE-NetZero-SO	From *Current policies* to *Net Zero 2050*
Medium-Quota	InvE-EUEA-QU	From *Current policies* to *Below 2ºC*

Notes: InvE: Investor expectations (3.5ºC median warming), TDT: technological diffusion trajectory (2.6ºC warming), EUEA: Europe and East Asia reach net zero targets. While the *Benign* realignment's TDT is compared with the NGFS' NDCs scenario, the TDT is driven by technological change, while the NDCs is driven by policies, see Methods and ref[35].

Results

Alternative expectations realignments (summarized in Supplementary Table 7 above) highlight the extent to which the results are sensitive to expectations about the future. Total stranded assets in Extended Data Fig. 1a increase monotonically from US$458 billion (*Benign*) to US$2.3 trillion (*Severe*) as realignments become more extreme. Losses are also higher under *Medium-Quota* than *Medium* because the loss per barrel stranded in the Middle East is larger than elsewhere due to lower production costs and therefore higher profitability for given oil and gas prices. While institutional and geographical shares vary (e.g. governments sustain 19% of losses under a *Benign* realignment compared with 41% under *Severe*), the percentage change in geographical shares between stages is surprisingly constant across realignments. The OECD share of losses rises in all realignments by between 17% and 20%, and then falls slightly (Extended Data Fig. 2). A robust result therefore emerges that about a sixth to a fifth of all losses and up to 60% of initial OECD losses (*Severe* realignment) are transferred to OECD-based entities between the physical stranded asset and the corporate owners' balance sheet. Moreover, the ranking of countries' losses at Stage 4 is also robust to different realignments and network sensitivity checks as well as to the potential unavailability of carbon capture and storage (Extended Data Fig. 3-8, Supplementary Notes 7-8 below).

Intriguingly, the total OECD loss appears insensitive to OPEC country production decisions, being the same in *Medium* and *Medium-Quota* realignments. This invariance masks a large variation of fortunes within this heterogeneous block. North American shale and tar sand producers significantly gain from OPEC *Quota* behaviour. The effects on international oil companies are more ambiguous. Their diversified operations include production sharing and service contracts in low-cost (high-profit) assets owned by national oil companies in the Middle East[36], so curtailment of production there in favour of higher-cost North American production actually increases losses in some American oil majors. The same is true of their European peers that trade off domestic offshore production against low-cost onshore service contracts in the Middle East and North Africa.

Extended Data Fig. 1b reports similar heterogeneity aggregated to the headquarters country level. *Quota* instead of *Sell-off* behaviour increases losses in companies headquartered in the UK, France, Netherlands, and Italy, while Canadian and Norwegian producers benefit. For the US, the gains of domestic shale producers are just counterbalanced by the additional losses of internationally active oil majors. In that sense, US producers as a group are diversified in their production assets to withstand varying OPEC behaviour. At the OECD level, too, there is nothing to gain, on average, for OECD wealth owners when OPEC restricts production.

OPEC member countries on the other hand dramatically increase their losses in the *Medium-Quota* realignment relative to the *Medium* alignment as they lose market share that is not compensated for by the resulting higher oil and gas prices. This confirms the suggestion that in decarbonization scenarios, the sell-off behaviour is the economically rational strategy to adopt from a low-cost producer perspective. This behaviour is feasible since low-cost producers have the competitive advantage necessary to capture a larger market share[21,22,37]. Therefore, a *Medium-Quota* realignment appears unlikely unless OPEC members attempt, for political reasons, to prop up prices via output curtailment, as Saudi Arabia has historically done[38].

To our knowledge and that expressed in a recent review[39], our analysis is the first peer-reviewed study to establish the actual ownership of upstream oil and gas stranded assets in terms of their net present value for investors. It is therefore difficult to compare our monetary results with equivalent peer-reviewed studies. Our results are overall consistent with those of the Carbon Tracker Initiative (an NGO), for 14 major oil and gas companies, in terms of stranded assets and company rankings for the *Severe* realignment (Supplementary Note 9 and Supplementary Fig. 1). In terms of oil and gas demand in energy units, our figures are in the range of those of other scenarios with similar warming potential including in the NGFS scenarios listed in Supplementary Table 2 (Supplementary Note 10 and Supplementary Fig 2-5 for detail).

Supplementary Note 7: Network sensitivity

An important way to assess the sensitivity of our network model to our assumptions is to refrain from any imputations of assets. To recall, in the model, companies that own others but do not report assets are imputed an asset number under the assumption of data missing at random and using non-missing covariates to predict assets (Methods). To understand the effect of these assumptions on where losses are located, we also run the network model without any imputations. That is, losses stay in that entity with reported assets that would have passed on losses to the first entity with imputations in any loss ownership chain. In other words, we remove all nodes with imputations from the network.

We compare network characteristics with and without imputed nodes for the *Medium* realignment of expectations in Supplementary Table 8. A significant fraction of the shocked companies have imputed assets, with the total number of companies shocked falling from 33,836 to 18,495 and the shock reaches only 15,623 instead of 26,998 ultimate owners. But these companies with imputations tend to be smaller. Larger companies, on average, tend to report more of their financial data. This may be because they are stock-market listed or because they fall under some local law that differentiates reporting requirements by company size. As a result, the total transmitted shock only falls by $119 billion from $791 billion, of which $65 billion is cross-border.

In relative terms, the share of the shock transmitted only falls by 8 percentage points (row 4) and the loss of transborder flows on balance sheet only affects 4.6% of the total shock (row 5). This small cross-border effect is illustrated in Supplementary Fig. 8, where most countries deviate little from their results with imputations. The biggest changes for countries are for tax havens such as the British Virgin Islands, where companies tend to disclose little information in our database. Extended Data Fig. 2 shows how the British Virgin Islands (VGB) drop from rank 22 to rank 80 of countries in terms of absolute losses once imputations are removed.

Very few funds are excluded (row 3) and the shock to funds even slightly increases in magnitude. This is because we scale company ownership that ORBIS reports as >100% down to 100% proportionally (see also Supplementary Note 5). When imputed owning nodes are removed from such companies, the remaining nodes' ownership is scaled down less or not at all. If funds are among those shareholders, they transmit a larger shock. At the coarser level, the shock transferred to OECD countries falls by 1.2 percentage points when removing imputations (Extended Data Fig. 2e). Almost all of this is because financial companies listed in OECD-based financial offshore centres that do not disclose much information, which we impute (including the UK's overseas territories British Virgin Islands and Cayman Islands).

Supplementary Table 8 I Comparison of shock transmission with and without imputation.

		INVE-EUEASO		INVE-EUEASO no imputations		percentag e point change
		Absolute	% of total shock	Absolut e	% of total shock	
	Column:	(I)	(II)	(III)	(IV)	(IV)-(II)
1	Shocked companies (count)	33,836		18,435		
2	Shocked ultimate corporate owners (count)	16,171		10,709		
3	Shocked funds (count)	1,592		1,379		
4	Total transmitted shock ($ billion)	790.881	56.1%	677.354	48.1%	
5	transmitted equity shock ($ billion)	508.761	36.1%	390.114	27.7%	-8.4
6	of which cross-border ($ billion)	156.163	11.1%	91.4217	6.5%	-4.6
7	transmitted managed shock ($ billion)	282.120	20.0%	287.240	20.4%	0.4
8	of which cross-border ($ billion)	120.042	8.5%	120.673	8.6%	0.0

Supplementary note 8: No CCS

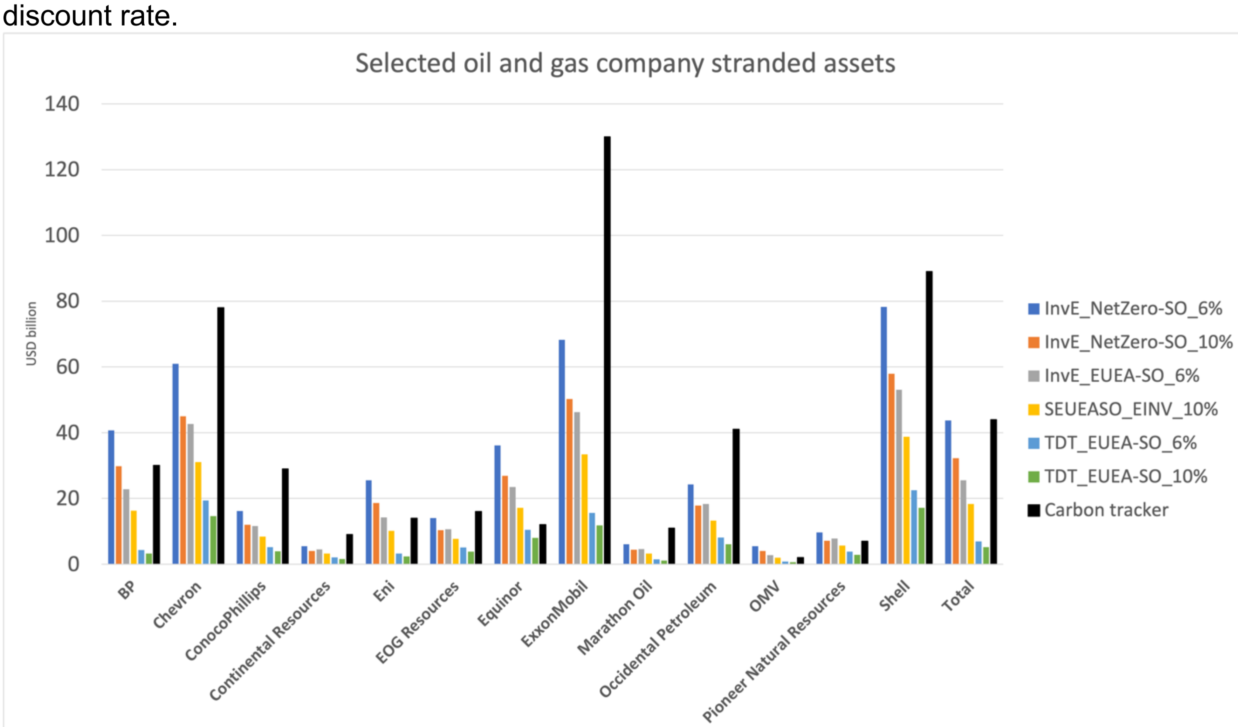
To test the sensitivity of our results to the availability of carbon capture and storage (CCS) we recalculate demand for fossil fuels without CCS availability until 2036. In the EUEA-SO scenario, 6.1 GtCO_2 are removed from the atmosphere using bioenergy CCS between 2022 and 2036. We split the emissions that need instead to be saved by reduced fossil fuel consumption equally across oil, gas and coal. Using the IPCC's fuel-specific carbon intensity factors, this leads to 29 EJ less oil and 36 EJ less gas demand over the time period, about 1% and 2% of total demand for the respective fuels in the EUEA scenario until 2036 (see also Supplementary

Fig. 4 below). Using an incremental ramp of annual savings, we then recalculate how this lower energy demand affects oil and gas field production and stranded assets. The modification increases total oil and gas stranded assets by 3% from USD 1.410 to 1.453 trillion. More detailed results and change from *Medium* realignment are shown in Extended Data Fig. 2d and 7.

Supplementary Note 9: Comparison with Carbon Tracker's stranded assets

In April 2021 Carbon Tracker undertook a stranded asset analysis for 14 major oil and gas companies calculating whether the profits they would earn under a (low) $35 per barrel oil price were enough to cover their reported property, plant and equipment assets[40]. Carbon Tracker found an overall $512 billion shortfall (a negative net present value) using a 10% discount rate on future earnings. This total compares with $435 billion in our *Severe* realignment for the companies as a group and as shown in Supplementary Fig. 1, our distribution of losses across companies is similar to that of Carbon Tracker. We apply both 6% and – like carbon tracker – a 10% discount rate to all of our sell-out scenarios. Our total is lower for every scenario and it is notable that our estimates are similar for European countries but smaller for US companies. We reason that this pattern arises from the bigger asset write-offs carried out by European companies relative to their American peers since our data snapshot that reflects balance sheets at the end of 2019. Overall, the similarity in losses suggests that our attempt to estimate what investors think they are worth using the *InvE* scenario's discounted future profits comes close to the reported plant, property and equipment investments reported on companies' balance sheets.

Supplementary Fig. 1 | Stranded assets for 14 major oil and gas companies in our realignments and Carbon Tracker analysis. Values are for each company's global operations (i.e. stage 2) and costs are calculated using both our regular 6% discount and the higher 10% discount rate.

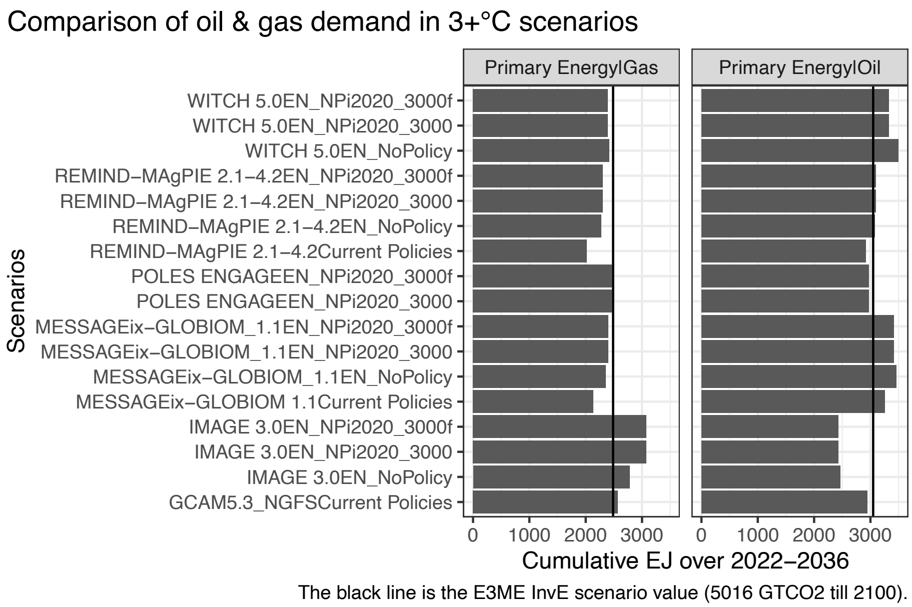


Supplementary Note 10: Comparison with other models' oil and gas demand

No other recent model to our knowledge calculates scenario-specific (or any) oil and gas profits or shares data on revenues[iii], but we can compare demand for oil and gas in EJ in our scenarios with those in other recent studies to illustrate where our 'realignments' fall with respect to other studies. Suppl. Fig. 2-5 classify scenarios according cumulative CO_2 emissions until 2100 or, where unavailable, by average global warming using the linear relationship in ref[41]. They show cumulative global oil and gas demand (including abated by CCS, which corresponds to a relatively small proportion through 2036) over the relevant period of 2022-2036 of scenarios from refs[35,41,42] including only those scenarios where policy action is assumed from 2020 (instead of delayed until 2030) and where we have linearly interpolated observations available in five or ten year intervals. The vertical black line represents oil or gas demand in one our four energy demand scenarios. It lies within the ensemble of results, so our realignments are unlikely to produce systematically different numbers from the ones we are analyzing. Interestingly, the Welsby et al. results[42] about 'unextractable fossil fuels in a 1.5ºC world' that use the TIAM-UCL model have among the highest oil and gas demand among all scenarios, suggesting their short-term projections of fossil fuel stranding would be relatively modest for a 1.5ºC scenario.

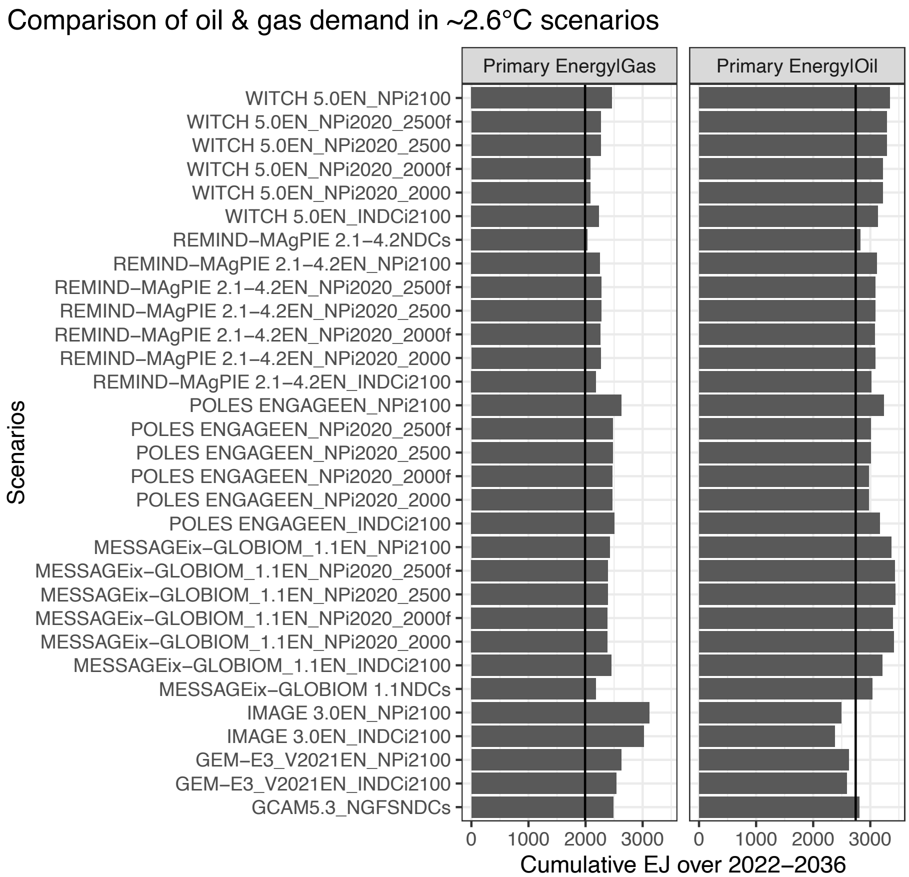
Supplementary Figures 2-5

Supplementary Fig. 2 | Oil and gas demand comparison in scenarios comparable to InvE.



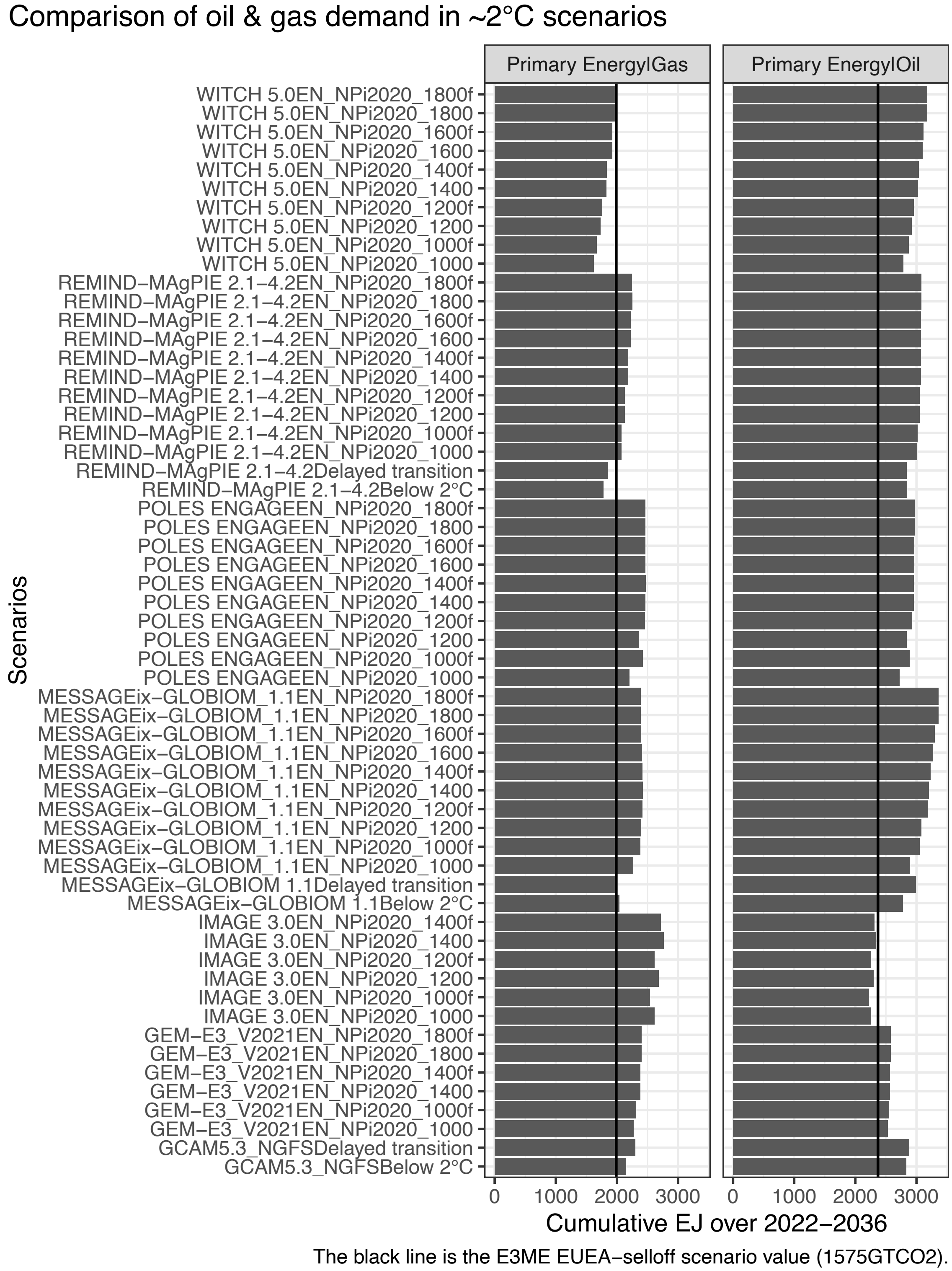
[iii] Welsby et al.[42] provide a production cost curve that excludes transport cost and royalties and so cannot be used to calculate breakeven prices. They also do not provide enough information in the SI data to calculate revenues under their scenarios without learning their model.

Supplementary Fig. 3 | Oil and gas demand comparison in scenarios comparable to TDT.

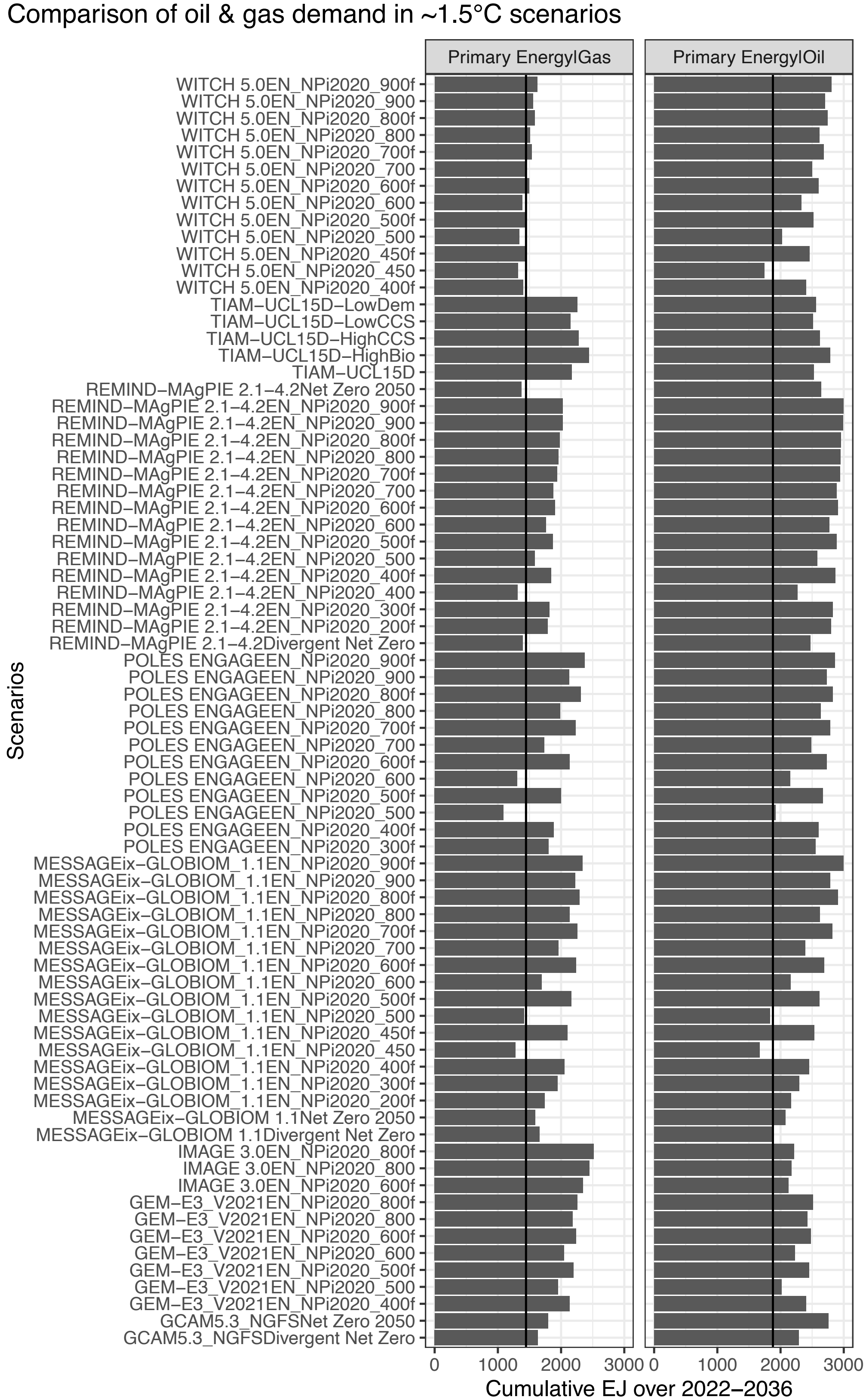


The black line is the E3ME TDT scenario value (2704 GTCO2 till 2100).

Supplementary Fig. 4 | Oil and gas demand comparison in scenarios comparable to EUEA.



Supplementary Fig. 5 | Oil/gas demand comparison in scenarios comparable to NetZero.



The black line is the E3ME NetZero−selloff scenario value (449 GTCO2).

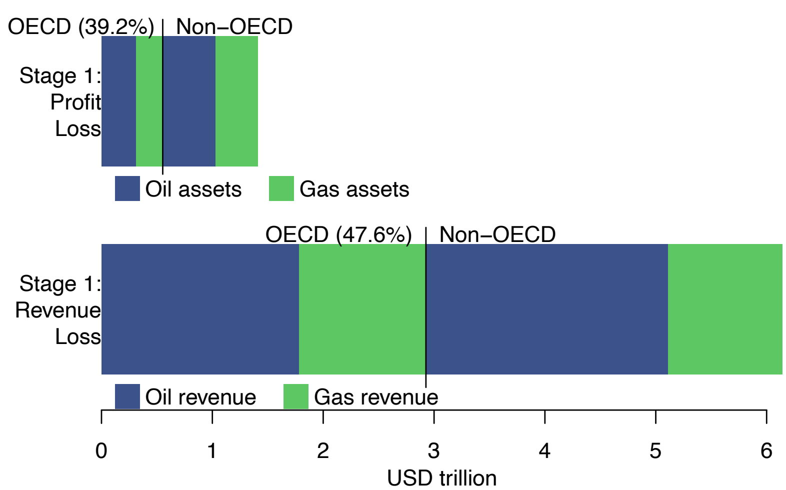
Supplementary Note 11: Funds

Fund managers earn revenue by their management of others' wealth (assets under management). This typically happens by charging fees for their management of their clients' investments. In our data, a significant amount of ownership is via funds, and at Stage 3, we report losses to funds, which are split geographically by the fund manager's headquarters. It is important to recognize, however, that losses to funds do not imply losses to fund managers' balance sheets. Rather, the loss accrues to the balance sheet of the corporate or net worth of the human client. The decline in assets under management instead impacts the income and cash flow statement of the fund manager, since fees (revenue) tend to be calculated as a share of assets under management (see, e.g., *ref*[43]). To the extent that this decline in revenue affects the expectations about future revenue earnings, the balance sheet as well as the market capitalization of fund managers can also suffer, leading to an amplification of the initial shock. However, just as we do not consider second-round effects in the banking system, we do not account for this potential loss to fund managers, as we focus on the direct equity channel of transmission of transition risks.

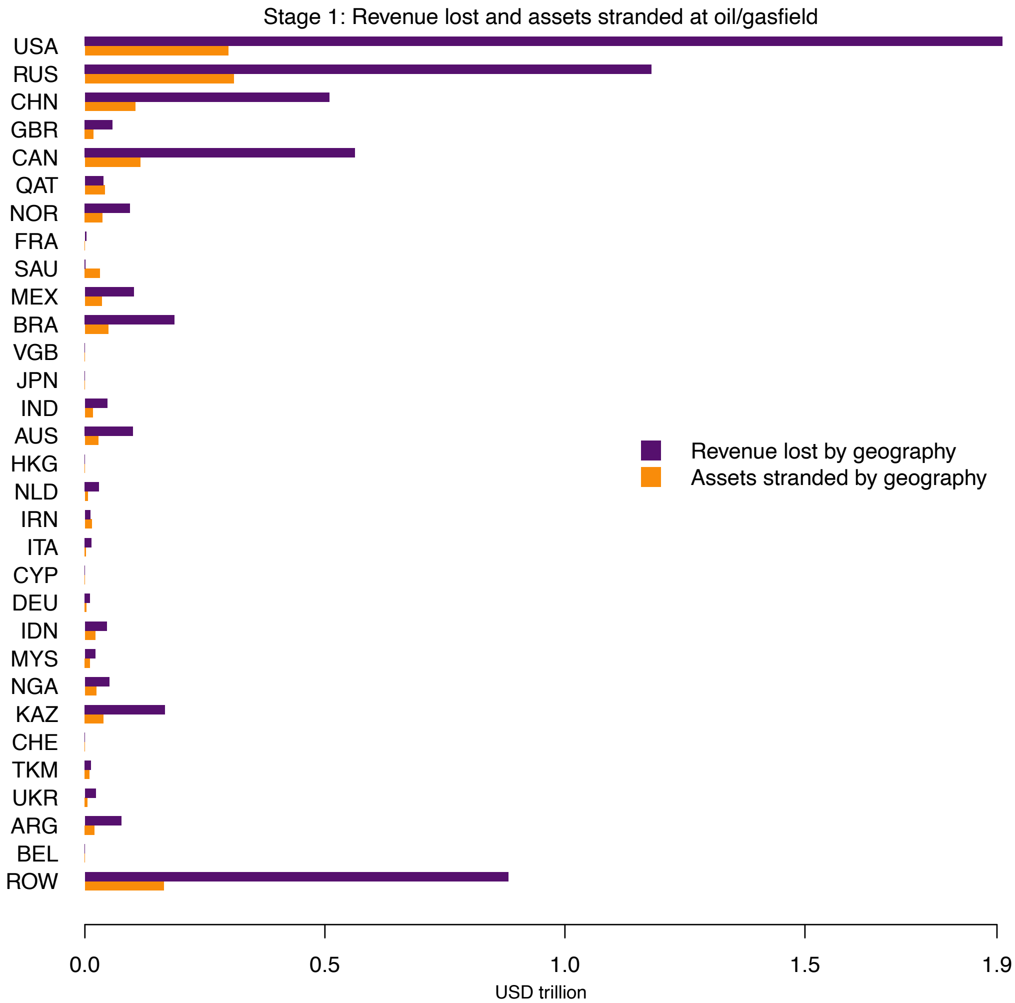
Supplementary Note 12: Revenue loss vs profit loss

The value of stranded assets is computed on discounted future profits, i.e. the difference between the market and breakeven price. The breakeven price covers production and transport cost as well as taxes and royalties as reported in the Rystad database. Supplementary Fig. 6 contrasts the $1.4 billion in lost profits with the more than $6 billion in lost revenue in the Medium realignment. The ratio of lost revenue to lost profits for oil and gas is roughly similar overall, however it is regionally different. The production cost in OECD countries is higher relative to the market price, owing the more favorable geographical profile on average in non-OECD countries. Supplementary Fig. 7 details the loss comparison at the country level for the top 30 losing countries. Russia and the US have roughly the same stranded assets but there is 1.5 times more lost revenue in the US, meaning that the primary energy stranded in the US in EJ is higher than in Russia. In Iran, Qatar and Saudi Arabia, total revenue is hardly affected thanks to higher sales volumes, but the lower oil price lowers profits. A detailed discussion of lost revenue in all scenarios in can be found in ref[22].

Suppl. Fig. 6 | Stage 1 stranded assets (profit loss) and revenue loss by OECD/non-OECD geography and oil or gas source in the *Medium* InvE_EUEA-SO realignment.



Suppl. Fig. 7 | Country level revenue and asset stranding comparison. Stage 1 stranded assets (profit loss) and revenue loss for the top 30 Stage 4 countries.



Supplementary Note 13: Loss relative to GDP

Losses from alignments so far have been computed in absolute (USD) terms. Dividing by GDP pictures the risks relative to the size of the economy as shown in Extended Data Fig. 9 (keeping in mind that GDP is an annual flow and the present value of losses a stock). The losses can be interpreted as a 'maximum' bailout and hence increase in debt to GDP ratios of governments. GDP at market exchange rates is from the World Bank for 2019 or the latest available year.

Supplementary Note 14: Comparison of financial risk with 2007-08 crisis

Stranded assets are often associated with financial instability. Comparing the US$681 billion financial sector exposure in a *Medium* realignment with the 2007-08 financial crisis is helpful to appreciate the risks. The latter was triggered by mispriced subprime housing assets of an estimated US$250-US$500 billion on financial sector balance sheets, which led to a US$25 trillion decline in world stock market capitalization over a year and was estimated to cause a cumulative US$5 trillion of global GDP loss due to the ensuing credit crunch[44,45].

The vulnerability of the financial system to mispricing depends on how exactly the losses are propagated and to what extent credit markets become impaired. Although our model does not allow us to predict specific implications for financial stability, the amount of assets at risk owned by the financial sector as well as the presence of technical insolvencies suggest that it would be imprudent to completely dismiss the potential of financial market disruptions from such a mispricing of fossil-fuel assets[46] as price corrections cascade through the financial sector, including also credit markets, as well as the supply chain and the use-sectors of oil and gas[47]. A key consideration here is that risk may also reside in mid- and downstream oil and gas, in the supply chain as well as in oil and gas demand sectors, none of which is included in our figures for the upstream oil and gas sector.

At the same time, some stranded asset risk may already have been realized. The recent purchase of whole oil fields by private equity groups at low prices may be a case in point.[48] Since the fields were sold at a low price, one could argue that this low price already priced in the risk of asset stranding.

Supplementary Note 15: Distributional effects within countries

Losses to ultimate wealth may impact households in a particular country unequally, raising the question how stranded assets may affect wealth inequality. To get a sense of the distribution within a country's household wealth, Supplementary Table 9 shows an estimate of how the total loss under the *Medium* InvE_EUEA-selloff realignment for the US is distributed across the size distribution of household wealth, and also reports the number for government. The figures are based on the US Survey of Consumer Finance and for government net worth on Piketty and Zucman's[49] estimate.[iv] Translating losses for the US displayed in main text Figure 3 Stage 4 into stock, fund and bond (for creditors) categories and distributing them in proportion in which they are held by different quantiles of the size distribution of household wealth, we can see that the richest 10% of wealth owners sustain by far the largest loss from stranded assets with $286 billion or about 82% of the total. This is first because they hold most of US assets (70.3%) and net worth (76.5%) but also because the loss takes place in asset categories in which the richest

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[iv] US Government net worth was 21% of GDP in 2010 and we use that same number and 2019 GDP of USD21.37 trillion (Federal Resourve of St. Louis FRED database) to calculate government net worth. We add half of government borrowing of 120% of GDP to calculate assets, to allow for debt financing of non-asset purchases.

households hold a share that is higher than their average share of assets, as the column on loss relative to assets shows. Here, the top 10% of wealth holders incur the largest loss relative to their assets. It is also clear that this share at 0.4% is small compared with annual capital gains and new investments of several percent in any usual non-crisis year. However, we stress here again that we only model the equity channel of loss transmission, which may be accompanied by additional losses via debt and additional negative macroeconomics effects.[50] The relative losses are closer to the average for all households when considering only net worth (assets minus liabilities). That is, poorer households have a higher ratio of assets to net worth and hence the loss of assets hits their net worth harder than their assets in relative terms. For instance, for the second quartile or 25th to 50th percentile, the loss relative to net worth is more than twice the loss relative to assets. The bottom quartile even has negative net worth, hence the ratio is negative.

While the top 10% of wealthiest households thus incur higher relative losses than others, Supplementary Table 10 shows that this difference has negligible effects on the US wealth distribution. The share in total household assets from a Medium realignment falls by 0.038 percentage points and that in net worth by only 0.021 percentage points. The biggest winners in the distribution are the 75-90th percentile, increasing their share in net worth by 0.014 percentage points, and the bottom quartile further falls into negative net worth.

Supplementary Table 9 | Asset loss distribution across the US house wealth size distribution from *Medium* InvE_EUEA-SO realignment.

Household wealth quantile:	Absolute wealth loss (USD billion)	Loss relative to assets	Loss relative to net worth
Less than 25	1.831	0.171%	-0.418%
25-49.9	6.074	0.146%	0.325%
50-74.9	18.344	0.165%	0.241%
75-89.9	36.032	0.221%	0.265%
90-100	286.202	0.371%	0.390%
Total	348.484	0.317%	0.363%
Memo: Government	13.740	0.073%	0.282%

Supplementary Table 10 | Effect of asset loss on US household wealth distribution from *Medium* InvE_EUEA-SO realignment.

Household wealth quantile:	Share in household assets			Share in household net worth		
	Share before	Share after	Difference	Share before	Share after	Difference
Less than 25	0.975%	0.976%	0.001%	-0.456%	-0.460%	-0.004%
25-49.9	3.776%	3.782%	0.006%	1.948%	1.949%	0.001%
50-74.9	10.147%	10.163%	0.016%	7.910%	7.920%	0.010%
75-89.9	14.843%	14.857%	0.014%	14.132%	14.146%	0.014%
90-100	70.259%	70.222%	-0.038%	76.466%	76.446%	-0.021%

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