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October 2021

WORKINGPAPER SERIES

Number 549

POLITICAL ECONOMY RESEARCH INSTITUTE

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

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Abstract:
The distribution of ownership of transition risk associated with stranded fossil-fuel assets remains poorly understood. We compute global stranded assets of US$1.4 trillion in the upstream oil and gas sector as expectations change to be consistent with stated climate policies. We trace the equity risk ownership from these 43,439 assets through a global equity network of 1.8 million companies to their ultimate owners. Most of the market risk falls on private investors, overwhelmingly in OECD countries, including substantial exposure through pension funds. Financial markets are exposed to a US$690 billion correction, comparable to the mispricing that triggered the 2007-08 crisis. The ownership distribution also shows the large stake OECD investors have in the continued operation of fossil-fuel facilities incompatible with climate change mitigation goals.

The transition to a global low-carbon economy entails deep and fast structural change that poses challenges for economic adaptation everywhere[1,2]. One key challenge both for the real economy and financial markets is the fast phase-out of fossil-fuel production that necessitates the write-down of major, functioning capital assets and reserves reflected as assets on fossil energy companies' balance sheets. But while over 100 studies have analyzed scenario-contingent early retirement of fossil-fuel facilities often with detailed plant-level data[3], this retirement has not been linked to financial ownership. As a result, academic and regulator studies undertaking stress tests of the financial system start from synthetic shocks to financial assets, rather than the underlying real assets[4–6]. The distribution of financial ownership and exposure to loss risk remains insufficiently understood.

Asset stranding is the process of collapsing expectations of future profits from invested capital (the asset) as a result of disruptive policy and/or technological change[7,8]. This loss of value in fossil-fuel assets is reflected in investor expectations of enterprise value and therefore market prices, including - where listed - stock market indices. Such price corrections lead to a wealth loss for the ultimate owners of these assets; additionally, further losses can propagate to other entities indirectly through highly connected modern financial networks.

Asset stranding becomes a social concern where these effects destabilize financial markets that have negative repercussions in the real economy such as on pensions and government finances[9,10]. The (premature) obsolescence of capital stock is a recurring feature of dynamic, capitalist economies, as new products and industries replace old 'sunset' ones, and it is not typically associated with systemic financial risks because the financial sector is buoyed by the new 'sunrise' sectors[2]. Yet, in the case of the low-carbon transition, the rate of industrial change required for achieving a 2ºC let alone 1.5ºC goal is so large[11] that it has generated concerns of transition risks from a rapid collapse of fossil-fuel 'sunset' industries[5,12].

Here we map comprehensively the current global financial geography of stranded oil and gas asset risk for equity ownership. We trace potential losses from extraction sites through corporate headquarters and their immediate shareholders (including banks, fund managers) all the way to ultimate owners (government and individual shareholders) for oil and gas extraction companies worldwide. We comprehensively link fossil-fuel stranded assets and transition risk studies at the asset level for the transmission channel of equity mispricing. We distinguish both geographic and functional characteristics of the organizations along the equity ownership path. Understanding what type of organizations own the risks is key for analyzing transition risk and formulating policy: whether companies could become bankrupt or default on debt obligations, whether pension funds are at risk of failing to meet their pay-out commitments and what financial burdens might befall governments. Understanding the geographic distribution is important not least for the debate about climate change mitigation that tends to be framed in terms of countries. We find that exposure to wealth losses is more evenly shared geographically than the distribution of oil and gas production assets may suggest. Therefore, private investors in rich countries face greater risk and moreover have a larger stake in the continued pressure to keep up fossil-fuel production from facilities incompatible with ambitious climate mitigation policy than the discussion of stranded assets has so far suggested.

Estimating stranded assets and wealth losses

We estimate stranded assets by comparing discounted profits under an initially expected (baseline) scenario, upon which prior financial value has been estimated, with a revised scenario representing updated expectations; we call such a combination a *realignment* (of expectations). The revised scenario is referred to as a policy scenario, given it includes stronger climate-protection policy relative to the baseline. Because the expectations underlying current asset prices vary, evolve continuously and are extremely difficult to quantify, we consider a range of alternative possible realignments, each yielding a magnitude and distribution of risk ownership. All scenarios, from which we build realignments, are generated by the E3ME-FTT-GENIE integrated assessment modelling framework. It couples a macroeconometric model of the economy that distinguishes 43 sectors and 61 regions and their trade (E3ME), an evolutionary energy technology model distinguishing 88 supply and demand-side technologies (FTT) and a carbon cycle and climate system model of intermediate complexity (GENIE).

We consider four possible near-term (in 2022) realignments, which are summarized in Table 1. They are built from combinations of two baseline and two policy scenarios. As baselines, we define two possible starting points for investors' current expectations towards oil and gas assets, and we assume 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 reflects current low-carbon deployment trajectories consistent with 2.6ºC warming. To represent revised expectations, the first policy scenario, termed *EU-EA Net-Zero,* incorporates the stated policies of the European Union and East Asia to reach net zero greenhouse gas/CO_2 emissions by 2050/2060 respectively, and is consistent with a median warming of 2ºC. The second is a more stringent policy scenario, *Global Net-zero*, which is consistent with 1.5ºC warming with policies ensuring global net zero CO_2 emissions by 2050. The *Medium* realignment, which we analyze most, shifts expectations from *InvE* baseline to *EU-EA Net-zero* policy scenario. The *Benign* realignment starts from a *TDT* baseline instead. The *Severe* realignment shifts from *InvE* to *Global Net-zero*. Table 1 also shows how these realignments relate to the recently published NGFS scenarios, by the Network for Greening the Financial System[13].

We further construct a fourth realignment by varying production strategy of low-cost OPEC producers from a breakdown of quota discipline (termed *Sell-off*) to strictly enforced declining national quotas (termed *Quota*). In line with the IEA's expectations[1], all three realignments discussed so far feature *Sell-off* behavior, whereby companies operating in the Middle East supply a larger and increasing share of the market as the global oil and gas demand peaks and declines. To study the effect of different supplier behavior, we also explore the *Medium-Quota* realignment. Here, investors shift expectations from *InvE* to *EU-EA Net Zero* with *Quota* behavior, where low-cost producers restrict their sales to today's market share. Scenarios are further described in the supplementary materials and ref[14].

The baseline and policy scenarios have global demand and price trajectories and thus revenues from oil and gas assets, a realignment therefore generates differences in revenues. Fig. 1A illustrates the implications for the *Medium* realignment. Annual revenue in the *InvE* baseline grows, while in the *EU-EA Net-zero* policy scenario it reaches an early peak and falls steadily. The dark green wedge represents the lost future undiscounted revenue under the expectations realignment. Since asset value springs from expectations about profits, we focus on the difference in profits (the light green wedge). It is a subset of the revenue loss, which also includes labor and material costs. We focus on upstream oil and gas profits, excluding those in the supply chain. Differences in expected profits discounted by 6%y^{-1} (see supplementary materials) in every year (Fig. 1B) serves to calculate stranded assets today. That is, investors realign their expectations of the ability of assets to generate profits from the baseline to the policy scenario in 2022 over a 15 year horizon of profits, and present value accounting translates deflated profit expectations into lower asset value.

Profits are calculated per asset. Energy is supplied from 43,439 oil and gas production assets based on Rystad's Ucube dataset. Whether an asset is expected to supply demand in each scenario depends on its present-day production cost and reserve profile. In the realignment process, some assets become unprofitable and stop producing: they are expected to strand. Since each asset is owned by one or more oil companies (we count 69,990 ownership links), asset stranding aggregated by location of the site of expected production stoppage is defined here as *Stage 1* in a four-stage description of who bears the loss. *Stage 2* aggregates the ownership of stranded assets by fossil-fuel company and allocates the loss to the country of parent company headquarters. 3,113 active oil and gas parent companies are reported in the Rystad database, of which we identified 1,759 owning 93.4% of all losses. 1,772,899 company nodes in the global equity ownership network are curated from Bureau van Dijk's ORBIS database, which allows us to further trace the financial losses through the directed graph of ownership using a network model. Losses pass through 33,836 separate corporate ownership and fund management nodes, including most of the world's large financial companies, to 16,171 ultimate corporate owners (*Stage 3*). All losses are ultimately owned by governments and individuals, as shareholders in companies or funds (*Stage 4*). To account for company-level losses, we subtract losses from shareholder equity on the balance sheet reported in ORBIS in the most recent year (typically 2019). The Methods detail our model and data.

The financial geography of risk ownership

The net present value of stranded assets in the *Medium* realignment is US$1.4 trillion, the sum of the annual discounted losses in Fig. 1B. Fig. 2 shows how these losses propagate at the global level through the four stages across major geographic and institutional categories. US$510 billion or 36% of stranded assets as tallied by oil and gas field location (Stage 1) occur in OECD countries. OECD-based companies' losses rise to US$688 billion or almost 50% of the total at headquarters level (Stage 2), since OECD-headquartered fossil-fuel companies own or have a claim on profits from production assets across the globe. Most losses, US$1.0 trillion, are booked by stock-market listed companies. The OECD share peaks at 55% for ultimate corporate owners at Stage 3, of which US$388 billion are on financial sector balance sheets or in funds, far more than in the rest of the world. Stage 4 redistributes 2% of losses back to non-OECD countries mainly via non-OECD clients of OECD-based asset managers.

Governments directly own (including via government pension funds) losses of US$484 billion (34%), most of which originate in non-OECD countries; however, private investors are likely to lobby for compensation[15], which could increase the government share. Losses exceed equity by a total of US$129 billion in 239 companies with total debt of US$361 billion and that report comprehensive balance sheet data (the supplementary information reports figures also for companies with limited financial information). These companies experience a technical insolvency, the excess loss ultimately 'belongs' to creditors (banks and bondholders). Technical insolvency does not hinder the company from operating, as long as cash-flow is positive, but would impair collateral in case of a subsequent cash-flow insolvency and so hurt creditors. Individuals own over half of losses, although there remains uncertainty over the allocation between shareholders in companies and funds, due to data limitations (see supplementary information).

At a more fine-grained geographic resolution, Fig. 3 shows the propagation in the *Medium* realignment for the top 30 wealth-losing countries and the rest of the world (ROW). At Stage 1, discounted profits drop mostly at sites in the USA and Russia (about US$300 billion each), followed by China and Canada (about US$100 billion each). Low-cost Middle Eastern producers (Qatar, Saudi Arabia, Iran) display comparatively modest losses of less than US$50 billion because their production sites are still economical, and producers engage in *Sell-off* behavior. Countries are ordered by their losses at Stage 4 (ultimate ownership), and the uneven ordering of Stage 1 thus prefigures the dramatic redistribution along the ownership chain at country level.

Notably, several countries prominent at Stage 4 show negligible losses at Stage 1. The headquarters (Stage 2) propagate the losses to the country of incorporation of fossil-fuel parent companies. For example, France here records losses similar to those of Saudi Arabia, while the UK increases its losses by a factor of nine, to a level comparable with China and Canada. Meanwhile, some countries such as Nigeria and Kazakhstan export more than half their loss since production is mainly foreign-owned, suggesting that the location of stranded assets is an imperfect indicator of the location of financial risk ownership.

The largest net transfers at Stage 3 are to the US, where the world's largest asset managers have investments in virtually all listed oil and gas companies[16]. Other countries, such as the British Virgin Islands and Switzerland, known as tax havens[17], also receive large transfers of losses. Furthermore, losses appear on the balance sheets of financial institutions, including banks and insurers, of advanced economies that own equity stakes in oil and gas companies. Stage 4 documents a redistribution of US, and to a lesser extent UK, managed funds to clients around the world. Total transborder redistribution shown from Stage 3 to 4 is a lower bound as significant unknown ultimate owners of companies may be foreign investors, with limited information in the public domain (supplementary information for further discussion). The institutional allocation within countries sees OPEC and other countries with major state-owned companies sustaining mainly government losses, whereas elsewhere the majority of losses sit with private investors.

Risk of loss amplification in financial markets

Financial markets can amplify equity losses as they propagate through ownership networks. The most direct way is via cascades of stock market losses. Any investor in the shares of a listed oil or gas company that is itself stock-market listed (e.g., Bank of America) will amplify the shock from stranded assets on a stock index as both companies' stock market valuation is likely to suffer. Fig. 4A shows that in addition to US$1.03 trillion (73%) of total stranded assets owned by listed oil and gas headquarters at Stage 2 (see also Fig. 2), a further total of US$70 billion affects balance sheets of listed (including intermediate) corporate owners as the shock propagates through the chain. Fig. 4A also shows that funds from listed fund managers suffer from US$165 billion in stranded assets. In total, therefore, listed companies are affected either on their balance sheet or via their managed funds, by US$1.27 trillion of stranded assets, of which 19% only become apparent in the ownership chain (supplementary materials discuss the potential impact of fund losses on fund managers).

Second, any financial institution in the ownership chain – listed or not – amplifies the shock, since returns on financial assets justify these companies' valuations. Figure 4B shows that if every financial institution along the ownership chain is added up, an upper bound of US$681 billion in potential losses could affect financial companies. Up to US$400 billion is lost on financial sector balance sheets, including through reduced collateral of technically insolvent firms, an amplification of the total loss by 29%. Notably, banks are only moderately exposed, funds own a much larger share of the risk, confirming previous studies[18]. Indeed, included in the equity loss are $90 billion owned directly by pension funds, that add to an unknown but likely substantial portion of pensions invested by asset managers. Figure 4C shows risk ownership by country. The US and UK financial sectors display losses an order of magnitude larger than other countries. Some of these losses are distributed to fundholders abroad, but both countries also feature large exposure to equity losses of domestic pension funds. In this study we focus on risks from the equity transmission channel but note possible further amplification via the debt channel within the financial sector. Here, second- and further-round effects may lead to additional sell-offs, and price declines risk cascades of defaults and instability[4,19–21]. Our results show that even in the 'first round' of the equity ownership, technical insolvencies can add to credit risk by impairing the collateral of highly exposed companies.

Alternative expectations realignments

Alternative expectations realignments (Table 1 above) lead to a different size and distribution of risks. Total stranded assets in Fig. 5A increase monotonically from US$458 billion (*Benign*) to US$2.3 trillion (*Severe*) as realignments become more extreme. Under *Severe*, technical insolvency almost doubles the creditor loss to $240 billion and governments sustain 41% of losses directly. The share of OECD falls from 66% (*Benign*) to 41% (*Medium-Quota*) but increases to 46% under a *Severe* realignment. The share of direct government losses is largest under *Medium-Quota*, as OPEC's state-owned enterprises curtail production. Total losses increase (with similar demand as under *Medium*) because the loss per barrel stranded in the Middle East is larger due to lower production costs and therefore higher profitability given oil and gas prices.

Intriguingly, the total OECD loss is the same in *Medium* and Medium-*Quota* realignments, regardless of OPEC country production decisions. This invariance masks a large variation of fortunes within this heterogeneous block. North American shale and tar sand producers significantly gain from OPEC *Quota* behavior. 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[22], so curtailment of production there in favor 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. Fig. 5B reports similar heterogeneity aggregated to the headquarters country level. *Quota* instead of *Sell-off* behavior 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 behavior. At the OECD level, too, there is nothing to win, on average, for OECD wealth owners by winning production restrictions from OPEC.

OPEC member countries dramatically increase their losses in the *Medium-Quota* realignment relative to the *Medium* alignment. This makes the *Sell-off* behavior the economically rational strategy to adopt from a low-cost producer perspective. This behavior is also feasible as low-cost producers have the competitive advantage necessary to capture a larger market share[1,14,23]. Therefore, a *Medium-Quota* realignment is perhaps unlikely unless OPEC members attempt to prop up prices via output curtailment, as Saudi Arabia has historically done[24].

More widely shared risk and responsibility

It is often noted that the overwhelming majority of unused oil and gas reserves are in the Middle East[25], and that local state-owned companies own most global reserves[26]. Results for our *Medium* expectations realignment show that despite this geographic setup, currently equity investors from mostly rich OECD countries are exposed to more than half of fossil-fuel assets at risk. This financial geography of fossil-fuel transition risk holds new information for modelers and policy makers. Domestic sectoral exposure can be a weak indicator of financial risks from asset stranding, and international linkages need attention from modelers. Even if international portfolios of financial institutions are known, as is the case for supervisory datasets used to conduct stress tests, simply assuming a uniform distribution of risk across a sector in the portfolio can be misleading. In fact, we show for the equity channel that depending on the pattern of expectations realignment, different companies and geographies can have highly variant exposures to stranded asset risk due to cost differentials, international ownership, and producer behavior. Stress tests and scenario exercises may therefore benefit from forming and reporting priors on risk distributions within, not just across, sectors.

Naturally, some oil companies may diversify away from oil and gas[27]. At the time of writing this appears to be happening especially for European majors[28], however the assets then simply move to other owners with their own potential to transmit transition risk in an 'ownership leakage'. Our results highlight that it matters which types of owners are holding the risk. In line with previous research, we document a strong exposure of non-bank financial institutions, in particular pension funds, to stranded-asset risk. One concern for supervisors should be that these are less regulated than banks[29], with lower understanding of contagion potential within the financial system[18]. While our model does not currently incorporate debt channel and second round propagation, a brief comparison of our upper bound of US$681 billion financial sector exposure with the 2007-08 financial crisis is helpful. That crisis was triggered by mispriced subprime housing assets of an estimated US$250-US$500 billion on financial sector balance sheets, which amplified to US$5 trillion of GDP loss across the global economy due to the ensuing credit crunch, and a total correction of US$25 trillion in world stock market capitalization[19,30]. Here, the amounts of assets at risk owned by the financial sector as well as technical insolvency suggests that it would be imprudent to dismiss the potential of financial market disruptions from such a mispricing of fossil-fuel assets[31] as it cascades through the financial sector as well as the supply chain and the use-sectors of oil and gas[32]. In this context, even if outright financial instability is avoided, the large exposure of pension funds and ultimate beneficiaries remains a major concern. All of this is in addition to the exposure to risks that are large relative to the size of their economy by oil-dependent developing countries that additionally lose employment and government revenue[33]. In all circumstances, the political implications of loss allocations at Stages 1 and 4 are likely to be major.

Lastly, while climate mitigation thus poses major risks for finance, the reverse channel of causality must also be mentioned[34]. Finance is not neutral, and what activities get financed ultimately depends on investors' choices[35]. Our results document a major responsibility of OECD investors for resistance of fossil-energy producers to the low-carbon transition, as they have a large financial stake in the continued operation of fossil-fuel production incompatible with widespread net-zero targets[36]. Efforts to negotiate coalitions for fast low-carbon transitions should bear these interests in mind.

Methods

E3ME-FTT-GENIE model

Here we use the IAM E3ME-FTT-GENIE[37,38] framework based on observed technology evolution dynamics and behavior measured in economic and technology time series. It covers global macroeconomic dynamics (E3ME), S-shaped energy technological change dynamics (FTT)[39–41], fossil fuel and renewable energy markets[42,43], and the carbon cycle and climate system (GENIE)[44]. We project economic change, energy demand, energy prices and regional energy production.

The E3ME-FTT-GENIE integrated framework is described below. The full set of equations underpinning the framework is given and explained in ref[37]. Assumptions for all scenarios are also given.

E3ME

The Energy-Economy-Environment Macro Econometric model (E3ME) is a highly disaggregated multi-sectoral and multi-regional, demand-led macroeconometric and dynamic input-output model of the global economy. It simulates the demand, supply, and trade of final goods, intermediate goods, and services globally. It is disaggregated along 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 15 econometric regressions calibrated on data between 1970 and 2010 and simulates on yearly time steps onwards up to 2070. The model is demand-led, which means that the demand for final goods and services is first estimated, and the supply of intermediate goods leading to that supply is determined using input-output tables and bilateral trade relationships between all regions.

The model features a positive difference between potential supply capacity and actual supply (the output gap), as well as involuntary unemployment of the labor 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[45,46] 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[45,46]. 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[37]. Final energy demand and the energy sector as a whole is treated in detail similarly but separately in physical energy quantities.

FTT

E3ME estimates energy demand and related investment in all sectors and fuel users of the global economy with the exception of the four most carbon-intensive sectors (power, transport, heat, steel), for which technological change is modelled with substantially higher definition using the Future Technology Transformations (FTT) family of models. FTT is a bottom-up representation of technological change that reproduces and projects the diffusion of individual technologies calibrated on recent trends. FTT:Power[39] 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[40,47] represents the diffusion of petrol, diesel, hybrid, compressed natural gas and electric vehicles and motorcycles in 3 engine size classes, with 25 technology options. FTT:Heat[41] looks at the diffusion of oil, coal, wood and gas combustion in households as well as resistive electric heating, electric heat pumps and solar heaters in 13 technology options. Lastly, FTT:Steel represents all existing steel-making routes based on coal, gas, hydrogen, and electricity in 25 types of chains of production. Technologies not represented in FTT currently have very low market shares, which necessarily implies, in a diffusion framework, that their diffusion to such levels that would invalidate the present scenarios is highly unlikely within the policy horizon of 2050 (e.g., nuclear fusion, hydrogen mobility).

FTT is a general framework for modelling technology ecosystems that is in many ways similar to modelling natural ecosystems, based on the replicator dynamics equation[48]. 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[48,49]. 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[49].

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 *ref*[40]).

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.[50], 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[38] based on cruder and more restrictive stability assumptions, that renewables can penetrate the grid more rapidly and effectively.

GENIE

GENIE, an intermediate complexity Earth system model, simulates the global climate carbon cycle to give the future climate state driven by CO_2 emissions, land-use change and non-CO_2 climate forcing agents. It comprises the GOLDSTEIN (global ocean linear drag salt and temperature equation integrator) 3-D frictional geostrophic ocean model coupled to a 2-D energy moisture balance atmosphere, a thermodynamic-dynamic sea-ice model, the BIOGEM ocean biogeochemistry model, SEDGEM sediment module, and the ENTSML (efficient numerical terrestrial scheme with managed land) dynamic model of terrestrial carbon storage and land-use change. GENIE has the resolution of 10º x 5º on average with 16 depth levels in the ocean and has here been applied in the configuration of refs[44,51] (see references therein).

The probabilistic projections are achieved through an ensemble of simulations for each emissions scenario using an 86-member set[52] 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[53] (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 Global Net-zero scenario (details below) reaches zero 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 (Global Net-zero and EUEA Net-zero scenarios) and RCP 6.0 (InvE and TDT scenarios). GENIE results for exceedance likelihoods for climate thresholds and median peak warming for each scenario are given in Table S1.

The GENIE ensemble has been validated[52] 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.

Scenarios

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.

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.

Global Net-zero: 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, as well as in the rest of the World as a whole.

Power generation:

- Feed-in tariffs for onshore and offshore wind generation, but not solar PV.
- Subsidies on capital costs for all other renewables (geothermal, solar CSP, biomass, wave and tidal) with the exception of hydro and solar PV.
- Hydro is regulated directly in most regions to limit expansion, given that in most parts of the world the number of floodable sites is limited and flooding new sites faces substantial resistance from local residents.
- Coal generation is regulated such that no new plants not fitted with CCS can be built but existing plants can run to the end of their lifetimes. However, all remaining coal plants are shut down in 2050.
- Public procurement is assumed to take place to install CCS on coal, gas, and biomass plants in many 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 IEA49, 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 $300-500/t$CO_2$ in 2033, going down thereafter following different country inflation rates to $250-350/t$CO_2$ in 2050 and $150-200/t$CO_2$ in 2070.

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

Sell-off (SO) and quota (QU) behavior 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 behavior. 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.

Energy supply

The allocation of oil and gas production, revenues and income is estimated by integrating data from the Rystad Ucube[54] dataset in the form of breakeven cost distributions at the asset-level into the integrated assessment model E3ME-FTT-GENIE. The Rystad dataset documents 43,439 oil and gas existing and potential production sites worldwide covering most of the current global production and existing reserves and resources. It provides each site's breakeven oil and gas prices, reserves, resources, and production rates. Rystad projected rates of asset production and depletion[55] are not used in our model. Instead, our projections are based on the energy market model of E3ME-FTT-GENIE, derived from a dynamical fossil fuel resource depletion model[37] that does not rely on Rystad assumptions.

The energy market model assumes that each site has a likelihood of being in producing mode that is functionally dependent on the difference between the prevailing marginal cost of production and its own breakeven cost. The marginal cost is determined by searching, iteratively with the whole of E3ME, for the value at which the supply matches the E3ME demand, which is itself dependent on energy carrier prices. Dynamic changes in marginal costs are interpreted as driving dynamic changes in energy commodity prices.

The Rystad dataset includes information about each asset's location (country of production), the owners of the asset (amongst 3,113 fossil fuel companies) and the country of the owners' headquarters. For each asset, annual levels of oil and gas production, revenue and income are estimated per scenario. Based on the ownership structure of each asset, these values are aggregated at the firm level (fossil fuel companies), at the country of production and at the headquarters country. We estimate stranded assets by comparing expected discounted profit streams under a realignment from a baseline to policy scenario at a high level of disaggregation (asset-level). Then, by aggregating the losses at the firm and country level, we can study the loss propagation from the asset level to the fossil fuel companies, and from the country of production to the headquarters countries (see detail below).

The regional production levels are based on production to reserve ratios, which are exogenous parameters representing producer decisions. Initial values are obtained from the data to reproduce current regional production according to the reserve and resources database. Future changes in production to reserve ratios for each region are determined according to chosen rules for the Quota and Sell-off scenarios. Changes are only imposed to production to reserve ratios of OPEC countries, in order to either achieve a production quota that is proportional to global output (Quota scenario, thereby reducing production to reserve ratios accordingly), or attempting to maintain constant absolute production while global demand is peaking and declining (Sell-off scenario, thereby increasing production to reserve ratios). While oil and gas output in OPEC are thus altered by these parameter changes representing producer decisions, this change affects the allocation of production globally so as to match global demand.

Renewables are limited through resource costs by technical potentials determined in earlier work[42].

We supplement the Rystad assets with additional oil and gas resources data used in earlier versions of E3ME that are based on national geological surveys and tapped as Rystad reserves decline in the future. This hardly affects our 15-year horizon but where such resources are tapped, the asset is split among companies active in the asset's country in 2019 according to their 2019 share in national reserves. We apply the same method of ownership allocation to Open Acreage assets in Rystad.

Company ownership

The company financial and ownership data are from Bureau van Dijk's ORBIS database. They were downloaded in January 2020, typically reporting financial data from 2019 and, where not yet available, from 2018. It is neither feasible nor desirable to download the entire database: 300 million companies, with the download interface allowing about 100,000 companies per download[1] and most companies small with missing financial and ownership data, and therefore separate from an ownership network. Instead, the download protocol relies on downloading first important (large) companies and then using a snowballing method to capture other companies that are reported as owners of these large companies but were not downloaded. In the first step, data for every company labelled 'large' or 'very large' was downloaded, as well as the 1,759 companies that were matched with Rystad oil & gas companies. Large and very large companies include all companies that have one of operating revenue > USD13 million, total assets > USD26 million, employees >149 or a stock market listing. Subsequently, via the snowballing method, all companies were downloaded that were listed as shareholders but were not among the initially downloaded companies. This iterative procedure was performed 6 times. Ultimately, the download resulted in 1,772,899 companies (including subsidiaries and their parents) connected by 3,196,428 equity ownership links, with a residual 12,876 owners for which no owners were in turn found in the database. Most ownership links connect companies; however, per country there is one node for individuals and a handful of other summary nodes reflecting partially missing information (e.g. unknown investors that are known to be pension funds), thereby summarizing a much larger number of nodes into one for every country. A concordance of types of companies, shareholders, and types of financial firms with ORBIS indicators is in Table S2 of the supplementary information. Further discussion of limitations of the data are in the supplementary text below.

Matching Rystad with Orbis data was done manually due to widely varying spelling conventions. For instance, many companies in Rystad were abbreviated, like NNPC, which is the Nigerian National Petroleum Corporation in Orbis. In total, 1,759 Rystad companies could be matched unambiguously, accounting for 93.4% of the total discounted profit loss calculated in Rystad for the *default* realignment.

Equity links occasionally summed to more than 100% of company ownership, most likely because the ORBIS dataset does not relate to a specific snapshot in time. When this happened, ownership fractions were scaled proportionately to sum to 100%. When ownership links summed to less than 100% ownership, the residual ownership would remain in the company as ultimate corporate shareholder (stage 3) and assigned on a country-by-country basis to an 'unknown' owner node in stage 4 or a 'government' node if the company is a state-owned company.

Imputation of missing company data

Roughly 1.3 million of the 1.77 million companies in the network have some missing balance sheet data. For the network analysis, for all companies we need to know the equity E to determine insolvencies and the total assets A to derive leverage. We estimate missing data from statistical models that are built from the 460,000 companies that have all data for equity E, total assets A, revenue R, number of employees W and size S.

Equity and total assets are the best predictors of each other (correlation of log-transformed

[1] The exact number of rows permitted depends on the number of variables selected.

variables 0.90). Therefore, if only one of these data is missing for a company, we estimate it from the other. If neither is present, we use revenue R to estimate assets A (correlation of log-transformed variables 0.71) and use the estimated A to estimate equity E. If none of these data are present, we estimate A (and then E) from the number of employees W (correlation of log-transformed variables 0.45). Linear regressions of natural log-transformed variables are used for these estimates, i.e.

$$\ln v_1 = a + b \ln v_2 \qquad \text{Eq. 1}$$

We apply these regressions stochastically in order to avoid artificially reducing the variance of the equity distribution, calculating the mean prediction from the regression relationship, and then adjusting the estimate by drawing randomly from the residual standard error. When applying the regressions, we enforce the inequality $A \geq E$, by simply applying $E = \min(A, E)$. The regression coefficients and standard errors are tabulated in Table S3.

All of these four data are missing for ~340,000 companies, and for these we estimate total assets using the categorical variable size S (large, medium, small, very large). For these companies, we do not use regression, but instead draw A randomly from a normal distribution of the log-transformed data which depends upon size. Randomly drawn assets less than $100,000 are assigned a value of $100,000. We then estimate equity from the regression against A (table S4), again enforcing the inequality $A \geq E$ by applying $E = \min(\mathrm{A}, \mathrm{E})$.

The imputation code is available with the supplementary materials.

<u>Asset-specific and aggregated stranding</u>

We now define an asset, indexed by k in $1,\ldots,K$, as the ownership by an oil or gas company of a share of the production of a particular oil or gas field including via service and revenue sharing contracts that give companies a claim on the share of the profits of that field *(21)*. There are 43,439 unique oil and gas fields with nonzero reserves, and these are partitioned into K = 69,990 ownership shares and hence assets. Oil and gas fields have a production profile at each time *t* (measured in years) for scenarios *a, b*. Revenue at asset *k* at time *t* in scenario *a* is defined as the price of oil or gas, $p_{t,a}$, multiplied by the output, $q_{k,t,a}$, from the oil or gas field accruing to the owner of *k*. Income is estimated in the same way, by subtracting asset-level costs, $c_k(q_{k,t,a})$, which are a function of the quantity produced, from revenue. Thus, we calculate the net present value (NPV) of asset-level profit losses, which we call asset stranding, A (a positive number is a profit loss and so stranding is positive), that occurs by an expectations realignment, from baseline, *a*, to policy scenario, *b*, as

$$A_{k,a,b} = \sum_{t=t_0}^{t_0+T} \left[\left(p_{t,a} q_{k,t,a} - c_k(q_{k,t,a}) \right) - \left(p_{t,b} q_{k,t,b} - c_k(q_{k,t,b}) \right) \right] (1-r)^{t-t_0} \qquad \text{Eq. 2}$$

where r is the discount rate, which we set to 6%, t_0=2022 is the time of change of expectations and T=14 years the horizon over which we assume companies to include future expected profits in their balance sheet.

These stranded assets are then aggregated at the firm level (fossil fuel companies) or country-level (country of production and headquarters country), using the database information described above. Thus, we calculate NPV of asset losses, σ, from expectations realignment for some group, G, of assets, from baseline *a* to policy scenario *b* as

$$\sigma_{G,a,b} = \sum_{k\in \mathrm{G}} \mathrm{A}_{k,a,b} \qquad \text{Eq. 3}$$

where G can be defined by company ownership and/or geography, up to G={1,…,K} for global asset stranding. To arrive at the loss distribution in Stage 1, we partition the set of stranded assets according to their geographic location. To move to further stages, we first partition stranded assets according to their fossil-fuel company ownership. In particular, if the *i*^th^ fossil fuel company owns the set of assets C_i we define the stranded assets of company *i* as

$$\sigma_{i,a,b} = \sum_{k\in C_i} A_{k,a,b} \qquad \text{Eq. 4}$$

This distribution of stranded assets across fossil fuel companies serves as the input for the propagation of ownership risk in our network model.

Network propagation

Stranded assets reduce the value of some assets to zero. When these assets are owned by another entity, the loss propagates to them. We call this propagation a 'shock' and we set up a network model to trace the propagation of these shocks, to ultimate owners. We have a network comprising N = 1,772,899 companies connected by 3,196,429 equity ownership links. Each link connects an owned company i with each of its owners j, and is defined by the fraction of equity f_{ij} of company i owned by company j. The initial shocks from Eq. 4, which are $s_i^0 = \sigma_{i,a,b}$ for i =1,…N, are distributed across the 1,759 fossil fuel companies within the network (yielding the loss distribution at Stage 2 and propagated through the ownership tree, to get to Stage 3.

At each iteration *l* we work through the owners and their respective ownership links in turn and transmit any shock s_i in owned company i to its owners, determined by either f_{ij}, the fractional holding of company i by company j, or f_{ij}^m, the fraction of company i owned by the managed funds of company j. Thus the iteration step for owner *j* can be expressed as

$$s_j^{l+1} = s_j^l + \sum_i f_{ij}(s_i^l - s_i^{l-1}) \qquad \text{for all } j \qquad \text{Eq. 5}$$

$$m_j^{l+1} = m_j^l + \sum_i f_{ij}(s_i^l - s_i^{l-1}) \qquad \text{for all } j \qquad \text{Eq. 6}$$

where m_j is the shock to managed funds, which are not propagated further. Note that s_j^l is the total shock experienced at company *j* accumulated up to iteration *l* but only the shock increase at the previous iteration is propagated onwards along the ownership chain at each iteration.

We apply these shocks to a company's balance sheet. We reduce the asset side by the amount of the shock, and to keep the sheet balanced, we reduce the liability side by subtracting an equal amount of equity. If the shock s_j felt by any company exceeds its equity, that company is considered technically insolvent, and any excess shock is not transmitted to the owners of the company. The excess shocks are accumulated to totals for the country and sector of the technically insolvent company (or as a domestic creditor liability in Stage 4). Fund managers' balance sheets are not affected by a shock to their managed funds. We continue looping until convergence, defined to be when the total transmitted shock during an iteration, $\sum_j (s_j^l - s_j^{l-1})$, is less than $100,000. At convergence, we discontinue the propagation algorithm, and then sum the shocks in all companies to derive the aggregated shock at Stage 3.

To derive the accounting summary (which integrates shocks and allocates them by country and sector at stages 3 and 4), we conservatively assume that the complete chain of ownership is consolidated into the ultimate corporate owner, so that no shock is ever counted twice, i.e. it is not counted for companies in intermediate steps of the ownership chain. To do so we weight the shock in each company by the fraction of its equity that is not owned by another company in the network. E.g. if company A is 30% owned by no other company (either because of lack of ownership data or because it is owned by ultimate owners such as individuals), 30% of the shock to that company will be recorded in the company itself as the ultimate corporate owner, while 70% of the shock will be recorded in the ownership chain. The globally integrated weighted shock is thus calculated as

$$S = \sum_{i=1,N} (1 - F_i) s_i + m_i \qquad \text{Eq. 7}$$

where $F_i = \sum_{j=1,N} f_{ij}$ is the fraction of each company that is owned by other companies in the network, noting that this definition means S is identically equal to the input shock $\sum_{i=1,N} \sigma_i^0$. By summing over subsets of companies, we arrive at the loss distribution at stage 3.

Finally, to allocate losses from ultimate corporate to ultimate owners (Stage 4) we pass on the shock in ultimate corporate owners to governments, shareholders (both via equity and fund ownership), creditors where losses exceed equity on balance sheets, and, where no ultimate owner is given for equity losses, to an 'unknown' ultimate owner.

Note 1: In the raw downloaded network data there were ~100 ownership loops of two or more companies through which companies own each other (most simply when company A owns company B which owns company A). These are unrealistic data errors which may for instance arise from the fact that ORBIS data do not relate to a precise snapshot in time. We searched for these 'bad links' by applying a uniform shock to every node in the network and iterating forwards. Ownership loops do not converge but instead amplify a shock to infinity. Using this approach, we identified 391 connections within circular loops, and we bypass these connections during the shock propagation. All other loops converge according to a geometric series with a common ratio below 1.

Note 2: Two alternative sets of imputed data were tested to check the robustness of our results with respect to uncertainty about company equity size driven by stochastic imputation of missing data (see above). The only effect of the size of a company's equity in the propagation algorithm is to determine whether or not a company is shocked hard enough to make it technically insolvent (at which point the shock stops propagating and is accounted for as a shock to unknown creditors rather than to the company's owners, see also supplementary text below). The shocks to unknown creditors in the default scenario agreed to within 5% between two alternative imputed networks ($402 billion and $417 billion). These two imputed datasets generated 1,479 and 1,448 insolvencies respectively and 1,303 of the insolvent companies were common to both analyses. These comparisons suggest that imputation uncertainties are modest at the highly aggregated level of results we provide, though clearly caution is demanded when interpreting outputs at the company level. Each company is associated with a flag that identifies whether its data has been imputed to aid such interpretation.

Note 3: To discuss how stock market-listed companies and financial companies are affected in the main text section "Risk of loss amplification in financial markets", we make one modification to the assumption of complete consolidation of the ownership chain into the ultimate parent company. Specifically, in main text Fig. 4, we do not integrate weighted shocks (Eq. 7), but instead integrate them as the unweighted sum $\sum_{i=1,N} s_i$. Since stock market indices record listed companies, regardless of where they are located in our order of propagation, this method allows us to calculate the impact of our realignments on the stock market. Similarly, since potentially all financial companies in an ownership chain are affected by the loss, this provides an upper bound to the effect on the financial system. Since some financial companies in the ownership chain may be subsidiaries of others, however, without an independent balance sheet, this complete disaggregation of companies can be seen as an upper bound of the effect on the financial system, while the complete aggregation into an ultimate corporate owner can be seen a lower bound.

The network code is available with the supplementary materials.

Data availability

Data from Rystad (on energy supply assets) and Orbis (on company owernship) were accessed under license and cannot be shared. Data is available, however, on reasonable request and with permission from Rystad and Orbis respectively from the authors. An implementation from 2018 of the E3ME-FTT-GENIE scenarios will be available with the IPCC's 6th Assessment Report database.

Code availability

The code of the network model and of imputing missing financial information is included with the summary information. The code that generates the network inputs from the E3ME-FTT-GENIE scenarios and from the company database is available from the authors on reasonable request. The code used by E3ME-FTT-GENIE to generate the underlying scenarios is available from the authors on reasonable request. The model is described in detail in ref[37].

Acknowledgements: We thank Nina Seega at CISL for critical support in effectively engaging stakeholders, Aaron Cantrell, Darren Hawkins, Isabella Weber, colleagues at ORTEC and participants at two stakeholder workshops for insightful discussions, and Aaron Cantrell, Yannis Dafermos, Edo Schets and Romain Svartzman for feedback on an earlier draft. GS, PH, JFM, PS, HP, NRE and JV acknowledge funding from the Natural Environment Research Council grant NE/S017119/1, PH and NRE from the Leverhulme Research Centre Award (RC-2015-029) from the Leverhulme Trust, and PS from the Prince of Wales Global Sustainability Fellowship supported by Paul and Michelle Gilding.

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Fig. 1. Changes in global profits and stranded assets from *Default* realignment of expectations. (A) Global revenue and profit trajectories over 2018-2036 in *Medium* realignment's initial and revised expectations. Green shades indicate reduction in revenue and profits under revised relative to initial expectations. **(B)** Annual asset stranding as a result of *Medium* realignment of expectations in 2022. The first year has negative stranded assets as sell-off behavior generates windfall profits for low-cost producers.

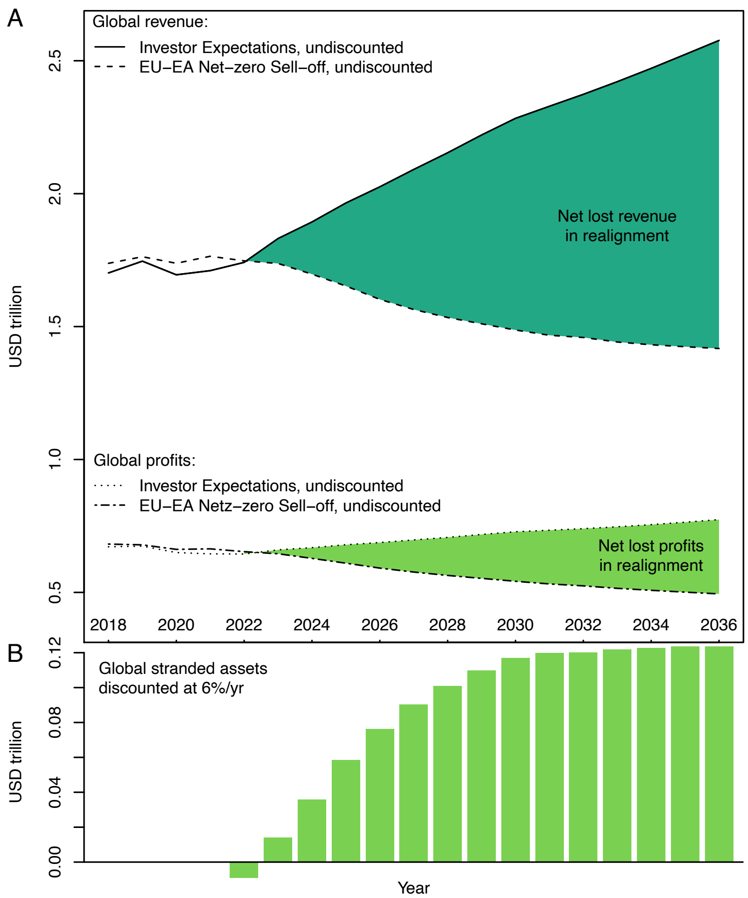


Fig. 2. Ownership chain of stranded assets by OECD/non-OECD geography and major institutional categories. Each bar represents $1.4 trillion in losses from *Medium* expectations realignment at successive ownership stages, divided into OECD and non-OECD losses, and within each geography into major institutional categories.

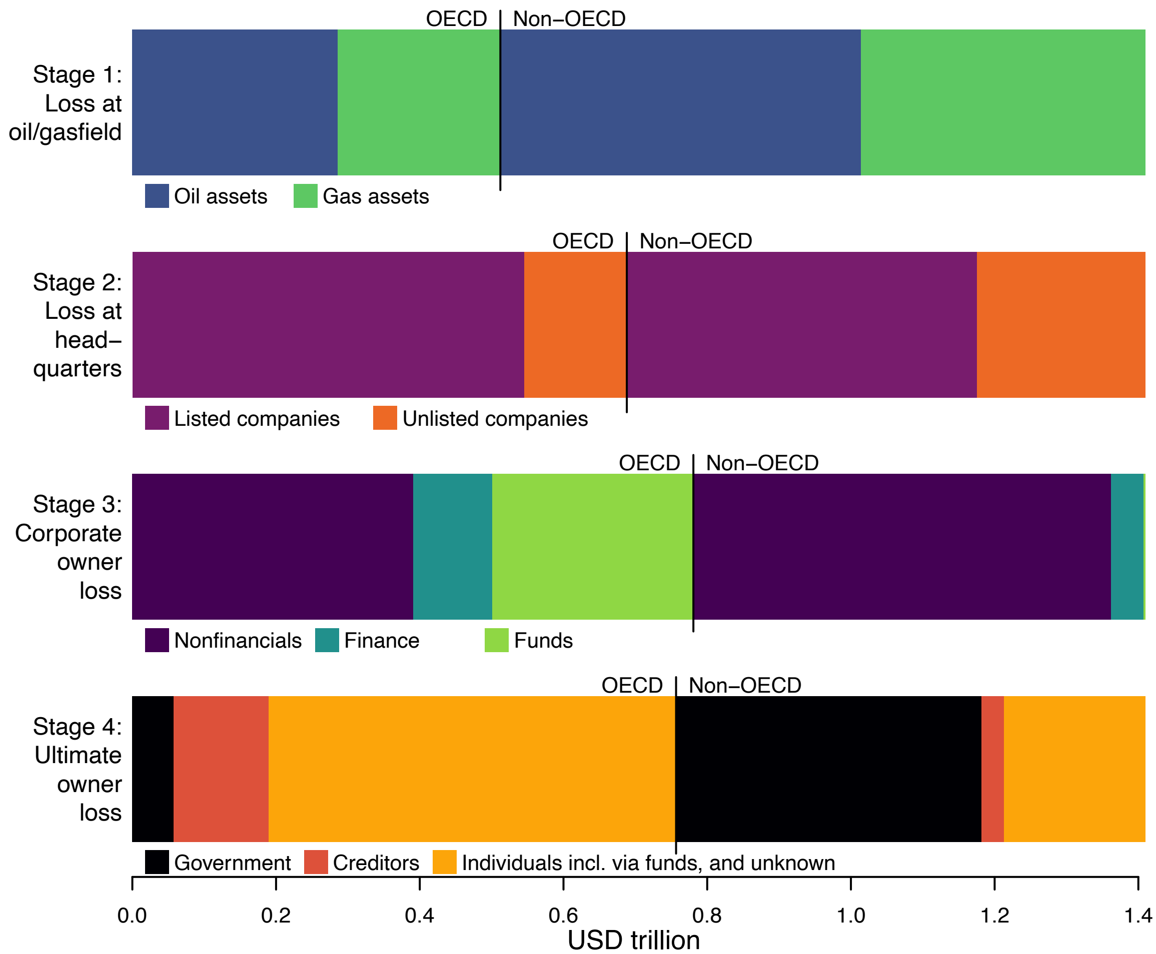


Fig. 3. Ownership chain of stranded assets by country and institutional category. Lost profits under *Medium* realignment allocated to **(A)** the country where stranded oil and gas fields lie (Stage 1); **(B)** fossil-fuel company headquarter country (Stage 2); **(C)** ultimate corporate owners by country by sector (Stage 3); **(D)** ultimate owners by country and institutional affiliation (Stage 4). Countries displayed in descending order of Stage 4 losses. Markers indicate country loss totals at previous stages.

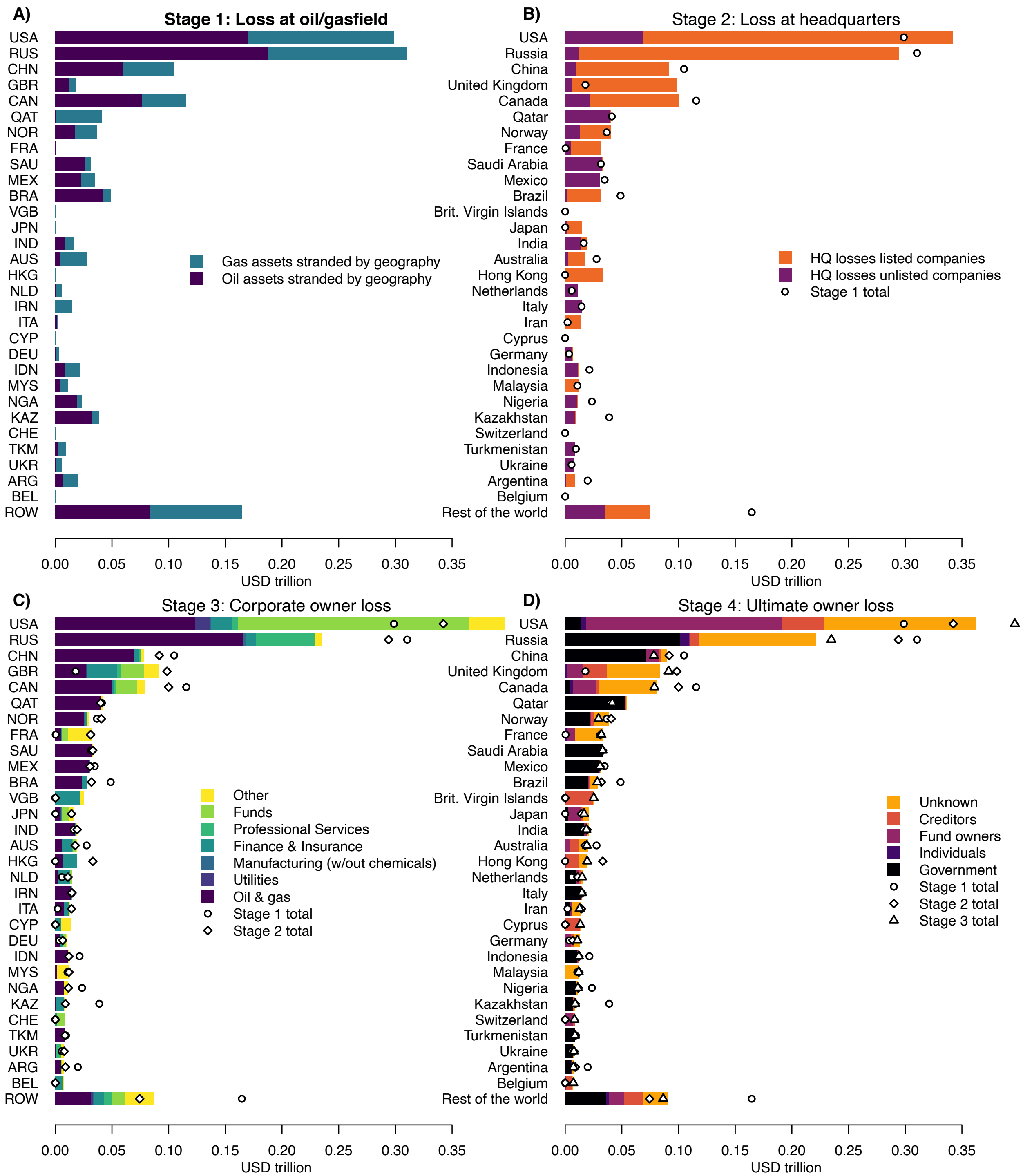


Fig. 4. Cumulative losses by listed companies and in financial markets: (A) Global losses affecting stock market-listed fossil fuel headquarters, intermediate and ultimate corporate owners, and listed fund managers in the *Medium* realignment. **(B)** As (A) but for all financial institutions. Legend is in part (C). Creditors equal negative equity, reducing creditors' collateral. **(C)** Like (B) but split by country. The y-axis is compressed between USD 0.10 and USD 0.28 trillion.

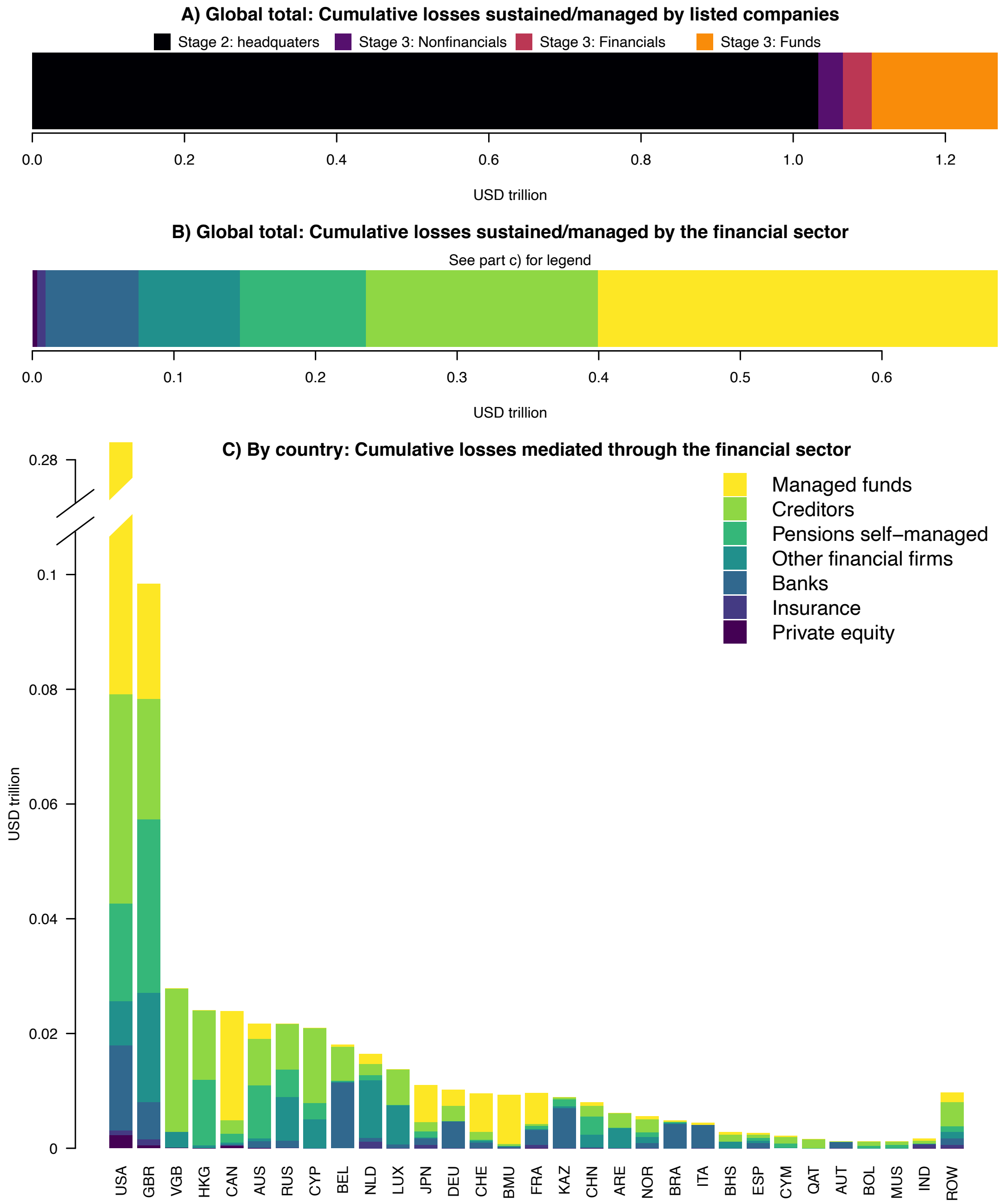
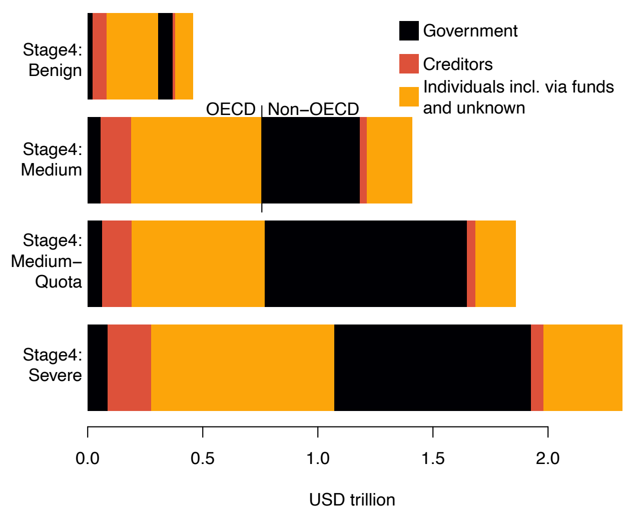


Fig. 5. Sensitivity to different expectations realignments. (A) Major loss categories at Stage 4 under four realignments. **(B)** Proportional change in major headquarter country losses at Stage 2 compared to *Medium* realignment in 3 alternative realignments. Domain truncated at plus and minus 100%. Larger values indicated with arrows. Values below -100% imply gain relative to baseline.

(A)



(B)

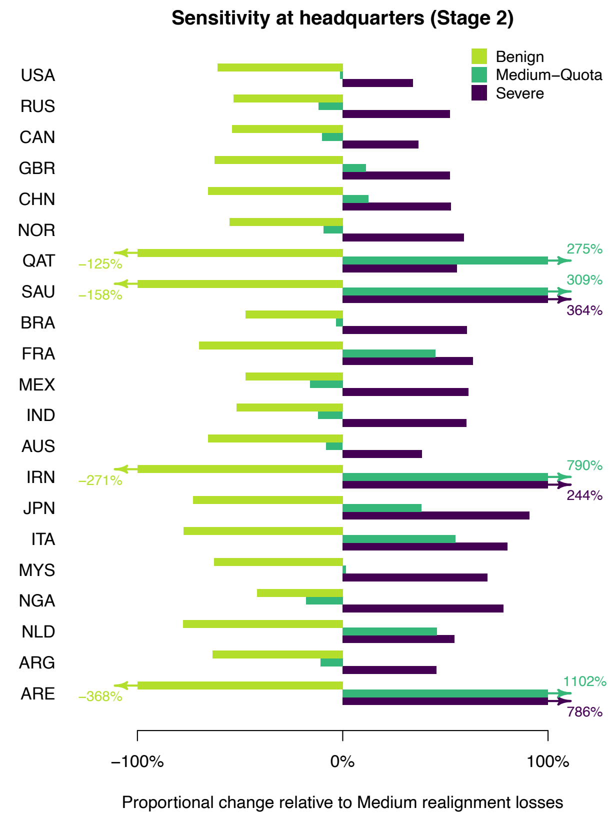


Table 1. Features of realignments of expectations.

Realignment	Initial expectations (baseline)	Revised expectations (policy scenario)	Producer behavior	Closest NGFS scenario couple
Default	Investor expectations (InvE): 3.5ºC median warming	EU-EA Net-zero: 2ºC median warming	Sell-off: Low-cost producers flood markets	From *Current policies* to *Below 2ºC*
Benign	Technological Diffusion Trajectory (TDT): 2.6ºC median warming	EU-EA Net-zero: 2ºC median warming	Sell-off: Low-cost producers flood markets	From *NDCs* to *Below 2ºC*
Severe	Investor expectations (InvE): 3.5ºC median warming	Global Net-zero: 1.5ºC median warming	Sell-off: Low-cost producers flood markets	From *Current policies* to *Net Zero 2050*
Medium-Quota	Investor expectations (InvE): 3.5ºC median warming	EU-EA Net-zero: 2ºC median warming	Quota: Countries maintain current market shares	From *Current policies* to *Below 2ºC*

Note: 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, resulting in possibly different oil price, revenue, and asset stranding profiles.

Supplementary Information:

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

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Contents:

Supplementary Text

<u>Choice of discount rate</u>

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[1]. 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.[2] 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[2]. 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[3], which can be explained by varying country risk premiums[4]. Ultimately discount rates are set by each organization itself. We believe that 6% reflects a reasonable average from an investor's perspective.[3]

Sensitivity of global stranded assets to variation in the discount rate is provided in Table S5. 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.

Technical insolvency including companies with limited information

When asset losses exceed shareholder equity, a company records negative equity on its balance sheet, and its debt is greater than its assets, impairing some of the collateral backing the debt. Such companies are called 'technically insolvent', but are still operational as long as they have enough cash flow to service their debt[5]. 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.

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 ownership share 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

[2] Discount rates in the oil and gas sector for their own project decision making can be significantly higher, especially for unconventional and offshore projects[11].
[3] 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.[12], who use a 5% discount rate to calculate the levelized cost of electricity.

of assets under management (see, e.g., *ref*[6]). 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.

Limitations of ownership data

Our results concerning redistribution of losses contain a considerable degree of uncertainty about ultimate ownership. As concerns geography, much suggests that the redistribution towards high-income, fossil energy importing countries shown in the main text is a lower bound. Similarly, it is likely that the exposure of the financial sector 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[7,8]. Similarly, Orbis only reports equity shareholdings of large investors, which may undercount overall foreign direct investment, which is more likely to flow from high-income to lower-income countries than the other way around[9]. On institutional redistribution, there is typically an underreporting of actual shareholders in the data, leading to a considerable share of losses at stage 3 accruing to ultimate corporate owners in the oil and gas sector and unknown ultimate owners at stage 4, due to our convention to keep the 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[10], there were only 123 current shareholders reported in the Orbis database at time of download that held 58.14% of ExxonMobil's stock. Since individual 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, too. This means that part of the 'unknown' ultimate owners at stage 4 is likely to be a placeholder for unknown 'fundholders' at stage 4 of our analysis.

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. Finally, ownership shares can also exceed 100% in rare cases. This occurs because Orbis records changes to ownership on an ongoing basis but give themselves one trailing year to implement 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.

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Table S1.

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

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

Table S2.

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,

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

Table S3.

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

Regression coefficients (Equation 1)

Table S4.

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

Total asset A distributions by company size S.

Table S5.

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

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