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

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The distribution of ownership of transition risk associated with stranded fossil-fuel assets remains poorly understood. We calculate that global stranded assets as present value of future lost profits in the upstream oil and gas sector exceed US$1 trillion under plausible changes in expectations about the effects of climate policy. We trace the equity risk ownership from 43,439 oil and gas production 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 and financial markets. The ownership distribution reveals an international net transfer of more than 15% of global stranded asset risk to OECD-based investors. Rich country stakeholders therefore have a major stake in how the transition in oil and gas production is managed, as ongoing supporters of the fossil-fuel economy and potentially exposed owners of stranded assets.

The transition to a global low-carbon economy entails deep and fast structural change that poses challenges for economic adjustment everywhere1,2. One key challenge both for the real economy and financial markets is the fast phase-out of fossil-fuel production, which will necessitate 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 analysed scenario-contingent early retirement of fossil-energy supply facilities, 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 assets3–5. 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 change6–8. 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 financial networks.

Asset stranding becomes a social concern where these effects destabilize financial markets with negative repercussions in the real economy such as on pensions and government finances9,10. The (premature) obsolescence of capital stock is a recurring feature of dynamic, capitalist economies, as new products and industries replace old ‘sunset’ ones, and is not typically associated with systemic financial risks because the financial system is buoyed by the new ‘sunrise’ sectors2. Yet, in the case of the low-carbon transition, the rate of industrial change required for achieving a 2 °C, let alone 1.5 °C, goal is so large11 that the rapid collapse of fossil-fuel ‘sunset’ industries presents major transition risks11–13.

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 and fund managers) all the way to the 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. 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 have both a larger stake in continued fossil-fuel production and greater exposure to stranded assets than the literature has so far suggested.

Estimating stranded assets and wealth losses

We operationalize asset stranding as the effect of a change in expectations on the present value of discounted future profit streams. We calculate profits given expectations 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 depends on its present-day production cost and reserve profile in relation to the expected market-clearing oil price. If investor expectations for total demand for oil and gas fall, some assets must become unprofitable relative to initial expectations; that is, the oil or gas price falls below the break-even price for those assets.

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Once the stranded assets are determined, we establish a four-stage description of who bears the loss. At stage 1, asset stranding is attributed to the country where sites are located. Stage 2 aggregates the ownership of stranded assets by fossil-fuel company. Each asset is owned by one or more oil companies (we count 69,990 ownership links). The loss is allocated to the country where the parent company has its headquarters. Out of the 3,113 active oil and gas parent companies reported in the Rystad database, our analysis identifies 1,759 as owning 93.4% of all losses. The 1,772,899 company nodes in the global equity ownership network are curated from Bureau van Dijk’s ORBIS database. At stage 3, this 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. At stage 4, we track all losses to their ultimate owners, governments and individuals, as shareholders or outright owners of companies or investors in funds, including pension funds. 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). We detail our stranding and loss propagation models in Methods.

To quantify profit losses from changing expectations, we use an initially expected (baseline) scenario of global oil and gas demand and prices, upon which prior financial value has been estimated, and a revised scenario representing updated expectations resulting from climate policies (policy scenario). We call the expectations shift a realignment.

Our focus is on the medium realignment, in which the baseline scenario follows IEA’s WEO 2019 current policies scenario, consistent with 3.5 °C median warming in the 21st century. We refer to this baseline as investor expectations, InvE. The policy scenario, termed EUEA, incorporates the stated policies of the European Union (EU) and East Asia (EA) to reach net-zero greenhouse gas/CO₂ emissions by 2050/2060, respectively, noting that non-SCO₂ emissions are exogenous and follow RCP2.6 (Methods). The EUEA scenario has a median warming of 2°C. In line with the IEA’s projections, the policy scenario features 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.

We assume expectations to realign in 2022. Because the expectations underlying current asset prices vary, evolve continuously and are extremely difficult to quantify, we consider three other possible realignments, each yielding a magnitude and distribution of risk ownership.

Oil and gas demand and prices in baseline and policy scenarios are produced by the E3ME-FTT-GENIE integrated assessment modelling framework, which like CGE models provides sufficient sectoral disaggregation, while remaining theoretically consistent with asset stranding. It couples a macroeconomic 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). The embedded energy market model determines which assets supply demand (Methods). The overall model and alternative scenarios are presented in Supplementary Notes 1 and 2.

We illustrate our calculation of total stranded assets in the medium realignment (Fig. 1a). Annual revenue in the InvE baseline grows, while in the EUEA policy scenario it reaches an early peak and falls steadily due to both lower quantities and prices. Upstream oil and gas lost profits, a subset of lost revenue after subtracting labour and intermediate input cost, is represented by the light green wedge. We discount differences in expected profits by 6% yr⁻¹ (Fig. 1b) to calculate the present value of stranded assets, which sums to US$1.4 trillion (see Supplementary Note 3 for a sensitivity analysis about the choice of discount rate). 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 yr horizon of

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**Fig. 1 | Changes in global profits and stranded assets from medium realignment of expectations. a.** Global revenue and profit trajectories over 2018–2036 according to the 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 behaviour generates windfall profits for low-cost producers.
profits, and present-value accounting translates deflated profit expectations into lower asset value.

Propagation of risk ownership
The ownership of the global US$1.4 trillion stranded assets propagates through the four stages across major geographic and institutional categories (Fig. 2). Geographically, losses are transferred to Organisation for Economic Co-operation and Development (OECD) countries. A total of US$552 billion, or 39.2%, of physical stranded assets sit in OECD countries (stage 1). Losses on balance sheets of OECD-headquartered oil and gas companies rise to US$728 billion or 51.7%, since these companies own or have a claim on profits from production assets across the globe (stage 2). The OECD share peaks at 57.1% for ultimate corporate owners at stage 3 due to financial investments of OECD-based companies in oil and gas companies elsewhere. Stage 4 redistributes 1.6% of losses back to non-OECD countries mainly via non-OECD clients of OECD-based asset managers.

Institutionally, most losses, US$1.0 trillion, are booked by stock-market-listed oil and gas companies. At stage 3, the financial sector owns losses of US$438 billion, 88% of which sit in OECD countries. At stage 4, governments directly own (including via pension funds) losses of US$484 billion (34%), most of which originate in non-OECD countries. Private persons thus own over half the losses. Losses exceed equity by a total of US$129 billion in 239 companies with a total debt of US$361 billion, leading to technical insolvencies. At stages 3 and 4, some uncertainty remains over the loss allocation due to data limitations (discussed in Supplementary Notes 4 and 5).

Physical stranding (Fig. 3a) is largest in the United States 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 remain profitable and they engage in sell-off behaviour. Several countries show different levels of exposure across stages, implying net exports of financial risk. For example, in stage 2 France imports nearly all of its losses, which are similar in magnitude to those incurred by Saudi Arabia at stage 1, while the United Kingdom increases its losses by a factor of nine, to a level comparable with China and Canada (Fig. 3b). Meanwhile, some countries such as Nigeria and Kazakhstan export more than half their losses to foreign companies, demonstrating that the location of physical assets is an unreliable indicator of the location of financial risk ownership.

The largest net transfers at stage 3 are to the United States, where the world’s largest asset managers hold investments in virtually all listed oil and gas companies (Fig. 3c). Other smaller countries, such as the British Virgin Islands and Switzerland, viewed as tax havens, also receive large transfers of losses. Stage 4 documents a redistribution of US- and UK-managed fund losses to clients around the world (Fig. 3d). Net trans-border redistribution shown from stage 3 to stage 4 is a lower bound as a notable portion of unknown ultimate owners of companies may be foreign investors, with limited information in the public domain (Supplementary Notes 4 and 5). The distribution between government and individuals within countries depends mainly on the presence of state-owned companies.

The international net transfer to OECD-based entities of a sixth to a fifth of all losses between the physical stranded assets and the corporate owners’ balance sheet is robust across realignments and represents up to 60% of stage 1 OECD losses (Extended Data Fig. 1). 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 and (Extended Data Figs. 2–8 and Supplementary Notes 6–8). Our results are overall consistent with those of the Carbon Tracker Initiative for 14 major oil and gas companies (Supplementary Note 9 and Supplementary Fig. 1) and our oil and gas demand is in the range of that in other scenarios with similar warming potential including those used by the Network for Greening the Financial System (Supplementary Note 10 and Supplementary Figs. 2–5).

Risk of loss amplification in financial markets
Financial markets may amplify equity losses as they propagate through ownership networks. One amplification channel 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 will amplify the shock from stranded assets as both companies’ stock market valuations are likely to suffer. In addition to US$1.03 trillion (73%) of total stranded assets owned by listed oil and gas headquarters at stage 2, a further total of US$70 billion affects balance sheets of listed corporate owners as the shock propagates through the chain (Fig. 4a). Funds from listed fund managers own US$165 billion in stranded assets. Overall, listed companies own US$1.27 trillion of stranded assets, of which 19% only become apparent in the ownership chain (Supplementary Note 11 discusses the potential impact of fund losses on fund managers).

Furthermore, any financial institution in the ownership chain—listed or not—amplifies the shock, since returns on financial assets justify these companies’ valuations. If losses at every financial institution along the ownership chain are summed, an upper bound of US$381 billion in potential losses could affect financial companies (Fig. 4b). Up to US$400 billion is lost on financial sector balance sheets, including through reduced collateral of technically insolvent firms, implying an amplification of the loss by 29%. Banks are only moderately exposed. Funds own a much larger share of the risk, confirming previous studies. Included in the equity loss is $90 billion owned directly by pension funds, which adds to an unknown but likely substantial portion of pensions invested by asset

![Fig. 3 | Ownership chain of stranded assets by country and institutional category. a–d. Lost profits under medium realignment allocated to: the country where stranded oil and gas fields lie (stage 1) (a); fossil-fuel company headquarters country (stage 2) (b); ultimate corporate owners by country by sector (stage 3) (c); ultimate owners by country and institutional affiliation (stage 4) (d). Countries displayed in descending order of stage 4 losses. Markers indicate country loss totals at previous stages.](image-url)
Geographically, the US and UK financial sectors display much larger losses than other countries (Fig. 4c). Although we focus on risks from the equity transmission channel, possible further amplification via the debt channel should also be considered. Here, second- and further-round effects may lead to additional sell-offs, and asset price declines4,24–26. 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.

**Political economy implications**

Which stage of loss propagation is of most interest depends on the stakeholder. Local employees in the sector and governments earning oil and gas royalties must worry about stage 1 losses. As we show in Supplementary Figs. 6 and 7, lost revenues that pay workers’ wages and suppliers’ revenue are four times as large on average as the lost profits we calculate. The lost revenue–profit ratio in OECD countries is larger and derives from differences in break-even prices. Despite this, the revenue losses relative to GDP are largest in oil-exporting developing countries (Extended Data Fig. 9)27.

While previous stranded assets studies have focused on producer countries (stage 1)28, our propagation calculation reveals the political economy of stranded assets at the more elusive stage of financial ownership. Stage 2 results show that about half of the assets at risk of stranding are operated by companies headquartered in OECD countries. Decarbonisation efforts by such countries may therefore be more effective in reducing oil and gas supply than stage 1 results would suggest.

Naturally, the present market outlook may incentivize some international oil companies simply to diversify away from oil and gas29, and some companies have recently sold major assets30. Who is buying these assets should interest financial regulators, as should the overall ownership distribution at stage 3. Asset ownership changes are, as such, unlikely to mitigate the systemic risk that regulators seek to mitigate. The assets then simply move to other owners with...
their own potential to transmit transition risk, leading to ‘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 key concern for supervisors should be that these are less regulated than banks37, with lower understanding of contagion potential within the financial system38. Supplementary Note 14 compares our estimated US$681 stranded assets potentially on financial institutions’ balance sheets with the mispriced subprime housing assets of an estimated US$250–500 billion on financial sector balance sheets that triggered the 2007–2008 financial crisis.

Stage 4 highlights that ultimately the losses are borne by governments or individual share and fund owners. The latter are likely to lobby governments for support and thereby to shift more stage 4 losses to the government. Investment decisions in oil and gas could already be pricing in potential bailouts32. Comparing stranded assets to GDP ratios (Extended Data Fig. 9) suggests that, as exposed private investments are mostly in wealthy countries, bailouts would be feasible. Compensating the entire loss under a medium realignment would amount to no more than 1–2% of GDP for most rich countries. The highest losses relative to GDP occur in countries where government ownership is significant, including in Norway and Russia. So the largest risks are already on governments’ balance sheets. Lobbying for bailouts may be more intense if influential groups are set to lose wealth31. As an example, in the United States, we estimate that the wealthiest 10% of households hold about 82% of the US stage 4 losses (Supplementary Note 15). This loss would amount to only 0.4% of the wealthiest households’ net worth and would hardly affect the US wealth distribution. Yet, those householders most affected might deploy their substantial political influence to lobby for compensation. The moral hazard of investing with a view to being bailed out could thus lead to investments consistent with pre-realignment demand even if certain investors or the oil and gas companies themselves have already realigned their expectations. This in turn could lead other, less forward-looking investors not to realign their expectations, making it easy to obtain financing for additional, ultimately unprofitable exploration and drilling, and delaying expectations realignment.

Financial geography of stranded assets

It is well documented that the overwhelming majority of unused oil and gas reserves are in the Middle East3,4, and that local state-owned companies own most global reserves5. Our results show that equity investors from mostly OECD countries are currently exposed to much more of global fossil-fuel stranded assets risk than the geographical view implies. Irrespective of which expectations realignment we apply, more than 15% of all stranded assets are transferred from countries in which physical assets lose their value to OECD country investors. This configuration suggests two conclusions about the energy transition.

First, financial investors and ultimate owners in OECD countries benefit from more profits on oil and gas than domestic production volumes suggest. As a result, there is a potentially perverse incentive in the financial sector of these countries to accept inertia or even slow the low-carbon transition and earn dividends from the continued operation of fossil-fuel production38. Even if unsuccessful, financial investors may lobby for bailouts from governments. OECD countries have the financial means to provide these bailouts, which might in turn affect financial investors’ expectations and ultimately investments in oil and gas production, influencing the amount of assets at risk39. Finance is not politically neutral, and which activities get financed ultimately depends on investors’ choices39. On the flipside, if they wish to take genuine action, rich country stakeholders have more leverage about global investments in the sector. In addition to guiding investments through green finance classifications and requirements39,40, policy-makers could work with activist investors to lower capital expenditure of oil and gas companies rather than allowing divestment to turn into ownership leakage.

Second, domestic sectoral exposure can be a weak indicator of financial risks from asset standing, and international linkages could increase the risk of financial instability. This problem needs attention from modellers and policy-makers. 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 variable exposures to stranded asset risk due to cost differentials, international ownership and producer behaviour. Stress tests and scenario exercises may therefore benefit from variable risk distributions within, not just across, sectors. Even if outright financial instability is avoided, the large exposure of pension funds remains a major concern. In all circumstances, the political implications of loss allocations at each stage are likely to be major. International cooperation on managing and financing the production and stable phase-out of fossil fuels is needed to lessen destabilizing expectation realignments and their social repercussions.

Online content

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were matched with Rystad oil and gas companies. Large and very large companies include all companies that have one of operating revenue >US$13 million, total assets >US$26 million, employees >149 or a stock market listing. Subsequently, via the snowballing method, all companies covered in the model that were listed as shareholders but were not yet downloaded. This iterative procedure was performed six times. Ultimately, the download resulted in 1,772,899 companies (including subsidiaries and their parents) connected by 3,196,429 equity ownership links, with a residual 12,876 unidentified owners. Most ownership links connect companies; however, in some cases there is a node for individuals and a handful of other residual summary nodes reflecting partially missing information (for example, 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 provided in Supplementary Table 2. Further discussion of limitations of the data is provided in Supplementary Note 5.

Matching Rystad with ORBIS data was done manually due to widely varying spelling conventions. Many companies in Rystad were abbreviated, for example, 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 medium 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%. Where ownership links were needed to less than 100% residual ownership would remain in the companies 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 1.777 million companies in the network have 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 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, that is

\[ \ln v_1 = a + b \ln v_2 \]  

(1)

where \( v_1 \) is the dependent variable, \( v_2 \) is the predictor, and a and b are fitting constants. We apply these regressions stochastically to avoid artificially reducing the variance of the equity distribution, calculating the mean prediction from the regression average and a standard error. When applying the regressions, we enforce the inequality \( A \geq E \), by simply applying \( E \left( \min(A,E) \right) \). The regression coefficients and standard errors are tabulated in Supplementary Table 3.

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 (Supplementary Table 4), again enforcing the inequality \( A \geq E \) by applying \( E = \min(A,E) \).

The imputation code is available at ref. 1.

Asset-specific and aggregated stranding. We define an asset, indexed by \( k \) in \( 1,\ldots, K \), as the present value of a sequence of a share of profits from a particular oil or gas field, accruing to an oil or gas company that owns that share including via service and revenue-sharing contracts. There are 43,439 unique oil and gas fields with non-zero 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, \( p_{k,t} \), multiplied by the output, \( q_{k,t} \) from the oil or gas field accruing to the owner of \( k \). Profits are estimated in the same way, by subtracting asset-level costs, \( c_{k,h} \), 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, \( A_k(a) \) (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

\[ A_k(a,b) = \frac{1}{1 + \lambda} \left( \sum_{t=0}^{\infty} \left( p_{k,t} q_{k,t} - c_{k,h} \right) - \left( p_{k,t} q_{k,t} - c_{k,h} \right) \right) \]  

(2)
where ρ is the discount rate, which we set to 6%, t = 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. Thus, we calculate the NPV of asset losses, σ, from expectations realignment for some group, G, of assets, from baseline a to policy scenario b as

\[ \sigma_{G,a,b} = \sum_{k \in K} A_{G,a,b} \]

where K 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 ith fossil-fuel company owns the set of assets \( C_i \), we define the stranded assets of company \( i \) as

\[ \sigma_i = \sum_{k \in K} A_{C_i,a,b} \]

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'. We have built a network model to propagate the stranded asset shock through to ultimate owners. Our study is focused explicitly on the flow of results we provide, although clearly caution is demanded when interpreting outputs at the company level. Establishment of a flag that identifies whether its data have been input to aid such interpretation.

Second, 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 Note 4). The shocks to unknown creditors in the default network agreed to within 5% between two alternative imputed networks (US$402 billion and US$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 where the network code is available at ref. 45.

**Data availability**

Data from Rystad (on energy supply assets) and ORBIS (on company ownership) were accessed under license and cannot be shared. Data are available, however, on reasonable request and with permission from Rystad and ORBIS, respectively, from the authors. Data underlying figures are available at ref. 46. An implementation from 2018 of the E3ME-FTT-GENIE scenarios will be available with the IPCC’s 6th Assessment Report database. Source data are provided with this paper.

**Code availability**

The code of the network model, for imputing missing financial information and for generating figures, are available at ref. 46. 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. 46.

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Author contributions
G.S., P.R.H., J.-F.M., P.S., H.P., N.R.E and J.E.V. designed and conceptualized the research. J.-F.M., H.P., P.V., U.C. and P.R.H contributed to and ran the E3ME-FTT-GENIE simulations to generate energy demand and supply. P.S. integrated the Rystad database and with contributions from P.R.H., G.S. and J.-F.M. calculated initial shock distributions from realignments. G.S. curated the ownership network database with contributions from K.J. P.R.H. designed the network model and ran the realignment scenarios with contributions from G.S., J.-F.M., P.S. and N.R.E. G.S. wrote the article with contributions from N.R.E., P.R.H., J.E.V., J.-F.M., H.P. and P.S. G.S. coordinated the research with contributions from P.R.H., J.-F.M. and N.R.E., and N.R.E. coordinated the overall FRANTIC grant project.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 1 | Ownership chain of stranded assets by OECD/non-OECD geography and major institutional categories for various realignments. a, Benign (TDT_EUEA-SO), b, Severe (InvE_NetZero-SO), c, Medium-Quota (InvE_EUEA-QU), d, Medium (InvE_EUEA-SO) without CCS, e, Medium without network imputations, f, Medium for reference.
Extended Data Fig. 2 | Sensitivity to different expectations realignments. a, major loss categories at Stage 4 under four realignments; b, proportional change in major headquarters 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.
Extended Data Fig. 3 | Country ranking at stage 4 of losses across realignments. All 210 countries are ranked for each realignment in ascending order of their losses at Stage 4. Individual country ranks are connected by a line. Highlighted countries show ‘typical’ cases of Norway with little rank change, low-cost OPEC countries (Kuwait and Saudi Arabia), a tax haven (British Virgin Island) affected by the imputation and a financial centre hit entirely after Stage 1 (Belgium).
Extended Data Fig. 4 | Detailed ownership chain of stranded assets under *Benign* (TDT_EUEA-Selloff) realignment. Lost profits 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 loss for *Medium* (InvE-EUEA-SO) realignment at the respective stage.
Extended Data Fig. 5 | Detailed ownership chain of stranded assets under Severe (InvE_NetZero-SO) realignment. Lost profits allocated to a, the country where stranded oil and gas fields lie (Stage 1); b, fossil-fuel company headquarters 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 loss for Medium (InvE-EUEA-SO) realignment at the respective stage.
Extended Data Fig. 6 | Detailed ownership chain of stranded assets under Medium-Quota (InvE_EUEA-QU) realignment. Lost profits 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 loss for Medium (InvE_EUEA-SO) realignment at the respective stage.
Extended Data Fig. 7 | Detailed ownership chain of stranded assets without availability of CCS under Medium (InvE_EUEA-SO) realignment. Lost profits 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 loss for Medium (InvE-EUEA-SO) realignment at the respective stage.
Extended Data Fig. 8 | Detailed ownership chain of stranded assets without network imputations under Medium (InvE-EUEA-SO) realignment.

Lost profits 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 loss for Medium (InvE-EUEA-SO) realignment at the respective stage.
Extended Data Fig. 9 | Loss as a share of GDP for major countries under Medium realignment. Lost profits divided by 2019 GDP at market exchange rates 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 in Fig. 3. Markers indicate country loss totals at previous stages.