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 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, both 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 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-energy supply facilities[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 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 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 the rapid collapse of fossil-fuel 'sunset' industries presents major transition risks[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. 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 with 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, i.e. the oil or gas price falls below the breakeven price for those assets.

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 analysiss 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 the 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 3.5ºC median warming by 2100. We refer to this baseline scenario 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/CO_2 emissions by 2050/2060 respectively, noting that non-CO_2 emissions are exogenous and follow RCP2.6 (see Methods). The EUEA scenario has a median warming of 2ºC. In line with the IEA's projectionss[1], 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 two other possible realignments, each yielding a magnitude and distribution of risk ownership. The alternative scenarios are presented in the supplementary notes xxx.

Oil and gas demand and prices in baseline and policy scenarios are produced by the E3ME-FTT-GENIE integrated assessment modelling framework (see SI xx), which as CGE models provides sufficient sectoral disaggregation,[13,14] while remaining theoretically consistent with asset stranding. 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) [15–17] and a carbon cycle and climate system model of intermediate complexity (GENIE)[18]. Here we use only the global oil and gas demand and price series from the model, implying that price differences are arbitraged away in global oil and gas markets. These figures are similar to comparable recent scenarios produced with other models[19] (see SI xxx for a detailed comparison).

Fig. 1A illustrates our calculation of total stranded assets in the *Medium* realignment. 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%y^{-1} (Fig. 1B) to calculate the present value of stranded assets, which sums to US$1.4 trillion (see Suppl. note xx 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-year horizon of profits, and present-value accounting translates deflated profit expectations into lower asset value.

Propagation of risk ownership

Fig. 2 shows how the ownership of the global US$1.4 trillion stranded assets propagates through the four stages across major geographic and institutional categories. Geographically, losses are transferred to OECD countries. A total of $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 net 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$1.0 trillion, are booked by stock-market listed oil and gas companies. At Stage 3, the financial sector owns losses of US$ xxx, 9x% of which sits in OECD countries. At Stage 4, governments directly own (including via pension funds) losses of US$484 billion (34%), most of which originates 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 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 (Suppl. note 3 and xxx).

Fig. 3 shows that physical stranding (Stage 1) is largest in the US 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 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 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 US, where the world's largest asset managers hold investments in virtually all listed oil and gas companies[20]. Other smaller countries, such as the British Virgin Islands and Switzerland, viewed as tax havens[21], also receive large transfers of losses. Stage 4 documents a redistribution of US-, and UK-managed fund losses to clients around the world. Net trans-border redistribution shown from Stage 3 to 4 is a lower bound as a significant portion of unknown ultimate owners of companies may be foreign investors, with limited information in the public domain (Suppl. note 3). The institutional allocation within countries is driven by whether domestic oil and gas companies are state-owned.

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. 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 (Suppl. Figures 2-7, Suppl. notes 5, 6, x). Our results are overall consistent with those of the Carbon Tracker Initiative for 14 major oil and gas companies (Suppl. note 7 and Suppl. Figure 8) and our oil and gas demand is in the range of that in other scenarios with similar warming potential listed in Table 2 (Suppl. note 8 and Suppl. Figures 9-12 for detail).

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 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, a further total of US$70 billion affects balance sheets of listed corporate owners as the shock propagates through the chain. It also shows that 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 (Suppl. note 4 discusses 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 losses at every financial institution along the ownership chain are summed, 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, 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[22]. Indeed, included in the equity loss is $90 billion owned directly by pension funds, which adds to an unknown but potentially substantial portion of pensions invested by asset managers. 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 declines[4,23–25]. 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 export revenues must worry about Stage 1 losses. As we show in Suppl. Fig. 14-15, lost revenues that pay workers' wages and suppliers' revenue are four times as large on average as the lost profits we calculate. The revenue lost in OECD countries is much larger than their Stage 1 profit loss and derives from the differential breakeven price. Despite this, the revenue losses relative to GDP are largest in oil-exporting developing countries.[27]

While previous stranded assets studies have focused on producer countries (Stage 1) [26], our propagation calculation reveals the political economy of stranded assets at the more elusive financial level. Stage 2 results show that about half of the assets at risk of stranding are operated by companies headquartered in OECD countries. Business diversification by such companies may therefore be more effective in reducing oil and gas supply than Stage 1 results would suggest.

Naturally, the present market outlook may incentivise some international oil companies to diversify away from oil and gas[28], and some companies have recently sold major assets[29]. 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 banks[30], with lower understanding of contagion potential within the financial system[22]. SI section xx compares our estimated US$681 stranded assets potentially on financial institutions' balance sheets with the mispriced subprime housing assets of an estimated US$250-US$500 billion on financial sector balance sheets that triggered the 2007-08 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 bailouts[31]. Comparing stranded assets to GDP ratios (Suppl. Figure 13) 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 sheet (further contributing to potential financial instability). Lobbying for bailouts may be more intense if influential groups are set to lose wealth[32]. As an example, in the US, we estimate that the wealthiest 10% of households hold about 82% of the US Stage 4 losses (Suppl. Note 11). This loss would amount to only 0.4% of the wealthiest households' net worth and hardly affect the US wealth distribution. Yet, those households 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. Worse, it could lead to a sense that ultimately unprofitable oil and gas fields are a going concern among less forward-looking investors making it easy to obtain financing for additional exploration and drilling, and delaying expectations realignments.

Financial geography of stranded assets

It is well documented that the overwhelming majority of unused oil and gas reserves are in the Middle East[33], and that local state-owned companies own most global reserves[34]. 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 production[35]. 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 risk[36]. Finance is not politically neutral, and which activities get financed ultimately depends on investors' choices[37]. 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 requirements, 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 stranding, and international linkages could increase the risk of financial instability. This problem needs attention from modelers 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 forming and reporting on 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 phaseout of fossil fuels is needed to lessen destabilizing expectation realignments and their social repercussions.

Methods

Energy supply

The allocation of oil and gas production, revenues and income is estimated by integrating data from the Rystad Ucube[38] 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[39] 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[13] 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[40].

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 discussed 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.

Asset-specific and aggregated stranding

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.

<u>Network propagation</u>

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 note 2). 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.

E3ME-FTT-GENIE model

To generate global oil and gas demand and price time sries for each scenario, we use the IAM E3ME-FTT-GENIE[13,14] framework based on observed technology evolution dynamics and behaviour measured in economic and technology time series. It covers global macroeconomic dynamics (E3ME), S-shaped energy technological change dynamics (FTT)[15–17], fossil fuel and renewable energy markets[40,41], and the carbon cycle and climate system (GENIE)[18]. We project economic change, energy demand, energy prices and regional energy production.

The E3ME-FTT-GENIE integrated framework is described in supplementary note 12. The full set of equations underpinning the framework is given and explained in ref[13]. Assumptions for all scenarios are described in supplementary note 13.

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[13].

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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 behaviour generates windfall profits for low-cost producers.

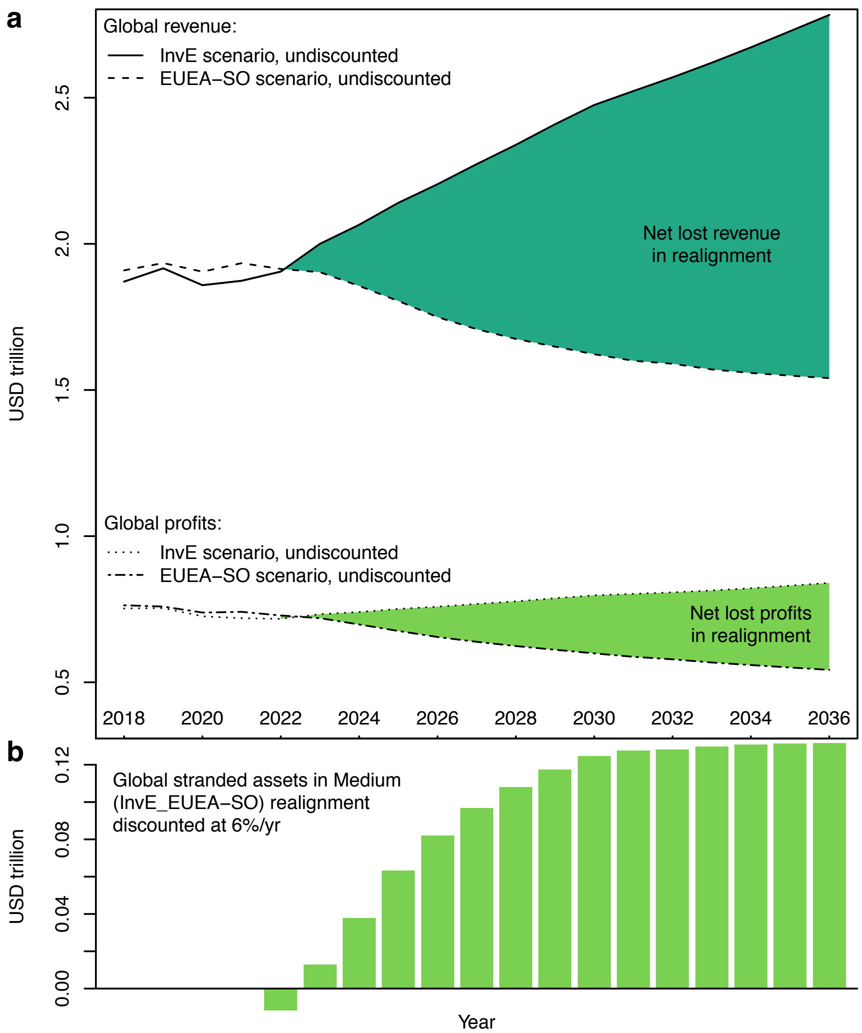


Fig. 2 | Ownership chain of stranded assets by OECD/non-OECD geography and major institutional categories. Each bar represents $1.4 trillion in losses from *Medium* expectations realignment at successive ownership stages, divided into OECD and non-OECD losses, and within each geography into major institutional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

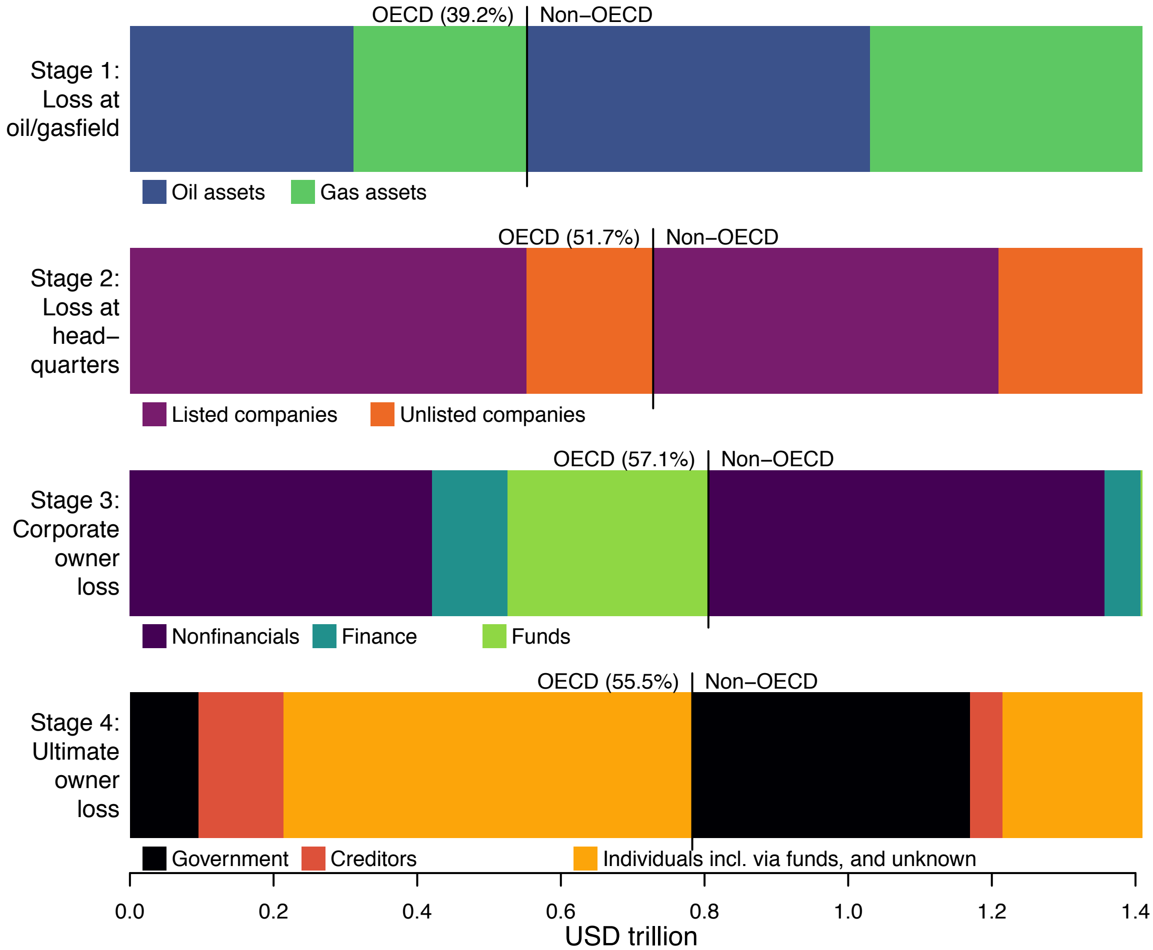


Fig. 3 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Medium* realignment allocated to **a,** the country where stranded oil and gas fields lie (Stage 1); **b,** fossil-fuel company headquarter country (Stage 2); **c,** ultimate corporate owners by country 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.

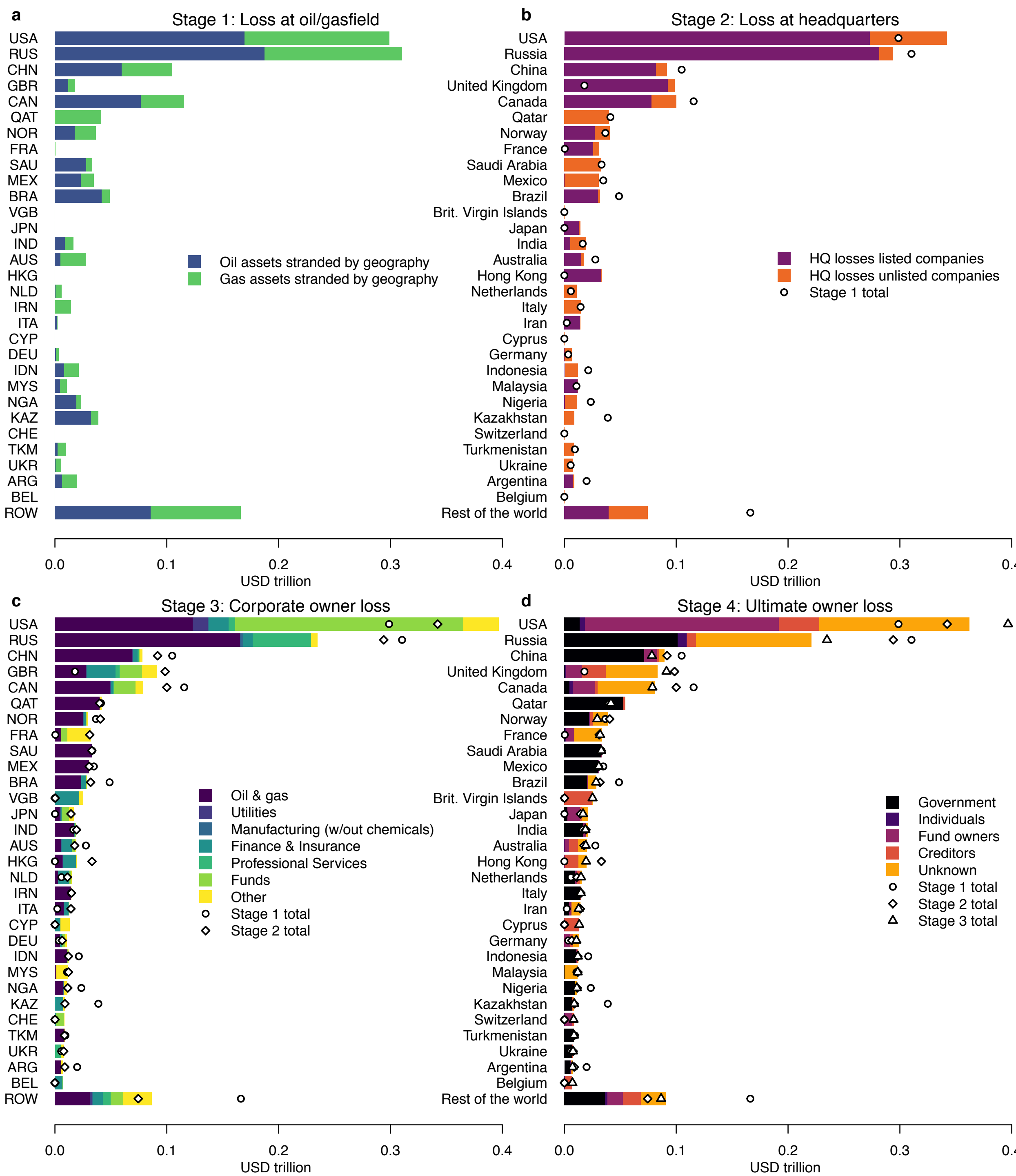
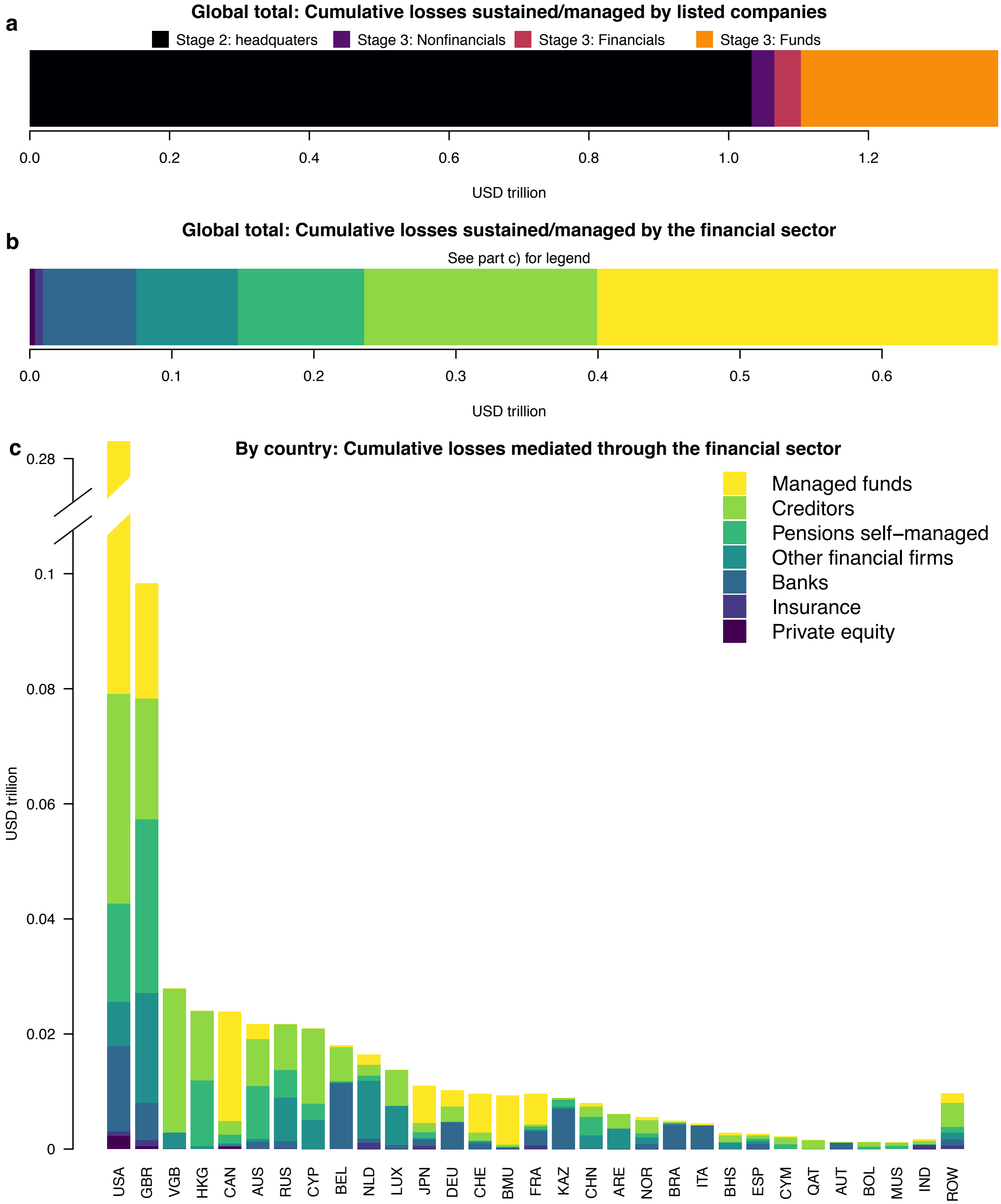


Fig. 4 | Cumulative losses by listed companies and in financial markets. a, global losses affecting stock market-listed fossil fuel headquarters, intermediate and ultimate corporate owners, and listed fund managers in the *Medium* realignment. **b,** as a, but for all financial institutions. Legend is in part c. Creditors equal negative equity, reducing creditors' collateral. **c,** as b, but split by country. The y-axis is compressed between USD 0.10 and USD 0.28 trillion.



Supplementary Information:

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

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

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

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

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

Supplementary Table 3 | Regression coefficients (Equation 1).

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

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

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

Supplementary Note 1: Choice of Discount Rate

The level of the private discount rate chosen affects the magnitude of the losses and can also have distributive consequences if asset loss time profiles vary across assets. We apply a discount rate of 6% to calculate the net present value of future cash flow from oil and gas fields. Rates in the literature on the oil and gas sector vary widely[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 Suppl. Table 5. This table also shows that ultimately the choice of expectations realignment, i.e. combinations of scenarios, is a more important determinant of losses, so uncertainty about losses is dominated by scenarios, not discount rate. Realignments dominating variation in losses is further illustrated for individual companies in Suppl. Figure 8, where in 9 out of 14 cases company-level losses under the *Severe* realignment with a 10% discount rate are still higher than under the *Medium* realignment with 6% discounting. And 14 out of 14 companies report higher *Medium* losses discounted at 10% than *Benign* losses with 6% discount rate.

Suppl. Table 5 | Equity shock (USD trillions) as a function of discount rate in each scenario.

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

[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[18].

[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.[19], who use a 5% discount rate to calculate the levelized cost of electricity.

Supplementary Note 2: Technical insolvency including companies with limited information

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

Supplementary Note 3: Limitations of ownership data

Our results concerning redistribution of losses contain a considerable degree of uncertainty about ultimate ownership. On institutional redistribution, the restriction of ownership reporting to investors holding no less than 0.01% of shares leads to a considerable amount of loss at stage 3 accruing to ultimate corporate owners in the oil and gas sector and unknown ultimate owners at stage 4. This is due to our convention to keep the residual shock in the company if shareholding sums to less than 100%. Any shareholder with less than 0.01% of the company's stock is not reported (or sometimes reported without a share but a note that the investment is 'negligible'). Thus, while ExxonMobil had 343,633 registered shareholders at the end of 2020[6], 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. This means that part of the 'unknown' ultimate owners at stage 4 is likely to be a placeholder for 'fundholders'.

As concerns geography, much suggests that the redistribution towards high-income, fossil energy importing countries shown in the main text is a lower bound. Because of the limits to shareholder reporting just explained, foreign ownership is likely to be undercounted. This may in particular undercount overall foreign direct investment of rich countries, with rich countries having on average a net positive investment position in developing countries[7]. Similarly, it is likely that the exposure of the financial sector in rich countries is a lower bound. For instance the unidentified creditors in developing countries are likely to include a share of high-income country-based foreign banks, while the reverse is much less likely[8,9].

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

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

Supplementary Note 4: Funds

Fund managers earn revenue by their management of others' wealth (assets under management). This typically happens by charging fees for their management of their clients' investments. In our data, a significant amount of ownership is via funds, and at stage 3, we report losses to funds, which are split geographically by the fund manager's headquarters. It is important to recognize, however, that losses to funds do not imply losses to fund managers' balance sheets. Rather, the loss accrues to the balance sheet of the corporate or net worth of the human client. The decline in assets under management instead impacts the income and cash flow statement of the fund manager, since fees (revenue) tend to be calculated as a share of assets under management (see, e.g., *ref*[10]). To the extent that this decline in revenue affects the expectations about future revenue earnings, the balance sheet as well as the market capitalization of fund managers can also suffer, leading to an amplification of the initial shock. However, just as we do not consider second-round effects in the banking system, we do not account for this potential loss to fund managers, as we focus on the direct equity channel of transmission of transition risks.

Supplementary note 5: No CCS

To test the sensitivity of our results to the availability of carbon capture and storage (CCS) we recalculate demand for fossil fuels without CCS availability until 2036. In the EUEA-SO scenario, 6.1 $GtCO_2$ are removed from the atmosphere using bioenergy CCS between 2022 and 2036. We split the emissions that need instead to be saved by reduced fossil fuel consumption equally across oil, gas and coal. Using the IPCC's fuel-specific carbon intensity factors, this leads to 29 EJ less oil and 36 EJ less gas demand over the time period, about 1% and 2% of total demand for the respective fuels in the EUEA scenario until 2036 (see also Suppl. Figure 11 below). Using an incremental ramp of annual savings, we then recalculate how this lower energy demand affects oil and gas field production and stranded assets. The modification increases total oil and gas stranded assets by 3% from USD 1.410 to 1.453 trillion. More detailed results and change from *Medium* realignment are shown in Suppl. Figures 1d and 6.

Supplementary Note 6: Network sensitivity

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

We compare network characteristics with and without imputed nodes for the *Medium* realignment of expectations in Suppl. Table 6. A significant fraction of the shocked companies have imputed assets, with the total number of companies shocked falling from 33,836 to 18,495 and the shock reaches only 15,623 instead of 26,998 ultimate owners. But these companies with imputations tend to be smaller. Larger companies, on average, tend to report more of their financial data. This may be because they are stock-market listed or because they fall under some local law that differentiates reporting requirements by company size. As a result, the total transmitted shock only falls by \$119 billion from \$791 billion, of which \$65 billion is cross-border.

In relative terms, the share of the shock transmitted only falls by 8 percentage points (row 4) and the loss of transborder flows on balance sheet only affects 4.6% of the total shock (row 5). This small cross-border effect is illustrated in Suppl. Figure 7, where most countries deviate little from their results with imputations. The biggest changes for countries are for tax havens such as the British Virgin Islands, where companies tend to disclose little information in our database. Suppl. Figure 2 shows how the British Virgin Islands (VGB) drop from rank 22 to rank 80 of countries in terms of absolute losses once imputations are removed.

Very few funds are excluded (row 3) and the shock to funds even slightly increases in magnitude. This is because we scale company ownership that ORBIS reports as >100% down to 100% proportionally (see also suppl. note 3). When imputed owning nodes are removed from such companies, the remaining nodes' ownership is scaled down less or not at all. If funds are among those shareholders, they transmit a larger shock. At the coarser level, the shock transferred to OECD countries falls by 1.2 percentage points when removing imputations (Figure 1e). Almost all of this is because financial companies listed in OECD-based financial offshore centres that do not disclose much information, which we impute (including the UK's overseas territories British Virgin Islands and Cayman Islands).

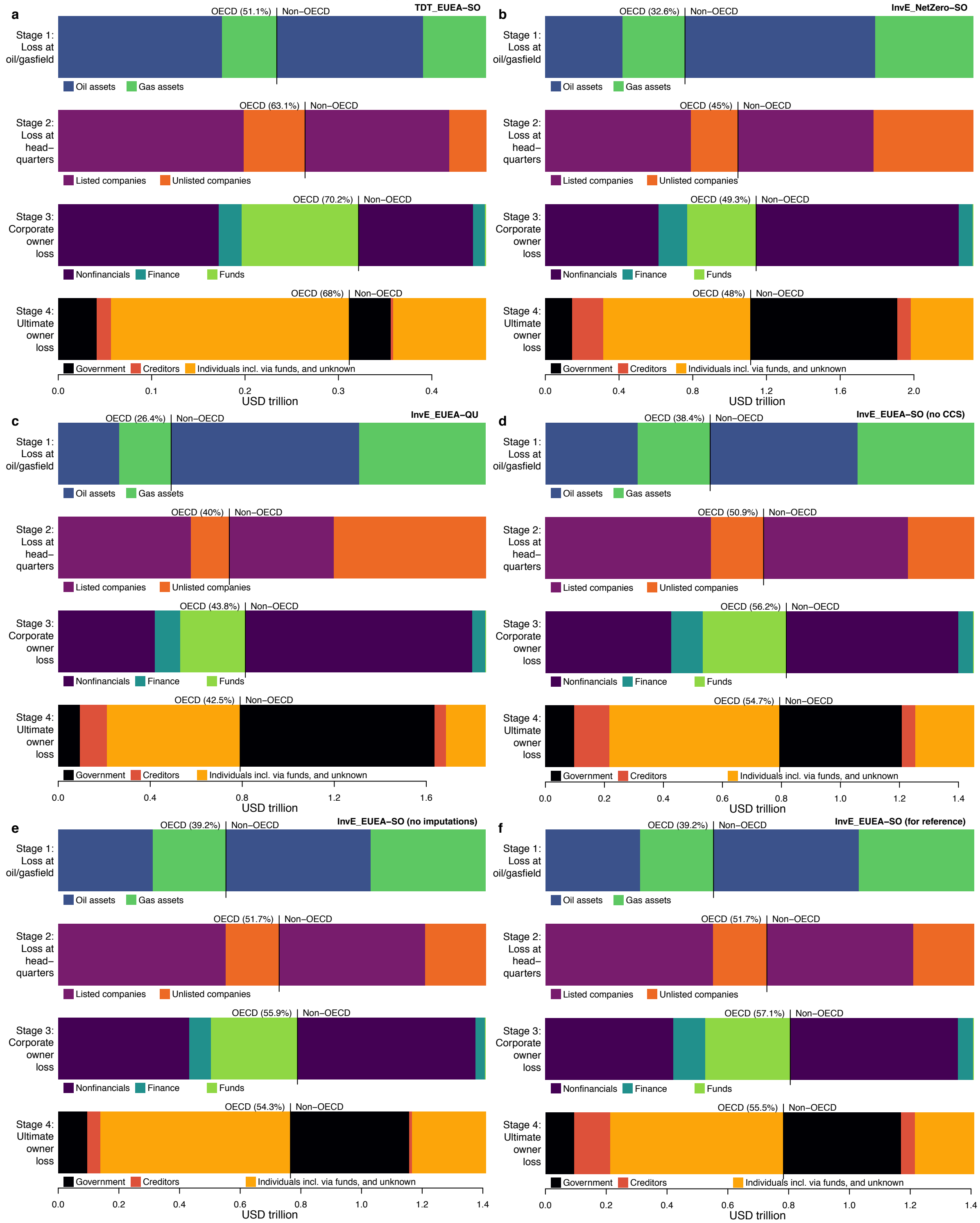
Suppl. Table 6 I Comparison of shock transmission with and without imputation.

		INVE-EUEASO		INVE-EUEASO no imputations		percentage point change
		Absolute	% of total shock	Absolute	% of total shock	

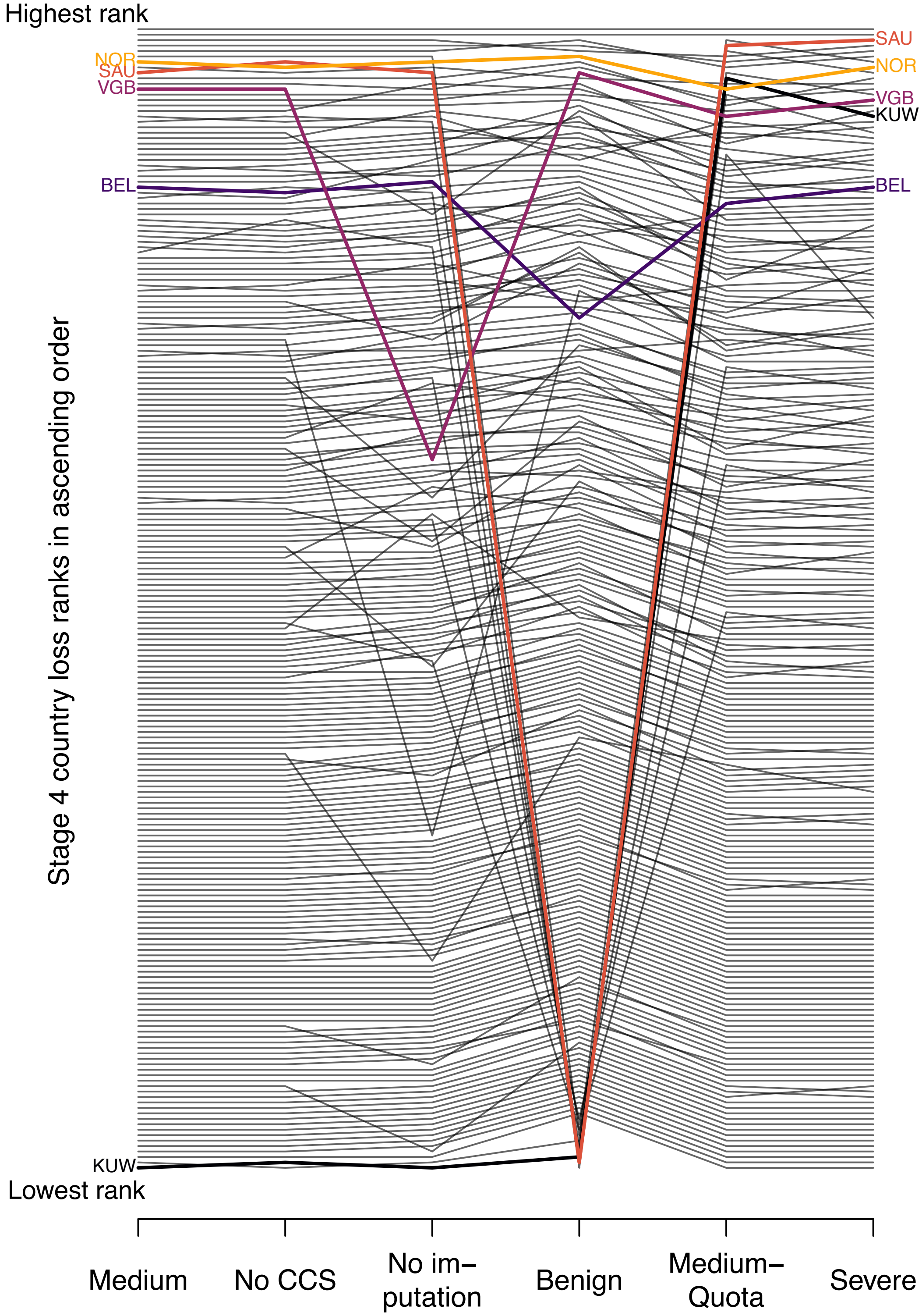
	Column:	(I)	(II)	(III)	(IV)	(IV)-(II)
1	Shocked companies (count)	33,836		18,435		
2	Shocked ultimate corporate owners (count)	16,171		10,709		
3	Shocked funds (count)	1,592		1,379		
4	Total transmitted shock ($ billion)	790.881	56.1%	677.354	48.1%	
5	transmitted equity shock ($ billion)	508.761	36.1%	390.114	27.7%	-8.4
6	of which cross-border ($ billion)	156.163	11.1%	91.4217	6.5%	-4.6
7	transmitted managed shock ($ billion)	282.120	20.0%	287.240	20.4%	0.4
8	of which cross-border ($ billion)	120.042	8.5%	120.673	8.6%	0.0

Supplementary Figures 1-7

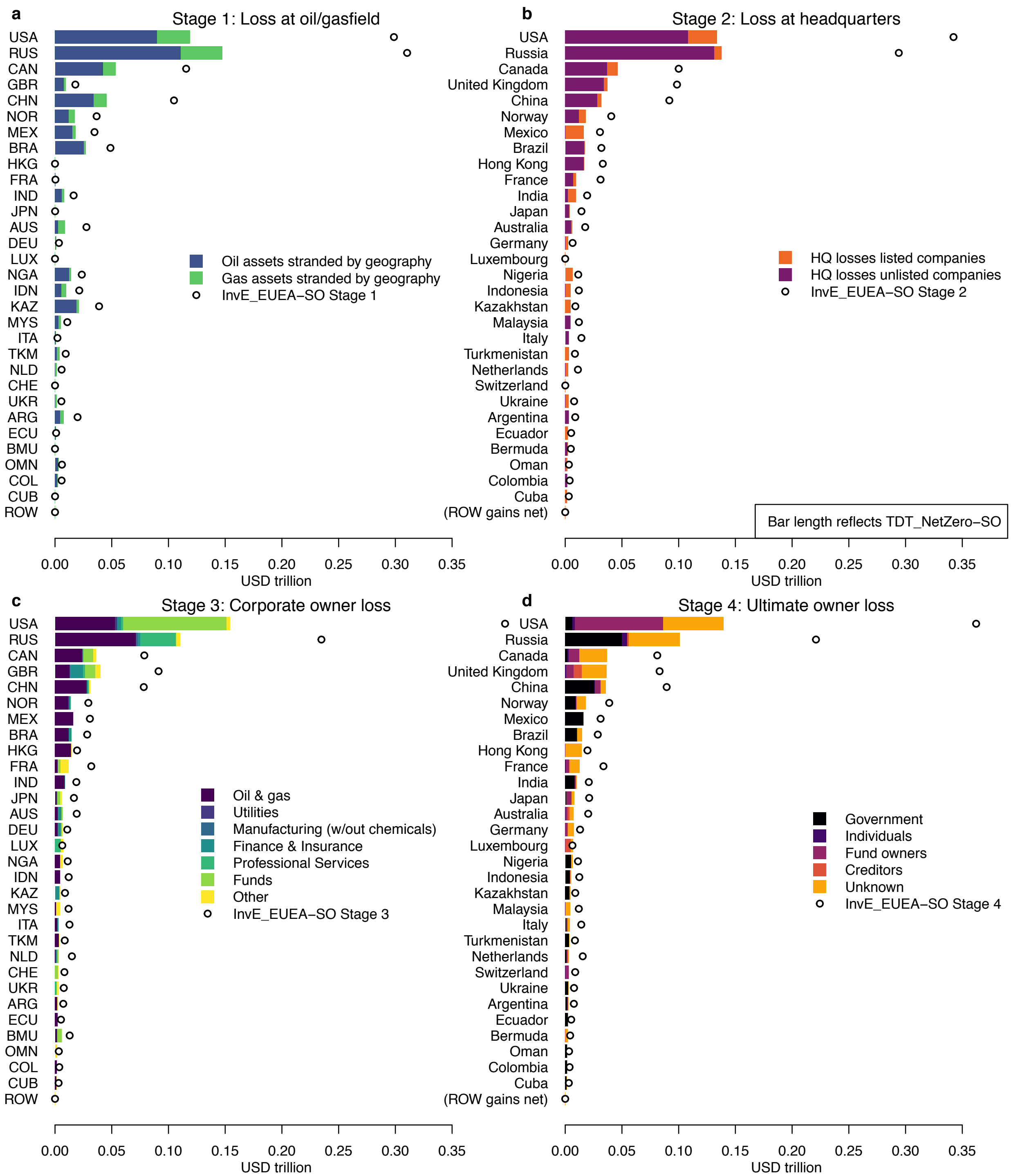
Suppl. Fig. 1 | Ownership chain of stranded assets by OECD/non-OECD geography and major institutional categories for various realignments. a, *Benign* (TDT_EUEA-SO), **b,** (InvE_NetZero-SO), **c,** Medium-Quota (InvE_EUEA-QU), **d,** *Medium* (InvE_EUEA-SO) without CCS, **e,** *Medium* without network imputations, **f,** *Medium* for reference.



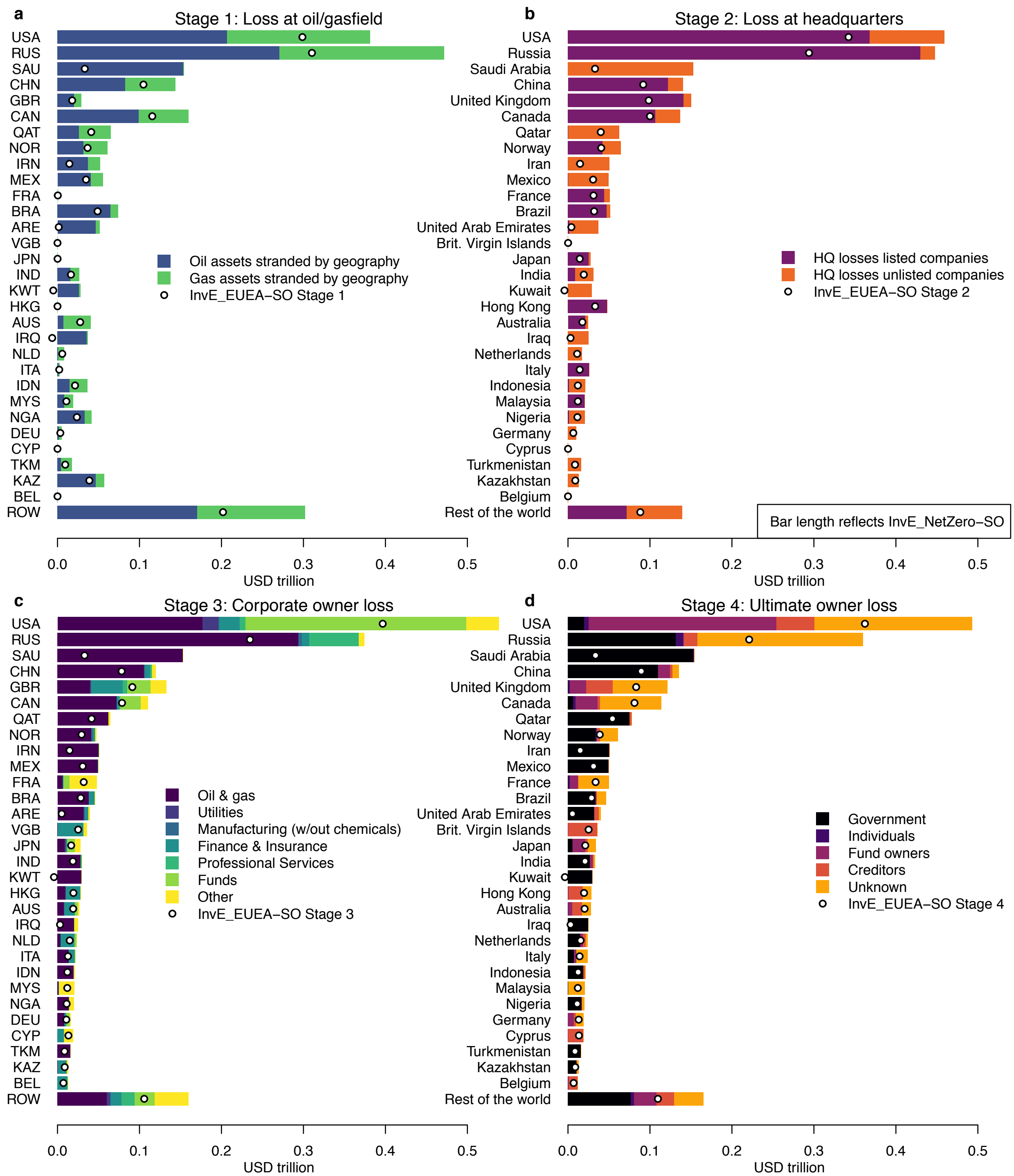
Suppl. Fig. 2 | Country ranking at stage 4 of losses across realignments. All 210 countries are ranked for each realignment in ascending order of their losses at Stage 4. Individual country ranks are connected by a line. Highlighted countries show 'typical' cases of Norway with little rank change, low-cost 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).



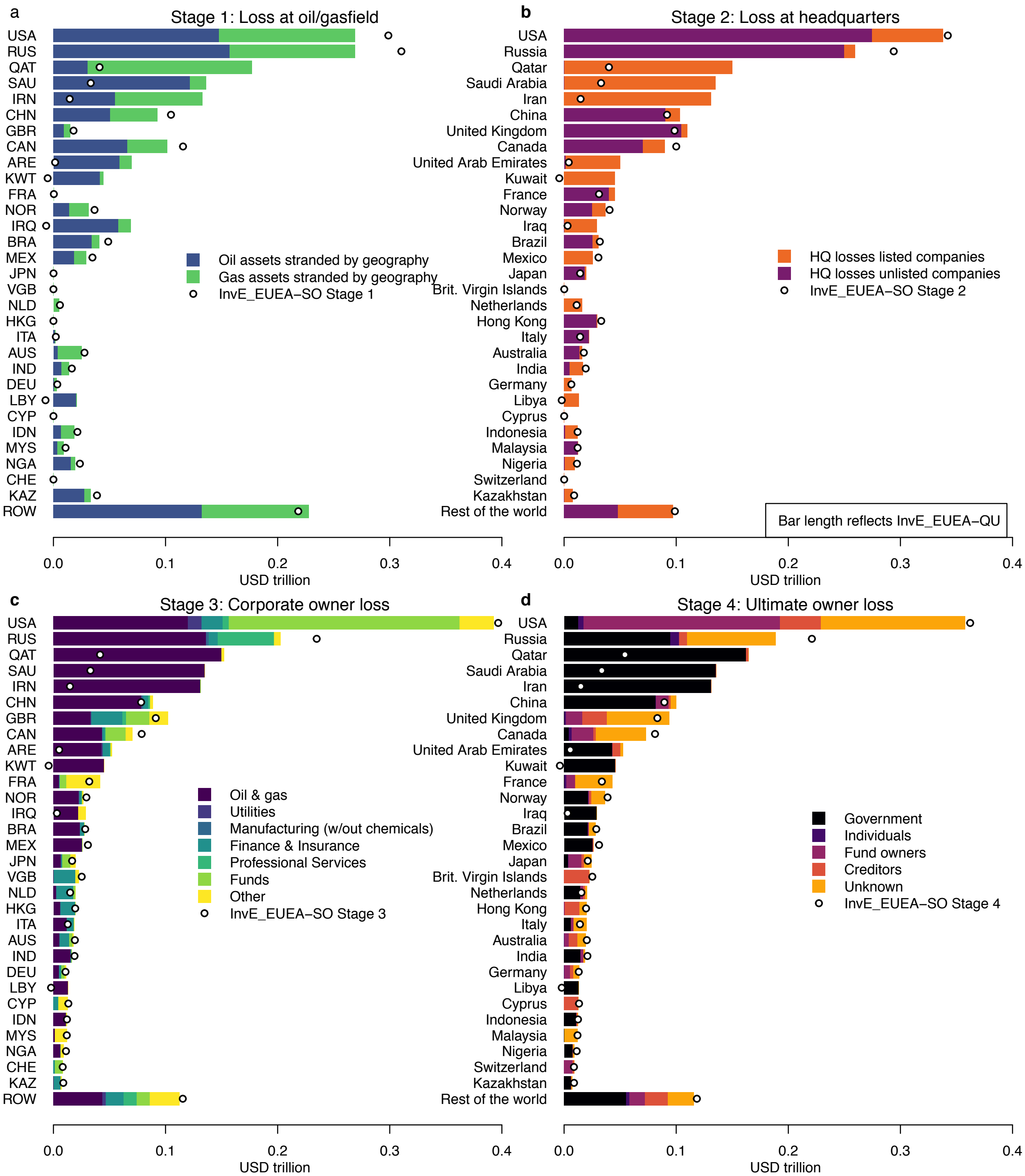
Suppl. Fig. 3 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Benign* (TDT_EUEA-Selloff) realignment allocated to **a,** the country where stranded oil and gas fields lie (Stage 1); **b,** fossil-fuel company headquarter country (Stage 2); **c,** ultimate 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 loss for *Medium* (InvE-EUEA-SO) realignment at the respective stage.



Suppl. Fig. 4 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Severe* (InvE_NetZero-SO) 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 loss for *Medium* (InvE-EUEA-SO) realignment at the respective stage.

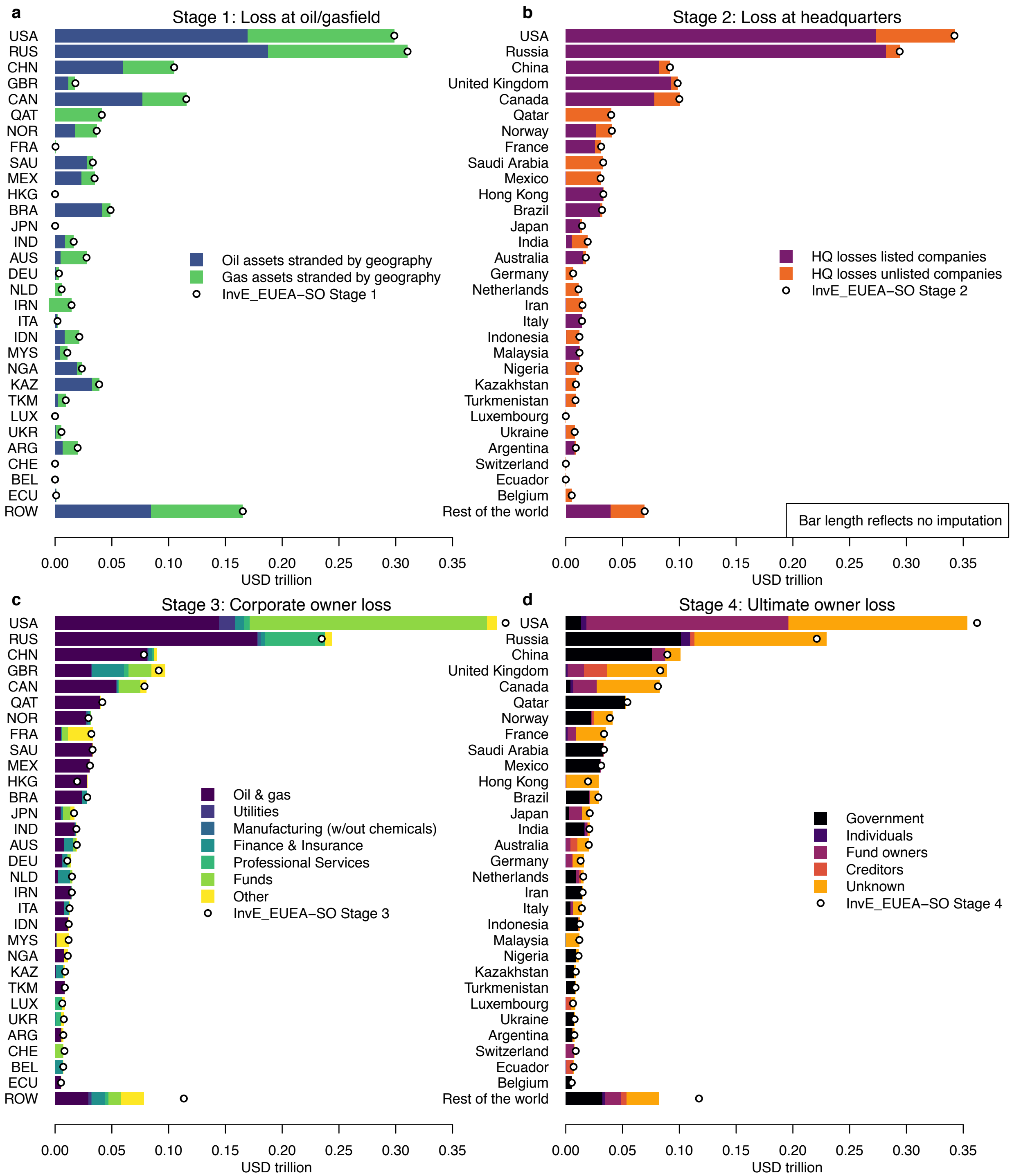


Suppl. Fig. 5 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Medium-Quota* (InvE_EUEA-QU) realignment allocated to **a,** the country where stranded oil and gas fields lie (Stage 1); **b,** fossil-fuel company headquarter country (Stage 2); **c,** ultimate 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 loss for *Medium* (InvE-EUEA-SO) realignment at the respective stage.



Suppl. Fig. 6 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Medium* (InvE_EUEA-SO) realignment without availability of CCS 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.

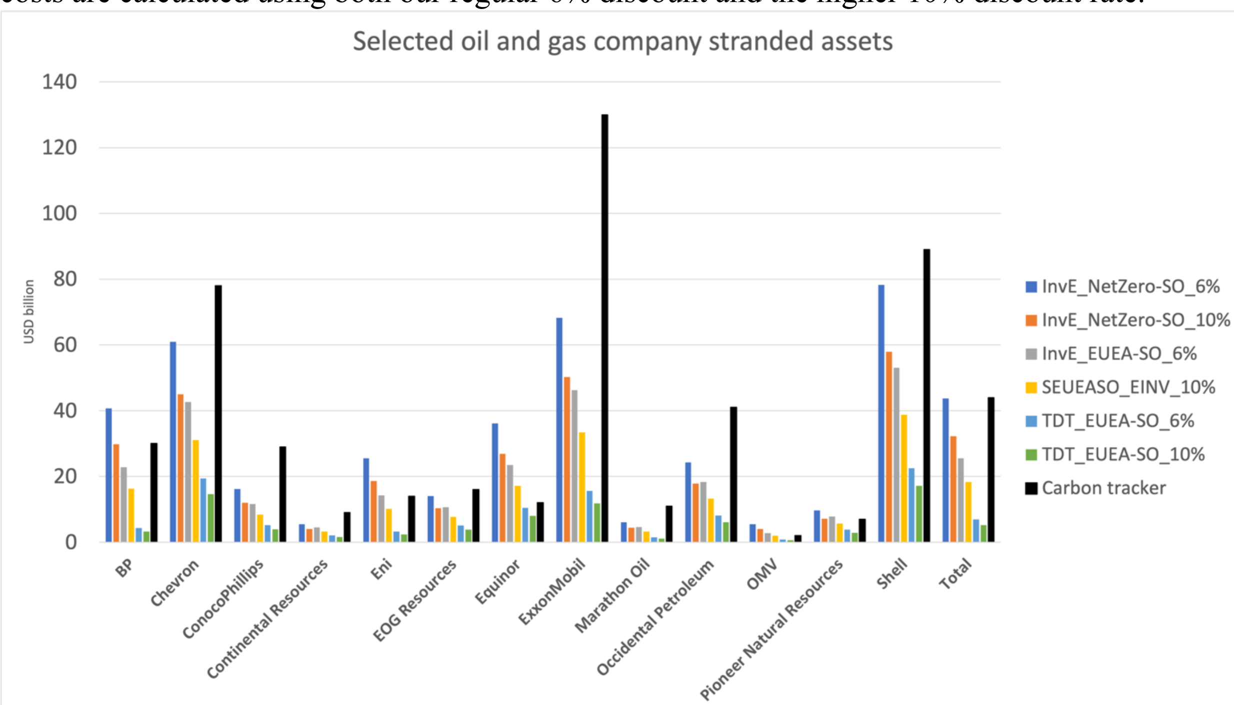
Suppl. Fig. 7 | Ownership chain of stranded assets by country and institutional category. Lost profits under *Medium* (InvE_EUEA-SO) realignment without network imputations allocated to **a,** the country where stranded oil and gas fields lie (Stage 1); **b,** fossil-fuel company headquarter country (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.



Supplementary Note 7: Comparison with Carbon Tracker's stranded assets

In April 2021 Carbon Tracker undertook a stranded asset analysis for 14 major oil and gas companies calculating whether the profits they would earn under a (low) $35 per barrel oil price were enough to cover their reported property, plant and equipment assets[11]. Carbon Tracker found an overall $512 billion shortfall (a negative net present value) using a 10% discount rate on future earnings. This total compares with $435 billion in our *Severe* realignment for the companies as a group and as shown in Suppl. Fig. 8, our distribution of losses across companies is similar to that of Carbon Tracker. We apply both 6% and – like carbon tracker – a 10% discount rate to all of our sell-out scenarios. Our total is lower for every scenario and it is notable that our estimates are similar for European countries but smaller for US companies. We reason that this pattern arises from the bigger asset write-offs carried out by European companies relative to their American peers since our data snapshot that reflects balance sheets at the end of 2019. Overall, the similarity in losses suggests that our attempt to estimate what investors think they are worth using the *InvE* scenario's discounted future profits comes close to the reported plant, property and equipment investments reported on companies' balance sheets.

Suppl. Fig. 8 | Stranded assets for 14 major oil and gas companies in our realignments and Carbon Tracker analysis. Values are for each company's global operations (i.e. stage 2) and costs are calculated using both our regular 6% discount and the higher 10% discount rate.

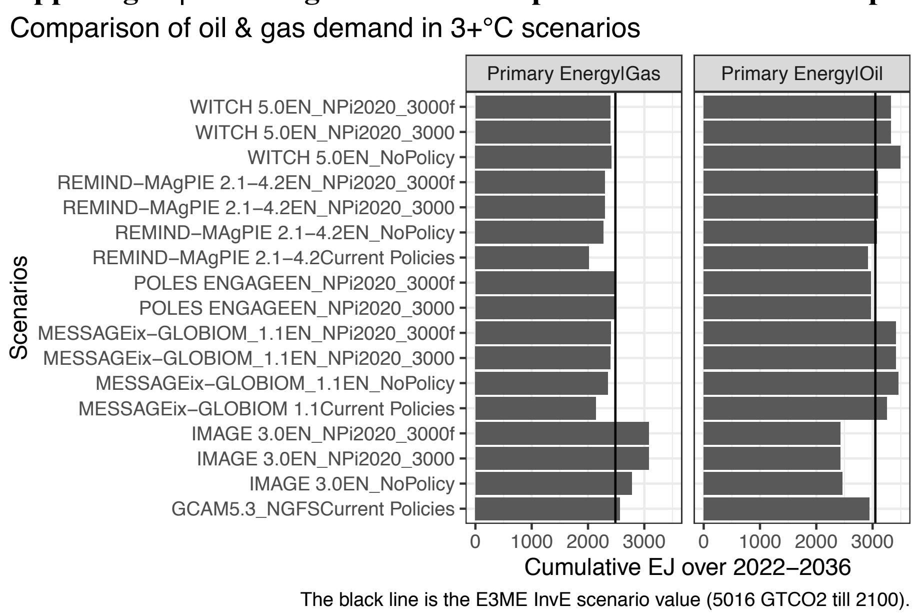


Supplementary Note 8: Comparison with other models' oil and gas demand

No other recent model to our knowledge calculates scenario-specific (or any) oil and gas profits or shares data on revenues[4], but we can compare demand for oil and gas in EJ in our scenarios with those in other recent studies to illustrate where our 'realignments' fall with respect to other studies. Suppl. Fig. 9-12 classify scenarios according cumulative CO_2 emissions until 2100 or, where unavailable, by average global warming using the linear relationship in ref[12]. They show cumulative global oil and gas demand (including abated by CCS, which corresponds to a relatively small proportion through 2036) over the relevant period of 2022-2036 of scenarios from refs[12–14] including only those scenarios where policy action is assumed from 2020 (instead of delayed until 2030) and where we have linearly interpolated observations available in five or ten year intervals. The vertical black line represents oil or gas demand in one our four energy demand scenarios. It lies within the ensemble of results, so our realignments are unlikely to produce systematically different numbers from the ones we are analyzing. An interesting observation about the results is that the Welsby et al. results[14] about 'unextractable fossil fuels in a 1.5ºC world' that uses the TIAM-UCL model has among the highest oil and gas demand among all scenarios, suggesting their short-term projections of fossil fuel stranding would be relatively modest for a 1.5ºC scenario.

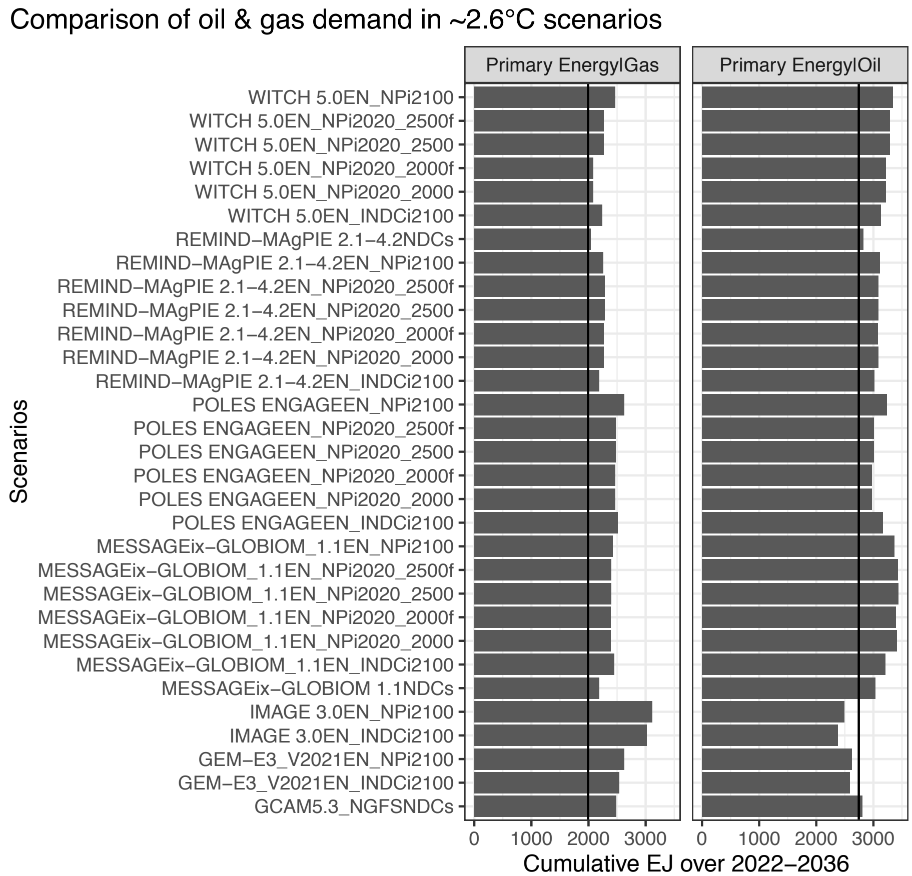
Supplementary Figures 9-12

Suppl. Fig. 9 | Oil and gas demand comparison in scenarios comparable to InvE.



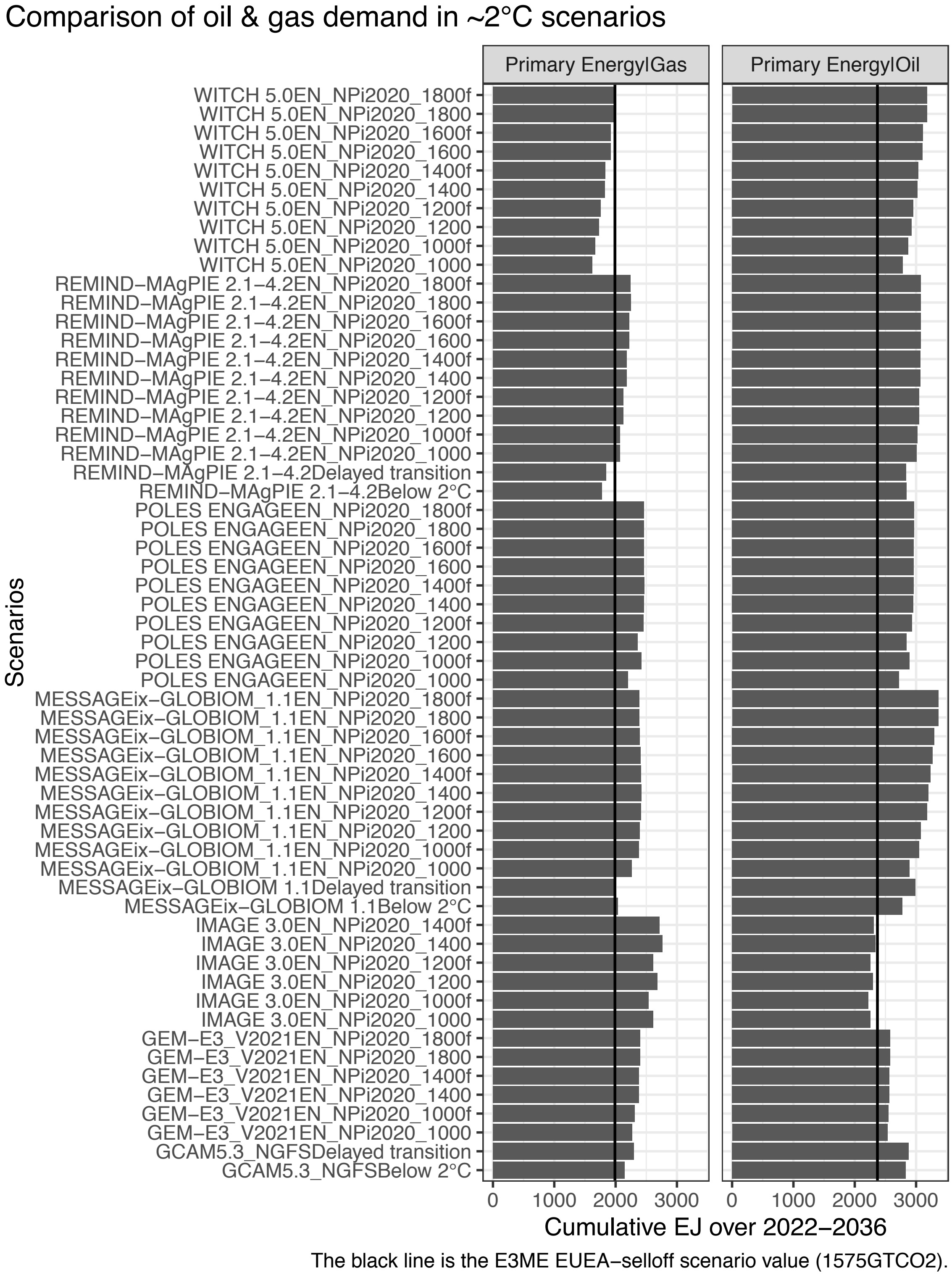
[4] Welsby et al. provide a production cost curve that excludes transport cost and royalties and so cannot be used to calculate breakeven prices. They also do not provide enough information in the SI data to calculate revenues under their scenarios without learning their model.

Suppl. Fig. 10 | Oil and gas demand comparison in scenarios comparable to TDT.

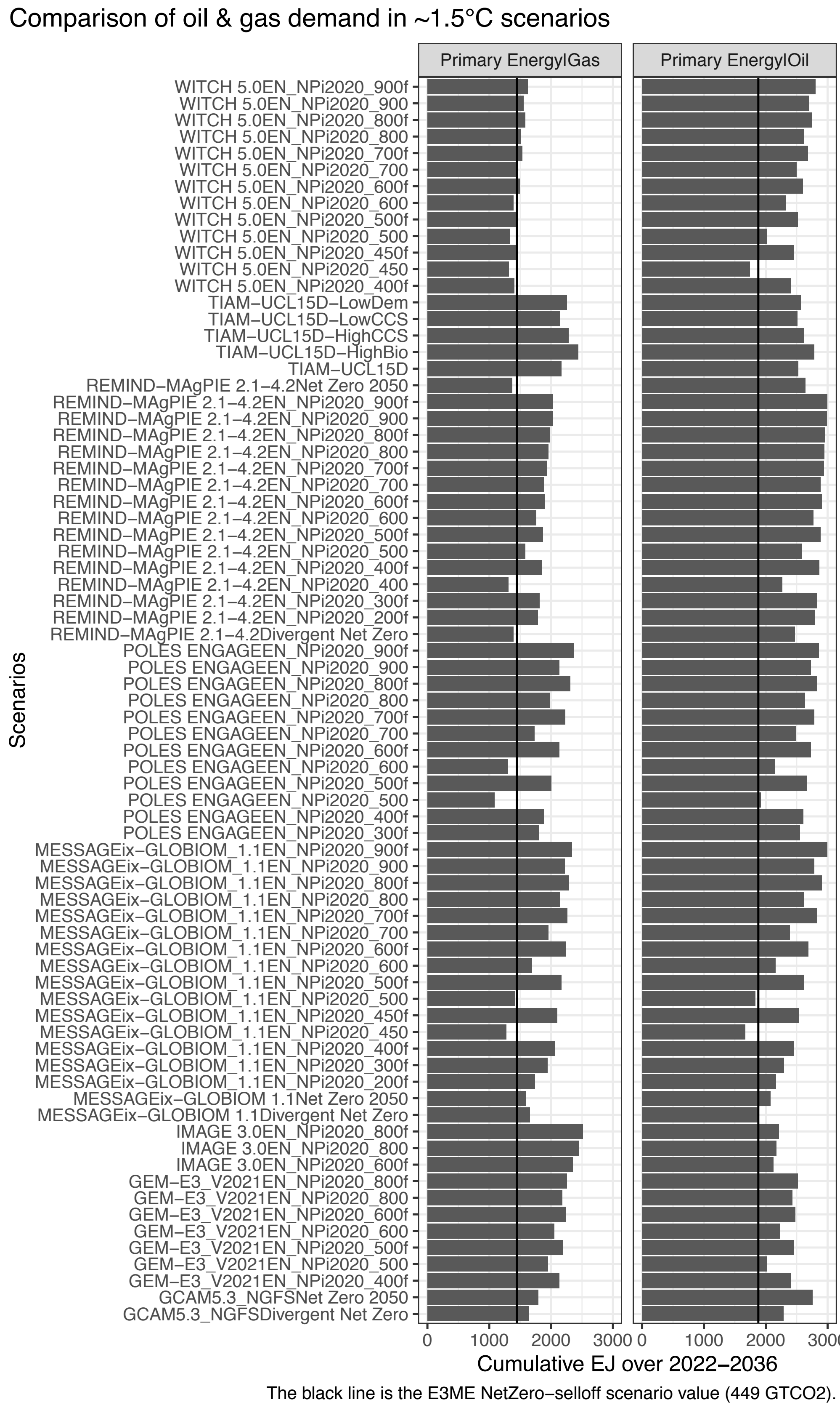


The black line is the E3ME TDT scenario value (2704 GTCO2 till 2100).

Suppl. Fig. 11 | Oil and gas demand comparison in scenarios comparable to EUEA.



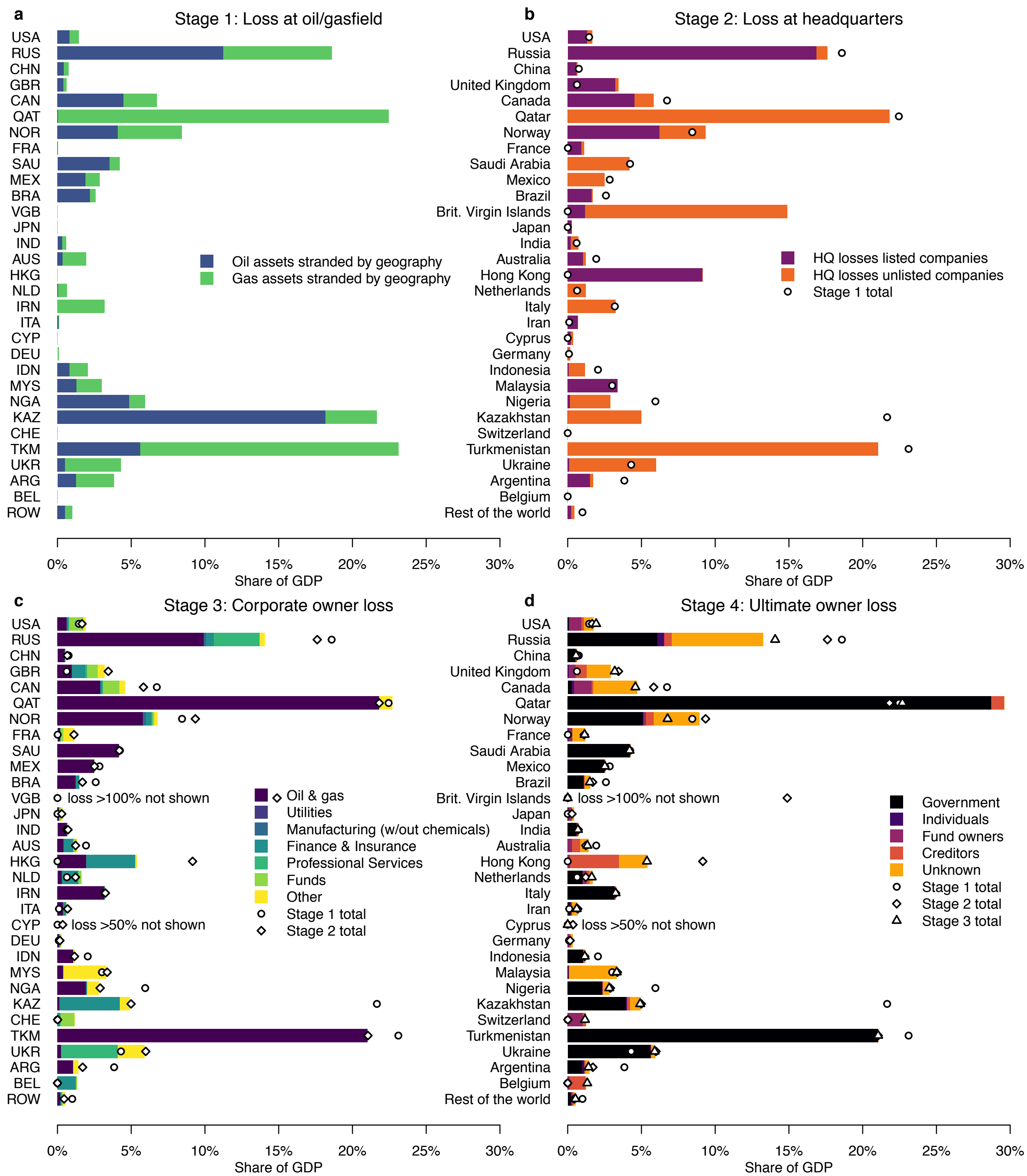
Suppl. Fig. 12 | Oil and gas demand comparison in scenarios comparable to NetZero.



Supplementary Note 9: Loss relative to GDP

Losses from alignments so far have been computed in absolute (USD) terms. Dividing by GDP pictures the risks relative to the size of the economy as shown in Suppl. Figure 13 (keeping in mind that GDP is an annual flow and the present value of losses a stock). The losses can be interpreted as a 'maximum' bailout and hence increase in debt to GDP ratios of governments. GDP is from the World Bank for 2019 or the latest available year.

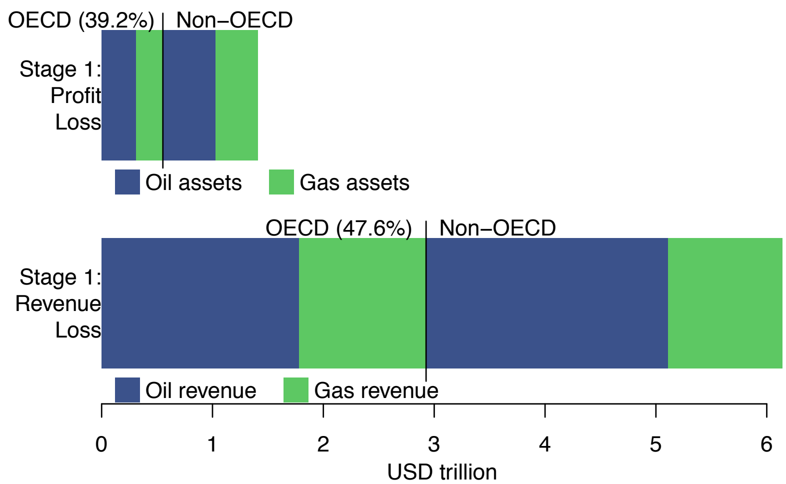
Suppl. Fig. 13 | Loss as a share of GDP for major countries under *Medium* realignment.



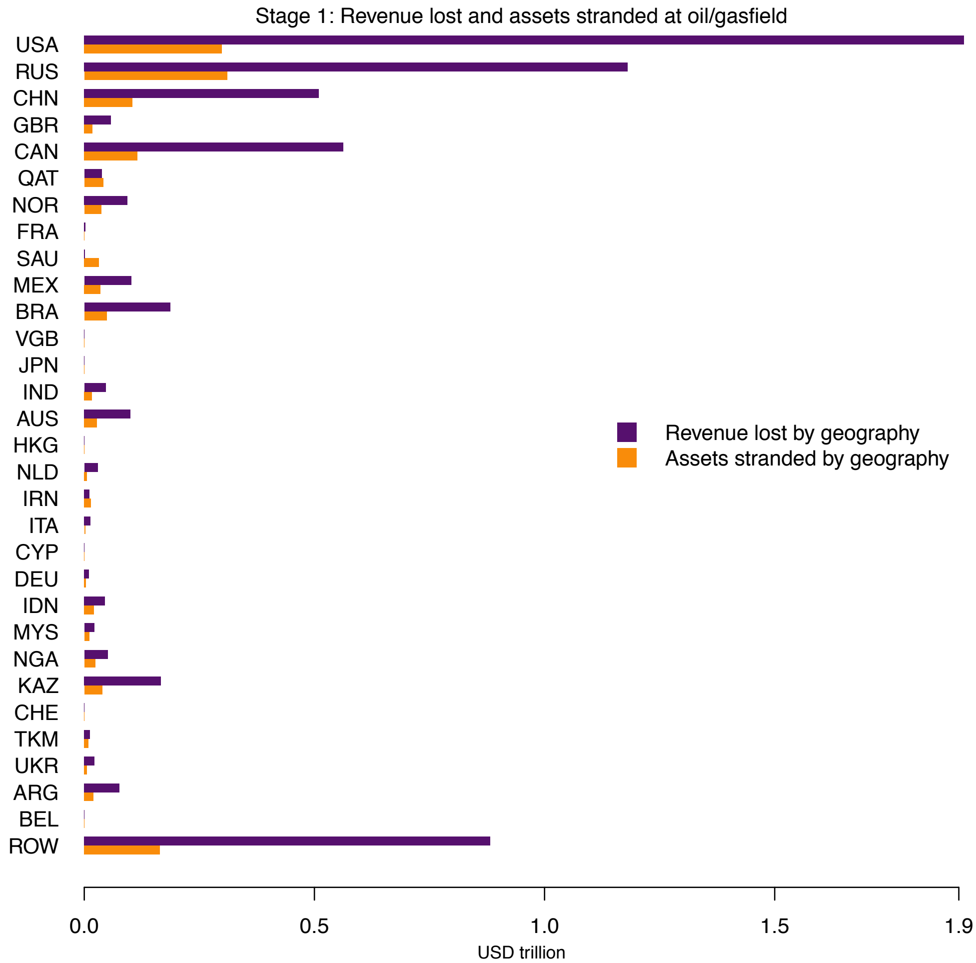
Supplementary Note 10: Revenue loss vs profit loss

The value of stranded assets is computed on discounted future profits, i.e. the difference between the market and breakeven price. The breakeven price covers production and transport cost as well as taxes and royalties as reported in the Rystad database. Suppl. Figure 14 contrasts the $1.4 billion in lost profits with the more than $6 billion in lost revenue in the Medium realignment. The ratio of lost revenue to lost profits for oil and gas is roughly similar overall, however it is regionally different. The production cost in OECD countries is higher relative to the market price, owing the more favorable geographical profile on average in non-OECD countries. Suppl. Fig 15 details the loss comparison at the country level for the top 30 losing countries. Russia and the US have roughly the same stranded assets but there is 1.5 times more lost revenue in the US, meaning that the primary energy stranded in the US in EJ is higher than in Russia. In Iran, Qatar and Saudi Arabia, total revenue is hardly affected thanks to higher sales volumes, but the lower oil price lowers profits. A detailed discussion of lost revenue in all scenarios in can be found in ref[15].

Suppl. Fig. 14 | Stage 1 stranded assets (profit loss) and revenue loss by OECD/non-OECD geography and oil or gas source in the *Medium* InvE_EUEA-SO realignment.



Suppl. Fig. 15 | Country level revenue and asset stranding comparison. Stage 1 stranded assets (profit loss) and revenue loss for the top 30 Stage 4 countries.



Supplementary Note 11: Distributional effects within countries

Losses to ultimate wealth may impact households in a particular country unequally, raising the question how stranded assets may affect wealth inequality. To get a sense of the distribution within a country's household wealth, Suppl. Table 7 shows an estimate of how the total loss under the "Medium" InvE_EUEA-selloff realignment for the US is distributed across the size distribution of household wealth, and also reports the number for government. The figures are based on the US Survey of Consumer Finance and for government net worth on Piketty and Zucman's[16] estimate.[5] Translating losses for the US displayed in Figure 3 Stage 4 into stock, fund and bond (for creditors) categories and distributing them in proportion in which they are held by different quantiles of the size distribution of household wealth, we can see that the richest 10% of wealth owners sustain by far the largest loss from stranded assets with $286 billion or about 82% of the total. This is first because they hold most of US assets (70.3%) and net worth (76.5%) but also because the loss takes place in asset categories in which the richest households hold a share that is higher than their average share of assets, as the column on loss relative to assets shows. Here, the top 10 percent of wealth holders incur the largest loss relative to their assets. It is also clear that this share at 0.4% is small compared with annual capital gains and new investments of several percent in any usual non-crisis year. However, we stress here again that we only model the equity channel of loss transmission, which may be accompanied by additional losses via debt and additional negative macroeconomics effects.[17] The relative losses are closer to the average for all households when considering only net worth (assets minus liabilities). That is, poorer households have a higher ratio of assets to net worth and hence the loss of assets hits their net worth harder than their assets in relative terms. For instance, for the second quartile or 25th to 50th percentile, the loss relative to net worth is more than twice the loss relative to assets. The bottom quartile even has negative net worth, hence the ratio is negative.

While the top 10 percent of wealthiest households thus incur higher relative losses than others, Suppl. Table 8 shows that this difference has negligible effects on the US wealth distribution. The share in total household assets from a Medium realignment falls by 0.038 percentage points and that in net worth by only 0.021 percentage points. The biggest winners in the distribution are the 75-90th percentile, increasing their share in net worth by 0.014 percentage points, and the bottom quartile further falls into negative net worth.

Suppl. Table 7 | Asset loss distribution across the US house wealth size distribution from *Medium* InvE_EUEA-SO realignment.

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

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

Memo: Government	13.740	0.073%	0.282%

Suppl. Table 8 | Effect of asset loss on US household wealth distribution from *Medium* InvE_EUEA-SO realignment.

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

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