The future of coal investment, trade and stranded assets

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Abstract

Coal is at a crossroads, with divestment and phase-out in the West countered by surging growth throughout Asia. Global energy scenarios suggest coal consumption could halve over the next decade, but the business and geopolitical implications of such a profound shift remain under-explored. This paper investigates coal markets to 2040 using a perfect competition model with technical and economic constraints. In a well-below 2°C scenario, we find over-capacity is a problem for Europe, North America and Australia, with 1/3 of today's mines becoming stranded assets. New mines must still be built to offset retirements, but a new investment cycle in the 2030s can be avoided. Coal prices gradually decline as only the most competitive mines survive, and trade volumes fall to give more insular national coal markets. Regions stand to gain or lose tens of billions of US dollars per year due to reducing import bills or export revenues. Understanding and preparing for these changes could lessen the barriers to transitioning away from coal after 150 years of dominance.

Highlights

- A high resolution coal market model develops regional insights into investment risks
- By 2040, one third of current mining capacity risks becoming stranded assets
- China benefits the most while Indonesia and Australia lose the most from coal phase-out
- Over 2.2 million jobs would suffer from early mine closures in the Sustainable scenario

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Context and Scale

The world spends almost half a trillion US dollars per year on coal. This could change abruptly if energy systems are transformed in line with the Paris Agreement to limit global warming to well below 2°C. While existing global energy scenarios provide a macro picture of demand for coal, they do not consider how profound reductions in demand would affect investment decisions and national economies. We explore the regional impacts of following business-as-usual and sustainable development scenarios from the International Energy Agency. We show that following a below-2°C pathway will see exporting countries lose tens of billions of US dollars per year as prices and global trade volumes fall. Reduced investment in new mines and the early retirement of existing ones will lead to stranded capital and labour. There is a limited window of opportunity for investors and decision-makers to react before a new commodity cycle begins. Building resilience to the human and financial impacts of a sustainable transition now could strengthen the prospects of moving away from the most carbon-intensive fossil fuel.

1. Introduction

Over 80% of the world's coal resources must remain below ground if CO_2 emissions are to fall by 80-95% to limit global warming to 1.5°C [1, 2]. Rapid coal phase-out is required among developed countries followed over the coming decades by developing countries [3]. No new coal power plants should be built other than those currently under construction, and the existing fleet should be progressively retired [4]. Reducing reliance on coal has substantial health co-benefits through improved air quality [5], as emissions of SO_2, NO_X, particulates and toxic heavy metals precipitate various respiratory and cardiovascular diseases, cancers and premature deaths [6]. Growing public concern, policy regulations and stakeholder pressure mean coal divestment is gaining traction. Over 100 countries, states, cities and business have joined the Powering Past Coal Alliance, committing themselves to transition away from unabated coal power generation [7, 8]. Meanwhile, 100 of the largest global financial institutions have divested from, or stopped lending to steam coal mining and/or power plant projects [9].

However, global coal consumption has continued rising, driven by growth in Asia [5, 10]. Despite modest falls in 2019 and 2020 [11], some suggest demand may remain stable on a long plateau until 2025 (post COVID-19 recovery) [12, 13]. 200 GW of new coal power plants are under construction worldwide, three-quarters of which in Asia [14]. Coal is key to economic growth in developing countries by supporting finance, railways, steel production and more; policymakers seeking to curb coal reliance may face a trade-off between climate change mitigation, environmental benefits, energy access priorities and economic interests [15]. Similarly, many countries are wrestling with political narratives around heritage, national pride, regional equity and industrial prowess surrounding the decline of their coal industries [16].

Investors are placed in a difficult position as the coal industry's future has perhaps never been more uncertain [10, 17, 18], evidenced by Rio Tinto exiting the coal sector in 2018 [19], and Glencore freezing global production in 2019 [20]. The world is potentially at a tipping point as the number of coal power stations declines for the first time on record [21], utilities are being paid to prematurely close coal power stations [22], and coal producers suffer extensive write-downs [23]. As the cost of renewable electricity generation and storage continues to fall [24, 25, 26], the economic case for building coal power stations is weakening, and in many cases it is now even cheaper to build new renewables than it is to continue operating existing coal [27]. Several open questions face the industry: will carbon capture and storage offer a new lease of life for coal within industry and power generation; is coal divestment justified financially, or would investors and mining companies remain profitable; will coal prices collapse; are coal markets heading towards over-supply; will coal compete with renewables on cost basis or will coal power plants suffer from likely future renewables cost reduction; will the competitiveness of coal become ever more constrained and regionally disparate; and which countries will see the greatest change in their prospects depending on how global climate mitigation effort evolves?

This paper sheds light on the outlook of hard coal (anthracite and bituminous coal with gross calorific value above 24 GJ/t [28]), specifically the impacts of phase-out on regional markets, investments, stranded assets, prices, profitability and trade. It compares a business-as-usual and sustainable scenario, taken from the International Energy Agency (IEA) [12], aiming to identify the main challenges to investors and policymakers in this uncertain future, and to provide energy modellers with greater granularity on future scenarios for coal. A partial equilibrium model is developed to determine the optimal allocations among regions for both scenarios and elucidate the implications for the future of coking and steam coal (known respectively as metallurgical coal used in the iron and steel industry, and thermal coal used for electric power generation [12, 18]). Lignite (non-agglomerating coal below 17.4 GJ/t [29]) was excluded from this study as it represents only around 10% of coal production and a negligible portion of international coal trade. High water content and low calorific value make it uneconomical to transport lignite over long distances (most consumption sites are located close to mines), and give limited substitutability between hard coal and lignite [28].

1.1. Coal stranded assets

Stranded assets are defined by the International Energy Agency (IEA) as *"investments which have already been made but which, at some time prior to the end of their economic life, are no longer able to earn an economic return as a result of changes in the market and regulatory environment brought about by climate policy"* [30]. Stranded assets resulting from the transition to a low-carbon economy have wide-ranging implications for different stakeholders, including unemployment, lost profits and reduced tax income for governments [31]. Delayed action is likely to result in more stranded assets, since prolonging business-as-usual will worsen efforts and corrections needed to meet Paris agreement climate target [32].

McGlade and Ekins estimated that 82-88% of the world's 1004 Gt of coal reserves must remain unburnt to limit global temperature rise to 2°C [2]. The US, Russia and Australia would be among the countries with the largest proportion of coal reserves stranded [2]. Coal-fired power station capacity may increase in developing countries, but would face stranded risks after 2030 to meet decarbonisation targets [32]. Pfeiffer et al. estimate that even if the entire planned power plant capacity was cancelled, 20% of global capacity would become stranded, four-fifths of which is coal and two-thirds would occur in Asia [33]. Similarly, IRENA's renewable scenario sees 40 GW of coal power capacity becoming stranded per year until 2050 [32].

While most studies focus on coal power capacity, this work analyses further the impact of stranded assets on upstream coal mines at regional level for different types of coal. It highlights the implications of unburnable coal reserves on mining assets in terms of production capacity and employment loss.

1.2. Scenarios for the global coal industry

Recent global energy scenarios show a great diversity of opinion around the future of coal (Figure 1). These range from coal consumption falling by 70% over the coming two decades (-5.2% per annum) through to increasing by 30% (+1.1% per annum). This contrasts with comparable scenarios from fifteen years ago, which converged around modest growth for the period of 2005 to 2020 (annual rates of +1.5% from the EIA [34]; +1.6% from the IEA [34]; +2% from the IEEJ [34]; and +2.2% from the EC [34]), which closely aligned to the realised outturn of +1.9% annual growth [28].

The outlook for coal is highly dependent on the level of environmental ambition, and will to a large extent determine the amount of global warming that will be experienced through this century. Figure 1 summarises the relationship between end of century temperatures and the near-term reduction in coal consumption [35]. Other areas of energy system development vary between the models (e.g. nuclear, carbon capture, negative emissions technologies) hence a range is seen across models and scenarios.

Despite the diversity in scenarios, strong regional trends are seen across them (Figure 2). Demand typically falls everywhere except for Asia, due to continued growth in India and other developing countries. North America and Europe are universally expected to lead the coal phase-out as less economic coal power plants are offset by natural gas and renewables [36, 37, 38].

Only two organisations separate out steam and coking coal in their scenarios [12, 39], leaving an area of uncertainty that this paper attempts to resolve. Limited information is given in these scenarios on the fate of major exporting and importing countries, and there is only limited agreement on the future trajectory of coal prices [12, 39, 40]. Further discussion of these scenarios is given in Note S1.

1.3. Modelling

We focus on two IEA scenarios from [12] as these are representative of the spread across other sources from Figure 1, and are the only ones to give the necessary disaggregation by region and coal type. The New Policies Scenario (NPS) considers where government ambitions may take the energy sector, and is central among business-as-usual scenarios with global coal consumption remaining flat, with a 1.6% increase between 2017 and 2040. The Sustainable Development Scenario (SDS) reflects the Paris Agreement's well-below 2°C target, with coal consumption falling by 57.4% from 2017 to 2040 (-3.6% per annum) [12].

Demand from these scenarios is combined with the Deloitte Coal Database, which contains asset-level data for cost, capacity, calorific value and age of existing mines and potential new investments, plus transportation costs from mines to export terminals and consumption hubs, and between ports. The database methodology and underlying sources stem from [41, 42, 43], and are described further in the Experimental Procedures. The database is maintained and quality controlled by Deloitte Economic Advisory who granted access for the scope of this paper (see Resource Availability).

We explore these scenarios using the global hard coal market model from [41, 42, 43], updated and extended to consider investments and stranded assets. This models the coking and steam coal markets using inter-temporal linear optimisation to determine the least-cost production, export and import for each region to satisfy the exogenous demand. It considers brownfield investments, starting from the mining capacity held in 2016, and considers investments on annual time steps to 2040 with perfect foresight. A discussion of contemporary models and full details of this model are given in the Experimental Methods, and validation is provided in the Note S2.

2. Results

2.1. Investment in coal mines

Total investment in coal mining capacity diverges considerably between the business-as-usual (BAU) and sustainable development scenario (SDS). Under BAU almost all current capacity is renewed by 2040 since coal demand remains generally flat (Figure 1); whereas in the SDS only half of the current capacity will be replaced. Total coal production capacity in 2017 was 4134 Mtce (million tonnes of coal equivalent extracted per year, where 1 Mtce equals 29.29 GJ). Cumulative investment up to 2040 under BAU equals 4070 Mtce, but this is 56% lower in the SDS (1790 Mtce). The financial size of total investments in new mining capacity up to 2040 are 411 billion USD_{2016} under BAU, dropping to 189 billion USD_{2016} in the SDS.

Figure 3 highlights the diverging evolution of investments over time, against the context of historical capacity additions. During the 2020s, annual investments increase slightly from 85 to 130 Mtce under BAU and from 55 to 75 Mtce in the SDS. Investments ramp up in both scenarios during the 2030s, peaking at 340 or 150 Mtce respectively. This is driven by the replacement of mines developed during the 2000s which reach retirement age. Figure S12 shows that steam coal is responsible for this difference between scenarios, as it faces greater pressure from decarbonisation policies and competition within electricity generation, whereas coking coal investment is relatively unaffected by scenario as there are fewer economically-viable options for replacement [37, 39, 38, 40].

Two peaks are observed in historical coal mine investment, one after the oil crises of 1973 and 1979 which provided strong incentives to move away from oil and towards alternative commodities such as coal [44]. The second in the 2000s was driven by the boom in Chinese industrial output and demand for electricity, and partly by replacement of mines from the first peak becoming exhausted. Our modelled investment under BAU shows coal entering a third investment cycle which peaks in 2035, underlining the need for substantial new investment even though demand remains flat under BAU. In contrast, it appears as though the SDS puts an end to coal's commodity cycles, ushering in a phase of managed decline.

As shown in Figure 4, China sees the greatest investment in both scenarios, with around 45% of the world's total. Although Chinese coal demand decreases in both scenarios, substantial investments are needed as almost the entire current mining fleet needs to be replaced by 2040. China therefore experiences a below-average fall in investment in the SDS.

India has the second highest investments up to 2040 across both scenarios, representing around 22% of the global total, driven by its rising primary energy demand. India is not projected to follow the Chinese coal boom, as it profits from 20 years of technical and economic progress on alternative energy sources which makes a diversified energy mix more feasible [12]. For this reason, India's coal investments are more strongly impacted by the SDS.

Developing Asia is the third largest investor in new mines, with around 10% of global investments up to 2040. Under BAU, investment in new capacity is driven by expanding domestic demand (see Table S3) and growing export opportunities, principally from Indonesia to neighbouring Asian countries due to its low cost of extraction. Under the SDS, export opportunities are more limited but resilient domestic coal demand drives new investment to replace retired mines, making Developing Asia's coal industry among the least impacted by this scenario.

The US and Australian coal industries are most strongly impacted by decarbonisation. Under the SDS, investment in US mines falls by 69% due to both falling domestic demand and exports to Europe. Its distance (and thus transportation cost) to more resilient markets in Asia puts the US at a disadvantage, along with Latin America and Canada. Decreasing demand in Asia similarly reduces the need for Australian exports. The scale of change in many regions is stark. Many parts of the world, especially North America, Europe and Australia, should anticipate workers needing to change careers to avoid unemployment in mining regions [16, 45].

In contrast, South Africa suffers the least due to its proximity to growing African markets and relatively low mining costs. It still sees a 44% decrease in investments in the SDS. The rest of Africa sees very little coal mining investments because African coal demand can be provided more cheaply by existing production from South Africa and the Americas. This is a competitive optimisation from the model, and Africa could use this transition to become a more energy independent continent.

2.2. Prices

The model's marginal costs for 2016-17 accurately match historical steam coal prices (Figure 5), but they were below coking coal prices. This can be explained by shortages or oligopolistic behaviour in real coal markets, which keeps prices higher than in the perfectly competitive situation modelled here [43]. We therefore expect the model's steam coal prices are reflective of future markets, whereas coking coal prices will give an indication of the direction of travel. See Note S2 for further discussion and validation.

In the SDS, oversupply causes the least efficient mines to retire, moving the steam coal market down the global supply curve. Prices fall in line with demand, by an average of 3% per year to 2040. Under BAU, increasing demand in developing countries outweighs coal phase-out in developed countries, so there is no substantial shift in the global supply curve. Steam coal prices remain comparatively flat, falling by 1.3% per year to 2040. Results are similar for coking coal, but as seen previously, the divergence is less between the scenarios. Prices fall by an average of 0.8% per year under BAU and 1.6% in the SDS.

2.3. Trade

Figure 6 shows that in the SDS, the global trade volume for hard coal halves between 2020 and 2035, falling at a comparable pace (28 Mtce per year) as it has risen over the last two decades. In contrast, trade volumes remain close to today's levels under BAU. These results are in line with the IEA's own projections for these two scenarios [12, 28]. Steam and coking coal see similar trade projections, following the same trend as the overall hard coal outlook.

Under BAU, 19% of global coal production is traded over the period to 2040. In the SDS coal trade falls proportionally with demand, so 18% of production is traded in the 2020s, falling to 14% by 2040. This could indicate a shift towards domestic markets, as countries begin supplying more of their own consumption when the lower value of coal cannot justify the cost of intercontinental trade routes.

Figure 7 shows the profound evolution of imports and exports at regional level to 2040 in both scenarios. Under BAU, China's imports decreases during the 2020s before rising again once old local mines are depleted in the 2030s. In contrast, India's imports increase until 2030 since the model needs to supply an exploding coal domestic demand. Then, imports fall more rapidly as the model manage to balance demand with domestic production. Imports to developing Asia rise, and to Europe fall, in line with local demand. BAU sees a period of stability for exporting regions, with slight falls in Australia and Indonesia offset by growth in the US and South Africa.

In the SDS, the most profound shifts are India becoming self-sufficient from 2035 versus representing 12% of global imports under BAU, and imports to developing Asia differing by a factor of ten between the scenarios (growing 2.2x to 2040 under BAU versus falling by three-quarters in the SDS). Falling global trade in the SDS drastically affects regional outlooks. Australia sees exports fall 60% between 2017 and 2030, while Russia and Indonesia see 40% reductions, the US and Latin America see 20% reductions. South Africa is the only region to increase exports under both scenarios, becoming the 2nd largest coal exporter in the SDS by 2040, overtaking Indonesia and Russia to supply a quarter of the world's export demand. This is enabled by growing markets in the rest of Africa, strategic connections to both Atlantic and Pacific markets and falling domestic demand in South Africa. China's imports during 2025-2030 are higher in the SDS than under BAU despite lower domestic demand. This is a feature of perfect foresight in the model (which could reflect policymakers with stable long-term objectives). With the depletion of old Chinese mines built in the 2000s, global mining overcapacity and gradually decreasing demand in China, the model finds it cheaper to accept a short period of increased imports than to invest in new mining capacity. In contrast, new capacity is built under BAU as future demand can sustain its long-term operation, which decreases the need for imports in earlier years.

Figure 8 highlights the economic implications of these changes to trade under both scenarios. The financial value of trade is calculated as the change in export revenue plus the change in import costs between 2017 and 2040. Exports in each region were valued according to their FOB (Free on Board) price, and imports according to their CIF (Cost, Insurance, and Freight) price. The difference between these is the cost of shipping [18], hence the reduction in trade volume in the Sustainable scenario gives a global net saving of USD 10 billion per year due to reduced coal transportation.

Europe, Japan and South Korea are the greatest beneficiaries under both scenarios as they gain from reduced coal imports and lower prices. India also benefits under both scenarios as greater domestic production reduces spending on imports. Indonesia and Australia are among the worst hit regions in both scenarios (along with Russia and the US) due to the declining value of their coal, combined with declining export volumes in the SDS. The fate of China and Developing Asian countries is scenario-specific: they either spend more money on coal imports under BAU, or substantially less in the SDS; giving combined difference is USD 35 billion per year between the scenarios.

2.4. Stranded assets

If demand declines more rapidly than the natural retirement of mines, assets will become 'stranded' when they are no longer economically competitive and shut down before reaching their technical lifetime. The presence of stranded assets can indicate the volume of worthless overcapacity.

Figure 9 shows that BAU offers a stable market with few mines becoming stranded. A total of 210 Mtce capacity becomes stranded between 2020 and 2040, less than 1% of new mines built. This indicates natural churn within the industry, such as decommissioning the least profitable mines in regions like North America, Europe and Australia where local coal phase-out occurs

In contrast, the SDS results in severe trouble for the industry. Demand for coal falls faster during the 2030s than old mines are depleted, resulting in overcapacity and less efficient mines being replaced by cheaper ones closer to growing coal markets. 1.5-2.5% of mines are decommissioned each year, which accumulates to around one quarter of current global mining capacity (966 Mtce) becoming stranded during the next decade and around one third by 2040 (1210 Mtce). Decommissioning on economic grounds slows sharply in the 2030s as mines built during the 2000s boom reach their natural retirement age, alleviating the continued overcapacity due to falling demand.

Relatively few coking coal mines become stranded under either scenario since steel industries preserve demand. The fate for steam coal diverges, with few stranded assets under BAU as the need for new capacity counterbalances old mines retiring.

It is worth noting that the capital expenditure for coal mines is relatively low, representing less than 5% of overall cost, lessening the financial impact for investors of early retirement [5]. Coal mining is generally labour intensive so stranding labour is at stake rather than capital. Table 1 estimates the impact of stranded assets on job losses worldwide, based on EXIOBASE data for labour factors per unit of coal production in different regions [46]. Under the SDS, over 2.2 million jobs would suffer from early mine closures, affecting mainly low- and medium-skilled jobs which represent respectively 48% and 46% of the total number.

There is a substantial difference in the extent to which mining countries suffer stranded assets under each scenario, as shown in Figure 10. Under BAU, only developed countries face stranded assets as their domestic demand falls. Under the SDS, developed countries are still most at risk, but Asian mining industries are also severely affected.

China has the highest level of decommissioning with over 500 Mtce of capacity stranded up to 2040, affecting 1.75 million jobs. However, in relative terms this represents 22% of current capacity, making China's coal mining fleet among the more resilient to climate change policies. Decommissioning is driven by falling Chinese coal demand forcing the closure of less efficient mines, which are then replaced by more efficient ones during the 2030s to fill the supply gap.

Over one third of current mines in the US and Canada would shut down before the end of their life, impacting more than 60,000 jobs and creating a considerable burden for mining companies and communities across North America. European and Eurasian coal mines mainly supply domestic markets, and as demand falls in both regions almost half of the current capacity become stranded. Falling domestic demand and increased competition mean Australia faces a similar fate under the SDS.

India and South Africa suffer the least in the SDS, with less than a tenth of current capacity becoming stranded. India is buoyed by high domestic demand, while South Africa benefits from the incremental growth of its coal industry in previous decades (rather than boom and bust cycles), giving sufficient natural retirements to avoid stranding. A fifth of Developing Asia's current mining fleet becomes stranded by 2040 in the SDS despite the having resilient local demand. This is most notable in Indonesia, as the low calorific value of coal in the region makes mines unprofitable in the face of falling prices (and thus growing importance of transport costs).

2.5. The impact of hubris

An additional model run was performed to investigate the impact of over-confidence in the future of coal. This considers a scenario where investors expect that coal demand will remain buoyant, but coal demand falls rapidly as the world decarbonises. This reflects one possible outcome of the wide uncertainty in current market projections, or of the international response to COVID-19 causing a sudden and potentially sustained shock to global energy demand after a renewed expansion of Asian coal power generation [47]. Model inputs were based on SDS as above, except that investments for the first period (2020–2025) were imposed from the BAU scenario. The optimisation was then free to adjust from 2025 onwards, modelling a period of market correction, identifying which regions face the greatest challenges if investments are out of line with demand.

Latin America, developing Asia and South Africa suffer the most from a misjudgement of coal's immediate future (see Figure S13). The volume of stranded assets increases by 40-50% relative to the SDS with correct anticipation, affecting around 240,000 additional jobs around the world. The distance between Latin America and the main importing markets could explain their disadvantage. North America faces around one-fifth increase in decommissioning, while Australia and China see around one-tenth increase. Other regions see almost no impact on decommissioning of incorrect forecasting of demand, as investments under the SDS and BAU were comparable up to 2025.

It must be remembered these results are based on a model of perfect competition, where uncompetitive mines are closed without delay if their future is unprofitable. In reality, geopolitical considerations may arise if investors (some of which are state actors) misjudge coal's future and overbuild. Countries may privilege their domestic production in a world of imperfect competition, shifting the burden of stranded assets to exporters such as Australia, the United States, South Africa or Russia.

3. Discussion

In a period of high uncertainty for coal, this paper performs a comparative analysis of the future of coal investment across two divergent futures: a Business-as-usual (BAU) and Sustainable Development scenario (SDS). It uses a partial equilibrium model with perfect competition and perfect foresight to capture the market fundamentals in these two scenarios up to 2040.

The risk of overcapacity and stranded assets is low under BAU, where global coal demand remains at current levels. The SDS sees half as much investment in new coal mines as BAU, a deficit of over 2000 Mtce in the two decades to 2040. North America and Australia have the largest differences in investment between scenarios, implying greatest exposure to climate policy risk. China, India and other developing Asian countries experience the highest investment in both scenarios, with investment still required in the Sustainable scenario to counterbalance the depletion of existing mines.

Some regions face more risk from future uncertainties regarding coal than others. Those most likely to retain strong coal investment have growing energy consumption (developing Asia, India), produce coal with high calorific value and coking coal (South Africa), are close to the growth centres of coal demand (Russia, Australia), or have rapidly depleting mining capacity in need of replacement (China, Indonesia).

China is in a special position, as when the coal mines built in the 2000s are gradually depleted and retire from the mid-2020s onwards, China will reach a critical juncture between igniting a new cycle of coal investment or switching to alternative energy sources. Coal prices at that time will be a crucial factor, and investors may be cautious if China's policy is to progressively move away from coal to renewables or other sources.

Demand falls sufficiently rapidly under the SDS to create overcapacity, forcing approximately one third of global mining capacity to be economically unviable by 2040. The least efficient mines close prematurely and become stranded assets as coal prices fall by a third. Mines that are distant from resilient coal markets, have high mining costs or low calorific value represent the greatest risk.

Correct anticipation of the industry's future is critically important for investors. The relative prices of coal, renewables and natural gas will likely have a major impact on which pathway developing countries' coal demand follows. If investments are halted, for example due to a strong coal divestment movement or strategic withholding of investments, mine retirements could lead to market tightness and high coal prices after 2030. Conversely, under-estimating the pace of demand reduction could result in excessive investments which place a heavy burden on the coal mining industry. Latin America, developing Asia and South Africa would be among the regions most impacted by over-investment; however, domestic industry protection policies could move this burden to other export-driven regions.

Governments must tread carefully to avoid institutional lock-in[48], and should consider support for industries and for the 2.2 million workers at risk worldwide during coal phase-out to mitigate socio-economic impacts. Job losses may not be considered high at the national level, and could be offset by job creation in other sectors [49], but local mining regions would be disproportionately affected.

The Paris Agreement, divestment, rapidly falling costs for renewables and storage, countries striving towards "zero coal" electricity generation and growing awareness of air pollution across Asia are all signs of an industry potentially facing terminal decline. This paper helps to quantify the impacts that may be felt within the global coal industry. From a climate policy perspective, it is imperative that the inevitable coal phase-out is guided by sound investment and socially protective policy to minimise the risks outlined here.

4. Experimental procedures

4.1. Resource availability

Source data for all charts and tables presented in this paper are available from the Zenodo repository at `https://doi.org/10.5281/zenodo.4629991`.

The computer code used in this study is described fully in Section 4.3 and was reported previously in the references contained therein. There are restrictions to the availability of code and the coal database used in this study as they remain the commercial property of Deloitte Economic Advisory. Licenses to use these can be obtained from Deloitte, which may require reasonable compensation to cover the cost of producing and maintaining them.

Further information and requests for resources should be directed to the Lead Contact, Iain Staffell (i.staffell@imperial.ac.uk).

4.2. Models of the coal industry

Modelling the international coal market is a subject of wide interest in the literature [41, 50]. Modelling competitive spatial markets dates back to Enke [51], who in 1951 used a simple electric circuit to estimate equilibrium prices and quantities. Samuelson (1952) [52], Takayama and Judge (1964) [53] demonstrated linear and quadratic programming to solve such problems. Later, Nelson and McCarl (1984) [54] and Kolstad and Abbey (1984) [55] worked on imperfect competition within spatial markets, developing Cournot and Stackelberg equilibria to examine monopolistic behaviour.

Coal market models are often encapsulated within broader energy system models like LIBEMOD [56], which models Western Europe's gas and electricity markets and integrates the world market for coal. Similarly, the EIA's Coal Market Module (CMM) is an international trade model embedded within the US National Energy Modeling System (NEMS) [57], which is used to develop the Annual Energy Outlook 2020 [58]. The CMM is an international trade model that produces annual forecasts of prices, production, consumption and import of steam and coking coal to 2050. It uses linear programming to determine the least-cost supplies of coal from a set of supply curves, assuming perfect competition with various constraints such as import diversification and sulfur penalty costs [57].

Haftendorn and Holz [59] and Holz et al. [60] developed COALMOD-World, a multi-period game-theoretic equilibrium model for global steam market. The model simulates market outcomes, investments, land transport, resource depletion and export capacity to outline market structure and study implications. Unlike LIBEMOD and CMM, COALMOD-World assumes profit-maximising players who optimise their expected discounted profit over the total model horizon. The COALMOD framework has been used to test for abuse of market power in steam coal, and the impacts of energy security and climate policies on Europe's coal market [59, 60].

Standalone coal market models also exist. Lorenczik and Panke applied various equilibrium problems with constraints to investigate market forces in the international metallurgical coal market in the late 2000s commodity super-cycle [50]. Rioux et al. developed a linear optimisation coal market model focused on Chinese coal supply to assess the economic impacts of relieving congestion in the Chinese coal supply chain [61]. Paulus and Trüby developed a spatial inter-temporal equilibrium model for the global steam coal market [41], and analyse the steam coal market equilibria structure between 2006 and 2008 with a Mixed Complementary Problems (MCP) model to determine if market structure derives from perfect competition or oligopolistic behaviours [42]. Trüby [43] models un-competitive behaviours from metallurgical coal market agents between 2008 and 2010 with perfect competition, Cournot and Stackelberg models. It concludes that only non-competitive models can reproduce market structure observed in that period.

The model used in this paper is a further development of these coal market models from [42, 43]. Here these models are used to explore future scenarios rather than to explore past price spikes, with a focus on long-term market fundamentals (i.e. a detailed representation of the economics of coal mining investment and depletion of existing mines) rather than short-term strategic behaviours. The models and the code have thus been adapted to capture the fundamental long-term trade-offs in the coal market that our analysis deals with and therefore bringing some new insights to the existing coal literature.

This paper integrates sustainable and business-as-usual demand projections into a detailed coal market partial equilibrium model for steam and coking coal. The objectives are to model and analyse the implications of these diverging demand projections in terms of investments, prices, trades, decommissioning and regional trends. This paper provides a new perspective on the future of coal via more granular modelling of the evolution and regional structure of coking and steam coal markets in the two divergent scenarios.

4.3. Model

The model of global coal markets is taken from [41, 42, 43]. Since those works, it has been updated with new data and extendeded to consider investments and retirements. The model is a multi-period perfect competition model with technical and economic constraints which models market behaviour for steam and coking coal. The model only considers hard coal, as lignite is primarily mined and consumed locally, with limited trade between regions.

It is a linear optimisation program which seeks the lowest total cost as it assumes a benevolent social planner. The solution of this problem is, under the condition of perfect competition, equivalent to the result of profit maximising players. The model is implemented in GAMS and runs on an annual times step from 2016 to 2050. Years 2016 and 2017 are compared with IEA's Coal Data [28] for historical validation (reported fully in Note S2). Although the model runs until 2050, the framework of this study stops in 2040 to avoid end-game issues, specifically investment distortion after 2040 due to shortening payback period.

The model ensures a cost minimisation among all players while satisfying demand in each region at all time. It considers production costs, transport costs, investment into new mines and associated capital costs, maximum mining capacity and maximum investment, mines depletion, mining fixed costs and mining decommissioning costs.

There are three types of nodes. Mine nodes optimise their coal production and sell it either to domestic customers or, via export terminals, to coal consumers abroad. Port nodes correspond to export terminals from which coal can be shipped to any importer via ocean-going vessels. Demand nodes can satisfy their coal needs from domestic mines or via imports from mines abroad. Coal allocation is subject to the minimisation of the total costs i.e. production, transport and investment costs.

This spatial model considers a set of regions, with the most significant coal producing and consuming countries considered individually. Other countries are grouped into regions which are listed in Table S1

4.3.1. Model formulation

Tables S4 and S5 outline the parameters and variables used in the model. The model formulation uses sets for nodes k, mines m, new mines i, ports h, demand regions j, years t, and coal types c; which are outlined in Table S6.

The model is a cost minimisation problem with technical and economic constraints, where demand is totally inelastic and must be satisfied in every region at all times. Supply and trade are obtained by minimising the total costs of the system under specific constraints. The objective function to minimise total costs (1) combines mining production costs, mining capital costs, mining operation fixed costs, as well as transport costs between mines, ports and demand regions. It results in a perfectly competitive model where allocation at each node k $\in K$, mining capacity investments, decommissioning and trade flows are optimised under marginal cost-based allocations to satisfy demand.

$$\begin{aligned}\min totalcost = &\sum_{\substack{m\in M\\ c\in C\\ t\in T}} (prodcost_{\mathrm{m,c,t}} + fixedcost_{\mathrm{m,c,t}})\\ &+ \sum_{\substack{i\in I\\ c\in C\\ t\in T}} capcost_{\mathrm{i,c,t}} + \sum_{\substack{(k,k')\in K\times K\\ c\in C\\ t\in T}} transcost_{\mathrm{k,k',c,t}}\end{aligned} \tag{1}$$

The production cost (2) is equal to the mining costs times the quantity produced, weighted by the calorific value of the coal. This calorific value is normalised to tonne of coal equivalent (tce) of 7000 kcal/kg [62]:

$$prodcost_{\mathrm{m,c,t}} = cost_{\mathrm{m,c,t}} \times X_{\mathrm{m,c,t}} \times \frac{7000}{cv_{\mathrm{m,c}}} \qquad \forall m,c,t \tag{2}$$

The fixed cost (3) is equal to the operational fixed cost times its total capacity, added to the cost of decommissioned mining capacity:

$$fixedcost_{\mathrm{m,c,t}} = fixcost \times minecapa_{\mathrm{m,c,t}} + decomcost \times decom_{\mathrm{m,c,t}} \qquad \forall m,c,t \tag{3}$$

The capital cost (4) is equal to the investment volume times the investment costs with consideration of interest rate ρ and amortization duration τ:

$$capcost_{\mathrm{i,c,t}} = \sum_{\substack{t'\le t\\ t'\le t-\tau}} invcap_{\mathrm{i,c,t'}} \times invcost_{\mathrm{i,c}} \times \frac{\rho}{1-(1+\rho)^{-\tau}} \qquad \forall i,c,t \tag{4}$$

Then the transport cost (5) is obtained from the sum of all transport volumes from a mine to a domestic region, from a mine to a port or from an exporting port to an importing port multiplied by the corresponding cost:

$$
\begin{aligned}
transcost_{\mathrm{k,k',c,t}} = {} & Q_{\mathrm{k}\in M,\mathrm{k'}\in J,\mathrm{c,t}} \times minetodom_{\mathrm{k}\in M,\mathrm{k'}\in J} + Q_{\mathrm{k}\in M,\mathrm{k'}\in H,\mathrm{c,t}} \times minetoport_{\mathrm{k}\in M,\mathrm{k'}\in H} \\
& + Q_{\mathrm{k}\in H,\mathrm{k'}\in H,\mathrm{c,t}} \times 2.2012 \times distance_{\mathrm{k}\in H,\mathrm{k'}\in H}{}^{0.24055} \qquad \forall c,t
\end{aligned}
\tag{5}
$$

The constraint applies to each node. As a result, at mines nodes (6), the production at the mine must be equal to the sum of flows to domestic ports or domestic demand region. There is no storage at a mine and all production must be sent away:

$$X_{\mathrm{m,c,t}} - \sum_{k\in H\cup J} Q_{\mathrm{m,k,c,t}} = 0 \qquad \forall m,c,t \tag{6}$$

At port nodes (7), for an exporting port, the sum of all flows from domestic mines must be equal to what is exported to other regions. For an importing port, the sum of all inflows from other ports must be equal to what is transferred to the domestic demand region:

$$\sum_{k\in K} Q_{\mathrm{k,h,c,t}} - \sum_{k\in K} Q_{\mathrm{h,k,c,t}} = 0 \qquad \forall h,c,t \tag{7}$$

At demand region nodes (8), the sum of what is received from domestic ports or domestic mines must equal demand:

$$\sum_{k\in M\cup H} Q_{\mathrm{k,j,c,t}} - demand_{\mathrm{j,c,t}} = 0 \qquad \forall j,c,t \tag{8}$$

The annual investment (9) in a mine must be below a cap fixed in parameters and calculated from mine characteristics, country features and coal reserves:

$$invcap_{\mathrm{i,c,t}} \leq investmentcap_{\mathrm{i,c,t}} - \sum_{t'<t} invcap_{\mathrm{i,c,t'}} \qquad \forall i,c,t \tag{9}$$

The annual mine production volume (10) must be below or equal to its annual capacity:

$$X_{\mathrm{m,c,t}} \leq minecapa_{\mathrm{m,c,t}} \qquad \forall m,c,t \tag{10}$$

Where the mine capacity is obtained in (11) from the mining capacity parameter, decommissioning and investment. This addition is weighted by the depletion rate, which is the percentage reduction in a mine's capacity due to the exhaustion of coal resources. It is 0 during the first years of operation, then increases by 20% annually over the last five years of mine's lifetime.

$$\begin{aligned} minecapa_{\mathrm{m,c,t}} = [miningcap_{\mathrm{m,c,t}} - \sum_{t' \leq t} decom_{\mathrm{m,c,t'}} + \sum_{t' \leq t} invcap_{\mathrm{m} \in I,\mathrm{c,t'}}] \\ \times (1 - depletion_{\mathrm{m,t}}) = 0 \qquad \forall m, c, t \end{aligned} \tag{11}$$

There are two reasons for retirement of coal mines. The first is technical and imposed as an exogenous constraint: mines become progressively depleted and are retired when they arrive at the end of their technical life. The second is an endogenous financial decision (i.e. a choice to be made by the optimisation), and such mines are called 'stranded assets' in this paper.

Each mine's technical lifetime was calculated by dividing its in-situ resource by its nameplate annual capacity. This makes the simplification that each mine operates at full capacity in every period, but it was preferred to using cumulative production capacity for computational tractability. Accounting for resource depletion increases inter-temporal complexity and thus problem size and solution time by an order of magnitude. It also offers little practical gain as there is no elasticity to mine production costs, so it is only marginal and extra-marginal mines which do not produce at maximum capacity in any given period. Most extra-marginal mines go into terminal decline due to falling demand, and thus are retired.

Mines could also be decommissioned before their technical end of life if they become unprofitable. Decommissioning costs were set to five times the value of the mine's fixed costs (from eq. 3), which cover the care and maintenance required when mines are mothballed. The model therefore considers it economically viable to shut down a mine when not used at all over a 5-year period, unless the mine is used again in future periods. Since the model has perfect foresight it will mothball mines that become competitive again in the future rather than shutting them down completely, although this is not widely seen due to demand either being steady or continually declining in our BAU and SDS scenarios. With real-world frictions and volatility in demand, this may be more widely employed. This assumption does not imply that mines cannot weather more than 5 years of being uncompetitive, but rather it gives the model an economic incentive (with a small consequential financial hurdle) to shut down mines, enabling us to assess the mining capacity at risk in this paper. Therefore, the presence of stranded assets is more an indicator of the volume of worthless over-capacity rather than the volume of mines that would be physically shut down. More complex socio-political factors (such as energy security or employment) will determine the latter, as some mines are owned by states who may be willing to subsidise production or mothball them for many years without fully shutting them down. Partial decommissioning and partial use of a mine are possible within the model, but because there is no elasticity of mining costs for individual mines, if one part of the mine is uneconomic, the whole mine would also be.

Prices at import and export ports are obtained from the model's marginal value of the equilibrium constraint at port nodes. A country will buy or sell a unit of coal only if the marginal benefit to the country is equal to its price. The marginal costs shown in Figure 5 cover the range seen across major export ports. The price at an export port mirrors the Free on Board (FOB) price - the price that importers are willing to pay without including the shipping costs and any other fees associated with transport (e.g. insurance). For steam coal, Figure 5 represents the range of FOB prices for ports in Australia, South Africa, Russia, the US, Indonesia and Colombia. While for coking coal, it represents the FOB prices range in Australia, Russia, the United States, Canada and Mozambique. The range of FOB prices among main exporters is tight and the fluctuations are similar across both coal types. Global harmonized prices were expected since the model features perfect competition. The main differences among exporting countries come from the cost of inherent domestic production, transportation costs from mines to export ports and the distances to importing markets - as only exporting countries close to importing regions will be in position to sell coal at a higher FOB price than competitors.

4.4. Data

4.4.1. IEA scenarios

This paper develops a comparative analysis on the future of coal under Business-as-usual (BAU) and a Sustainable Development Scenario (SDS). The aim of this study is not to evaluate which trend is the most realistic or attach probabilities to the different trends. Instead, this paper aims at comparing the implications of scenarios. The two scenarios only differ by the level of demand which is used as an input parameter in the coal market model described above. Both scenarios take demand projections from IEA's 2018 World Energy Outlook 2018 [12], using the Sustainable Development Scenario for SDS, and New Policies Scenario for BAU.

The SDS assumes a world in line with the Paris Agreement where global warming is kept well below 2°C at the end of the century from pre-industrial level and efforts are made to limit it to 1.5°C. This scenario reflects a world where international targets are achieved including climate change, air quality and universal access to modern energy. Power generation is driven by renewables which provides 65% of global electricity generation by 2040 [63]. 210 GW of coal-fired capacity with carbon capture, utilisation and storage (CCUS) is operational in 2040, generating 1300 TWh annually, and unabated coal is almost phased-out, generating 700 TWh per year by 2040 [64].

The BAU scenario gives an outlook of where current policies will lead to. However, under this scenario, emissions continue to rise slowly and Paris Agreement's targets are not reached with at least a 2.7°C global warming from pre-industrial level in 2050. Coal-fired power generation CCUS remains marginal under this scenario [12]. These two IEA scenarios provide granular and transparent demand data for different regions and coal types based on clear assumptions.

Data for 2016 and 2017 were obtained from the IEA [28]. Projections from each scenario were taken for 5-year steps from 2020 to 2040, except for 2035 which is not stated for the Sustainable scenario. Input demand data are provided in Tables S2 and S3. The intervening years were inferred using linear interpolation. To obtain annual detailed projections by regions and by coal type simultaneously, the growth rates from IEA's regional projections were applied for each year and each region to demand for both coal types (equation 12).

$$\begin{aligned} Demand_{\text{region,coal type,year+1}} &= Demand_{\text{region,coal type,year}} \\ &\times \frac{IEAprojection_{\text{region,year+1}}}{IEAprojection_{\text{region,year}}} \qquad \forall region, coaltype, year \end{aligned} \tag{12}$$

Then values for each coal type are proportionally recalibrated among regions to have a total demand by coal types matching IEA's projections (equation 13).

$$Demand'_{\text{region,coal type,year}} = \frac{Demand_{\text{region,coal type,year}}}{\frac{\sum_{r\in J} Demand_{\text{r,coal type,year}}}{IEAprojection_{\text{coal type,year}}}} \qquad \forall region, coaltype, year \tag{13}$$

4.4.2. Coal market database

This paper uses the Deloitte Coal Database, which contains mine-level data for various countries regarding the fixed and variable mining costs, nameplate mining capacity, calorific value of the coal, expected year of decommissioning based on available resources, investment cost of new mining capacity, maximum investment capacity for new mines, transportation cost between mines and export terminals and between coal fields and the primary consumption hubs for mines serving domestic markets. For transport between ports, the database contains distance data between each port in nautical miles which serve as a basis for transport cost determination (see eq. 5). Table S4 outlines the different elements that are included in the database.

The database methodology and many of its underlying sources are given in Section 5 of Paulus and Trüby (2011) [41], Section 4 of Trüby and Paulus (2012) [42] and Section 4 of Trüby (2013) [43]. The data have been updated using various industry reports [1], and the cost escalation logic outlined in [42] (Section 4.1), based on input price evolution collected from national statistical offices [2]. For countries where mine-level data are unavailable, basin-level data were instead used based on national statistical publications (e.g. provincial coal production in China from the National Bureau of Statistics [65], coal production by state in India from the Ministry of Coal [66]). For this study, the database was updated with data from the IEA Coal Information 2018 [28], specifically calorific values, demand and trade levels.

The database is now maintained and quality-controlled by Deloitte Economic Advisory who kindly granted access for the scope of this paper. The database has been used in various consulting engagements with coal industry stakeholders, allowing for reality checks through interviews with coal sector experts (mining companies, traders, analysts and banking sector). The database is also verified with third party publications where possible, for example against third-party coal market data from the International Energy Agency (IEA) [12, 28] and IHS Markit [67].

Figure S9 provides a comparison between between the coal supply cash curve used in this paper and the data from IEA World Energy Outlook 2018 [12]. The two cost curves are generally well aligned, with differences which might stem from coal classification (certain types of coal have properties that make them suitable for use in both metallurgical and steam generating applications), attribution to

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[1] Specific sources include annual reports from listed coal companies, investor presentations, the VDKI Annual Report - Facts and Figures, IEA World Energy Outlook, IEA Coal report, IEA Coal Information, EIA Annual Energy Outlook, EIA coal industry datasets, McCloskey Coal Market Report and other industry newsletters.

[2] Specific sources include the US Bureau of Labour Statistics, DANE – Colombia, Statistics South Africa, Chinese Bureau of Statistics, Federal Statistics Service – Russia, Badan Pusat Statistik - Indonesia

domestic or international markets, washing yields, etc. Further validation of the database against historical outturn for 2016-17 is given in Note S2.

The results from this paper with asset-level granularity could be reproduced with access to the Deloitte Coal Database (see the Resource Availability section), or by constructing a comparable database from the sources outlined here. They could potentially be approximated at country-level granularity using the model described in this paper (section 4.3) and national coal data available in IEA Coal Information [28] and World Energy Outlook [12] reports as model input parameters.

4.5. Assumptions and limitations

This study focused on two scenarios from the IEA, which are broadly representative of the spread of scenarios produced by other organisations. Further study could focus on the influence of a wider range of scenarios, with different timings and regional differentiation for coal phase-out.

A key assumption is the perfectly inelastic regional demand fixed from IEA's scenarios. On the one hand, the model consequently includes all the assumptions and uncertainties from IEA World Energy Outlook's New Policies and Sustainable Development Scenarios [12]. On the other hand, as demand is fixed and therefore inelastic, coal cannot be substituted by other commodities when coal price peaks and vice versa. However, this is mitigated by the fact that the IEA demand scenarios were created by modelling which did allow fuel substitution and thus are elastic. Since the price evolution predicted here is in line with IEA's price prediction (see Figures S7 and S8), long term substitutions are indirectly represented.

The assumption of perfect foresight means the model will decommission mines that are unprofitable without delay, using full knowledge of future revenues. In reality, mine owners (some of which are state actors) might continue operating in the hope of regaining profitability, because of misjudgement about future prices, or for socioeconomic or geopolitical reasons not included in this model. This would lead to overcapacity which would depress prices and turn more mines into uneconomical assets. As a consequence, the decommissioning of stranded assets modelled here can be thought of as an indicator of unprofitable mining capacity, since even if mines are not actually retired, they would be losing money (after subsidies or other distortions are accounted for). Similarly, countries may promote their own mines, even if imports were cheaper, to protect local jobs and energy independence. As a result, stranded assets could in reality be transferred to exporting countries like Australia, the

United States, South Africa or Russia.

The model has perfect foresight, meaning it optimises production, transport and investments with full knowledge of future demand, price, and the costs of all other players in the market. Each player rationally acts to optimally satisfy demand in a perfectly informed situation to maximise global outcome and not its self-interest.

Both inelastic demand and perfect foresight mitigate short-term frictions and cycles. Short-term fluctuations are attenuated, meaning the model gives broader projection of long-term trends. This is countered by the model not including storage of coal over time, and therefore no possibility of arbitrage by storing coal surplus for shortage periods.

The evolution of transport costs over time is not considered in the model, and these remain flat over time. Fluctuations of transport fuel cost and technological improvements are not considered. The model is deterministic, there is no uncertainty among the input parameters considered.

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Author Contributions

T. Auger - investigation, writing original draft. T. Auger and J. Trüby - data curation and analysis. J. Trüby, P. Balcombe and I. Staffell - supervision. All authors contributed to the conceptualisation, methodology, review editing.

Declaration of Interests

One of the authors is employed by Deloitte, a global provider of professional services, but worked on this project in a personal capacity. One of the authors is employed by the European Commission but worked on this project in a personal capacity. The study was commissioned, conducted, written and submitted independently by the authors. The information and views set out in this article are those of the authors and do not necessarily reflect the official opinion of Deloitte or the European Commission.

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Figure legends

Figure 1: Future global coal demand from different scenarios, and its relation to global temperature rise. *Left panel shows the relative change in global coal consumption from 2017. The two highlighted scenarios are used for this study. Data from [12, 68, 36, 69, 70, 37, 39, 38]. The right panel shows the relationship between the near-term change in global coal consumption and the level of global warming experienced in 2100, based on 405 integrated assessment model (IAM) scenarios presented in Huppmann et al. [35]. The range seen across scenarios is represented by shaded boxes covering the 10th to 90th percentile across all models. The near-term coal pathways from the left panel are presented as coloured circles.*

Figure 2: Projections of coal demand in major world regions from different scenarios. *Boxes highlight the mean, 25th and 75th percentile. Data from [12, 39, 69, 70, 37]. The countries included in each region are defined in Table S1.*

Figure 3: Historical and projected global investment in coal mining capacity. *Historical data sourced from the US EIA [71] assuming an average coal mine lifespan of 25 years. Values shown in Mtce per annum extraction capacity.*

Figure 4: Investment in new mining capacity over the period 2020-2040 by world region. *Panels show cumulative investment in hard coal mines in Mtce per annum extraction capacity, comparing the business as usual (left) and Sustainable Development scenario (right). Regions are defined in Table S1.*

Figure 5: Historical and future prices for steam coal (left) and coking coal (right). *The range of future prices in each case represents the minimum and maximum seen across major exporting ports. Historical prices are taken from BP 2019 Energy Outlook [37], and show the three-year average to smooth out short-term fluctuations. This gives a fairer comparison to the model, as its perfect foresight yields marginal costs which do not reflect short-term frictions, transitory scarcity and surplus due to a mis-estimation of the future. Real prices would fluctuate more intensely, but could be expected to follow the general trends shown.*

***Figure 6:* Historical and projected global trade in hard coal under both scenarios.** *Historical hard coal trade volumes are estimated from IEA data for all coal types (including hard coal, lignite and derived products) [28], rescaled by a factor of 0.86 to match 2016 trade in hard coal only from our model.*

***Figure 7:* Projected regional trade in hard coal under both scenarios.** *Panels show imports (top) and exports (bottom) under the business as usual scenario (left) and Sustainable scenario (right). Trade volumes are stacked so that the total coloured area in each panel represents global imports and exports. Due to the significance of Indonesia's exports, it is separated from Developing Asia to become its own region in these charts. The corresponding monetary value of regional trade is shown in Figure S10. Regions are defined in Table S1.*

Figure 8:* Aggregate impact on regional economies due to international coal trade. Charts show the difference in 2040 financial flows compared to 2017 under the business as usual (left) and Sustainable scenario (right). Regions are defined in Table S1.*

***Figure 9:* Projected decommissioning of global hard coal mining capacity that becomes financially unviable.** *Charts show the annual volume of coal mining capacity that becomes stranded averaged across each five-year period, under Business-as-usual (left) and the Sustainable Development Scenario (right) in Mtce per annum extraction capacity. Inset values show the proportion of newly-built coal mines becoming stranded assets in each year of the period (values below 0.25% are not shown).*

***Figure 10:* Stranded hard coal mining capacity by region over the period 2020-2040.** *Panels show the cumulative capacity (in Mtce per annum extraction capacity) of hard coal mines that must be decommissioned on economic grounds under Business-as-usual (left) and the Sustainable Development scenario (right). Regions are defined in Table S1.*

Table legends

Table 1:* *Jobs lost due to stranded assets over the period 2020-2040. *Estimates are based on decommissioned capacity from Figure 9 and EXIOBASE [46].*

Region	Business-as-usual	Sustainable
Australia	8,550	19,520
Canada	3,220	3,970
China	-	1,765,190
Developing Asia	3,300	72,540
Europe	21,800	38,760
Latin America	-	8010
Russia	3,070	122,610
United States	8,790	59,080
India	-	133,480
South Africa	-	21,230
Total	48,730	2,244,390