Stranded assets and early closures in global coal mining under 1.5°C

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July 19, 2022

Preprint

Abstract

With the Glasgow Climate Pact 2021, the global community has committed explicitly to phasing down coal consumption. Yet the coal supply sector continues to develop new capacities, despite the risk of asset stranding. This article presents the first assessment of the implications of 1.5°C mitigation pathways for the coal mining industry. Based on open coal mine data and a new version of the open coal sector model COALMOD-World, the prospects for individual coal mining regions and their risk of early mine closures and asset stranding are analyzed. Results show that global cumulative production capacity from operating thermal coal mines exceed the remaining consumption values for 2020 through 2050 by more than 50 %. This supply-consumption discrepancy would hit Russia and the USA especially hard, causing the stranding of 75 % of operating capacities in each case. But the premature retirement of operating coal mines would affect all of the world's major thermal coal producing regions, with most regions seeing more than half of their mine capacity closing early by 2030. Stranded assets from operating coal mines would total some USD_{2015} 100 to 130 billion until 2050, with an additional USD_{2015} 100 billion should currently proposed new coal mining projects be realized. If demand declines in accordance with 1.5°C pathways, new coal mines or mine extensions would be redundant in all coal regions. Although the stranded asset value of mines is relatively small compared to that of the coal power plant sector, early closures would especially affect workers and local communities. Thus, efforts are urgently needed to ensure a just transition in coal mining regions and to pass credible climate policies that can convince investors to stop expanding coal production capacities.

Keywords— coal mining, 1.5°C, Paris Agreement, stranded assets, investments, international coal trade, numerical modeling, just transition

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1 Introduction

In the first major international agreement of its kind, the COP26 Glasgow Climate Pact explicitly seeks to phase-down (unabated) global coal-fired power generation. This goal is urgently needed in order to limit global warming to 1.5°C, which requires a phase-out of most coal use within the next two to three decades [1, 2]. Yet the coal supply sector and national energy planning in many countries still seem oblivious to the need to cut future coal production [3, 4]. Annual global investments in coal supply have remained continuously high in recent years [5], and are set to remain at current levels for the coming decades [4, 6].

The decoupling of coal supply capacities from future admissible levels of coal consumption could place coal mines at an increased risk of becoming stranded assets [7, 8]. While it is well known that coal-fired power plants face a substantial risk of asset stranding [9–11], the potential asset stranding of coal mines has received limited attention so far [12]. Compared to oil and gas production, capital expenditure costs make up only a minor share of the total production costs for coal mining [13]. Nevertheless, in the past coal miners have experienced large asset value write-downs due to excess investments and coal price drops [14]. Apart from the financial risks they pose to owners and investors, early closures of coal mines affect coal workers and local the economies of coal-producing regions [7, 15].

Moreover, excess long-lasting coal supply infrastructure can cause lock-in effects, hindering the transition away from coal [12, 16, 17]. Trout et al. [18, p. 7] find that the emissions from developed coal reserves alone – that is, the coal stored in running mines and those under development – would exhaust almost 80 % of the remaining 1.5°C emission budget. In order to keep the 1.5°C target within reach, approximately 88 % of the total global coal reserves need to remain unextracted until the end of the century [19, p. 233]. Actively limiting coal supply could serve as an important complement to demand-side climate policies [20, 21].

This is the first study to offer a detailed assessment of the implications of 1.5°C mitigation pathways for the global coal mining sector. This analysis focuses on investments, premature mine closures, and the stranding of production assets in coal regions. Identifying misaligned coal supply developments that contradict mitigation efforts can help governments to address these and reduce lock-in risks. A better understanding of future regional coal production developments can also enable national and regional governments to address inevitable structural changes in affected regions early on, thereby reducing the negative socio-economic impacts of coal phase-outs [15, 22].

This study also provides a new version of the open partial equilibrium model of the global steam coal sector COALMOD-World (CMW). The model uses data from the open-source coal mine database 'Global Coal Mine Tracker' (GCMT) provided by Global Energy Monitor [23] to approximate and consider lifetimes of existing and new coal mines. This new version of CMW now also allows for the assessment of remaining coal supply capacities, investments, and asset stranding. Previous model versions either entirely overlooked or only partially considered the retirement of existing infrastructure [24–26].

The focus of the study is on steam coal – that is, thermal coal excluding lignite. Worldwide, steam coal comprises approximately 3/4 of current total coal consumed, and about 90 % of thermal coal consumed [27]. The 1.5°C compatible coal demand scenarios are based on IPCC

[28] mitigation pathways, which fulfill additional sustainability criteria [e.g., no or limited global warming overshoot, 29]. These are contrasted with a stable coal demand scenario, based on the IEA [30] 'Stated Policy Scenario' (STEPS), which approximates existing production planning fairly well [compare 4].

2 Methods and data

To assess the global coal supply sector in a 1.5°C world, a scenario analysis using a new version (v2) of the open COALMOD-World model is performed. CMW is a comprehensive model of the global steam coal market, covering about 90 % of global steam coal production and consumption (see Appendix A.1). Previous model versions have been used to assess international coal market dynamics and various climate policy implications for the supply, trade, and consumption of coal [cf., 24, 25, 31–34]. The new version of CMW applied here considers the limited lifetimes of existing and new coal mines, which makes it possible to assess investments, remaining capacities, and stranded assets in the coal mining sector. The data on coal mines' lifetimes comes from the GCMT [23], the first comprehensive open-access database to provide worldwide data on coal mines.

2.1 Lifetime of coal mines

New (proposed) coal mines have an average lifetime of 29 years, according to the GCMT (where data is available, and excluding China).[1] The reported lifetimes are generally in the range of six to 50 years per mine. In contrast, Baruya [35, p. 75] assumes an amortization time of 20 years for coal mine projects. However, according to coal sector experts, major mines rarely operate for fewer than 20 years due to the high end-of-life costs for such mines (personal communication, March to May 2021). Based on this information, average lifetime of new mines is set here as 25 years. This is a rather conservative estimate for the technical lifetime of a mine; however, it is meant to represent the entire techno-economic lifetime of coal mine assets.

The GCMT also provides limited information on remaining lifetimes of operating coal mines. The GCMT covers approximately 800 (540 outside of China) operating steam coal mines (excluding lignite and pure met coal mines), with a total annual production of about 4.3 Gt (2.7 Gt outside of China). However, a value for 'Reported Life of Mine (Remaining)' is only given for 99 mines outside of China. By contrast, a 'Reserve to Production Ratio (R/P)' value is available for 388 mines. However, while R/P values provide information on available physical resources, the technical lifetime of a mine also depends – among other things – on the available infrastructure and physical accessibility of reserves. To improve the representation of regionally disaggregated remaining lifetime estimates, the relationship of remaining mine lifetime to R/P for operational thermal coal mines is estimated with a logarithmic regression function and applied to GCMT entries, providing only R/P values (for details and resulting estimates of regional remaining lifetimes, see Appendix A.1.2).

[1] According to industry experts, lifetime and reserve data for Chinese coal mines is very inaccurate, tending to overestimate the remaining exploitable reserves and mine lifetimes (Source: personal communication with coal industry experts, March to May 2021).

2.2 New features of the COALMOD-World version 2.0

The latest version of CMW features a new retirement mechanism for coal production capacities, which yields an improved representation of available mining capacity and necessary investments. In CMW, a coal production asset comprises all equipment and capital stock at coal mines that enable the extraction of a certain amount of coal per year. The investment in coal production capacity represents the initial investment needed to make available the new coal mining capacity. The previous model version allowed mine capacities to be idle for indefinite times and be restarted without additional costs. However, as experts noted, keeping inactive mines in operational conditions is very costly and is rarely done for more than 1-1.5 years. Thus, the new retirement mechanism is based on coal mine ages and lifetimes, not prior production (for details, see Appendix A.1.1).

2.3 Coal demand scenarios

To increase the robustness of results and to represent the uncertainty of 1.5°C compatible coal demand scenarios, a *lower bound*, a *central*, and an *upper bound* 1.5°C coal demand scenario are included. These three *1.5°C* coal demand scenarios represent 0.25, 0.5 (median), and 0.75 percentile values for annual coal consumption of 20 IPCC [28] 1.5°C mitigation pathways with no or limited global warming overshoot and limited use of Biomass with Carbon Capture, Transport and Storage (BECCTS) and carbon uptake in the land sector [for details, see 29]. Furthermore, coal consumption of power plants with Carbon Capture, Transport and Storage (CCTS) is excluded [for a discussion of mitigation approaches based on carbon dioxide removal and CCTS, cf. 36–38]. The *1.5°C* scenarios are compared against the *WEO19-STEPS* scenario. The latter represents a state of continuous high global coal demand throughout the year 2050 – a demand scenario that aligns with the current coal production plans for many actors in the coal sector [4]. Coal demand growth rates for this scenario are based on the IEA [30] STEPS scenario. Further details on the scenarios are provided in Appendix A.2 and all scenario input data files are available in Hauenstein [39].

2.4 Excess capacities, early closures, and stranded assets in coal mining

Excess coal production capacities and stranded assets in the case of 1.5°C pathways are calculated for the period 2020-2050 in this study. These ex-post calculations are based on CMW data for the lifetimes and investment costs (overnight capital cost, OCC) of capacities, and on CMW results for available mining capacities ($PCap_{af}$) and realized production ($Prod_{af}$) in year a in production node f. Early closures are calculated for the year 2030, representing general trends towards the end of the current decade. The share of early closures in year a is defined here as the share of idle capacities in year a that also do not resume production in later model years.

Excess capacities are calculated as the difference between available capacity and realized production over the considered time period (2020-2050) for the production node f (Eq. 1).

$$\text{Excess capacity}_f = \sum_{2020}^{2050} \text{PCap}_{af} - \sum_{2020}^{2050} \text{Prod}_{af} \tag{1}$$

In this study the monetary value of stranded assets is calculated based on the non-recovered share of initial overnight capital cost (OCC; Eq. 2), following an approach similar to that of Edwards et al. [9]. A full recovery of the OCC is assumed when the mine produces at full capacity for 25 years (lifetime of new mines). For coal production capacities that started production before 2020, a total lifetime of 25 years and production at full capacity for the time prior to 2020 is assumed. Thus, only the share of OCC that is assigned to the remaining lifetime from 2020 on (RL) can potentially become stranded. Node specific OCC figures are taken from the CMW input data [cf. 26, 39].

$$\text{Stranded Assets}_f = \text{OCC}_f \cdot \text{PCap}_{2020,f} \cdot \frac{\text{Excess capacity}_f}{\sum_{2020}^{2050} \text{PCap}_{af}} \cdot \frac{\text{RL}}{25} \tag{2}$$

Calculating stranded assets based on recovered OCC of initial investments over an assets lifetime is a widely used approach [9, 12]. However, financial asset devaluation can be significantly higher than just the value of unrecovered OCC, as the asset's value also depends on expected future cash flows [13, 14]. Thus, the stranded asset values calculated in this study are relatively low-end estimates.

3 Results

3.1 New coal mines redundant globally under 1.5°C

Global steam coal consumption drops by 73 % (central *1.5°C* scenario; values for the upper and lower bound *1.5°C* scenarios given in brackets, here 65-88 %) in the *1.5°C* scenario between 2020 and 2030 (Figure 1, top panel). This is in stark contrast to the *WEO19-STEPS* scenario, in which coal consumption increases slightly until 2030, and only decreases marginally thereafter. For all major producing regions, a 1.5°C demand path means drastically reduced output compared to a scenario with continuously high demand (lower three panels of Figure 1). However, the speed of the decline varies among producing countries. Of the remaining global coal production in 2030, 83 % (80-89 %) come from only three countries: China, Indonesia, and India. China and India produce exclusively for their domestic markets, while Indonesia continues to produce for both domestic and export use. The amount of internationally traded steam coal is reduced by almost two-thirds (53-80 %) between 2020 and 2030, eroding export opportunities for most traditional exporting countries (see Figure 9 in Appendix A.3). Only Indonesia remains as major exporter in 2030 due to its low production costs and its central position in the Asian market, where consumption is increasingly concentrated.

Investments in coal mine additions or new coal mines become redundant in the *1.5°C* scenarios (Figure 2). In all coal-producing regions the operating coal mining capacities suffice to meet the remaining demand until 2050. Only in the upper bound *1.5°C* scenario three Mtpa of new

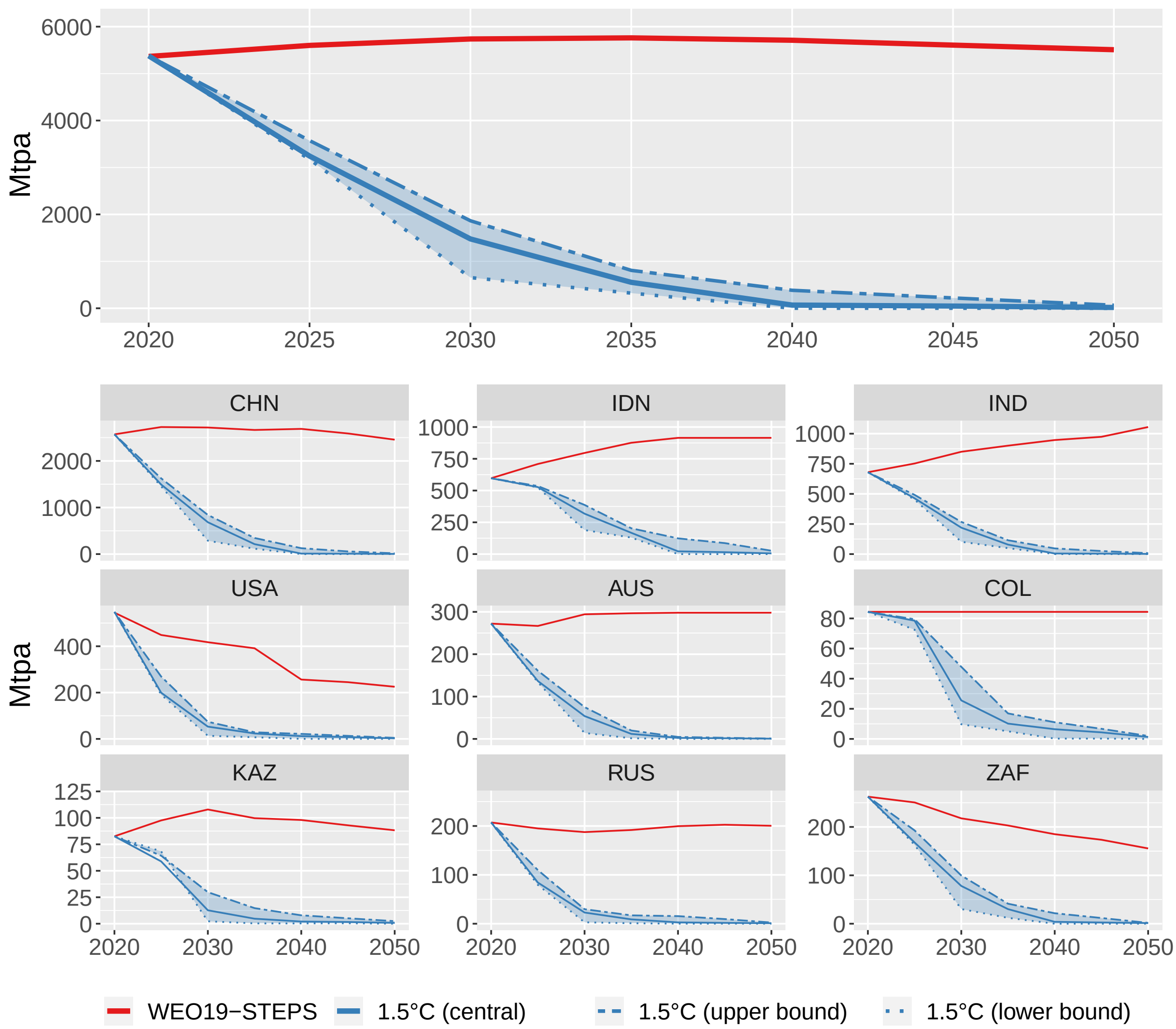

Figure 1: Global annual steam coal consumption (Mtpa) in all scenarios (top panel) and annual steam coal production (Mtpa) in major producing countries.

Note: Shaded blue area shows range of *1.5°C* scenarios. For detailed nodal production results see Appendix A.3.

capacities are added in Kazakhstan from 2035 onward. Additional sensitivity runs show that these results are robust also in case of reducing the assumed remaining lifetimes of existing coal mines. In case of by 20 % reduced lifetimes, less than one Mtpa are added in the central, and five Mtpa in the upper bound *1.5°C* scenario, respectively, between 2020 and 2050 (see sensitivity analysis in Appendix A.3.3). By contrast, in the *WEO19-STEPS* scenario the cumulative global capacity needs to be replaced about once before 2050 (Figure 2), with some regional shifts in available capacity, mostly towards Indonesia and India. The currently proposed new steam coal mining capacities amount to about 1.4 Gt, with comparatively large shares going to traditional coal exporting countries (Australia, Russia, and South Africa). However, if coal consumption is reduced to 1.5°C-compatible levels, all of these new projects would face a substantial risk of asset stranding, as there is no demand for additional coal supplies. The asset value at risk of stranding – the overnight capital cost (OCC) of all proposed new mine projects – would sum up to about USD$_{2015}$ 100 billion (Figure 2). If capacity investments continue to follow the *WEO19-STEPS* path, cumulative OCC spending on new coal mines (which are at risk of stranding) could amount up to some USD$_{2015}$ 380 billion by the year 2050. However, not only new coal mines are at risk of stranding, as the following section shows.

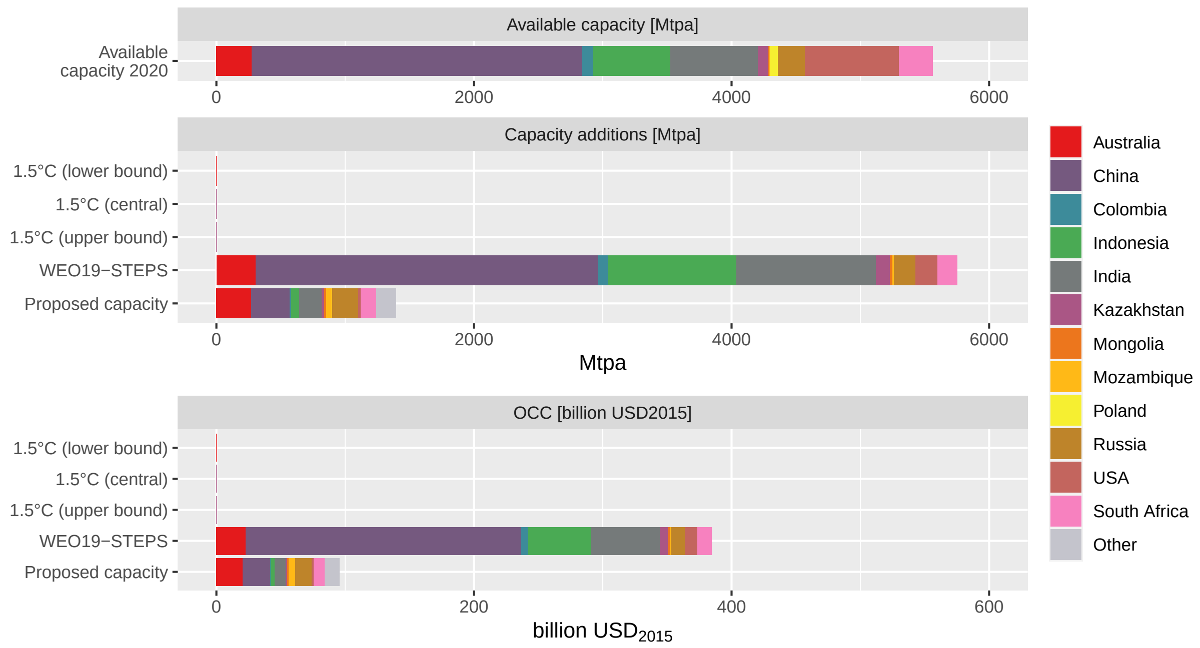

Figure 2: Investments in new steam coal mine capacities: cumulative capacity additions and related overnight capital costs (OCC) in major coal producing countries, 2020-2050, in the *1.5°C* and *WEO19-STEPS* scenarios, as well as proposed capacity additions as of June 2021. Capacity additions in Mtpa, OCC in billion USD$_{2015}$. Available coal mine capacity in 2020 shown for comparison. Zero capacity additions in all three *1.5°C* scenarios.

Sources: Proposed capacity in Mtpa based on data from [23]. Proposed capacity OCC based on [23] and CMW OCC data. All other results from CMW.

3.2 1.5°C requires the premature retirement of existing coal mines

The remaining cumulative production capacity from existing steam coal mines amounts to roughly 87 Gt between 2020 and 2050. However, the remaining coal production between 2020 and 2050 in the *1.5°C* scenarios only amounts to 40 Gt (34-48 Gt) (Figure 3). More than half of the remaining global cumulative capacity would need to remain unused. This would affect all major coal-producing countries, yet with some variation, for example, due to remaining domestic demand and access to the remaining demand centers in Asia. Russia and the USA would incur the largest shares of excess capacities, with 72 (64-77 %) and 76 % (71-80 %), respectively. The USA already have large excess capacities today, while both countries would see plummeting domestic demand and exports. Indonesia faces the lowest overall capacity stranding (31 %, 26-41 %) due to its low production costs and proximity to the remaining demand centers. China and India – the two countries with the highest remaining demand, and currently the largest producers of coal worldwide, both of which serve only their domestic markets – would be affected by their domestic demand declining faster than their coal mining capacities are depleting.

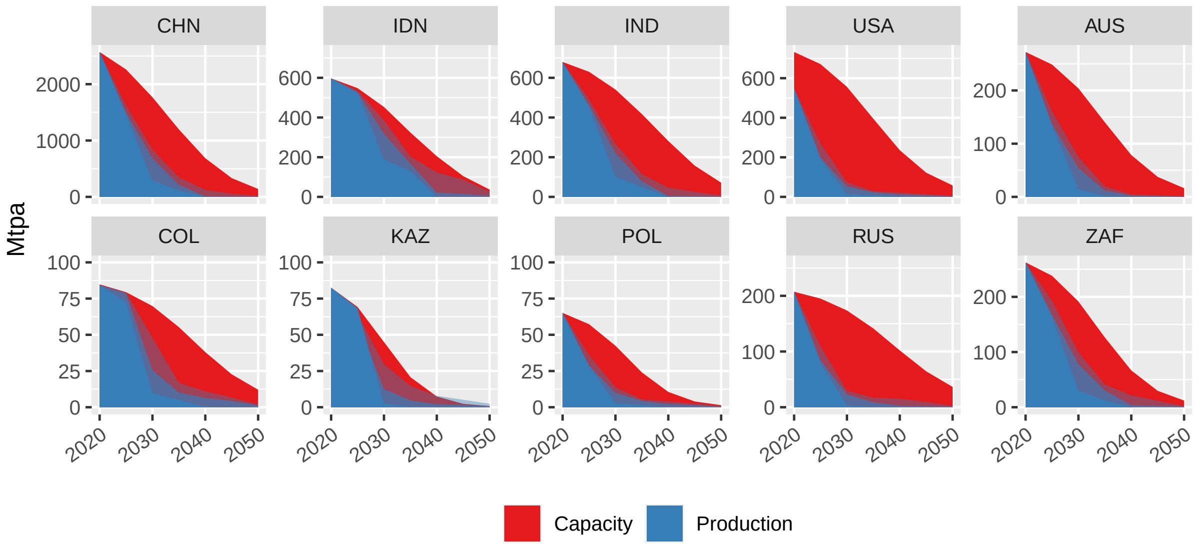

Figure 3: Stranded coal capacity: Countries' annual steam coal production capacity (red) vs. production in *1.5°C* scenarios (blue, with shaded area representing the range of the *1.5°C* scenarios).

Except for some regions in China, large shares of the existing coal mines in all major coal producing regions would have to close before reaching their retirement age (Figure 4a). Outside of China, only in some Indian regions and Indonesia would fewer than 50 % of mines have to close early by 2030. In all other coal mining regions, the majority of mining capacities would have to close prematurely by 2030. Exports of all major exporting countries, except Indonesia, would drop by more than 50 % between 2020 and 2030. Remaining exports would almost exclusively go to the Asian market.

Thus, currently operating capacities are also at risk of becoming stranded assets. Early closures of steam coal mines between 2020 and 2050 could lead to stranded assets of some USD_{2015} 120 billion (Figure 4b). Asset stranding of existing mines would be highly concentrated in China and the USA, with India following at a substantial distance. If all of the proposed new coal mines were to be built (Figure 2), however, Australia, Russia, and South Africa in particular would catch up to the group of countries with large asset values at risk of stranding.

4 Discussion

Trout et al. [18] have shown that, in order to limit global warming to 1.5°C, a substantial share of developed coal reserves would have to remain unused. This study further fleshes out that analysis, assessing the implications of a 1.5°C policy environment for the steam coal mining sector and its exposure to the risk of asset stranding. Global coal consumption in line with the 1.5°C target would lead to a significant reduction of coal output and cause excess capacities across all major coal producing regions. The finding that any new coal mining capacities after 2020 would be redundant is in line with IEA [45]. For the case of a less ambitious global climate policy, Auger et al. [7] find that still some additional coal mines would be required. Yet their scenario also includes coal demand from coal-fired power generation equipped with CCTS, which

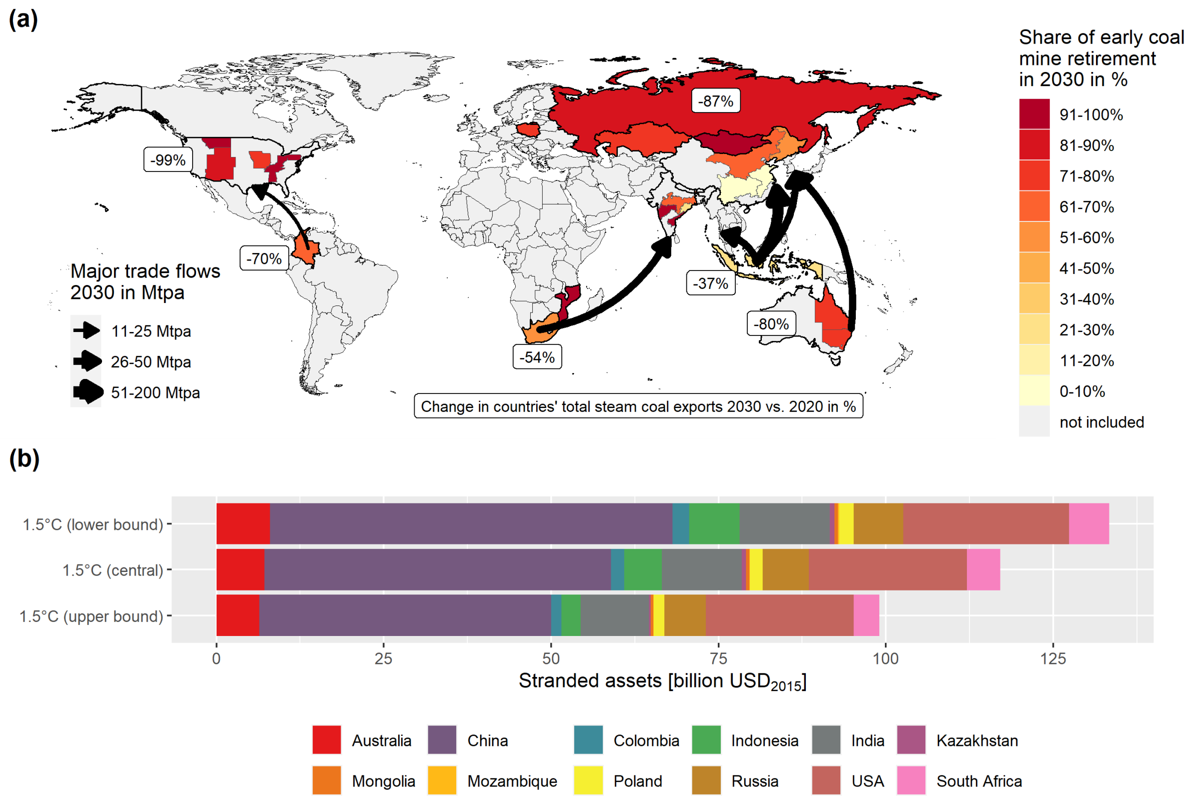

Figure 4: Early coal mine closures in 2030, trade flows, and stranded assets from operating mines under 1.5°C: (a) share of coal mine capacity that will retire early by 2030 in the central *1.5°C* scenario, remaining major trade flows in 2030, as well as change in total national steam coal exports compared to 2020, and (b) value of stranded coal mine assets (2020-2050) across the *1.5°C* scenario range. Source: Own illustration. Geographical data from [40–44].

might be rather optimistic considering recent developments in the power sector and CCTS [37, 46].

Not only new coal projects but also currently operating mines would be significantly impacted by a required rapid reduction in coal demand. About 54 % (45-61 %) of their cumulative capacity until 2050 would have to remain unused, and more than half of all operating capacities in almost all coal mining regions would need to retire early by 2030. Only mines in Indonesia and some Chinese and Indian regions would remain mostly unaffected by early closures in 2030. Thus, the risk of asset stranding is also substantial in the coal mining sector. The stranded asset value from currently operating coal mines alone could represent about USD_{2015} 120 billion. If all of the currently proposed new coal mines were to be built, this sum could nearly double. Nevertheless, this is still a comparatively small figure in comparison to the asset value at risk of stranding for coal-fired power plants, which is about six times as high [9]. In part, this is because the initial investment costs for coal mines represents a relatively low share of their total coal production costs. The financial market valuations of coal mine assets might be significantly higher than the value of the initial capital investment [13]. Furthermore, the results of this study assume intertemporal optimization with perfect foresight. The real-world coal market is characterized by cyclical effects, characterized by periods of excess investment in mining capacities when coal prices rise, and early write-offs of uneconomic capacities when coal prices dip [14]. Thus, the results of this study can be seen as minimum estimates of asset values at risk of stranding in the coal mining sector.

Although Global Energy Monitor [23] provides the first comprehensive open database for coal mines with the GCMT, the data on coal mine lifetimes is still quite limited – even more so on OCC for coal mines. While the results obtained for required capacity additions across the *1.5°C* scenarios are robust to further reductions of remaining lifetimes, the amount obtained for stranded assets could vary in case of changes in OCC. Furthermore, CMW does not depict individual mines but rather coal basins. At best, therefore, these results can represent average regional investments, early closure, and stranded assets. Yet the findings for investments in new coal mines in a scenario marked by continued high coal consumption align with the results of other studies [cf. 7, 30]. For this study, the potential stranding of transportation and export infrastructure in the coal supply sector was not considered, since transport and export infrastructure account for only a minor share of investments in the coal supply sector [30]. Maintenance investments for coal mines were also considered only indirectly in CMW, as part of production costs. In the past, these maintenance investments comprised about 40 % of total coal sector investments [30, p. 229]. In the case that they are not adapted to changing production outlooks, this could further increase the stranded asset values reported here.

While 1.5°C pathways imply drastic changes for the global coal supply sector, major coal producers are still planning for a continuously high coal demand [4]. As the *WEO19-STEPS* scenario shows, this could once again double the value at risk of stranding. To avoid making further investment decisions that oppose climate change mitigation efforts and that increase the risk of asset stranding, credible climate policies are required early-on [8]. A first step could be a moratorium on new coal mines [32, 47].

Yet the early retirement of coal mines also needs to be addressed. While coal mine owners face the risk of financial asset stranding, the socio-economic consequences of mine closures –loss of jobs and local tax revenues, for example – also need to be considered [7, 48]. While renewable energy industries can provide new jobs and added value, these are often located in regions other than those of today's currently operating coal mines [49–51]. Early planning and an effort to address structural changes are needed to limit negative consequences for local stakeholders and gain societal support for the required changes [15, 22, 52].

5 Conclusion

While previous studies have shown that the majority of global coal reserves need to stay in the ground if global warming is to be limited to 1.5°C, this is the first study to assess the effects on the operative global steam coal mining sector. A 1.5°C compatible coal demand would lead to a global slump of coal production. Any coal mine capacity additions from 2020 on would be redundant and at risk of becoming stranded assets. Furthermore, the majority of coal mines would have to be retired early, and about half of the current global cumulative production capacity would be stranded. The value of stranded assets in the coal mining sector from operating mines alone would amount to some USD_{2015} 120 billion by 2050. If all of the currently proposed new coal mines and coal mine additions were to be built, this would almost double the amount of stranded assets. In comparison to that of coal power plants in 1.5°C scenarios, the asset stranding of coal mines is minor. Nevertheless, the number of jobs in the sector and local economic dependencies on coal mining mean that declining coal production and early closures of coal mines can have severe local effects.

To avoid increasing the risk of stranded investments, we need credible climate policies that can convince investors to stop expanding coal production capacities. Supply-side policies are also necessary to reduce excess coal supply capacities, which bear the risk of further fueling the climate crisis. Finally, the socio-economic consequences of unavoidable coal mine closures must be addressed in timely manner to limit hardship for affected workers and communities, and to gain support for reducing coal supply in line with climate targets.

Acknowledgments

First and foremost, I would like to thank Paul Baruya, Graham Chapman, Fabio Gabrieli, Jitendra Roychoudhury, and Bill Simes for their time and valuable insights in the coal mining sector. Nico Bauer, Stephen Bi, Ruud Egging-Bratseth, Roman Mendelevitch, Sauleh Siddiqui and the participants of the 39th International Energy Workshop also deserve a hearty thanks for discussions of early versions of this work. Special thanks go to Franziska Holz, Konstantin Löffler, Pao-Yu Oei, and Paola Yanguas Parra for continuous and intense discussions of this work, and their critical and always helpful feedback, as well as to Thomas Mitterecker for his excellent research assistance. I gratefully acknowledge funding from the Heinrich-Böll-Foundation. This work was supported by the German Ministry for Education and Research (BMBF) under grant number 01LN1704A (‘CoalExit’ project). Language editing was kindly provided by the Europa-Universität Flensburg. All remaining errors are mine.

Declaration of interests

The author declares that he has no conflict of interest.

Data availability statement

The data that support the findings of this study is openly provided in Hauenstein [39] and in the Global Coal Mine Tracker (Juni 2021), provided by Global Energy Monitor. All model code can be found in `https://github.com/chauenstein/COALMOD-World_v2.0`.

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A Appendix

A.1 COALMOD-World version 2.0

CMW covers about 90 % of global steam coal production and consumption, represented by 22 coal producing nodes (geographically distinguishing the major coal producing regions), and 45 coal consuming nodes (major consuming countries and regions) [1]. It is a dynamic partial equilibrium model formulated as mixed complementarity problem. The model features two stylized types of players, namely producers and exporters, which are represented by profit maximizing behavior under specific operational and technical constraints (compare Figure 5). Players have perfect foresight and optimize profits over the entire model horizon. In line with empirical findings the steam coal market is modeled as being perfectly competitive [cf. 2–4]. Consumers are represented by inverse demand functions. Regional prices are endogenously determined in accordance with market clearing conditions. Hence, the decision to rely on imports or on domestic production of steam coal is an endogenous outcome of the model. Quality differences of steam coal across production regions are taken into account.

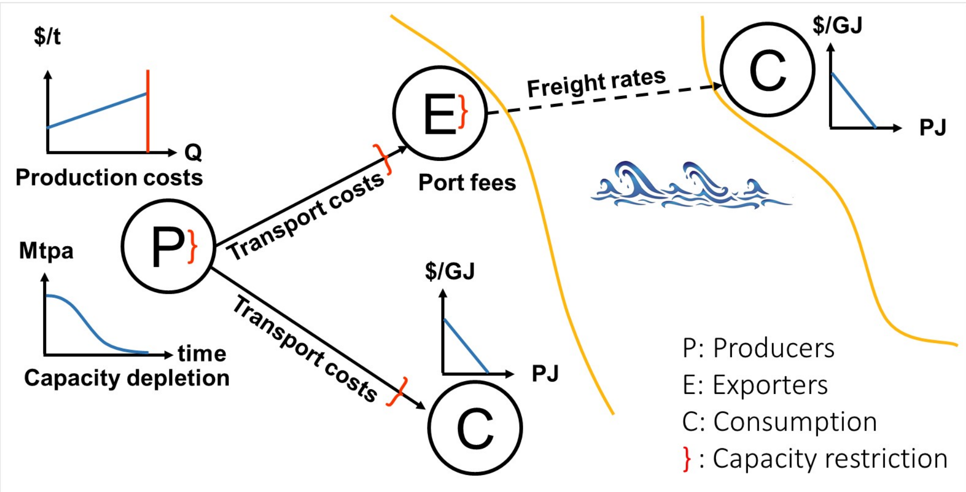

Figure 5: Basic features of COALMOD-World v2.0 model structure

Source: Adapted from Haftendorn, Holz, and Hirschhausen [5].

Furthermore, the model features endogenous investment into production, transportation, and export capacities.[2] Once an expansion is profitable over the model horizon, an investment decision is made. The new capacity becomes operational in the subsequent period. Marginal production costs are assumed to increase with cumulative extraction. The model is calibrated for the year 2015, and 2020 consumption levels are fixed to values extrapolated from the 2015 to 2019 trends [6] in order to take into account the market development trends of the past years instead of the COVID-19 induced short term effect on coal markets [7, 8].

The newly added retirement mechanism is explained in detail in the following sections. An additional new feature of the new model is a Chinese coal import quota that restricts the amount

[2]Maintenance investments, which are necessary to keep mines and other infrastructure functioning at their initial production capacity (for example, investments in equipment maintenance and replacement), are not considered separately in the model; rather, they are included in production and transportation costs.

of annual imports into China, which is explained in section A.1.3. The complete mathematical description of the here introduced model version is provided in the Supplementary Material (5). For the model code see `https://github.com/chauenstein/COALMOD-World_v2.0`.

A.1.1 Retirement mechanism in CMW v2.0

CMW production nodes represent coal mining regions or countries, which in turn generally depict numerous coal mines. To approximate the retirement of individual mines the model is adjusted to take into account node-specific average remaining lifetime of existing production capacities, as well as an average lifetime for new mines. The time-dependent physical retirement of mining capacities is integrated in the production capacity constraint of the producer's profit optimization problem (see Eq. 9 in the Suppl. Material A.5.1). Eq. 3 shows the new production capacity constraint.

$$\begin{aligned} & cap^P_f \cdot RE^P_{af} \\ & + \sum_{a'<a} \left(inv^P_{a'f} \cdot RN^P_{af} \right) \\ & - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \geq 0, \quad (\alpha^P_{af}) \end{aligned} \tag{3}$$

Line one in Eq. 3 defines the remaining capacity in time period a as the product of the initial capacity of producer f (cap^P_f) and the retirement factor for existing mines RE^P_{af}. The second line defines the remaining capacity in time period a of all investments (inv^P_{af}) made in previous periods and the respective retirement factor for new capacities RN^P_{af}. The sum of lines one and two need to be greater or equal to the total production of producer f in the period a (total production of producer f is the sum of coal delivered to domestic consumers c (x_{afc}) and to exporters e (y_{afe}); κ_f is the producer dependent energy-content factor converting from energy to mass units). α^P_{af} is the dual variable (shadow price) of the production capacity constraint.[3]

In order to implement the time dependent retirement, existing capacity and new investments are multiplied with inverse logistic functions (retirement factors) which determine the time specific remaining share of the these capacities, respectively. RE^P_{af} and RN^P_{af} represent the retirement factors for existing and new capacities, respectively:

$$RE^P_{af} = \frac{1}{1 + (depe^P_f)^{-(ord(a)-(mlexist^P_f/5+1))}} \tag{4}$$

$$RN^P_{af} = \frac{1}{1 + (depn^P_f)^{-(ord(a)-(mlnew^P_f/5+1)-ord(a'))}} \tag{5}$$

The newly introduced parameters $mlexist^P_f$ and $mlnew^P_f$ are the average (remaining) lifetime of a producer's initial capacity and of new capacities, respectively, both with the unit 'years'

[3]For a full list of sets, parameters and variables used in CMW v2.0, see Tables 7 to 9 in the Suppl. Material A.4.

(not model periods).[4] The parameter $depe_f^P$ is the base in the retirement factor for existing mines (Eq. 4). It is defined for each producer, depending on the remaining lifetime of its initial production capacities.[5] In case $mlexist_f^P$ is small, a rather steep retirement curve is assumed, thus a small $depe_f^P$. In case $mlexist_f^P$ is larger, $depe_f^P$ is increased, which translates into a flatter retirement curve with increasing tails around the average lifetime (partial retirement of the node's mining capacity starts earlier and continues further into the future relative to $mlexist$, respectively, than in the case of a smaller $mlexist$). $ord(a)$ returns the relative position of a in the set of model years (e.g., $ord(2015)$ would return 1).

For new mines the base in the retirement factor (Eq. 5) is denoted by the parameter $depn_f^P$. For new mines an average lifetime ($mlnew$) of 25 years is assumed (see Appendix A.1.2 below), with a $depn_f^P$ of 0.2. This rather small value for $depn_f^P$ is chosen based on the assumption that new mines will be able to produce in the first periods almost at their full initial capacity, with few mines producing much shorter or longer, respectively, than the average lifetime $mlnew$.

The new formulation of the capacity constraint (Eq. 3) does not include the mine mortality term of previous model versions anymore,[6] assuming that also idle production capacities will need new investments if idle for some time. Retirement of capacities therefore is implemented as independent of production in previous years.[7] CMW includes also a constraint on maximum production capacity additions per period a, which is adjusted to allow for additional investments to replace capacities retired in previous periods (see Eq. 10 in the Suppl. Material A.5.1).

A.1.2 Estimating coal mines' lifetimes based on GCMT data

The newly added retirement mechanism is based on the mines' age. It differentiates between newly added capacities (endogenous investment decisions by model) and in the model's base-year (2015) existing capacities. For the former, a global applicable average lifetime is assumed, while for the latter coal basin specific remaining average lifetimes are applied. The lifetimes are based on the 'Global Coal Mine Tracker' (GCMT; version of June 2021), an open access database on

[4] Mine lifetimes (given in years in the input file) need to be transformed to model time periods and increased by one for the retirement functions (e.g, 10 years need to enter as 3 etc.): $mlexist_f^P/5 + 1$

[5] $depe_f^P$ is set to the following values:

$$depe_f^P = 0.2 \quad \forall mlexist_f^P < 10$$
$$depe_f^P = 0.2 + (mlexist_f^P - 10)/5 \cdot 0.1 \quad \forall 10 \leq mlexist_f^P \leq 25$$
$$depe_f^P = 0.5 \quad \forall mlexist_f^P > 25$$

[6] In previous model versions, the mine mortality mechanism represented the process of how fast the cheapest mines in a coal basin are mined out [1]. The induced loss of production capacity was implemented as a function of cumulative extraction. The average mine mortality rate amounted to about 1 % p.a. [1, p. 52]. Hence, for a node producing at full capacity and with continuous capacity replacement investments, the full initial capacity would have to be replaced only every 100 years.
The removal of the mine mortality term from the capacity constraint is considered to be acceptable, as the reduction of mining capacity due to mine mortality is only a minor share of removal compared to the new retirement mechanism. Furthermore, considering remaining mine lifetime and reserve/production ratios in the retirement of existing mines also considers the basin specifics to some degree.

[7] The model is run in 5-year time steps, thus, it seems reasonable, that mines also "degrade" even if not producing.
Personal communication with coal industry experts: Idle mines are very expensive to keep in operational conditions (more so for underground mines). In case of an expected return to production idle mines are kept in operational conditions for possibly one to one and a half years.

coal mines [9].

Approximating the remaining average lifetime of existing capacities in each represented production node is more difficult. Information on remaining lifetimes is available only for a minority of the reported operating mines in the GCMT. More generally available is the reserve to production ratio (R/P) of mines, which represents the possible remaining years of production at full capacity if all reserves are exploited. However, while R/P values provide information on available physical resources, the technical lifetime of a mine also depends, i.a., on available infrastructure, physical accessibility of reserves, governmental permits, etc. To approximate the remaining lifetime of mines with R/P reported only, the relationship of remaining mine lifetime to R/P for operational steam coal mines with both values reported is estimated here with a logarithmic regression function (see Figure 6). For this regression analysis, data for mines from the GCMT data is filtered to include only steam coal mines (excl. lignite and pure met coal mines)[8] with both, remaining lifetime and R/P, included. From this set, all Chinese mines are excluded (see 2.1). Additionally, mines with an R/P of less than ten or more than 45 years, respectively, are excluded due to the limited number of data points for those categories. Furthermore, mines with reported remaining lifetime larger than their reported R/P were excluded, as the R/P ratio implies a physical limit to the maximum lifetime (considering production at full capacity).

From this regression analysis, the following relationship of remaining lifetime of existing mines ($mlexist$) to R/P is derived for all mines with $10 \leq R/P \leq 45$. For mines with $0 \leq R/P < 10$ a simple linear correlation is considered, and for all mines with $45 < R/P$ the lifetime is set to the lifetime of new mines of 25 years:

$$\begin{aligned}
&mlexist = 0.7 \cdot R/P \quad \forall R/P < 10 \\
&mlexist = 12.297 \cdot \ln(R/P) - 21.522 \quad \forall 10 \leq R/P \leq 45 \\
&mlexist = 25 \quad \forall R/P > 45
\end{aligned} \tag{6}$$

These approximations are then applied to the reported R/P of mines in order to obtain remaining lifetime estimates for a larger number of mines. Then, for each node the weighted average of the respective approximated remaining lifetimes is taken, weighted by each mine's share of the total represented nodal capacity. In order to account for the difference in the model's starting year (2015) and the data in the GCMT, representing the year 2020, resulting remaining lifetimes for all nodes are extended by five years.

The results of the regression analysis were then verified by triangulation with literature information and expert judgements. For the following nodes, $mlexist$ was adjusted thereupon to better represent local conditions: P_KAZ reduced by ten years (relatively old mines with limited remaining lifetime according to coal sector experts); P_IND_Orissa reduced by eight years (very limited coverage of mines in GCMT; similar mine structure as in P_IND_North); all Chinese production nodes minus ten years, except P_CHN_SIS, for which it is reduced by eight years (according to industry experts, reserve data for Chinese coal mines should be considered only as rough estimates, and not as actually explored reserves, which leads to overestimation of remaining mineable reserves (Personal communication with coal industry experts, March to

[8] Applying the following filters to the GCMT database categories: 'Status' = 'Operating', AND 'Coal Type' = 'Anthracite' & 'Bituminous' & 'Subbituminous', AND 'Coal Grade' = 'Thermal' & 'Thermal & Met' & '(Blanks)'.

May 2021); according to Auger et al. [10, p. 13] most existing Chinese coal mines will reach their end-of-life within the next 20 years). Table 1 shows the resulting remaining lifetime values for all CMW v2.0 producer nodes.

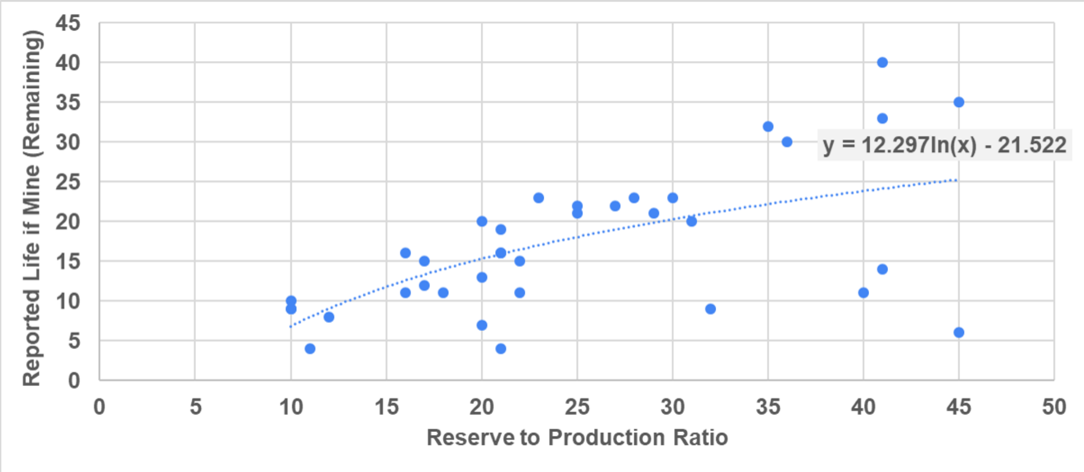

Figure 6: Relationship of remaining mine lifetime to R/P ratio of thermal coal mines (excl. Chinese mines). Source: Own calculation based on data from [9].

The implemented retirement for nodal coal production capacities is illustrated in Figure 7. It shows the decline of the cumulative global steam coal production capacity available in 2015 (excluding capacity additions). Nodal production capacities are retired following an inverse logistic curve, with 50 % of the capacities retired when the node-specific average retirement age is reached. About half of the operating coal production capacities operating in 2015 will be retired by 2035, and by 2050 almost all capacities will be out of service.

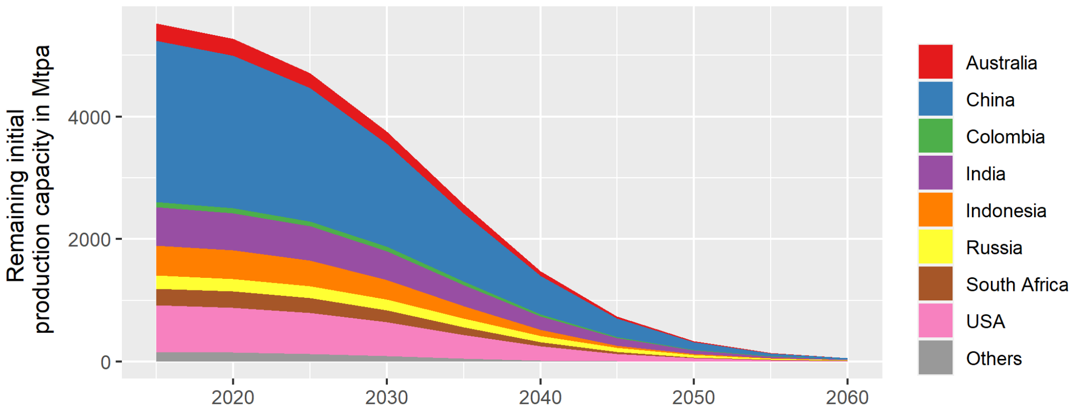

Figure 7: Retirement of initial (2015) coal mine capacities in COALMOD-World v2.0: decline of cumulative production capacity (grouped by countries) in case of zero new capacities from 2015 on.

Assumptions on lifetimes are a critical factor for the assessment of investments in new production capacities. Particularly, as there is only limited data available and generalization for coal mine lifetimes is difficult. Therefore, effects of lifetime assumption variations on investment results were assessed. Results of this sensitivity analysis are presented in Figure 8. Results for investments react as expected to an increase/decrease of the lifetime of existing and new

Table 1: Average remaining lifetimes of coal production capacities for all CMW producer nodes in years (for start year 2015).

CMW producer node	Average remaining lifetime (mlexist)
P_USA_PRB	21
P_USA_Rocky	20
P_USA_ILL	23
P_USA_APP	17
P_COL	23
P_POL	17
P_KAZ	15
P_RUS	24
P_ZAF	19
P_IND_North	22
P_IND_Orissa	22
P_IND_West	13
P_IND_Soutth	19
P_IDN	18
P_CHN_SIS	20
P_CHN_Northeast	18
P_CHN_HSA	15
P_CHN_YG	10
P_AUS_QLD	21
P_AUS_NSW	19
P_MNG	30
P_MOZ	30

Source: Own approximations, based on [9].

mines. Shorter lifetimes require significant additional capacity additions in the considered period in a high demand scenario, while longer lifetimes significantly decrease capacity additions. In contrast, results for (regional) production volumes are relatively robust.

A.1.3 China's import quota

An additional new feature of the new model is a Chinese coal import quota that restricts the amount of annual imports into China. Although the model generally focuses on operational and technical constraints, this politically defined restriction of the largest global coal consumer is included because of its potentially significant impact on the international coal market. China officially has no import quota, but *de facto* annual coal imports are restricted [11, 12]. Here, the annual quota for all international seaborne imports into China is set to 300 million tons (Mt) from 2020 on, representing the maximum imports in the past few years [11]. This is a rather conservative estimate given that China might further restrict imports in the future, as a recent study on current developments in the Chinese coal sector [12] has shown.

To include the *de facto* Chinese import restriction, equation 7 is added as constraint for all non-Chinese exporters in CMW v2.0 and imposes a limit on the sum of annual seaborn coal

Figure 8: Sensitivity of CMW results (*WEO19-STEPS* scenario) to changes in coal mine-lifetime assumptions.
(a) and (b) show the sensitivity of global 5-year and cumulative (2020-2049) coal mine capacity investments to an increased/decreased remaining lifetime of existing production capacities (*mlexist*) by +/- 20 % (a), as well as increased/decreased lifetime of new capacities (*mlnew*) by +/- 20 % (b), respectively. Reducing *mlexist* leads to preponed investments in the first periods. Vice versa, increasing *mlexist* leads to a slightly less pronounced postponement of investments. Decreasing *mlnew* increases required investments from 2030 on, and vice versa, required investments decrease from 2030 on for increased *mlnew*, respectively.
(c) and (d) show the sensitivity of selected countries' and global cumulative production (2020-2049) results to changes in *mlexist* ((c), +/- 20 %) and *mlnew* ((d), +/- 20 %). Cumulative global production is not significantly influenced by changes in *mlexist* and *mlnew*, respectively. Regional production, however, can be affected significantly. In case of increased (decreased) *mlexist*, for example, the USA produce more (less). The USA have a large fleet of existing mines, but only few new investments are made in the USA in a *WEO19-STEPS* scenario. Additional (reduced) U.S. production is compensated by slightly reduced (increased) production in other countries in this scenario. Sensitivity of regional production volumes to changes in *mlnew* is less pronounced.

Note: In (a) and (b) investments in model years represent total investments per period, e.g., 2020-2024.

imports to China.[9] The sum of all coal shipped from non-Chinese exporters to Chinese sea ports in period a need to be less or equal to the annual import quota $China\_IQ_a$ (in million tons per year). ρ_a^{CHN} is the dual variable of the constraint.

$$China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \geq 0 \quad \left(\rho_a^{CHN}\right) \tag{7}$$

A.2 Coal demand scenarios

CMW runs are based on exogenous coal demand scenarios. Coal demand growth data is derived from the applicable sources, such as IPCC [13], and these growth rates are applied to CMW demand node specific historic steam coal demand data. Real-world coal demand in 2020 was influenced significantly by the COVID-19 pandemic (-4.5 % compared to 2019 [14, p. 322]), yet long-term effects of the pandemic on coal demand are less clear [8, 15]. Thus, CMW node-specific coal demand for the model year 2020 is based on an extrapolation of 2015-2019 nodal trends, in order to avoid an overestimation of the pandemic induced demand reduction.

Table 2 summarizes the scenarios included in this study and their data sources. Only 1.5°C coal demand scenarios are considered that do not imply high temperature overshoots, large scale implementation of carbon dioxide removal, or large scale implementation of CCTS in coal-fired power plants. Temperature overshoot pathways, as well as BECCTS and other land-use based approaches to withdraw carbon dioxide from the atmosphere are debated intensively regarding their potentials and risks [cf. 16–19]. Regarding CCTS, many have argued that its adoption could enable an extended use of coal [cf. 20]. However, so far CCTS is not deployed on large-scale and it is highly questionable if CCTS-(retro)fitted coal-fired power plants will play a significant role in the future power sector [cf. 21, 22].

Table 2: Summary of scenarios and underlying data.

Name	Description
1.5°C (*lower bound*, *central*, *upper bound*)	Set of three coal phase-out scenarios based on the growth rates of unabated coal consumption results of 20 IPCC [13] 1.5°C mitigation pathways, which fulfill additional sustainability criteria as described in Yanguas Parra et al. [23]. Out of these 20 pathways, annual 0.25-0.75 percentile values for coal consumption are used to build the *1.5°C* scenario set. Growth rates of 0.25, 0.75, and 0.5 (median) percentile values were taken for the *lower bound*, *upper bound*, and *central 1.5°C* scenarios, respectively.
WEO19-STEPS	Coal demand growth rates are derived from IEA's 'World Energy Outlook 2019' 'Stated Policies Scenario' data for 'Coal' in 'Power sector' in 'Energy demand' [24, pp. 682–742].

The three *1.5°C* scenarios represent the annual 0.25-0.75 percentile range for unabated coal consumption in the 20 considered IPCC [13] pathways [cf. 23]. The considered coal demand projections are based on coal demand in the power sector. The power sector accounts for about

[9] Chinese steam coal imports via land make up a very small share of its total imports only and are not considered here.

70 % of total steam coal demand [25, p. II.17]. Other major steam coal users include the iron and steel (besides metallurgical coal), cement, and chemical industry. With the switch to less fossil fuel dependent production processes [26, cf.], coal demand in these sectors is considered to develop similarly to the power sector. Coal demand values from the IPCC [13] pathways are available for five world regions, R5ASIA, R5LAM, R5MAF, R5OECD90+EU, and R5REF, to which CMW demand nodes are mapped to according to the respective country [27]. The regional growth rates are then applied to the respective nodal 2020 steam coal demand values.

IEA [24] provides projections only until 2040. For 2045-2060 values are forecasted linearly based on the values for 2030-2040. For regions with positive 2030-2040 growth, demand is kept flat at 2040 demand.

A.3 Additional results

A.3.1 Annual steam coal exports

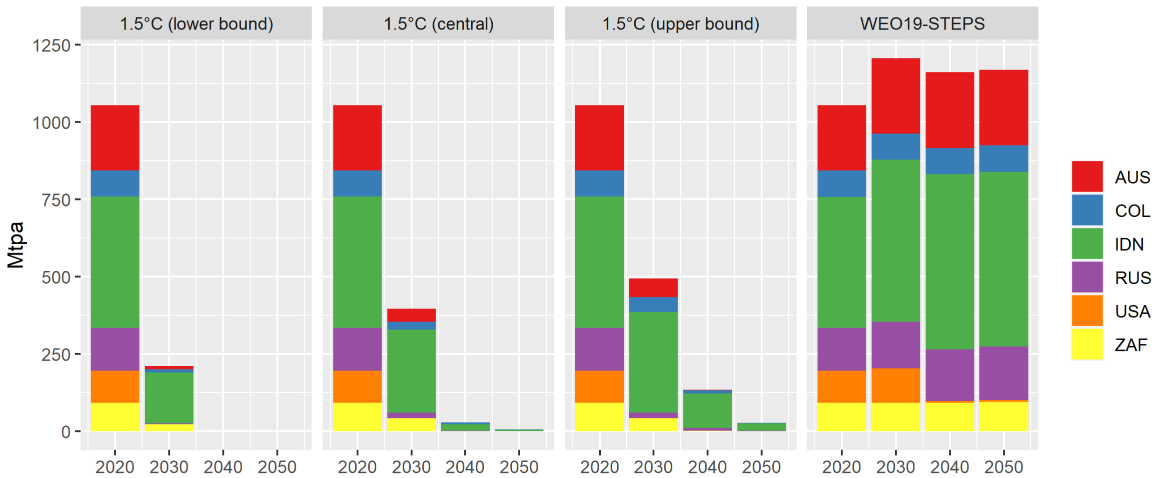

Figure 9: Results for annual steam coal exports (Mtpa) of major exporting countries in all scenarios.

A.3.2 Nodal results

Table 3: Nodal annual steam coal production (selected years) in *1.5°C* and *WEO19-STEPS* scenarios in Mtpa.

	1.5°C (lower bound)			1.5°C (central)			1.5°C (upper bound)			WEO19-STEPS		
Node\Year	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
P_AUS_NSW	178	10	0	178	36	0	178	50	0	178	190	194
P_AUS_QLD	94	4	0	94	18	0	94	25	1	94	104	104
P_CHN_HSA	248	35	0	248	135	0	248	135	0	248	200	355
P_CHN_Northeast	103	9	0	103	32	0	103	45	0	103	71	54
P_CHN_SIS	1962	205	0	1962	465	3	1962	609	17	1962	2203	1773
P_CHN_YG	258	38	0	258	52	0	258	52	0	258	243	274
P_COL	84	10	0	84	26	1	84	48	2	84	84	84
P_IDN	597	189	0	597	318	6	597	387	26	597	796	915
P_IND_North	406	67	0	406	133	1	406	156	8	406	508	567
P_IND_Orissa	150	35	0	150	86	0	150	105	0	150	178	248
P_IND_South	66	0	0	66	0	0	66	0	0	66	75	91
P_IND_West	59	0	0	59	0	0	59	6	0	59	89	149
P_KAZ	83	2	0	83	13	1	83	30	2	83	108	88
P_MNG	7	0	0	7	0	0	7	0	0	7	17	19
P_MOZ	2	0	0	2	0	0	2	0	0	2	6	10
P_POL	65	3	0	65	10	0	65	14	1	56	42	2
P_RUS	207	3	0	207	23	1	207	30	2	207	187	200
P_USA_APP	111	1	0	111	5	0	110	9	0	106	67	8
P_USA_ILL	104	7	0	104	26	1	105	34	2	106	78	40
P_USA_PRB	265	2	0	267	11	1	267	19	1	269	228	171
P_USA_Rocky	68	3	0	67	11	0	67	13	1	64	44	6
P_ZAF	263	30	0	263	78	1	263	100	2	263	218	156

Note: Geographical representation of production nodes (P_ ...): AUS_NSW = New South Wales, Australia; AUS_QLD = Queensland, AUS; CHN_HSA = Henan & Shandong & Anhui & Jiangxi & Jiangsu, China; CHN_Northeast = Liaoning & Heilongjiang & Jilin, China; CHN_SIS = Shanxi & Inner Mongolia & Shaanxi & Hebei & Ningxia & Gansu, China; CHN_YG = Yunnan & Guizhou & Sichuan & Hunan & Chongqing & Hubei, China; COL = Colombia; IDN = Indonesia; IND_North = Arunachal & Assam & Chhattisgarh & Jammu Kashmir & Jharkhand & Madhya Pradesh & Meghalaya & Uttar Pradesh & West Bengal, India; IND_Orissa = Odisha; IND_South = Telangana; IND_West = Maharashtra; KAZ = Kazakhstan; MNG = Mongolia; MOZ = Mozambique; POL = Poland; RUS = Russia; USA_APP = Alabama & Kentucky (East) & Maryland & Ohio & Pennsylvania & Tennessee & Virginia & West Virginia, USA; USA_ILL = Arkansas & Illinois & Indiana & Kansas & Kentucky (West) & Louisiana & Mississippi & Missouri & Oklahoma & Texas, USA; USA_PRB = Wyoming; USA_Rocky = Alaska & Arizona & Colorado & Montana & New Mexico & North Dakota & Utah & Washington, USA; ZAF = South Africa.

Table 4: Nodal excess capacities (2020-2050) in *1.5°C* and *WEO19-STEPS* scenarios in Mtpa and %.

	1.5°C (lower bound)		1.5°C (central)		1.5°C upper bound)		WEO19-STEPS	
Node	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%
P_AUS_NSW	1746	65	1568	58	1379	51	0	0
P_AUS_QLD	1093	69	984	62	889	56	0	0
P_CHN_HSA	963	34	396	14	188	7	0	0
P_CHN_Northeast	709	49	565	39	460	32	0	0
P_CHN_SIS	20524	64	18541	58	####	50	0	0
P_CHN_YG	84	5	15	1	0	0	0	0
P_COL	920	59	730	47	543	35	1	0
P_IDN	4046	41	3005	31	1519	16	0	0
P_IND_North	4718	63	4220	56	3622	48	0	0
P_IND_Orissa	1407	52	1083	40	857	32	0	0
P_IND_South	739	75	728	74	685	69	0	0
P_IND_West	433	52	433	52	401	48	0	0
P_KAZ	367	39	324	35	134	14	0	0
P_MNG	134	80	131	78	125	75	0	0
P_MOZ	31	70	30	67	30	67	0	0
P_POL	532	62	460	54	384	45	36	4
P_RUS	3056	77	2869	72	2560	64	0	0
P_USA_APP	1610	77	1544	74	1457	70	593	28
P_USA_ILL	1693	75	1512	67	1400	62	291	12
P_USA_PRB	4976	83	4869	81	4580	76	1009	14
P_USA_Rocky	1166	78	1095	73	1022	68	398	27
P_ZAF	2268	57	1879	48	1454	37	0	0

Table 5: Premature coal mine capacity retirements in 2030 in *1.5°C* scenarios in Mtpa and %.

	1.5°C (lower bound)		1.5°C (central)		1.5°C upper bound)	
Node	Mtpa	%	Mtpa	%	Mtpa	%
P_AUS_NSW	121	93	94	72	80	62
P_AUS_QLD	69	94	56	76	49	66
P_CHN_HSA	100	74	0	0	0	0
P_CHN_Northeast	63	88	39	55	27	38
P_CHN_SIS	1304	86	1045	69	901	60
P_CHN_YG	14	27	0	0	0	0
P_COL	60	86	44	63	22	31
P_IDN	264	58	135	30	66	15
P_IND_North	269	80	203	60	180	54
P_IND_Orissa	87	71	36	29	17	14
P_IND_South	48	100	48	100	48	100
P_IND_West	35	100	35	100	28	82
P_KAZ	43	95	32	72	15	34
P_MNG	7	100	7	100	7	100
P_MOZ	2	100	2	100	2	100
P_POL	40	94	32	76	29	67
P_RUS	171	98	151	87	144	83
P_USA_APP	102	99	98	96	94	91
P_USA_ILL	93	93	75	74	67	67
P_USA_PRB	279	99	270	96	262	93
P_USA_Rocky	69	96	61	85	59	82
P_ZAF	161	84	114	59	92	48

Table 6: Nodal coal mine stranded assets (2020-2050) in *1.5°C* scenarios in billion USD_{2015}.

Node	1.5°C (lower bound)	1.5°C (central)	1.5°C upper bound)
P_AUS_NSW	5	4	4
P_AUS_QLD	3	3	3
P_CHN_HSA	4	2	1
P_CHN_Northeast	3	2	2
P_CHN_SIS	53	48	41
P_CHN_YG	0	0	0
P_COL	3	2	2
P_IDN	8	6	3
P_IND_North	8	7	6
P_IND_Orissa	3	2	2
P_IND_South	1	1	1
P_IND_West	1	1	1
P_KAZ	1	1	0
P_MNG	1	1	0
P_MOZ	0	0	0
P_POL	2	2	2
P_RUS	7	7	6
P_USA_APP	6	6	5
P_USA_ILL	5	4	4
P_USA_PRB	11	10	10
P_USA_Rocky	4	3	3
P_ZAF	6	5	4

A.3.3 Sensitivity analysis

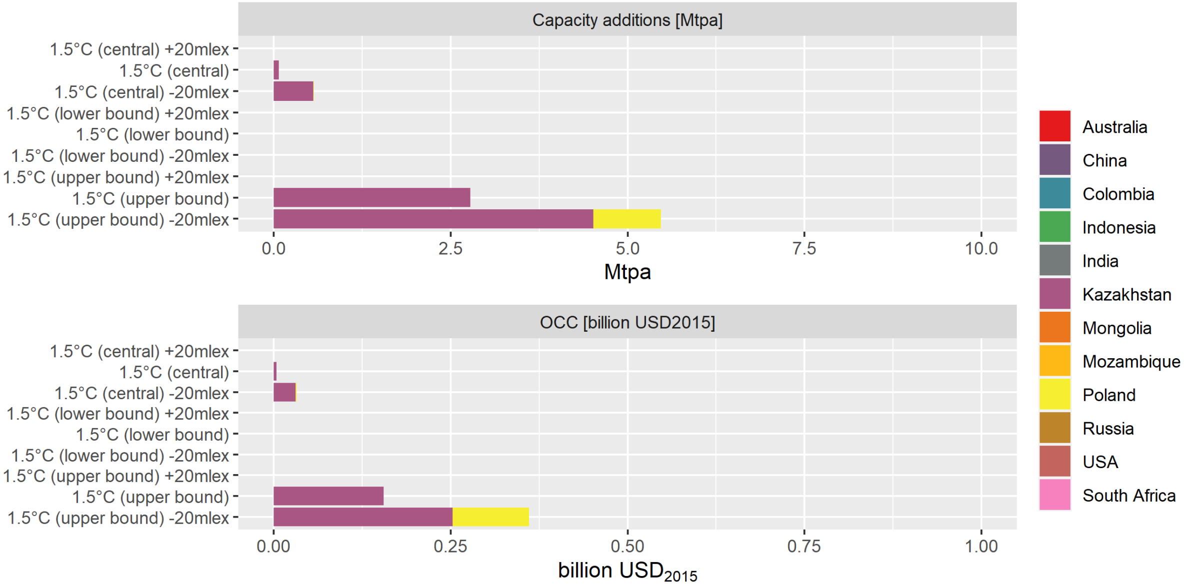

Figure 10: Sensitivity of cumulative investments (2020-2049) in new coal mine capacities in *1.5°C* scenarios to changes in lifetime of existing mines (*mlexist*). *mlexist* increased (+20mlex)/decreased (-20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Capacity additions in Mtpa, as well as related overnight capital costs (OCC) in billion USD_{2015}.

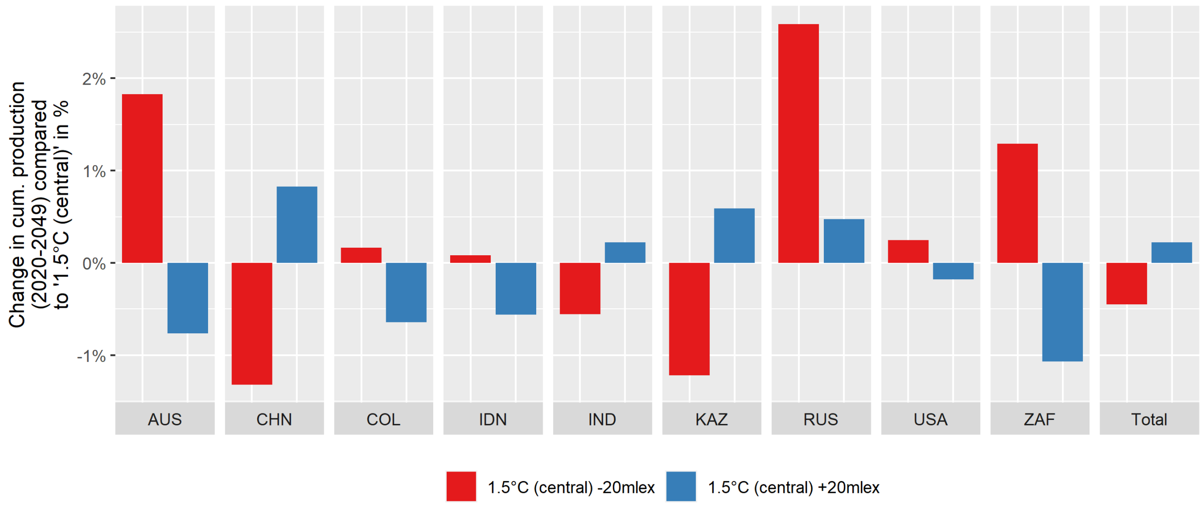

Figure 11: Sensitivity of selected countries' and global cumulative production (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Relative change of resulting cumulative production compared to base case of central *1.5°C* scenario. Generally increasing/decreasing *mlexist* leads to marginal changes in results for countries' and global cumulative production only.

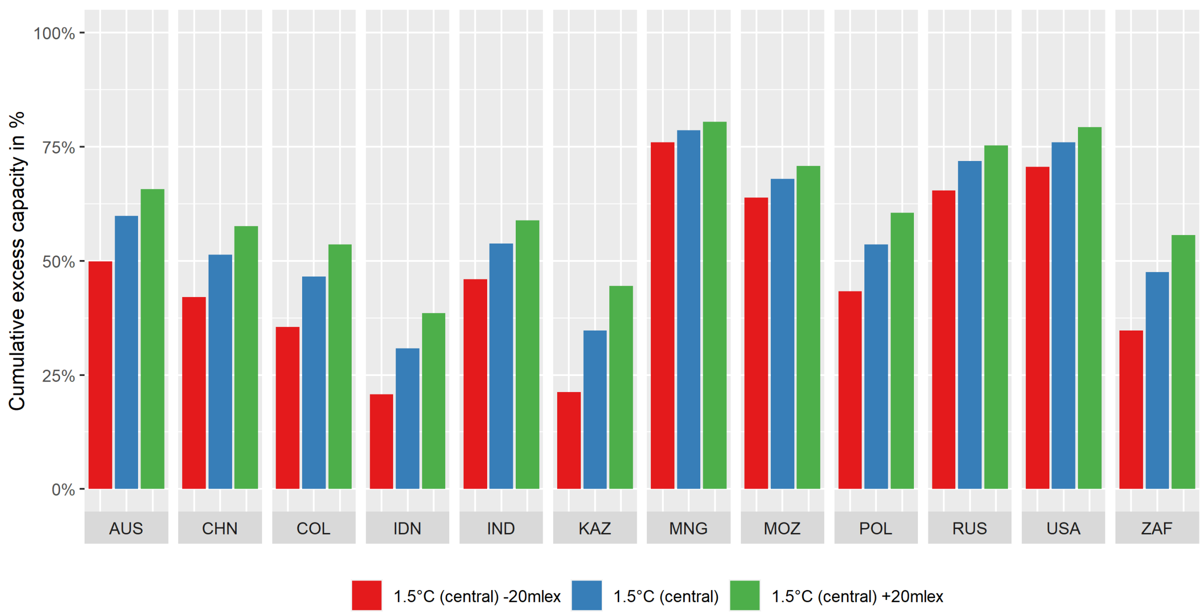

Figure 12: Sensitivity of countries' cumulative excess capacity (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Shorter remaining lifetimes for existing mines lead as expected to reduced cumulative excess capacities. The order of magnitude remains the same for a country's excess capacity. However, the effect of changes in *mlexist* to excess capacity results differ among countries.

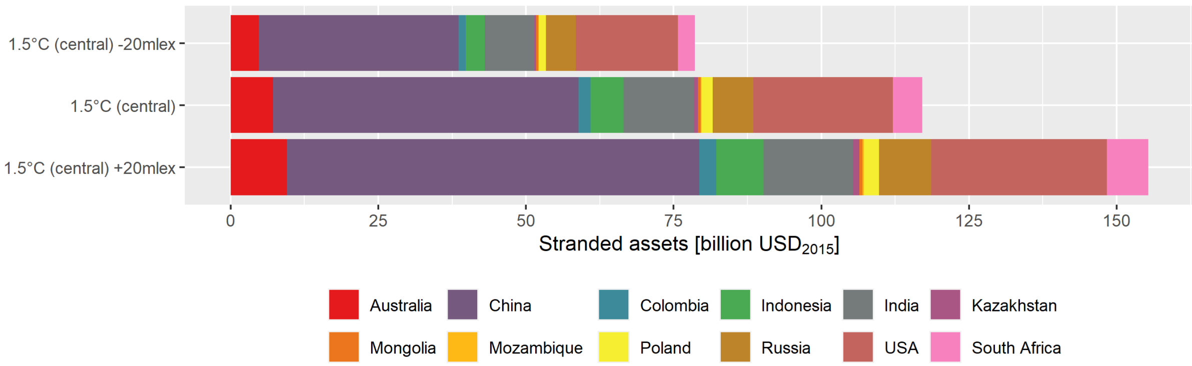

Figure 13: Sensitivity of stranded assets' volume (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. The volume of stranded assets is highly dependent on assumptions regarding the remaining lifetime, and thus the already recovered share of overnight capital cost, of existing mines.

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Supplementary material

Mathematical formulation of CMW v2.0, its sets, parameters, and variables.

A.4 CMW v2.0: Sets, parameters, variables

Table 7: List of sets in the COALMOD-World model version 2.0.

Set name	Description	Range
a	model year	[2015, 2020, 2025, 2030, 2035, 2040, 2050, 2055, 2060]
c	consumer nodes	see Holz et al. [1]; node removed for Ukraine; nodes added for Bangladesh, Pakistan, and Vietnam
$China\_sea_c$	subset of c, all Chinese consumers with port	
e	exporter nodes	see Holz et al. [1]; nodes removed for Ukraine and Venezuela; node added for Russia West
f	producer nodes	see Holz et al. [1], nodes removed for Canada, Ukraine, Venezuela, and Vietnam
$land_c$	subset of c, all consumers only reachable by land	
$NoChina\_exp_e$	subset of e, all exporters except Chinese exporters	
$NoChina\_sea_c$	subset of c, all consumers with port except Chinese consumers	
sea_c	subset of c, all consumers with port	

Table 8: List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
b_{ac}	demand curve slope of demand node c in period a	[USD/GJ^2]
cap^E_e	initial export capacity of exporter e	[Mt/a]
cap^P_f	initial production capacity of producer f	[Mt/a]
cap^{TC}_{fc}	initial transport capacity from producer f to consumer c	[Mt/a]
cap^{TE}_{fe}	initial transport capacity from producer f to exporter e	[Mt/a]
$China\_IQ_a$	import quota for maximum annual imports via sea into China in period a	[Mt/a]
$China\_lic_a$	Chinese export licence restricting maximum annual Chinese exports in period a	[Mt/a]

Continued on next page

Table 8: *(continued)* List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
$Cinv^E_e$	investment cost for export capacity expansion for exporter e	[USD/t]
$Cinv^P_f$	investment cost for producer capacity expansion for producer f	[USD/t]
$Cinv^{TC}_{fc}$	investment cost for transport capacity expansion from producer f to consumer c	[USD/t]
$Cinv^{TE}_{fe}$	investment cost for transport capacity expansion from producer f to exporter e	[USD/t]
$DemInter_{ac}$	demand curve intercept of demand node c in period a	[USD/GJ]
$depe^P_f$	base of inverse logistic function determining retirement of cap^P_f	[ ]
$depn^P_f$	base of inverse logistic function determining retirement of inv^P_{af}	[ ]
$epsi_{ac}$	price elasticity of demand node c in period a	[ ]
fee_e	port handling fee for exporter e	[USD/t]
$\overline{inv}^E_e$	maximum export capacity expansion of exporter e	[Mt/a per 5 year period]
$\overline{inv}^P_f$	maximum production capacity expansion of producer f	[Mt/a per 5 year period]
ι_{ec}	binary parameter for Chinese import quota; 0 for all e and c, except for $e = NoChina\_exp_e$ and $c = China\_sea_c$	[ ]
κ_e	energy content of coal shipped by exporter e	[t/GJ]
κ_f	energy content of coal produced by producer f	[t/GJ]
$mc\_int\_start_f$	starting value of intercept of marginal cost curve for producer f	[USD/t]
$mc\_int\_var_f$	intercept variation factor	[ ]
mc_slp_f	slope of marginal cost curve for producer f	[USD/t^2]
$mlexist^P_f$	average remaining lifetime of cap^P_f	[years]
$mlnew^P_f$	average lifetime of new capacity investments inv^P_{af}	[years]
p^{ref}_{ac}	reference steam coal price in demand node c in period a	[USD/GJ]
$plength$	period length	(5) years
r_e	discount factor applied by exporter e	[ ]
r_f	discount factor applied by producer f	[ ]
res_f	resource endowment (coal reserve) of producer f	[Mt]
$searate_{ec}$	freight rate for transport from exporter e to consumer c	[USD/t]
$t\_i_{ae\,sea}$	Import tax for import from port e to port sea in period a	[USD/t]

Continued on next page

Table 8: *(continued)* List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
θ_{ec}	binary parameter for Chinese export restriction; 0 for all e and c, except for $e = CHN_E$ and $c = NoChina\_sea_c$	[ ]
$trans^C_{fc}$	transportation cost from producer f to consumer c	[USD/t]
$trans^E_{fe}$	transportation cost from producer f to exporter e	[USD/t]
y^{ref}_{ac}	reference steam coal consumption of demand node c in period a	[PJ]

Table 9: List of variables in the COALMOD-World model version 2.0.

Variable name	Description	Unit
$\alpha_{afc}^{cap^{TC}}$	shadow price of transport capacity constraint from producer f to consumer c in period a	[USD/t]
$\alpha_{afe}^{cap^{TE}}$	shadow price of transport capacity constraint from producer f to exporter e in period a	[USD/t]
$\alpha_{af}^{inv^{P}}$	shadow price for maximal production capacity expansion constraint for producer f in period a	[USD/t]
α_{af}^{P}	shadow price of production capacity constraint for producer f in period a	[USD/t]
α_{f}^{res}	shadow price of resource constraint for producer f over entire model time horizon	[USD/t]
inv_{ae}^{E}	investment in export capacity by exporter e in period a	[Mt/a]
inv_{af}^{P}	investment in production capacity by producer f in period a	[Mt/a]
inv_{afc}^{TC}	investment in transport capacity from producer f to consumer c in period a	[Mt/a]
inv_{afe}^{TE}	investment in transport capacity from producer f to exporter e in period a	[Mt/a]
μ_{ae}^{E}	shadow price of exporter capacity constraint for exporter e in period a	[USD/t]
$\mu_{ae}^{inv^{E}}$	shadow price of maximal exporter capacity expansion constraint for exporter e in period a	[USD/t]
p_{ac}^{C}	price paid by consumer to exporter or producer in period a	[USD/GJ]
p_{ae}^{E}	price paid by exporter or producer in period a	[USD/GJ]
π_{a}^{CHN}	shadow price of Chinese export restriction constraint in period a	[USD/t]
ρ_{a}^{CHN}	shadow price of Chinese import quota constraint in period a	[USD/t]
x_{afc}	sales from producer f to consumer c in period a	[PJ]
y_{afe}	sales from producer f to exporter e in period a	[PJ]
z_{aec}	sales from exporter e to consumer c in period a	[PJ]

A.5 Mathematical formulation of CMW v2.0

A.5.1 CMW v2.0: producer's problem

The producers maximize their profit $\Pi_f^P(x_{afc};\, y_{afe};\, inv_{af}^P;\, inv_{afc}^{TC};\, inv_{afe}^{TE})$ over the total model horizon A for all model years $a \in A$. The producers extract and treat (produce) the coal and can sell it either to local demand nodes (x_{afc}) or to the exporters (y_{afe}). They bear the production (C_{af}^P) and the inland transport costs ($trans^C fc$, $trans_{fe}^E$). Further, they can invest in additional production capacities (inv_{af}^P) and in transport capacities to local demand (inv_{afc}^{TC}) or to the exporter (inv_{afe}^{TE}). These investments are subject to constraints.

$$
\begin{aligned}
&\max_{x_{afc};\, y_{afe};\, inv_{af}^P;\, inv_{afc}^{TC};\, inv_{afe}^{TE}} \quad \Pi_f^P(x_{afc};\, y_{afe};\, inv_{af}^P;\, inv_{afc}^{TC};\, inv_{afe}^{TE}) \\
&= \sum_{a\in A} \left(\frac{1}{1+r_f}\right)^a \cdot \Big[\sum_c p_{ac}^C \cdot x_{afc} + \sum_e p_{ae}^E \cdot y_{afe} \\
&- C_{af}^P[x_{afc},\, y_{afe}] \\
&- \sum_c trans_{fc}^C \cdot x_{afc} \cdot \kappa_f - \sum_e trans_{fe}^E \cdot y_{afe} \cdot \kappa_f \\
&- inv_{af}^P \cdot Cinv_f^P \\
&- \sum_c inv_{afc}^{TC} \cdot Cinv_{fc}^{TC} - \sum_e inv_{afe}^{TE} \cdot Cinv_{fe}^{TE}\Big]
\end{aligned} \tag{8}
$$

s.t.

Production capacity constraint:

$$
\begin{aligned}
&cap_f^P \cdot RE_{af}^P + \sum_{a'<a} \left(inv_{a'f}^P \cdot RN_{af}^P\right) \\
&- \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe}\right) \geq 0, \quad \left(\alpha_{af}^P\right)
\end{aligned} \tag{9}
$$

Maximum production capacity additions constraint:

$$
\begin{aligned}
&\overline{inv\_start}_f^P + (RE_{af}^P - RE_{af}^{P'}) \cdot cap_f^P + \sum_{a'<a} \left(inv_{a'f}^P \cdot (RN_{af}^P - RN_{af}^{P'})\right) \\
&- inv_{af}^P \geq 0 \qquad \left(\alpha_{af}^{inv^P}\right)
\end{aligned} \tag{10}
$$

Resource endowment (reserve) constraint:[10]

$$
res_f - \sum_{a\in A} \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f\right) \cdot plength \geq 0 \qquad \left(\alpha_f^{res}\right) \tag{11}
$$

[10] This constraint was slightly updated compared to previous model versions. So far, the last period a (2050) was considered to be only a period of one year, yet there is no reason why $plength = 5$ should not apply to $a\$ord(a) = card(a)$ (the last period). Thanks to Ruud Egging for pointing that out!

Transport capacity from producer f to consumer c constraint:

$$cap^{TC}_{fc} + \sum_{a'<a} inv^{TC}_{afc} - x_{afc} \cdot \kappa_f \geq 0 \qquad \left(\alpha^{cap^{TC}}_{afc}\right) \tag{12}$$

Transport capacity from producer f to exporter e constraint:

$$cap^{TE}_{fe} + \sum_{a'<a} inv^{TE}_{efc} - y_{afe} \cdot \kappa_f \geq 0 \qquad \left(\alpha^{cap^{TE}}_{afe}\right) \tag{13}$$

Non-negativity constraints:

$$x_{afc} \geq 0;\ y_{afe} \geq 0;\ inv^{P}_{af} \geq 0;\ inv^{TC}_{afc} \geq 0;\ inv^{TE}_{afe} \geq 0 \tag{14}$$

Production cost function:

$$\begin{aligned} C^{P}_{af} = &\left(mc\_int_{af} + \frac{1}{2} \cdot mc\_slp_f \cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f \right)\right) \\ &\cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f \right) \end{aligned} \tag{15}$$

Endogenous cost mechanism:

$$\begin{aligned} mc\_int_{af} = &\ mc\_int\_start_f \\ &+ mc\_slp_f \cdot mc\_int\_var_f \cdot \sum_{a'<a} \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f \right), \\ &mc\_int_{af}\ \text{(free)} \end{aligned} \tag{16}$$

Retirement factors for existing RE^{P}_{af} and new mines RN^{P}_{af}, as well as the respective factors ($RE^{P'}_{af}$ and $RN^{P'}_{af}$) with a shift by one unit in the exponent of the inverse logistic function (used in Eq. 10 to depict the difference between model periods of available capacity cap^{P}_{f} and cumulative investments $inv^{P}_{a'f}$, respectively):

$$RE^{P}_{af} = \frac{1}{1 + (depe^{P}_{f})^{-(ord(a)-(mlexist^{P}_{f}/5+1))}} \tag{17}$$

$$RE^{P'}_{af} = \frac{1}{1 + (depe^{P}_{f})^{-(ord(a)-(mlexist^{P}_{f}/5+1-1))}} \tag{18}$$

$$RN^{P}_{af} = \frac{1}{1 + (depn^{P}_{f})^{-(ord(a)-(mlnew^{P}_{f}/5+1)-ord(a'))}} \tag{19}$$

$$RN^{P'}_{af} = \frac{1}{1 + (depn^{P}_{f})^{-(ord(a)-(mlnew^{P}_{f}/5+1-1)-ord(a'))}} \tag{20}$$

A.5.2 CMW v2.0: exporter's problem

The exporters maximize their profit $\Pi_e^E(z_{aec}; inv_{ae}^E)$ over the total model horizon A for all model years $a \in A$. The exporters buy the coal from the producers for the price p_{ae}^E and sell it to the consumers at price p_{ac}^C. They bear the harbor fee (fee_e), the sea transport costs ($searate_{ec}$), as well as potential import taxes (t_i_{ec}). They can invest in additional harbor capacities (inv_{ae}^E). These investments are subject to constraints.

$$
\begin{aligned}
&\max_{z_{aec};\, inv_{ae}^E} \quad \Pi_e^E(z_{aec};\, inv_{ae}^E) \\
&= \sum_{a \in A} \left(\frac{1}{1+r_e} \right)^a \cdot \Big[\sum_c p_{ac}^C \cdot z_{aec} \\
&- \sum_c p_{ae}^E \cdot z_{aec} \\
&- \sum_c z_{aec} \cdot fee_e \cdot \kappa_e \\
&- \sum_c z_{aec} \cdot searate_{ec} \cdot \kappa_e \\
&- \sum_c z_{aec} \cdot t\_i_{ec} \cdot \kappa_e \\
&- inv_{ae}^E \cdot Cinv_{ae}^E \Big]
\end{aligned} \tag{21}
$$

s.t.

$$
cap_e^E + \sum_{a' < a} inv_{ae}^E - \sum_c z_{aec} \cdot \kappa_e \geq 0 \quad \left(\mu_{ae}^E \right) \tag{22}
$$

$$
\overline{inv}_{ae}^E - inv_{ae}^E \geq 0 \quad \left(\mu_{ae}^{inv^E} \right) \tag{23}
$$

$$
z_{ec} \geq 0;\, inv_{ae}^E \geq 0 \tag{24}
$$

Furthermore, Chinese imports and exports are restricted. Equation 25 imposes a limit on the sum of annual seaborn coal imports to China.

$$
China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \geq 0 \quad \left(\rho_a^{CHN} \right) \tag{25}
$$

The model includes also the option to restrict Chinese coal exports, which has been a political intervention in the past. This constraint, if enabled, is applied on the one Chinese exporter E_CHN and its exports to all consumption nodes with a non-Chinese import port (i.e., countries $NoChina(c)$) using equation (26). $China\_lic_a$ represents the level of Chinese export licenses for a given year in million tons.

$$China\_lic_a - \sum_{NoChina(c)} z_{a\,CHN\_E\,c} \cdot \kappa_e \geq 0 \quad \left(\pi_a^{CHN}\right) \tag{26}$$

A.5.3 Final demand and market clearing

Demand is defined via a linear inverse demand function of the type $p_{ac} = DemInter_{ac} + b_{ac} \cdot y_{ac}$ with $b_{ac} = \frac{p_{ac}^{ref}}{y_{ac}^{ref}} \cdot \frac{1}{\varepsilon_{ac}}$ and $DemInter_{ac} = p_{ac}^{ref} - b_{ac} \cdot y_{ac}^{ref}$, following the demand elasticity definition $\varepsilon_{ac} = \frac{y_{ac} - y_{ac}^{ref}}{p_{ac} - p_{ac}^{ref}} \cdot \frac{p_{ac}}{y_{ac}}$. This gives the following inverse demand function depending on the consumed quantity $y_{ac} = \sum\limits_f x_{afc} + \sum\limits_e z_{aec}$:

$$p_{ac} = p_{ac}^{ref} + \frac{1}{\varepsilon_{ac}} p_{ac}^{ref} \left(\frac{y_{ac}}{y_{ac}^{ref}} - 1 \right) \tag{27}$$

The following market clearing condition determines the price given the demand function $p_{ac}\left(x_{afc}, z_{aec}\right)$ at the demand node c:

$$p_{ac}^C - p_{ac}\left(\sum_f x_{afc}, \sum_e z_{aec} \right) = 0 \quad , p_{ac}^C \text{ (free)} \tag{28}$$

A second market clearing condition determines the the price p_{ae}^E at the exporting node e:

$$0 = y_{afe} - \sum_c z_{aec} \quad , p_{ae}^E \text{ (free)} \tag{29}$$

A.5.4 CMW v2.0: KKTs

- **Karush-Kuhn-Tucker conditions (KKTs) of producer's problem**

Need to consider "endogenous cost mechanism" (Eq. 16) when taking derivative - substitute 16 in 8 before taking derivative.

$$
\begin{aligned}
0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot \Big[&- p^C_{ac} \\
&+ mc\_int\_start_f \cdot \kappa_f + mc\_slp_f \cdot \kappa_f \cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f\right) \\
&+ mc\_slp_f \cdot mc\_int\_var_f \cdot \kappa_f \cdot \sum_{a'<a} \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f\right) \\
&+ trans^C_{fc} \cdot \kappa_f \Big] \\
&+ mc\_slp_f \cdot mc\_int\_var_f \cdot \kappa_f \cdot \sum_{a'>a} \left(\frac{1}{1+r_f}\right)^{a'} \cdot \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f\right) \\
&+ \alpha^P_{af} \cdot \kappa_f \\
&+ plength \cdot \alpha^{res}_f \cdot \kappa_f \\
&+ \alpha^{cap^{TC}}_{afc} \cdot \kappa_f \\
&\perp x_{afc} \geq 0
\end{aligned} \tag{30}
$$

KKT for y_{afe}, accordingly to x_{afc}:

$$
\begin{aligned}
0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot \Big[&- p^E_{ae} \\
&... \\
&+ trans^E_{fe} \cdot \kappa_f \Big] \\
&... \perp y_{afe} \geq 0
\end{aligned} \tag{31}
$$

$$
\begin{aligned}
0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot Cinv^P_{af} &- \sum_{a'>a} \left(\alpha^P_{a'f} \cdot RNR^P_{af}\right) \\
&- \sum_{a'>a} \left(\alpha^{inv^P}_{a'f} \cdot (RNR^P_{af} - RNR^{P'}_{af})\right) \\
&+ \alpha^{inv^P}_{af} \perp inv^P_{af} \geq 0
\end{aligned} \tag{32}
$$

$$
0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot Cinv^{TC}_{fc} - \sum_{a'>a} \alpha^{cap^{TC}}_{afc} \perp inv^{TC}_{afc} \geq 0 \tag{33}
$$

$$
0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot Cinv^{TE}_{fe} - \sum_{a'>a} \alpha^{cap^{TE}}_{afe} + \alpha^{inv^{TE}}_{afe} \perp inv^{TE}_{afe} \geq 0 \tag{34}
$$

$$
\begin{aligned}
&0 \leq cap_f^P \cdot RE_{af}^P + \sum_{a'<a} \left(inv_{a'f}^P \cdot RN_{af}^P \right) \\
&\quad - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \perp \alpha_{af}^P \geq 0
\end{aligned} \tag{35}
$$

$$
\begin{aligned}
&0 \leq \overline{inv}_f^P + (RE_{af}^P - RE_{af}^{P'}) \cdot cap_f^P + \sum_{a'<a} \left(inv_{a'f}^P \cdot (RN_{af}^P - RN_{af}^{P'}) \right) \\
&- inv_{af}^P \perp \alpha_{af}^{inv^P} \geq 0
\end{aligned} \tag{36}
$$

$$
0 \leq res_f - \sum_{a \in A} \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f \right) \cdot plength \perp \alpha_f^{res} \geq 0 \tag{37}
$$

$$
0 \leq cap_{fc}^{TC} + \sum_{a'<a} inv_{afc}^{TC} - x_{afc} \cdot \kappa_f \perp \alpha_{afc}^{cap^{TC}} \geq 0 \tag{38}
$$

$$
0 \leq cap_{fe}^{TE} + \sum_{a'<a} inv_{afe}^{TE} - y_{afe} \cdot \kappa_f \perp \alpha_{afe}^{cap^{TE}} \geq 0 \tag{39}
$$

Retirement factor for new mines with reversed order of a and $a^{'}$ in exponent RNR_{af}^P (needed in Eq. 32), as well as the respective factor $RNR_{af}^{P'}$ with a shift by one unit in the exponent of the inverse logistic function:

$$
RNR_{af}^P = \frac{1}{1 + (depn_f^P)^{-(ord(a') - (mlnew_f^P/5+1) - ord(a))}} \tag{40}
$$

$$
RNR_{af}^{P'} = \frac{1}{1 + (depn_f^P)^{-(ord(a') - (mlnew_f^P/5+1-1) - ord(a))}} \tag{41}
$$

- **KKTs of exporter's problem**

$$
\begin{aligned}
&0 \leq \left(\frac{1}{1 + r_e} \right)^a \cdot \Big[- p_{a\,sea}^C \\
&+ p_{ae}^E + fee_e \cdot \kappa_e + searate_{e\,sea} \cdot \kappa_e + t\_i_{ae\,sea} \cdot \kappa_e \Big] \\
&+ \mu_{ae}^E \cdot \kappa_e + \theta_{e\,sea} \cdot \pi_a^{CHN} \cdot \kappa_e + \iota_{e\,sea} \cdot \rho_a^{CHN} \cdot \kappa_e \perp z_{aec} \geq 0
\end{aligned} \tag{42}
$$

$$0 \leq \left(\frac{1}{1+r_e}\right)^a \cdot Cinv_{ae}^E - \sum_{a'>a} \mu_{ae}^E + \mu_{ae}^{inv^E} \perp inv_{ae}^E \geq 0 \tag{43}$$

$$0 \leq cap_e^E + \sum_{a'<a} inv_{ae}^E - \sum_c z_{aec} \cdot \kappa_e \perp \mu_{ae}^E \geq 0 \tag{44}$$

$$0 \leq \overline{inv}_{ae}^E - inv_{ae}^E \perp \mu_{ae}^{inv^E} \geq 0 \tag{45}$$

China's import restriction:

$$0 \leq China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \perp \rho_a^{CHN} \geq 0 \tag{46}$$

China's export restriction:

$$0 \leq China\_lic_a - \sum_{NoChina(c)} z_{a\,E\_CHN\,c} \cdot \kappa_e \perp \pi_a^{CHN} \geq 0 \tag{47}$$

- **Final demand and market clearing**

$$p_{ac}^C - p_{ac}\left(\sum_f x_{afc}, \sum_e z_{aec}\right) = 0 \quad , p_{ac} \text{ (free)} \tag{48}$$

$$0 = y_{afe} - \sum_c z_{aec} \quad , p_{ae}^E \text{ (free)} \tag{49}$$

A.5.5 Previous CMW capacity and maximum investment constraint

The production capacity constraint in its previous form (Eq. 50) as represented in Holz et al. [1] and used in recent applications of the model [i.a., 2–4]], including the mine mortality mechanism (second line):

$$\begin{aligned}
&cap_f^P + \sum_{a'<a} inv_{af}^P - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \\
&- \sum_{a'<a} \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \cdot mc_int_var_f \geq 0
\end{aligned} \tag{50}$$

As well as the previous formulation of the maximum investment constraint 51:

$$\overline{inv}_f^P - inv_{af}^P \geq 0 \qquad \left(\alpha_{af}^{inv^P} \right) \tag{51}$$