WORKING paper

BANQUE DE FRANCE
EUROSYSTÈME

# High Voltage:
# Financing the Path to Zero Coal

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## ABSTRACT

Keeping global warming under 1.5°C requires a complete phase-out of coal for electricity generation by 2040 according to the International Energy Agency's Net Zero Emissions by 2050 (NZE) scenario. In this paper, we use unit-level data from the Global Coal Plant Tracker database to build a phase-out priority score and identify the coal-fired power plants that would need to be decommissioned now to comply with this pathway. We assume the other coal power plants continue to operate to the end of their lifetime. We show that 70% of the capacity of the operating coal fleet should be shut down now, which corresponds to stranded assets worth \$842 billion globally. Replacing the coal capacities by equivalent low-carbon capacities would imply a much larger one-off cost of \$4.5 trillion worldwide. This upfront investment would also imply large debt financing costs, estimated at \$3.1 trillion globally, which would drive up the total cost to \$8.4 trillion. But coal plants have much higher operational costs than low-carbon ones, in part because they need fuel to operate, and the cost of CO2 emissions need to be priced. We show that cumulated net operational gains linked to replacing coal plants with low-carbon alternative to comply with the 1.5°C would amount to \$3.8 trillion worldwide, thus offsetting close to half of the total costs. By lowering financing costs and increasing carbon pricing in line with the International Energy Agency's NZE scenario, the total equation could become positive, that is, total savings from the transition to clean energy would be higher than the total costs.

Keywords: Coal Phase-out, Transition Pathways, De-carbonization, Early Retirement Strategy, Just Transition

JEL classification: Q58, Q48, Q50

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# NON-TECHNICAL SUMMARY

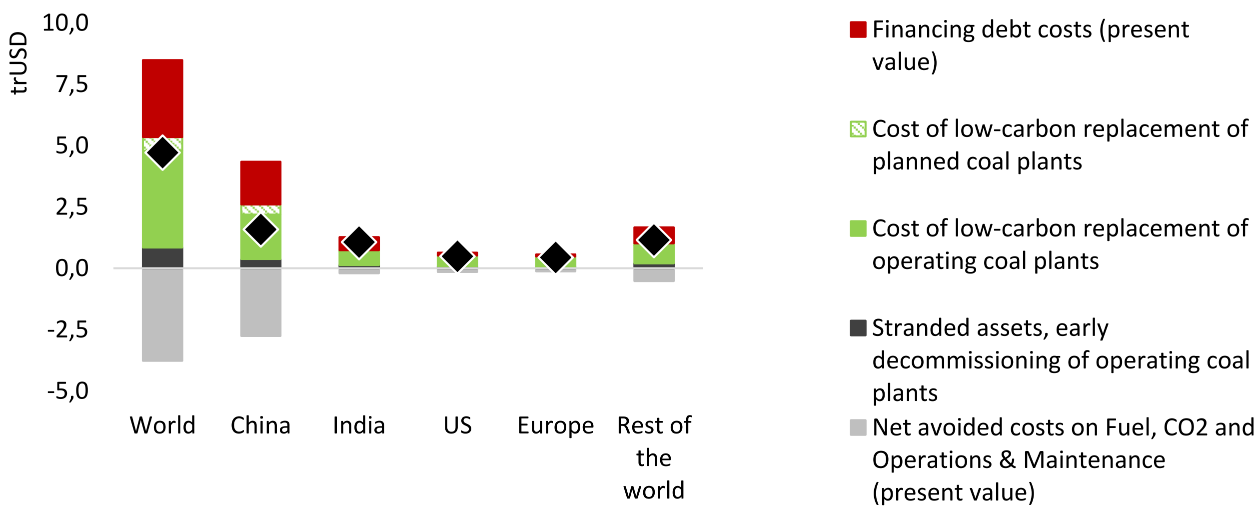
Coal is the largest single source of CO2 emissions, making its phase-out a critical objective for mitigating climate change. As mentioned in the press release of the COP28 initiative "Coal Transition Accelerator," the IPCC, UN, and IEA projections emphasize the urgent need to accelerate the phasing out of unabated coal in the global energy mix to maintain the 1.5°C target set by the Paris Agreement. This paper addresses the question of where to start and the extent of efforts needed.

We focus on coal-fired power plants, which account for two-thirds of total coal emissions and a quarter of global CO2 emissions. We develop a multi-layered scoring system based on plant characteristics (age, emissions, and technology) and the transition readiness of host countries. This analysis encompasses the 7,573 coal plants currently operating or under construction as listed in the Global Coal Plant Tracker database. Our findings suggest that prioritizing the decommissioning of older, higher-emission plants in countries more prepared for transition is essential. Under such strategy, the plants that need to be shut down account for 70% of the global current coal power capacity, with associated stranded asset costs amounting to $842 billion. Remaining coal power plants could continue operating until the end of their lifetimes, assuming no new plants are built.

However, merely shutting down coal power plants is not feasible without replacing them with low-carbon energy capacity. We estimate the cost of this replacement, including upfront costs (stranded assets and investment capital for new low-carbon plants) and the present value of operating costs (debt interest and differences in fuel, CO2, and operation and maintenance costs). Upfront investment needs are high, and the cost of debt exacerbates this challenge, creating a "high voltage" danger zone for the net-zero transition. Replacing coal capacities with equivalent low-carbon capacities to meet the NZE scenario is estimated to cost $8.4 trillion, including $3.1 trillion in debt financing costs.

Despite these high costs, exiting coal can yield substantial net savings due to lower operating costs for low-carbon energy, amounting to $3.8 trillion. Additionally, increasing the cost of CO2 emissions through carbon pricing and reducing the cost of capital for developing countries would further strengthen the business case for replacing coal with renewables. Under certain scenarios, such as the IEA NZE carbon pricing trajectory with lower capital costs, the coal phase-out required by the NZE scenario could result in net economic gains of $2.6 trillion globally.

**Total cumulated costs implied by the 1.5°C pathway, trillion USD**




Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors.

# Haute tension : financer la voie vers la sortie du charbon


## RÉSUMÉ

Selon l'Agence internationale de l'énergie, pour maintenir le réchauffement climatique en deçà de 1,5 °C, il faut éliminer complètement la production d'électricité à partir du charbon d'ici à 2040. Si le parc actuel de centrales à charbon continuait à fonctionner en l'état, les émissions mondiales de CO2 ne diminueraient que d'un quart d'ici à 2040. Dans cet article, nous étudions une stratégie de fermeture anticipée des centrales à charbon. Nous utilisons la base de données *Global Coal Plant Tracker* pour déterminer quelles centrales à charbon pourraient être fermées en priorité, et combien devraient l'être pour respecter le scénario 1,5 °C. Nous évaluons ensuite les coûts qui y sont associés. Nous montrons que 70 % de la capacité du parc de centrales au charbon en activité devrait être mise hors service dès maintenant, ce qui correspond à des actifs échoués d'une valeur de 842 milliards de dollars au niveau mondial. Le remplacement des centrales à charbon, actuellement en service ou dont la construction est planifiée, par des sources d'énergie bas-carbone, impliquerait un coût beaucoup plus important de 4,5 Mds de dollars au niveau mondial. Ces investissements impliqueraient également d'importants coûts liés à la dette, estimés à 3,1 Mds de dollars au niveau mondial, ce qui porterait le coût total à 8,4 Mds de dollars. Cependant, les coûts opérationnels des centrales à charbon sont beaucoup plus élevés que ceux des infrastructures énergétiques bas-carbone, notamment parce que les centrales ont besoin de combustible pour fonctionner et parce que les émissions de CO2 devraient être tarifées. Nous montrons que les gains opérationnels nets cumulés liés au remplacement des centrales au charbon par des alternatives bas-carbone dans le cadre d'un scénario 1,5 °C s'élèveraient à 3,8 Mds de dollars dans le monde, compensant ainsi près de la moitié des coûts totaux. En réduisant les coûts de financement et en augmentant la tarification du carbone, l'équation totale pourrait même devenir positive, c'est-à-dire que les gains de la transition seraient supérieurs aux coûts totaux à long-terme.



Mots-clés : élimination progressive du charbon, scénarios de transition, décarbonisation, fermeture anticipée des centrales à charbon, transition juste

# 1. Introduction

There is a broad consensus that phasing out coal is essential for achieving global net-zero emissions (Welsby et al., 2021). Coal is both the largest source of electricity generation and the largest single source of $CO_2$ emissions (IEA, 2023). It is the most carbon-intensive fossil fuel, and its usage has almost been constantly increasing since its discovery as an energy source. The amount of $CO_2$ emitted per unit of energy is two times higher for coal compared with natural gas, and around 1.5 times compared with oil (US Energy Information Administration, 2022). $CO_2$ emissions represent around two-thirds of total greenhouse gas emissions (IPCC, 2022).[1] The Global Carbon Project estimates that overall global $CO_2$ emissions in 2023 represented 40.9 $GtCO_2$ (Friedlingstein et al., 2023). In 2022, coal emissions were at an all-time high of 15.3 GtCO2. Out of these emissions, emissions from coal-fired power plants reached a record level of 10.88 GtCO2, with the remaining coal-related emissions mostly emanating in the industry (notably for iron, steel, cement productions) and buildings sectors (IEA, 2023).

In this paper, we focus specifically on emissions from coal-fired power plants. They represent a quarter of global $CO_2$ emissions. And if anything, coal is gaining, not losing momentum. All pathways that limit warming to 2°C (or less) require substantial reductions in fossil fuel consumption and a near elimination of the use of coal. If we do not do anything, coal emissions from the power sector alone are sufficient to consume all the remaining global carbon budget and overshoot the 1.5°C trajectory. While there is a consensus that coal needs to be phased out, it is not clear what a just transition entails or where to start (Jakob et al., 2020). Nor do we know the cost of shutting down coal-fired power plants and replacing them with alternatives.

In this paper, we build a phase-out priority score for identifying plants for early retirement and calculate how many and which power plants need to be shut down now under the 1.5°C scenario. We assume that the remaining coal power plants continue to operate until the end of their lifetime and that all current coal-fired power plant construction projects are cancelled. We find that 70% of the capacity of the operating coal fleet should be shut down immediately. Taking into account the age of each plant, and assuming linear capital depreciation over the lifetime of a plant, this corresponds to stranded assets worth of $842 billion globally. In addition, all future coal-fired power plant construction projects should be cancelled. In capacity terms, they represent an additional 16% of the capacity of the current fleet.

While the cost of stranded assets is non-trivial, it pales in comparison to the cost of replacing coal-fired plants with low-carbon energy generation capacity. We assess as a first step the upfront costs of such replacement, assuming it is made with a mix of low-carbon technologies in each country. The replacement cost would amount to $4.5 trillion worldwide, of which $2.2 trillion is in China alone. The added value of our approach is to give a clear and agnostic order of magnitude of the one-off cost of removing coal plants to realistically attain the International Energy Agency (IEA) 1.5°C-sectorial climate targets concerning the coal power sector.

In addition of these upfront losses and costs, we also estimate the debt financing costs of replacing coal-fired plants with low-carbon energy generation capacity, i.e. future flows linked to interest payments. The cost of financing is relatively low for advanced economies and China. But it can be as high as around 10% for India or 13% for Brazil according to the IEA's Cost of Capital Observatory (IEA, 2022a). The net present value of such financing costs is estimated at $3.1 trillion worldwide – equaling a staggering 69% of the total global investment cost for replacing coal-fired power plants. The high cost of capital of financing the new renewable capacity to replace coal is a major barrier to the net zero transition. This is the danger zone that we call "high voltage".

[1] Total GHG emissions (excluding LULUCF) are estimated at 52, 8 $GtCO_2eq$ in 2021 (UN, 2022). In 2019, total GHG emissions (including LULUCF) were around 59 $GtCO_2eq$ (IPCC, 2022).

The very large one-off costs linked to stranded assets and infrastructure investments, as well as heavy debt costs, darken the outlook. Yet the difference in daily operational costs make the business case for a transition look much better. Coal power plants need fuel to operate and cause (priced) $CO_2$ emissions while the operating costs of low-carbon energy are much smaller. This implies that such replacement generates net gains in operating costs. At the global level, those gains offset close to half of all costs. However, our analysis also shows that by lowering financing costs and increasing carbon pricing in line with the International Energy Agency's NZE scenario, the total equation could become positive, that is, total savings from the transition to clean energy would be higher than the total costs.

Going forward, it will be critical to lower the cost of financing renewable energy in developing countries and make the transition possible. Yet, finances are not the only reason why coal plants are not a thing of the past yet. It is difficult to get rid of coal because countries also consider extra-financial issues such as energy security and jobs (people working in mining industries) and because of vested interests and lobbying power of the coal industry. While recognizing the great importance of the political economy around phasing out coal, we focus in this paper on these financial aspects only. We discuss policy options for supporting the transition away from coal in low- and middle-income countries including through the provision of grants and concessional finance through multilateral development banks (MDBs) or special investment vehicles and increases in the costs of running coal plants through higher carbon pricing. Several international initiatives going in this direction are already on the table, such as the Coal Transition Accelerator announced during the COP28.

Our contribution is to bring a holistic view of net costs of an early retirement of coal plants, by adding stranded assets, low-carbon energy infrastructure investment needs, financing costs, as well as net gains from operational cost differences. It is important to highlight that the estimated replacement costs are only part of the total costs associated with our climate targets. Greening the current energy mix is not sufficient. Investment in low-carbon energy will also have to match the growing energy demand at the global level, especially in the developing world.

The remainder of the paper is structured as follows. Section 2 reviews the literature on the premature retirement of coal coal-fired power plants. Section 3 provides an overview of the data used for our analysis, followed by on overview of how we construct a transition priority score for coal power plants in Section 4 and the three coal plant transition scenarios that we use in our subsequent analysis in Section 5. Building on these elements, Section 6 then estimates the cost of phasing out coal plants to meet the 1.5°C target, including the value of stranded assets, the cost of replacing coal with low carbon technologies, the debt costs related to financing new investments, and the foregone cost related to fuel and maintenance to operate coal-fired power plants and the resulting $CO_2$ emissions. Section 7 discusses options for supporting the transition in low- and middle-income countries. Section 8 concludes.

## 2. Literature review

Stranded assets are assets that suffer from "unanticipated or premature write-downs, devaluations or conversion to liabilities" (Caldecott, 2017). The literature highlights two types of stranded assets (IPCC, 2022). First, fossil fuel reserves that cannot be burned (McGlade and Ekins, 2015; Hauenstein, 2023). And second, premature retirement of fossil infrastructure. Here we focus on the second case: infrastructure in the form of coal-fired power plants. Globally, stranded assets in coal power generation are estimated between \$1 and \$2.3 trillion according to the literature (IEA, 2021; Chen et al., 2023; Suski et al., 2022; Edwards et al., 2022). Our article builds on a larger literature quantifying the stranded asset level related to the premature retirement of fossil infrastructure consistent with mitigation pathways (Jonson et al., 2015; Kefford et al., 2018; Pfeiffer et al., 2018; Fofrich et al., 2020).

An early retirement strategy implies a shorter duration of lifetime and a part of non-amortized capital. For estimating the corresponding stranded asset value, different measures can be used. Shearer et al. (2017) and Edwards et al. (2022), for instance, use the unrecovered capital cost as a measure of stranded assets, without accounting for fuel or maintenance costs for instance. Such quantifying exercise can be applied at a country-level: Shearer et al. (2017) focus on India; Zhang et al. (2021) on China. Zhang et al. (2021) for instance estimate the stranded value of coal-fired power capacity in China between \$55 billion and \$396 billion for a pathway consistent with 2°C scenario. Other conduct such assessment at an international level: Edwards et al. (2022) find that stranded assets from the global coal fleet may reach \$1.4 trillion under a 1.5°C policy and \$1 trillion under 2°C.

Some articles resort to an early retirement strategy for prioritizing plants for early retirement. This strategy permits cost-effective retirement pathways. In a first paper, Cui et al. (2019) use an operational lifetime metric at an international level: there is an immediate retirement for plants whose lifetimes exceed 35 years of service for a 2°C goal (20 for 1.5°C). With the same lifetime limits, ageing units in developed countries shut down first, while newer fleets in developing countries can stay online longer. This is due to the fact that power plants are still relatively young in developing and emerging economies compared to high-income countries (IMF, 2023). Besides, retired plants tend to be older, smaller, less efficient, and highly polluting. Such strategy eliminates 95% and 89% of existing capacity in the United States and European Union by 2030, respectively, but only 65% in China and 43% in India for 1.5°C. Cui et al. (2021) build a multi-layered score with more granular data on the technical attributes, profitability, and environmental impacts of the coal power plants, but for China only. They find that a small set of existing plants (18%) should be rapidly shut down in the near term, since they perform poorly across all the technical, economic, and environmental criteria assessed. The remaining plants can operate through a lifetime of 20 to 30 years, but with a lower utilization rate. Other papers rely on a similar multi-dimensional approach at the country or international levels, sometimes taking into account country or region specifics. Mammoun et al. (2023) deploy a multi-dimensional strategy considering age, operating costs and air pollution. They emphasize that each regional strategy should prioritize the criteria that resonates the most with local issues. The age limit is the most relevant criteria in countries or regions with older coal fleet such as the United States, the European Union or Russia. But in China the retirement pathway should prioritize air pollution as Chinese plants have detrimental effects on the local population's health. Edianto et al. (2023) build a coal lock-in index among 66 countries to depict the degree of difficulty each country is forecasted to face when attempting to retire its coal power plant fleet.

The literature also offers estimates of the cost of replacing fossil fuel or existing coal capacities with low-carbon sources at the international level. Way et al. (2022) find that even without accounting for climate damages or climate policy co-benefits, transitioning to a net-zero energy system by 2050 is likely to result in trillions of net savings. Some papers focus on coal and resort to a cost-benefit analysis (Rauner et al., 2020; Adrian et al., 2022). Rauner et al. (2020) and Adrian et al. (2022) internalize negative externalities. They use a social cost of carbon defined as the incremental expected present discounted social harm (air pollution or climate damages from temperature rise) from an additional ton of CO2 emissions. Adrian et al. (2022) for instance price avoided emissions at \$80/t$CO_2$ in the central scenario. Doing so, they find that replacing coal by renewable energy could yield net economic gains in the long run. The estimate of net economic gains is at \$85 trillion in their central scenario, with a bracket from \$9 trillion to \$221 trillion.

Our paper is building on the literature focusing on the supply-side of climate policy with direct effects on energy mix, targeting energy production rather than consumption (Harstad, 2012; Collier and Venables, 2014; Adrian et al., 2022; Brutschin et al., 2022). Our approach goes beyond previous analyses gauging the cost of coal phase out. Using plant-level data, we account for several layers of costs – stranded assets, infrastructure investments, debt costs, and operational costs –, which allows for more precise cost estimates of the transition away from coal than provided by previous analyses.

## 3. Data

We use a unit-level dataset of coal power plants generating 30MW and above named the Global Coal Plant Tracker (Global Energy Monitor, 2023). It includes all currently operating coal-fired units, as well as units proposed since 2010 and units retired since 2000. The tracker lists over 16,650 single coal-fired power units in over 107 countries, including units retired or cancelled since 2000. Each plant is composed of several units, and the database is at the unit level. It is the most comprehensive dataset available. The database provides information on technical characteristics, such as combustion technology and $CO_2$ emission factor, as well as the remaining lifetime, annual $CO_2$ emissions, and location of each unit. We focus on units that are currently operating or under construction or are planned to be operating in the future (the latter category includes "announced", "pre-permit", "permitted"), i.e. 7,573 units. The data is displayed in Figure 1, aggregated by region. It shows the major role of Asia in global emissions by coal-fired power plants and highlights the geographical differences in the average remaining lifetime, which is particularly long in emerging Asia.

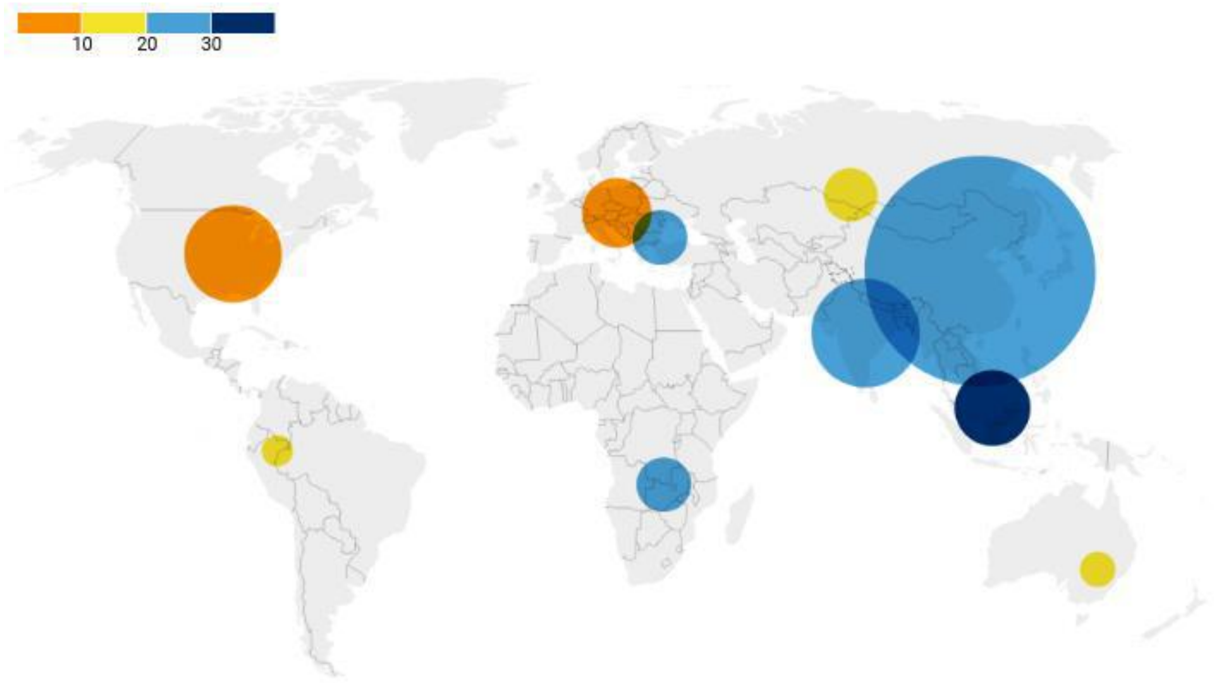



Fig. 1 – Coal plants: annual $CO_2$ emissions (size) and average remaining lifetime (color)

*Source: Compiled by authors with data from Global Coal Plant Tracker (2023)*

The operating units listed in this database have an aggregated capacity of 2,223GW, responsible for 10.3Gt$CO_2$ emissions per annum. It is supposedly covering close to the whole global coal-fired power plants park, for which $CO_2$ emissions were estimated at 10.5Gt$CO_2$ in 2021 by the IEA (IEA, 2022b).

To account for the performance and readiness of energy systems across countries for transition, we use the World Economic Forum's Energy Transition Index (World Economic Forum, 2021). It is a composite score aggregating 40 variables covering aspects of different dimensions. The 40 variables are aggregated with equally distributed weights to provide scores for the two sub-indices (System Performance Index and Transition Readiness Index described in the next section). Assignments of equal weights might not be ideal, but it reflects empirical limitations of the relative importance of each variable and is consistent with the approach taken by other composite indices, such as the United Nation's Human Development

Index (World Bank, 2022). The contribution of the World Economic Forum's Energy Transition Index is that it provides a framework to the interdependencies of energy system transformation with the macro-economic, political, regulatory and social factors determining a country's readiness for transition. Each of the two sub-indices constitutes one of the five layers of our synthetic score described below.

# 4. Building a phase-out priority score for coal power plants

We start by building a 5-layer score for the coal units in the Global Coal Plant Tracker. We focus on currently operating units and units under construction, putting aside planned units at this stage. Based on the criteria explained below, the lower the score, the more urgent the transition is.

This scoring system aims to lead to a better stranded asset value to avoided emissions ratio (better abatement cost) for our early retirement strategy. This reduces the value of stranded asset for a given total amount of emissions reduction globally. It is a way to optimize transition in financial terms. We follow the literature establishing technical criteria for identifying coal power plants best suited for decommissioning (Cui et al., 2019; Maamoun et al., 2021; Cui et al., 2021; Jindal and Shrimali, 2022). We also integrated three technical criteria from the Global Plant Tracker database: remaining lifetime (in years), combustion technology (subcritical, super-critical, ultra-super), and emission factor (kg of $CO_2$ per TJ).[2]

Our score differs from the literature as it incorporates country characteristics showing the transition readiness of the country where the plant is operated. We add two sub-scores reflecting this readiness from the Energy Transition Index established by the World Economic Forum. The first one is the System Performance Index. It reviews how well a country's current energy system is performing. The review is based on the country's ability to support economic development and growth, to the level of access to a secure and reliable energy supply, and to the environmental sustainability across the energy value chain. The second sub-score is the Transition Readiness Index. It assesses whether the country is promoting and ready for renewable energy systems. It analyses the business environment, policy for innovations and human capital among other metrics.

To incorporate these multiple criteria, we normalize the five sub-indices for each plant assigning a score between zero and one for each individual criterion, in the vein of Cui et al. (2021). A lower score is assigned to characteristics pleading for an early retirement at the plant level (lower remaining lifetime, less sophisticated combustion technology, larger emission factor), and for plants located in countries with higher system performance and transition readiness sub-indices.

We calculate the normalized score using the following commonly used methodology equation (1):

$$X_i = (x - x_{\min})/(x_{\max} - x_{\min}) \quad (1)$$

We then aggregate the scores, all ranging from zero to one, through a non-weighted average, following equation (2):

$$X_i = \sum_{i=k} \text{Score for metric } X_i/k \quad (2)$$

with $k$ being the number of sub-indices, namely 5.

All sub-indices are equally weighted, meaning that technical characteristics at the plant level are slightly overweighed (3 out of 5) compared to the level of country readiness (2 out of 5). Overweighting technical characteristics values more micro aspects that are useful in the process of picking up specific plants. That said, results remain similar if we weight those two dimensions equally.

[2] Note that coal-fired power plants with unknown combustion technology are classified as mid-range in our exercise.

The synthetic score helps identify plants that will be more difficult to transition. These plants will be the hardest to decommission, either because of their long remaining lifetime or high technological standards making their present value still high, or because of the low level of readiness by the country, or, in many cases, both.

According to the repartition of scores, subcritical coal-fired power plants, with low remaining lifetimes, mainly located in developed countries with higher transition readiness, receive a lower score. These are the darker colors at the left of Figure 2.

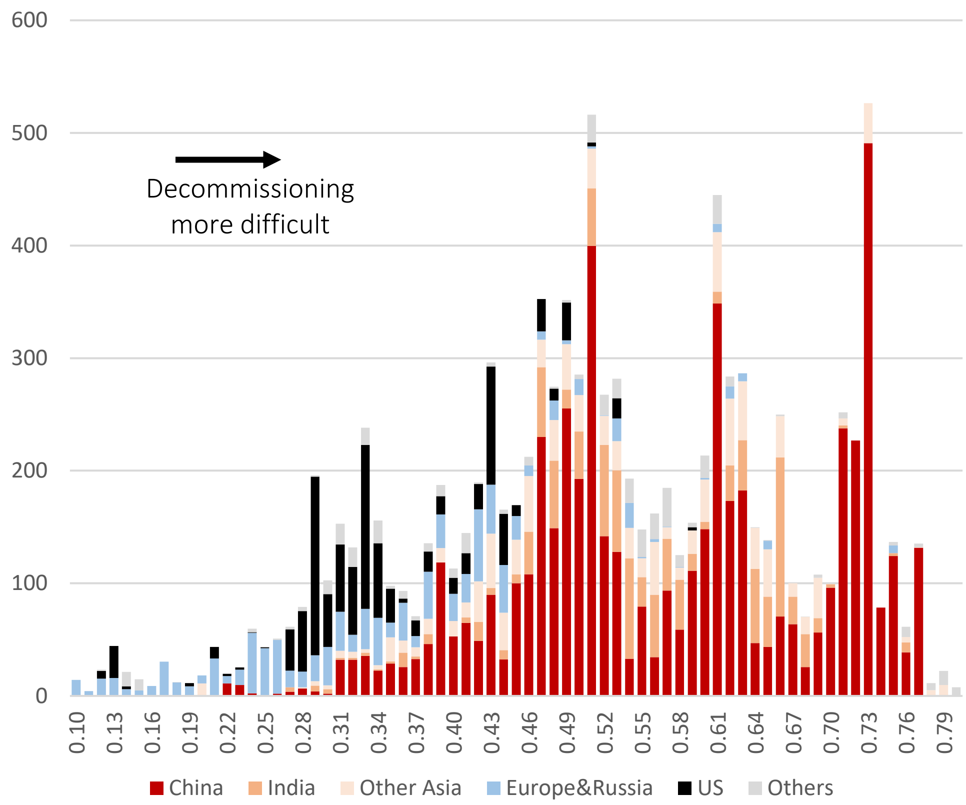



Fig. 2 – Transition readiness score of existing coal plants (horizontal axis) depending on their annual CO2 emissions (million tons, vertical axis) by location (color).

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021)*

Figure 2 shows the profile of aggregated annual emissions by synthetic score and by geography. Due to China's weight in the global fleet, China has a central role to play in this phase-out strategy. However, the synthetic score shows that developed countries also have a role to play since they host plants that could easily be decommissioned, especially in Europe and the United States.

Lastly, we assign the lowest score of 0 to all planned coal plants for which construction has not started, i.e., they need to be cancelled first. Future projects are the quicker wins, since capital investments are still low and locked-in capital is almost nil.

# 5. Three coal plant transition scenarios

We simulate the annual $CO_2$ emissions from coal that would derive from the 1.5°C trajectory. Under the IEA's Announced Pledges Scenario consistent with well-below 2°C scenarios, coal use in the power sector drops by 20% by 2030 and by 75% by 2050. Under the Net Zero Emissions by 2050 (NZE) scenario, to achieve the 1.5°C goal, coal use in the power sector drops by 55% by 2030 and there is no more use of unabated coal for electricity generation by 2040 (IEA, 2022c). The differences in terms of coal capacity between the IEA's scenarios are detailed in Appendix Table A.[3] We suppose a similar path between coal use and coal emissions. To assess the impact of decommissioning the identified low-hanging fruits coal plants, we construct three different scenarios and compare the annual and cumulative $CO_2$ emissions for each of them.

**Scenario 1 (red line, Figures 3 and 4):** We assume that all existing coal-fired power plants are replaced totally with 100% low-carbon energy at the end of their lifetime. Although the decrease in annual $CO_2$ is steep, it is still not sufficient to attain the 1.5°C or even the 2°C pathway (Figure 3). This means that not replacing all power plants, or replacing them with low-carbon solutions only, at the end of their lifetime, is not enough to achieve the objectives, even for 2°C. Under this scenario, cumulative CO2 emissions from the coal power sector would amount to around 300 GtC02, by far overshooting the remaining carbon budget for coal power emissions of around 100 $GtC0_2$ according to the IEA NZE scenario (green dotted line Figures 3 and 4, right hand side panel). This confirms that it will be necessary to close plants early. Due to data construction, this scenario implies a cliff in 2062, since the maximum remaining lifetime registered in the database is 40 years.

**Scenario 2 (black line, Figure 3):** We assume cancellation of all future projects, combined with a non-replacement of all other plants at the end of their lifetime, or replacement with low-carbon technologies. By cumulating all annual emissions, we show that this scenario will not meet the 1.5°C scenario or the 2°C scenario (Figure 3).

**Scenario 3 (black line, Figure 4):** By cumulating annual emissions, we calculate the minimum threshold along our synthetic score scale defining which plant requires immediate decommissioning to meet the 1.5°C scenario (equivalent to a remaining carbon budget for coal power emissions of around 100 $GtC0_2$ according to the IEA NZE scenario), assuming the others continue to operate to the end of their lifetime. For this purpose, we consider that the target would be met if the cumulative emissions of the remaining fleet reach the cumulative emissions under the 1.5°C scenario. To meet the 1.5°C scenario, the threshold under which a coal plant should be decommissioned would be 0.626 on our synthetic score. The score does not have an inherent meaning but allows one to choose which plants to shut down first depending on their characteristics (age, emissions and technology) and their host country.

[3] IPCC projection is consistent with this: change in primary energy from coal without CCS in 2050 is due to fall by 100% relatively to 2019 level for reaching the 1,5°c target (IPCC, 2022).

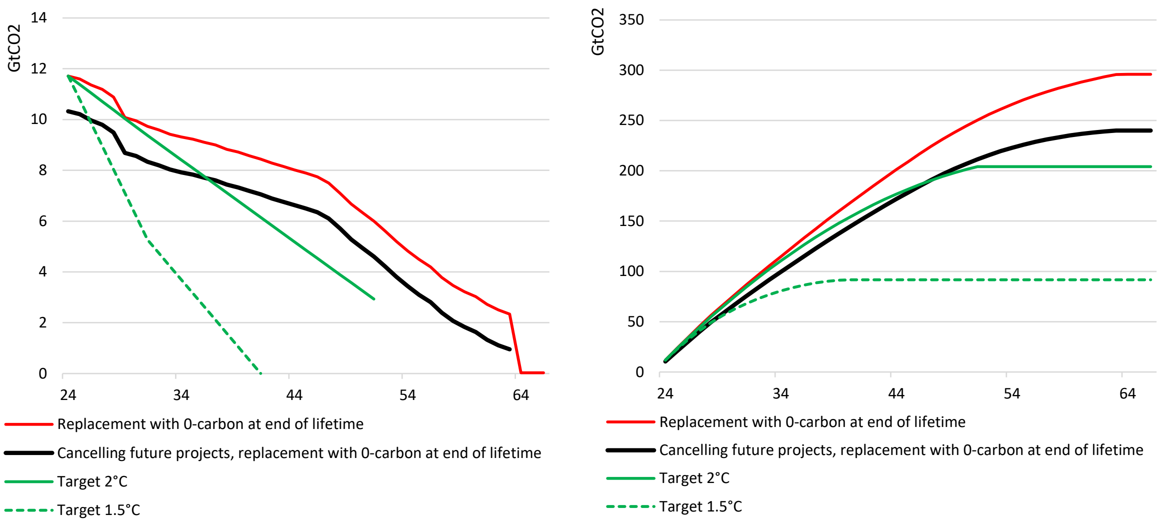



Fig. 3 – Annual (left) and cumulated (right) $CO_2$ emissions under Scenario 1 (no replacement) and 2 (no replacement and cancelling new projects)

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021)*

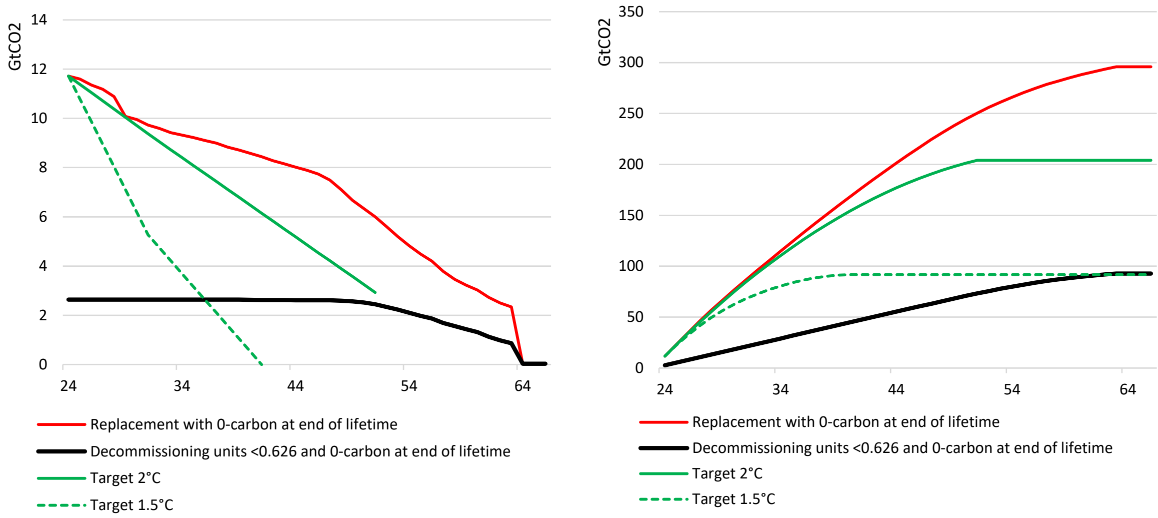



Fig. 4 – Annual (left) and cumulated (right) $CO_2$ emissions under Scenario 3 (respecting the 1.5°C path)

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021)*

In capacity terms, this means that 70% of the existing global fleet needs to be decommissioned now (Figure 5 and Table 1). The United States and Europe would need to decommission all their fleet (100% and 97% of their fleet, respectively), while China and India would need to decommission close to two third (61% and 64%, respectively). In addition, all future planned coal-fired power plant should be cancelled. In capacity terms, they represent an additional 16% of the capacity of the current global fleet (21% for China).

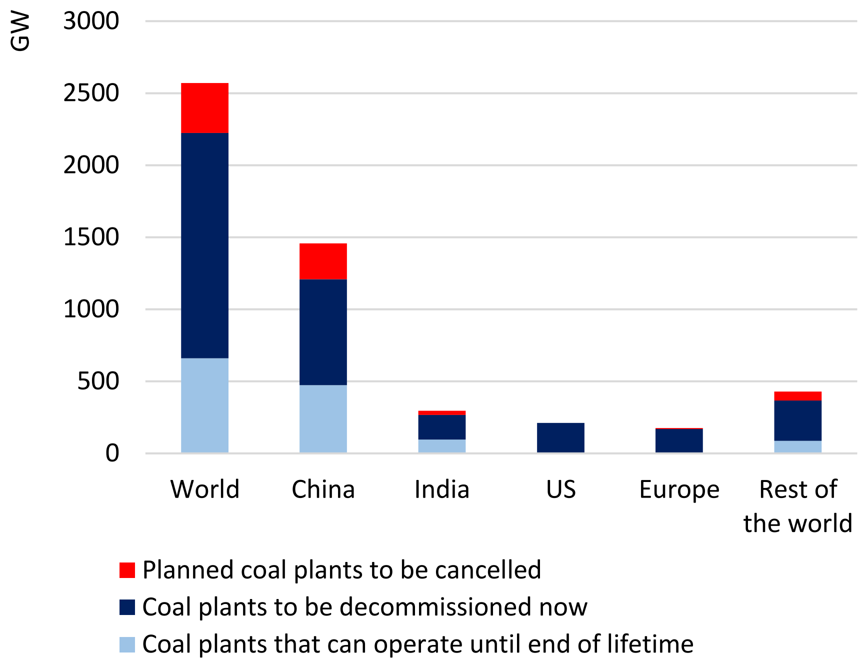



Fig. 5 – Total capacity of coal plant fleet (in GW), operating and planned, under our scenario 3

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021)*

Table 1 – Capacity of coal plant fleet to be decommissioned or cancelled under our scenario 3, as a percentage of total capacity currently in service

| | Plants to be decommissioned now as share of total capacity of currently operating capacity | Cancellation of all planned plants, expressed as share of total capacity of currently operating capacity |
|---|---|---|
| World | 70% | 16% |
| China | 61% | 21% |
| India | 64% | 11% |
| US | 100% | 0% |
| Europe | 97% | 4% |
| Rest of the world | 77% | 17% |

# 6. Estimating the cost of phasing out coal plants to meet the 1.5°C target

We proceed to estimate the one-time cost of decommissioning coal plants according to the 1.5°C target identified above (scenario 3). We take a four-step approach. First, we estimate the value of non-amortized capital still locked in plants that would face an early decommissioning (that is the capital that would become stranded). Second, we provide broad estimates of the cost of building new low-carbon plants to replace the energy capacity of decommissioned coal plants. Third, we assess the cost of debt financing for these infrastructure investments. Lastly, we estimate the differential in daily operational costs between coal and low-carbon plants.

## 6.1. Estimating the value of stranded assets

First, to estimate the value of stranded assets, we build on Edwards et al. (2022) and use the following formula:

$$\text{Stranded Asset} = OCC \times K \times (L-R)/L$$

OCC is the overnight capital cost (in $ per kW) of each plant, i.e. the cost of building a plant as if no interest were incurred during its construction; K the capacity of each plant (in kW); (L-R)/R the fraction of its expected lifetime (L) that it does not live out due to an earlier-than-expected retirement age (R). K, R and L are given for each plant by the Global Coal Plant Tracker presented in the data section. We assume that the capital is amortized each year linearly through the total duration of the lifetime. For the overnight capital cost, we use the World Energy Outlook from the IEA. The World Energy Outlook offers electricity generation costs, including capital costs, with a breakdown by technology and region (United States, European Union, China, and India).

We calculate the value of stranded assets in our various simulations. We obtain the results depicted in Figure 6. Note that future plants are meant to be dismantled in all scenarios. Amounts of assets linked to planned projects are featured with stripes since they are still not locked in real assets and could be avoided by cancelling those projects.

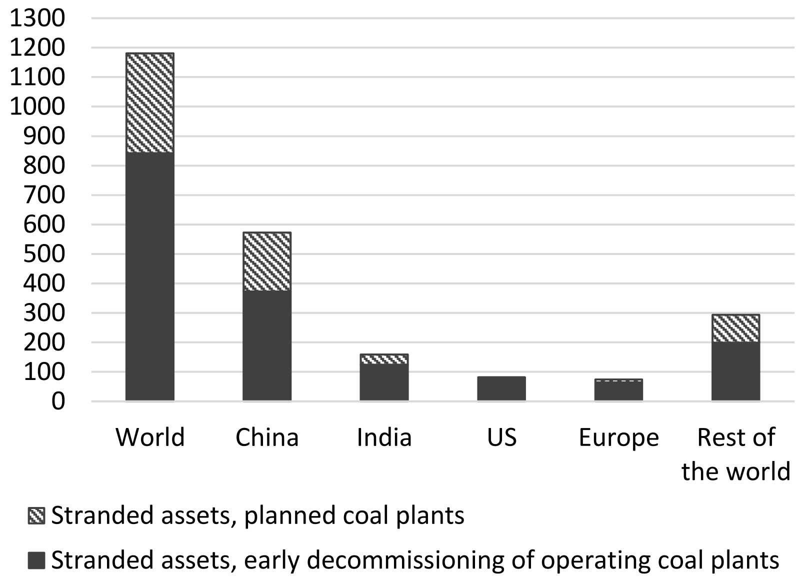



Fig. 6 – Stranded assets under the 1.5°C scenario (scenario 3), billion USD

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021)*

We find that the amount of non-amortized capital locked in coal plants that would need to be decommissioned to match the 1.5°C scenario amounts to $842 billion globally. In addition, the value of planned plants for which construction has not started yet amounts to $338 billion. Those are the plants that need to be cancelled urgently, since if the plants were to be constructed, they would instantly become stranded assets according to our score, not to mention the new projects that could come up in the coming years. We consider in our calculations that they are indeed canceled and do not become stranded assets.

China would suffer the largest losses, with a loss of capital linked to the decommissioning of operating coal plants amounting to $373 billion. China would also have to forgo $200 billion worth of new coal plants planned to be constructed in the coming years.

## 6.2. Cost of replacing coal with low carbon technologies

We now estimate the investment needs for the replacement of these coal capacities by low-carbon technologies. Decommissioned plants will indeed need to be replaced with clean energy generation capacity since energy demand is not expected to fall. We rely on strong assumptions to make a calculation of the cost of replacing coal plants that would need decommissioning in our scenarios. These assumptions, while simplifying, provide an indication of the order of magnitude of the cost to replace coal with clean sources of energy generation.

The first strong simplifying assumption we make is that coal plants will be replaced only with low-carbon sources of energy. While this is an ideal scenario, it is likely that some coal plants would be replaced by less carbon-intensive fossil-based plants, such as gas. This is not taken into account here. Note that coal-to-gas replacement would reduce the benefits of phasing out coal as reduced emissions from coal would be partly offset by emissions from natural gas. Besides, replacing coal by gas could represent additional lock-in and stranded assets and could require another round of replacement in the future, therefore wasting financial resources compared to a direct coal-to-low carbon replacement. Adrian et al (2022) for instance find that it is efficient to rely as little as possible on natural gas for coal replacement.

Secondly, an important simplifying assumption in our calculation is that we do not consider the emissions linked to the construction of alternative energy sources (life-cycle assessment). Thirdly, the replacement costs reflect the current level of global energy consumption. Yet, almost all countries or areas are expected to see an increase in energy consumption, with an average annual increase of 1.1% from 2022 to 2050 at a global level according to the United States' Energy Information Administration (EIA, 2023). This is especially true for developing and emerging economies such as India (+3.9%), in Africa (+2.5%), or in the Asia Pacific region (+1.4%). Also, we do not take into account the costs of energy storage and grid extension. Adrian et al. (2022) consider these costs as relatively marginal.

We assess the additional cost linked to the construction of new low-carbon plants to replace the coal plants that would face early decommissioning. We use the World Energy Outlook from the IEA. The IEA database gives capital costs not only for coal (which we used for assessing the value of stranded assets above), but also for gas and low-carbon technologies (solar, wind onshore, wind offshore, nuclear). It also provides capacity factors for the different technologies. Using these metrics featured detailed in Appendix Table B, we calculate the value of replacement for each kW of coal by alternative technologies. Since our simulation is about decommissioning coal plants now and replace them with low-carbon alternatives, we take as an input the low-carbon capital costs for the year 2022. As a caveat, using this methodology is a rather conservative approach as it might overestimate costs. Even if there was a spike since late 2020 (with a peak in 2022), renewable energy costs have fallen exponentially over the last decades. Capital costs for installing low-carbon plants are likely to continue to fall in the future.

For our calculations, we first consider the overnight capital costs and the capacity factor. For example, in China, the capital costs of coal plants are 800 $/kW, but the capacity factor is quite high (50%). For solar, capital costs are now lower than for coal (720 $/kW), but the capacity factor is very low (13%). This means that, for a plant producing an equivalent amount of energy each year, the price of solar facilities would be 3.5 times more expensive than coal in China. We calculate the capital costs needed to build a kW of capacity with a 100% capacity factor. Figure 7 shows the result.

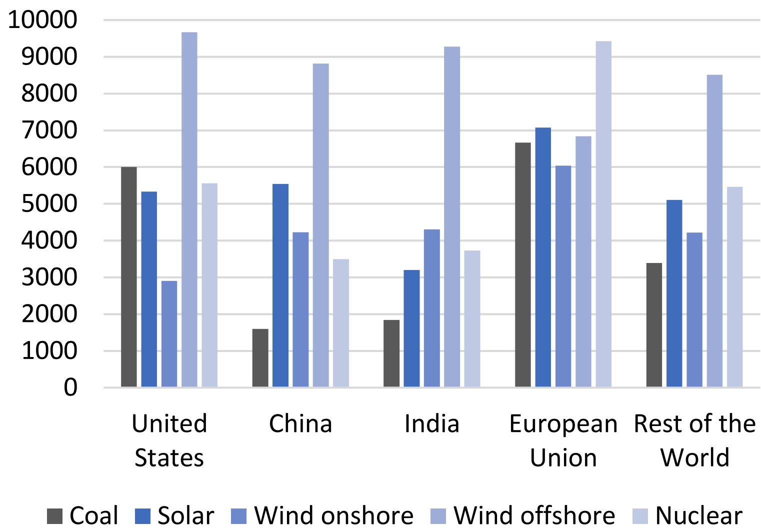



Fig. 7 – Capital costs, adjusted by the capacity factors, 2022, $/kW

*Sources: Compiled by authors with data from IEA (2023)*

Note that we use a non-weighted average of metrics from the United States, China, India and the European Union to assess the capital and operational costs and capacity factor of the rest of the world. This is a grossly simplifying assumption, but since most of the coal power is generated in these four jurisdictions, it does not bias our results in an important manner.

We make the assumption that the early decommissioning of coal plants is compensated by the construction of low-carbon plants with an energy mix composed of equally-weighted solar, onshore wind, offshore wind and nuclear plants, which are the low-carbon options for which the IEA gives capital costs, capacity factors, and operational costs. A more granular approach would allow us to adjust the potential energy mix to make it more optimal for each country, depending on its situation and characteristics. Due to data limitations and for the sake of simplicity, we apply the same equally-weighted mix for all countries. For planned coal plants, we assess the excess cost of switching the projects to low-carbon alternatives.

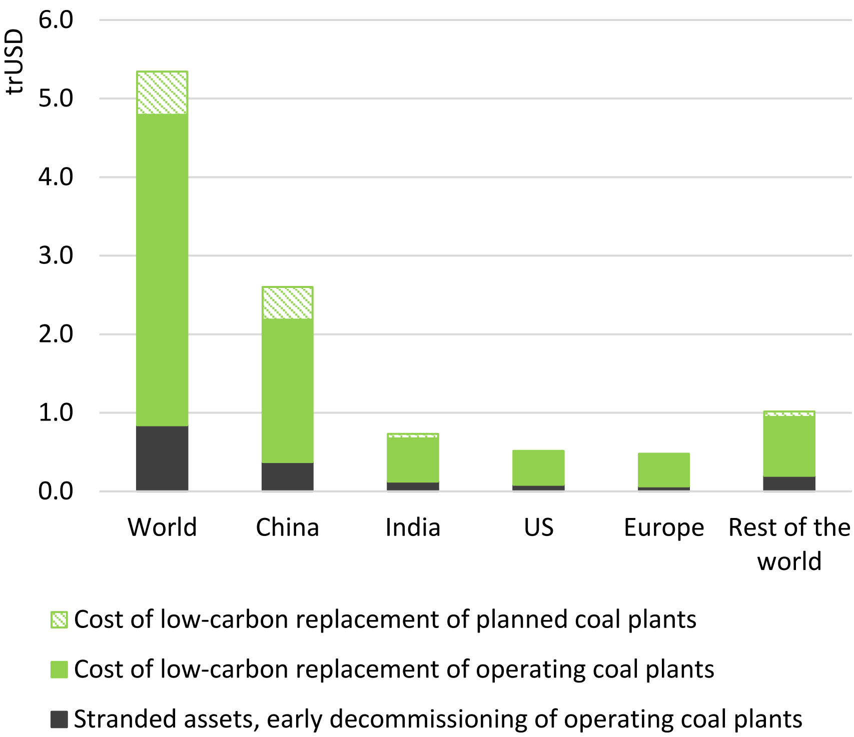



Fig. 8 – Total upfront costs implied by the 1.5°C pathway, including early decommissioning of operating coal plants (stranded assets), replacement of those plants with new low-carbon capacities, and cancelling plans to build new coal plants and replace capacities with new low-carbon plants, trillion USD.

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023)*

Figure 8 shows that, in terms of upfront costs, stranded assets (estimated at $842 billion) would compose only a fraction of the total incurred costs. Building new low-carbon plants able to produce a quantity of energy equivalent to that of the decommissioned coal plants and replacing future coal plants by low-carbon projects, would incur a more substantial cost, estimated at $4.5 trillion worldwide, amongst which $2.2 trillion in China and $0.6 trillion in India. Note that these costs imply the buildup of a brand-new fleet of plants, while it replaces coal plants that have on average 20 years of remaining lifetime. Nevertheless, it is an estimate of the one-off amount of capital needed to be mobilized to replace decommissioned coal plants.

We also estimate the stranded assets and cost of low-carbon replacement of coal plants in the context of a gradual phase out, i.e. a phase-out that would match the annual emission target under the NZE scenario. This scenario implies a decrease of annual CO2 emissions to zero by 2040. A gradual phase-out would imply lower investment costs for the construction of renewable power plants thanks to innovation (we take the IEA's cost-of-capital projections), but an increase in the cost of stranded assets since all plants would have to be decommissioned by 2040 (compared with 70% today in our baseline scenario). All in all, we find that both paths would imply similar total costs for stranded assets and investment in new plants (see Table E in the Appendix), but with a different composition: a gradual phase-out would imply more stranded assets and less investments in renewable plants, comparatively to our base scenario.

## 6.3. Debt costs related to financing new investments

Energy investments are not only about are not only about upfront investments or stranded assets. It is also important to estimate and compare the running costs of both coal and low-carbon energy plants to assess the net costs of the decommissioning and new investments throughout time. We focus on two categories of costs: debt interests from upfront investments, and the cost of fuel, $CO_2$ emissions, and operations and management.

First, we assess the cost of financing (debt interests). We take the 2021 indicative Weighted Average Cost of Capital (WACC) of utility-scale solar PV projects as estimated by the IEA (IEA, 2022a). Onshore wind is assumed by IEA to have the same WACC as utility-scale solar PV. We assume that all low-carbon energy have the same WACC. For the mean of WACC applied to the rest of the world, we take a non-weighted average of means of WACC reported in the IEA report (IEA, 2022a) for eight countries or jurisdictions (detailed in Appendix, Table F). These assumptions are in line with the literature.[4]

To assess the total debt cost, we incur the WACC to the investments needed to build the new low-carbon plants and to switch coal plants projects into low-carbon plants projects. We take into account the debt interests incurred during what would have been the remaining lifetime of the decommissioned coal plants. We also suppose that the level of debt interests are equal each year (i.e. we suppose no reimbursement of capital throughout this period). We discount these future interest payment flows by the WACC. Under these assumptions, we show that cumulated debt interests are substantially higher than stranded assets or upfront investments. The net present value of such interest payments are estimated at $3.1 trillion worldwide, among which $1.7 trillion in China and $0.5 trillion in India. As we use WACC from 2021, note that these costs could be increased in the current context of high interest rates.

## 6.4. $CO_2$, fuel and maintenance related costs

We then consider daily running costs. Operational costs of coal power plants are much higher than the ones of low-carbon plants, notably because coal power plants need fuel to operate, and emit more $CO_2$ that implies additional costs through carbon credits (when they are applicable). Replacing coal by low-carbon solutions can thus lower the operational costs of electricity generation. We incorporate into the calculations the saved operational cost for the remaining lifetime of coal plants that have been shut. We discount these future flows with the WACC.

$$\text{Saved operational costs}_{\text{year i}} = \text{Operational costs}_{\text{coal}} - \text{Operational costs}_{\text{low carbon}}$$

Operational costs are given in USD per MWh.

Operational costs include costs stemming from carbon pricing, fuel inputs, and operations and maintenance. The IEA report (IEA, 2022a) shows both the relatively conservative benchmark of the IEA STEPS scenario and the Net Zero Emissions by 2050 Scenario (NZE Scenario) that is designed to achieve net zero $CO_2$ emissions by 2050 (both scenarios are detailed on these aspects in tables G and H in Appendix).[5] The gap between the two scenarios concerning coal power plants is notably explained by the difference in carbon pricing trajectory.

Using the STEPS Scenario, that is, the least ambitious of the IEA scenarios in terms of carbon pricing, we highlight the fact that the differences in daily costs have a very significant impact on the business cases

[4] Adrian et al. (2022), for instance, also use the same WACC for different energy sources, and the cost of capital of obtaining financing for renewables is considered to be the same across countries.

[5] Between all the IEA scenarios, the STEPS scenario has the less ambitious carbon pricing trajectory from 2030 to 2050 (this scenario does not take for granted that governments will reach all announced goals).

for the different technologies. We calculate the fuel, $CO_2$ and operations and maintenance costs for all coal plants that would need to be decommissioned now under the 1.5°C scenario according to our calculations, accumulated from now and until the end of their initial lifetime, and take their present value. We then compare with the accumulated daily costs of low-carbon solutions (with a balanced mix between the four technologies as described above), during a similar timespan.

We show that the net present value of operational gains related to running low carbon plants instead of coal plants would amount to $3.7 trillion, among which $2.7 trillion in China. At the global level, those net gains offset close to half of all other costs. Figure 9 shows both the upfront costs (stranded assets and investment capital needed to build new low-carbon plants), and the accumulated present value of running costs (debt interest and difference in fuel, CO2 and operation and maintenance costs). The figure shows that running costs are actually a major share of the equation. Detailed results are displayed in Table I in the appendix.

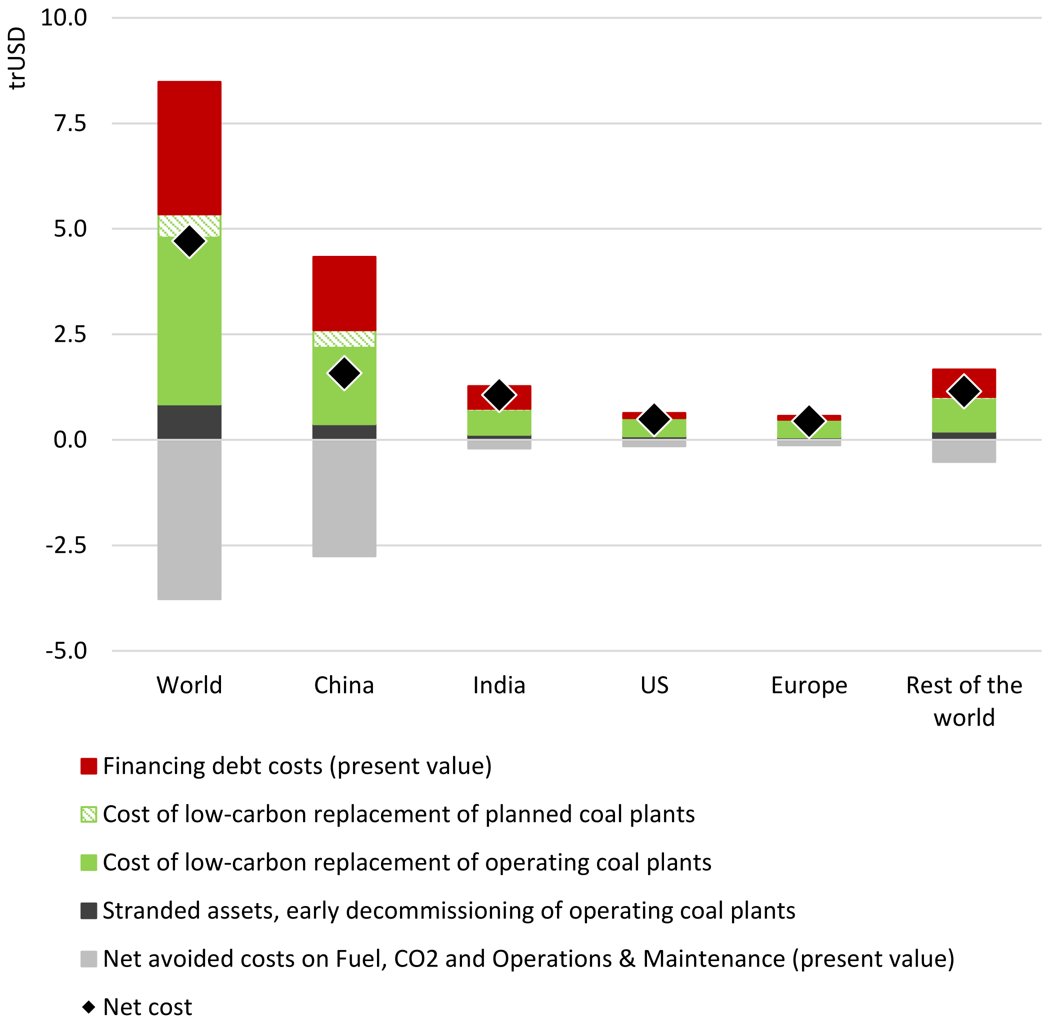



Fig. 9 – Total cumulated costs implied by the 1.5°C pathway, including fixed costs (stranded assets and investments to build low-carbon plants), and net operating costs (debt interests and difference in fuel, $CO_2$ and operations and maintenance costs, present value), trillion USD

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023)*

To illustrate those findings, we show the example of financing a new plant with a 600MW-equivalent capacity (adjusted for the capacity factor) and a 40-year lifetime, in China and India, showing the initial investment needed, as well as the accumulated present value of future debt interests and operational costs. India is an example of a country facing high financing costs (9.75% average WACC), which can illustrate the situation of other developing countries.

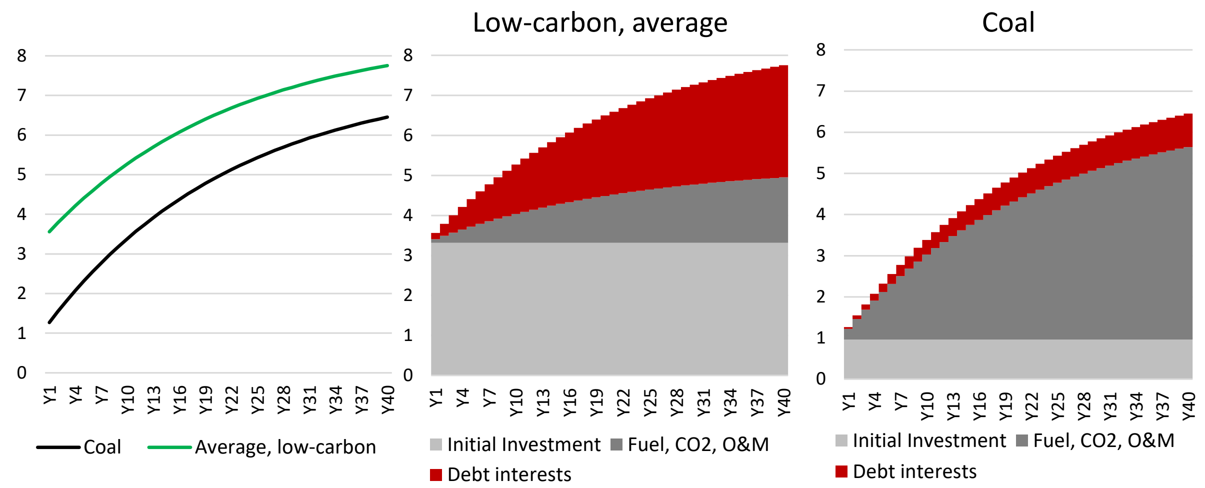



Fig. 10 – Total cumulated costs of a 40-year, 600MW-equivalent power plant in China, including fixed costs (investments to build the plant), and cumulated present value of operating costs (debt interests and cost of fuel, $CO_2$ and operations and maintenance costs), billion USD

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023)*

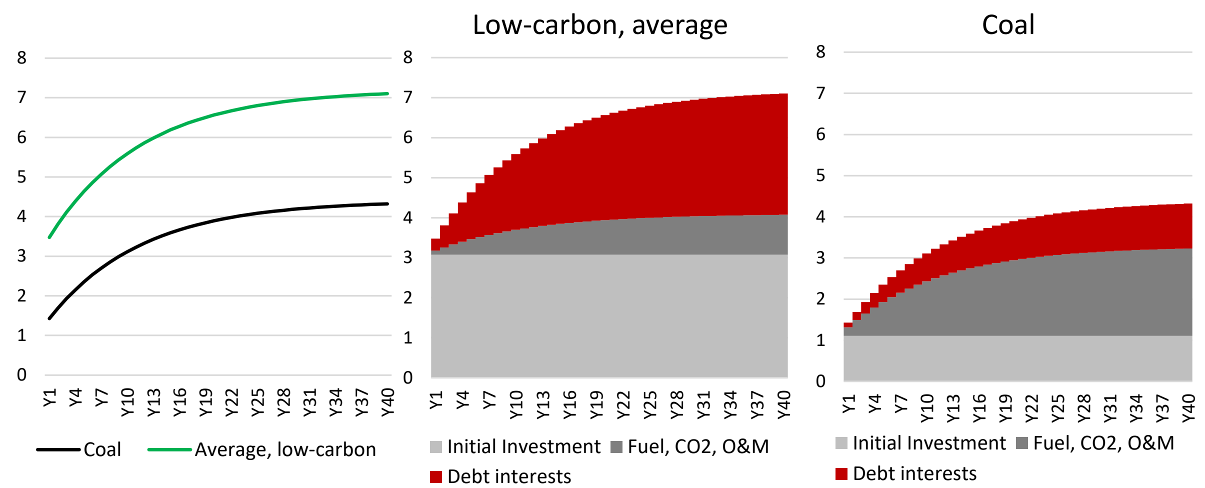



Fig. 11 – Total cumulated costs of a 40-year, 600MW-equivalent power plant in India, including fixed costs (investments to build the plant), and cumulated present value of operating costs (debt interests and cost of fuel, $CO_2$ and operations and maintenance costs), billion USD

*Sources: Compiled by authors with data from Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023)*

For brand new projects, the total cumulated costs of building a low-carbon plant would be, on average after 40 years, almost the same than for building a new coal plant in China. Upfront costs would be higher, but daily operational gains would mean that cumulated costs between coal and low-carbon would be close to breakeven after 40 years. For India, because debt cost is so high, investing in low-carbon plants remains much more costly than investing in a coal plant.

# 7. Supporting the transition through institutional set-ups

It is critical to develop solutions that help to overcome barriers preventing countries from retiring their coal-fired power plants and investing in renewable energy projects that require large, upfront capital. These barriers are particularly high in low- and middle-income countries that have difficulties mobilizing large amounts of capital for infrastructure projects and countries already in debt distress. In the following, we discuss three complementary approaches that would help to advance the transition away from coal in the Global South: (i) grants for low- and lower-middle-income countries to invest in renewable energy capacity; (ii) lowering financing costs for low-energy projects, and (iii) increasing operating costs for coal plants.

First, to support low- and lower-middle income countries – which have contributed next to nothing to global climate change and most of which are currently facing serious sovereign debt sustainability problems – in building low-carbon energy systems, rich countries should provide grants to cover the costs of decommissioning coal plants and replacing them with new low-carbon alternatives. Kraemer and Volz (2024) propose the establishment of a Finance Facility against Climate Change. Funds raised through the facility's bond issuance would be earmarked for emission reduction programs in poor countries, and the bonds would be backed by rich nations' commitments of future disbursements to cover debt service obligations of the bonds. This would allow the necessary frontloading of climate spending in poor countries, while minimizing the short-term impact on donor countries' budgets.

It should be noted, however, that most low- and lower-middle-income countries currently have no or only very small coal fleets. The unit-level dataset of coal power plants we use in this study, the Global Coal Plant Tracker, tracks plants generating 30MW and above. No country categorized as low-income by the World Bank is listed in this database, because their fleets are small. If we include the lower-middle-income category by the World Bank, we find that total upfront costs (stranded assets plus investment in new low-carbon plants) needed under our 1.5°C scenario would amount to $235 billion, excluding India. Providing grant support to low-income and lower-middle-income countries excluding India to decommission their coal fleets would make a big difference in helping them transition, but the amounts at stake are relatively modest both in terms of financing needs and emissions reduction. The cost of phasing out coal-fired power plants and replacing them with clean alternatives would be much heftier for India, however, amounting to $732 billion.

Second, given the high cost of capital problem facing most countries in the Global South, ways need to be found to lower the cost of capital and reduce the financing barriers facing the transition away from coal. An option would be to provide concessional finance, for instance through loans by MDBs, or through facilities that could be set up like the above-mentioned Finance Facility against Climate Change. If low-income and lower-middle-income countries excluding India would have to finance the total cost of coal-phase out and new infrastructures by themselves (amounting to $235 billion), and assuming an average WACC for those countries of 8.25% (the average for the rest of the world as calculated above), then they would be faced with an additional $204 billion of total debt financing costs. Lowering the WACC to, say, the one of China (4.75%), would reduce the debt financing costs for those countries to $173 billion. Upper-middle-income countries such as Indonesia or Malaysia would also benefit greatly from a reduction in their cost of capital.

Some initiatives are already on the table. For instance, the Energy Transition Mechanism, set up by the Asian Development Bank, is exploring ways to use concessional and commercial capital to accelerate the retirement of fossil fuel power plants and replacing them with clean energy alternative in some countries of Southeast and Central Asia (e.g. Nedopil et al., 2023). Moreover, France, Canada, the European Commission, Indonesia, Malaysia, Senegal, the United Kingdom, the United States, Vietnam, and several organizations announced during the COP28 the launch of the Coal Transition Accelerator. It notably encompasses a strategy to decrease the cost of capital for the investment in clean energies in developing and emerging markets, to be developed by the World Bank. It will propose options and solutions to unlock new sources of public and private financing for transitioning the existing unabated coal fleet.

Third, a higher price for carbon would make low-carbon alternatives more attractive in relative terms. For example, using the NZE scenario in our previous calculations of operating costs (for the year 2030) rather than the STEPS scenario changes the estimated costs of coal plant retirement significantly. The STEPS scenario we used in our calculations is much less ambitious in terms of carbon pricing than the NZE scenario. For instance, for China the price per ton of $CO_2$ is \$28 for 2030 in STEPS, against \$90 in NZE. Because operating coal plants would become much more expensive in the NZE scenario due to a high cost of carbon, net gains from fuel, $CO_2$ and operations and maintenance of switching to low carbon alternatives would increase by \$7 trillion globally (see the alternative NZE scenario in Figure 12).

If we combine these two hypothetical scenarios (WACC at 4.75% for all countries except the United States and the European Union, which have a lower WACC of 4.25%, and carbon pricing in line with the 2030 NZE scenario), the net costs of switching to low-carbon energy would be negative or close to zero in all regions, and globally negative by \$2.6 trillion (instead of a positive cost of \$4.7 trillion globally, see Figure 12). In other words, a lower cost of capital and a higher price of carbon would significantly strengthen the economic incentives for phasing out coal.

Developing voluntary carbon markets would be a way of bringing in private finance, but serious concerns have been raised regarding the integrity of such markets. Moreover, even though carbon pricing may be efficient in strengthening the business case for lower-emitting alternatives, it may lead to higher costs during the transition which can cause hardship for those at the base of the economic pyramid and social disruptions. Carbon pricing is also very difficult politically. At the same time, the carbon border adjustment mechanism introduced by the European Union (which will take effect in 2026) puts pressure also on developing and emerging economies to introduce and raise carbon prices. In the end, a pragmatic approach blending these different options will be needed.

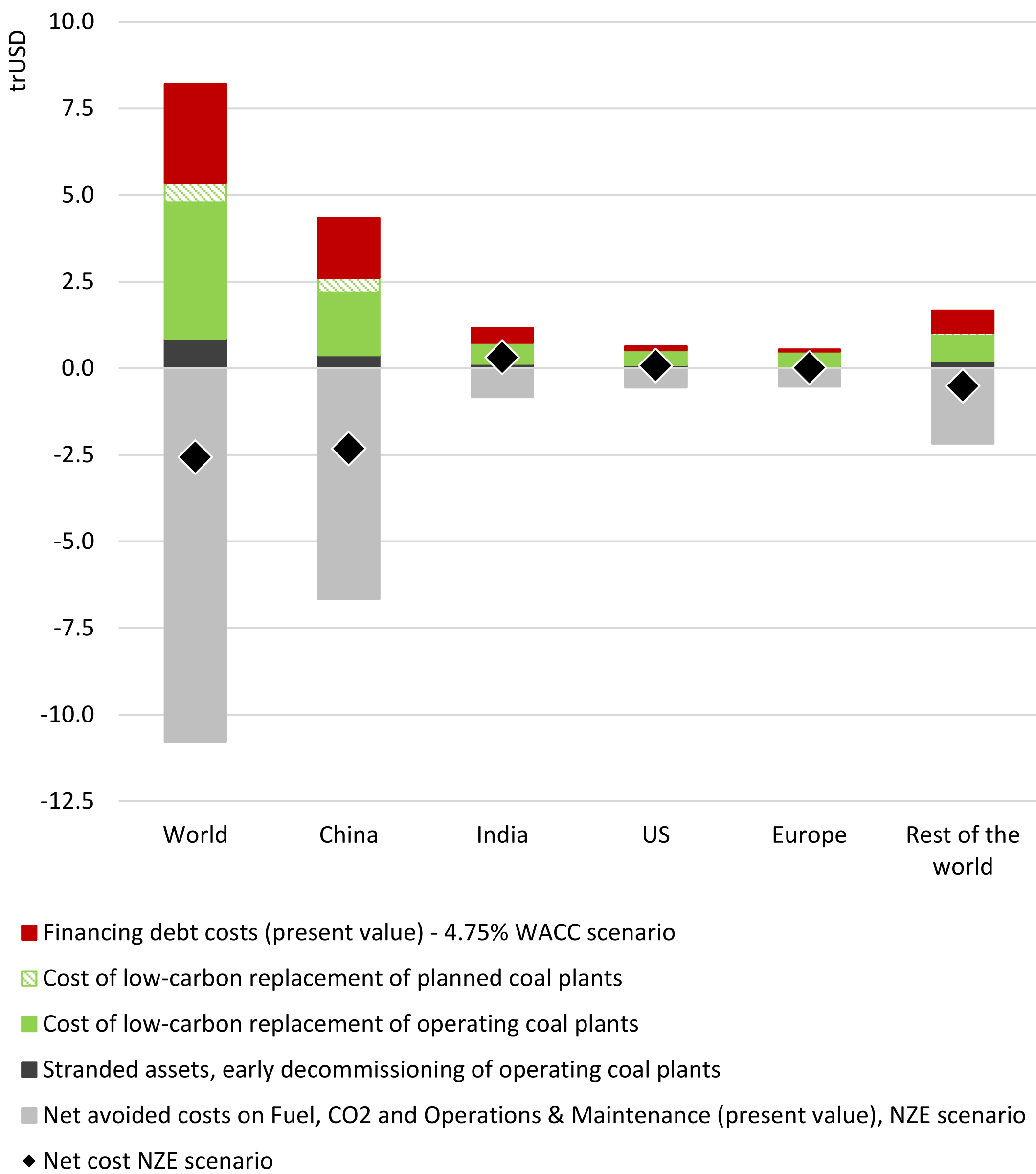



Fig. 12 – Total cumulated costs implied by the 1.5°C pathway, including fixed costs (stranded assets and investments to build low-carbon plants), and net operating costs (debt interests and difference in fuel, $CO_2$ and operations and maintenance costs, present value), supposing a fixed WACC at 4.75% for all countries (except the United States and the European Union) and a carbon pricing in line with the 2030 NZE scenario, trillion USD. Detailed results in Appendix table J.

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

# 8. Conclusion

A transition out of coal is essential to achieve the 1.5°C target by 2050. In this paper, we use the IEA NZE scenario of no coal-generated energy by 2040 to gauge the cost of the transition relating to a decommissioning of coal plants and a replacement of existing coal capacity with clean energy. Our approach is original as the cost is calculated using plant-level data, accounting for several layers of costs – stranded assets, investments in low-carbon energy infrastructure to replace decommissioned coal capacities, debt costs to finance upfront investment, and operational costs of coal plants –, which allows for more precise cost estimates of the transition away from coal than provided by previous analyses.

We find that stranded assets linked to an early decommissioning of coal plants to attain the IEA 1.5°C target amount to \$842 billion at a global scale. Replacing these coal plants with low-carbon technologies implies high one-off capital needs of \$4.5 trillion worldwide, among which \$2.2 trillion is in China alone.

Yet, one-off costs are not the only part of the equation. First, cumulated interests are a huge drag for infrastructure projects. We estimate that the present value of debt interests for replacing the (stranded) coal plants with a low-carbon alternative at \$3.1 trillion worldwide, which is as high as 60% of all one-off costs. The burden is particularly acute for countries with high costs of capital. Second, we highlight the role of operational costs. They are much higher for coal power plants than the ones of the low-carbon plants, notably because coal power plants need fuel to operate and emit $CO_2$ that would create costs in the presence of a carbon pricing regime (or a cross-border adjustment mechanism). We show that the avoided costs linked to replacing coal with low-carbon alternatives, accumulated throughout the lifetime of the coal plant, are substantial, at \$3.8 trillion globally. They offset close to half of all other costs at the global level. And by lowering financing costs to 4.75% and increasing carbon pricing in line with the IEA's NZE scenario, the total equation could become positive. That is, net long-term gains of the transition would be higher than long term costs.

We draw from our findings three main policy suggestions. First, some countries, in particular low-income and lower-middle-income countries, especially those already in debt distress, will need financial support – including through grants – to phase out coal and invest in a low-carbon transition. Second, lowering the cost of capital through concessional finance or guarantees will be critical to lower the very substantial debt financing cost that constitute a big barrier to investing in clean energy solutions. And third, the cost-benefit calculation can be improved in favor of renewables through a higher cost of carbon.

Under these policy conditions, the business case for phasing out coal and replacing it with low-carbon sources would be clearer. This urgently needed coal phase-out and the associated replacement would generate a pool of low-carbon projects. This brings two main questions for further research: (i) what type of actors will manage these projects? Are coal-fired power plant companies or current energy companies going to turn into renewable plant companies? Or are coal-fired power plants shutting down and other companies building out renewables? Also, (ii) to what extent can a decommissioned coal power plant can be repurposed for low-carbon sources electricity generation? The degree of substitutability from one to another is still to be explored (reuse for energy generation with energy storage; grid connection; land use; partial retention of workforce…).

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# Appendix

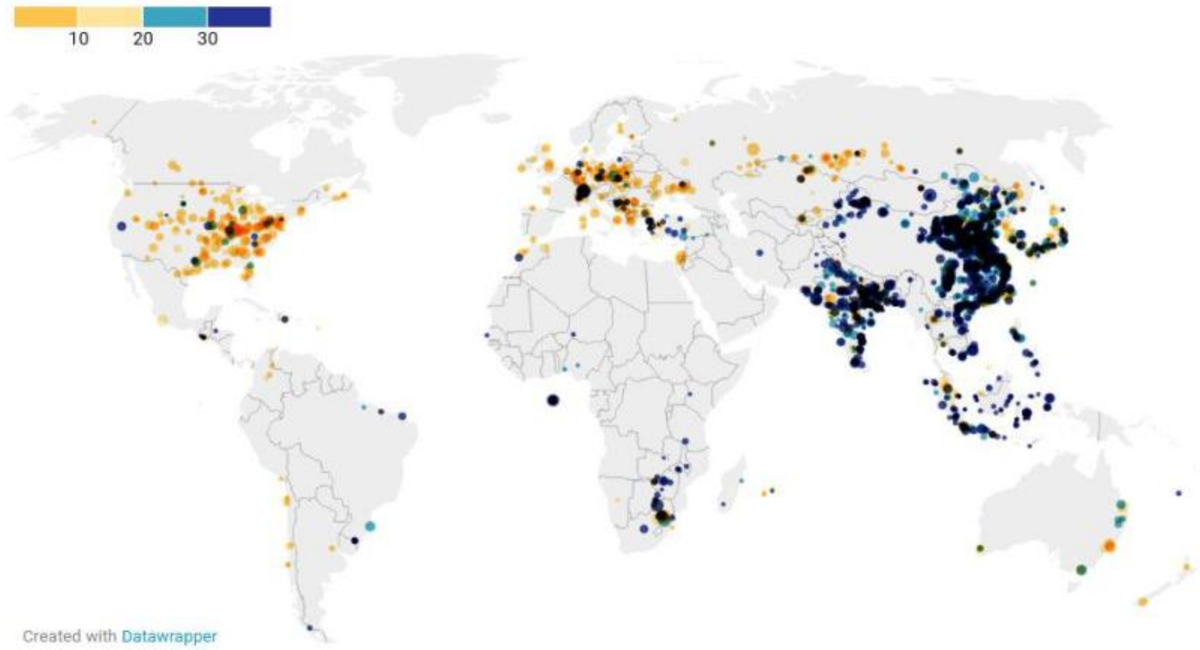



Fig. A – Coal plants: $CO_2$ emissions (size) and average remaining lifetime (color)
*Sources: Global Coal Plant Tracker (2023), authors*

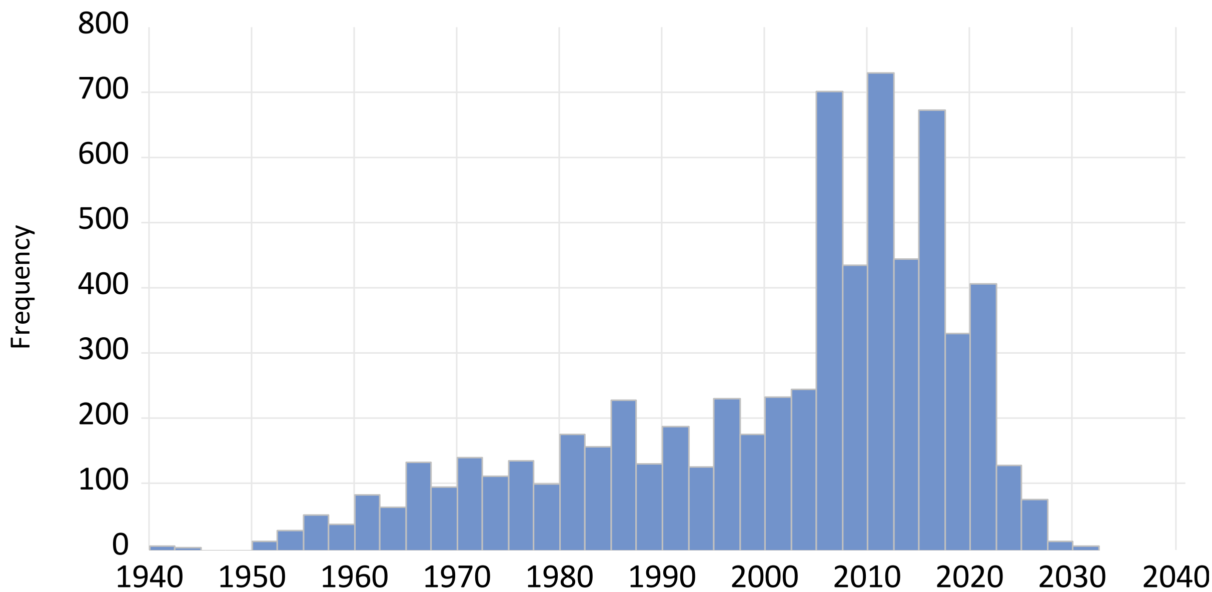



Fig. B – Distribution of coal units by construction date
*Sources: Global Coal Plant Tracker (2023), authors*

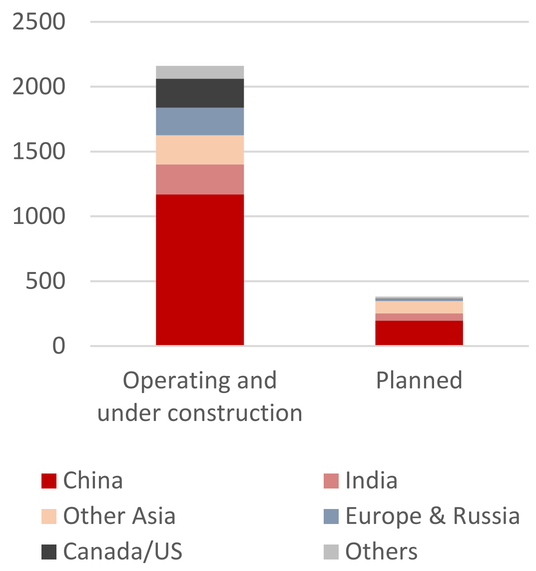



Fig. C – Capacity of coal units, by status (GW)

*Sources: Global Coal Plant Tracker (2023), authors*

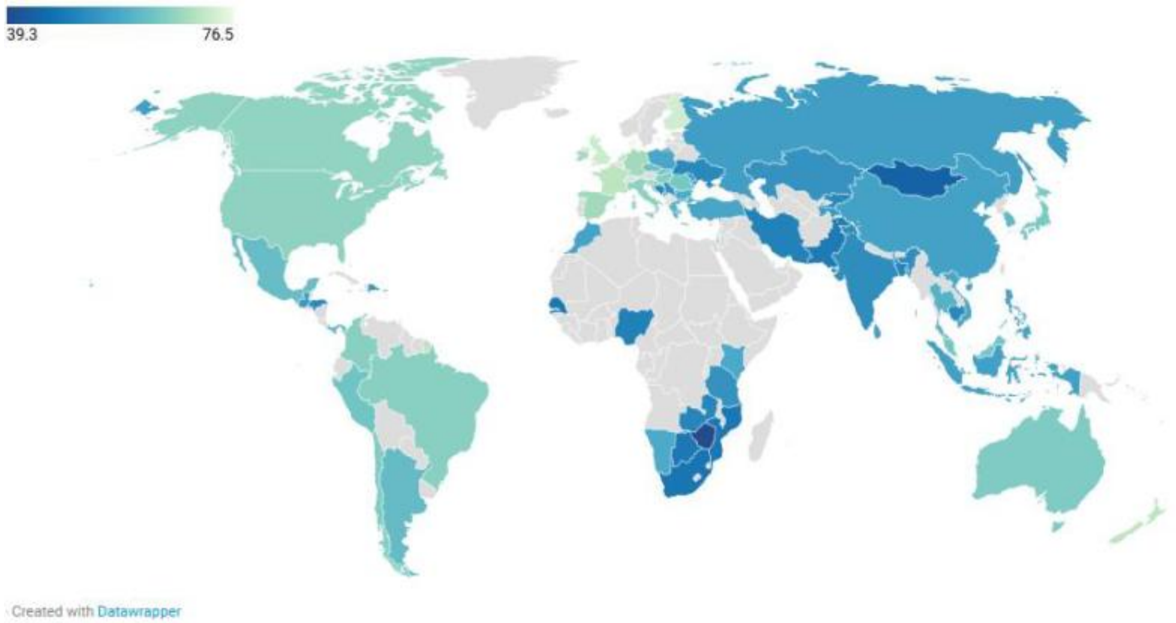



Fig. D – Energy Transition Index, country level

*Sources: World Economic Forum (2021), authors*

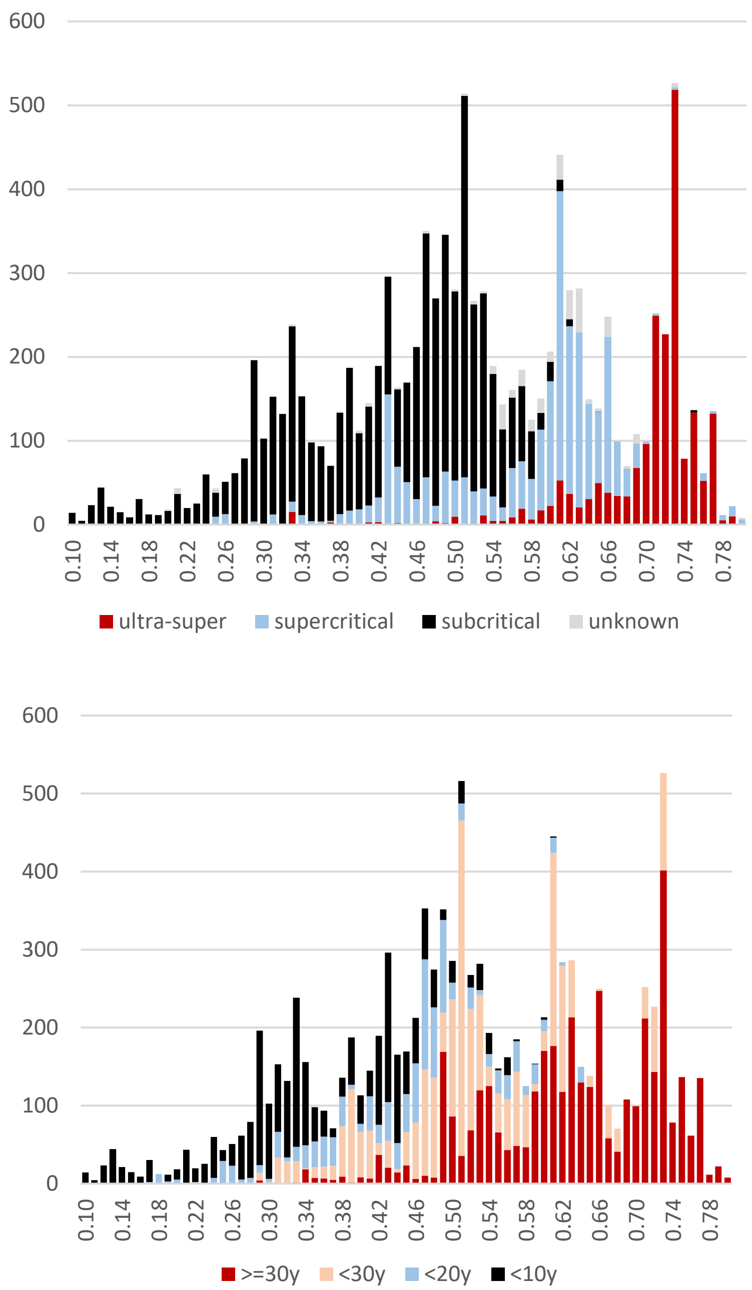



Fig. E – Transition readiness score of existing coal plants (horizontal axis) depending on their annual emissions (million tons, vertical axis) with colors highlighting combustion technology (top) and remaining lifetime (bottom)

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), authors*

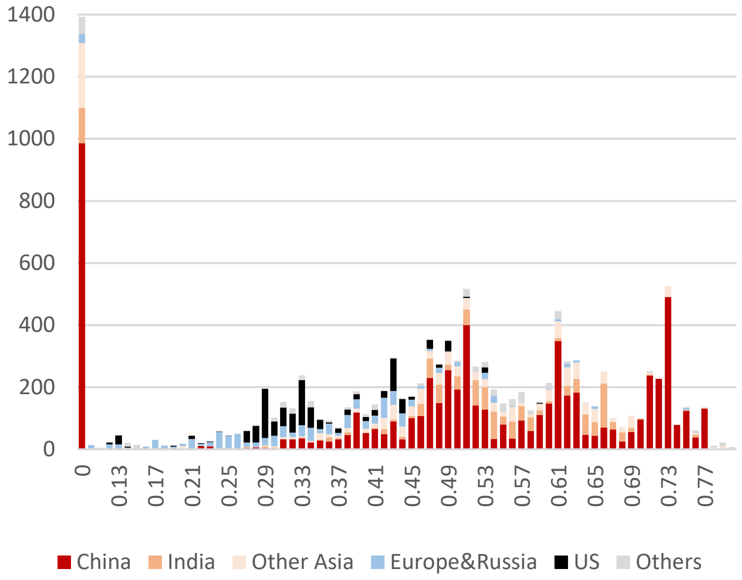



Fig. F – Transition readiness score of existing coal plants (horizontal axis) depending on their annual emissions (million tons, vertical axis) with colors highlighting combustion technology (top) and remaining lifetime (bottom), including planned plants which get a score of zero

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), authors*

Table A. World electricity sector (in GW)

| | 2010 | 2021 | 2022 | 2030 | 2035 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| STEPS scenario | | | | | | | |
| Total Capacity | 5 187 | 8 230 | 8 643 | 14 168 | 17 923 | 21 328 | 25 956 |
| Coal | 1 614 | 2200 | 2236 | 2 126 | 1956 | 1795 | 1363 |
| Coal with CCUS | | | | 1 | 6 | 11 | 13 |
| APS scenario (2°C) | | | | | | | |
| Total Capacity | 5187 | 8230 | 8643 | 15 285 | 20 332 | 25 195 | 32 100 |
| Coal | 1 614 | 2200 | 2236 | 2036 | 1749 | 1474 | 911 |
| Coal with CCUS | | | | 4 | 50 | 88 | 53 |
| NZE scenario (1,5°C) | | | | | | | |
| Total Capacity | 5187 | 8230 | 8643 | 16 180 | 23 067 | 29 354 | 36 956 |
| Coal | 1 614 | 2200 | 2236 | 1 457 | 910 | 548 | 242 |
| Coal with CCUS | | | | 36 | 95 | 131 | 153 |

*Source: IEA (2023)*

Table B – Capital costs and capacity factor in 2022

| | Coal | | Solar | | Wind onshore | | Wind offshore | | Nuclear | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Capital costs $/kW | Capacity factor | Capital costs $/kW | Capacity factor | Capital costs $/kW | Capacity factor | Capital costs $/kW | Capacity factor | Capital costs $/kW | Capacity factor |
| United States | 2,100 | 35 | 1120 | 21 | 1,220 | 42 | 4,060 | 42 | 5,000 | 90 |
| China | 800 | 50 | 720 | 13 | 1,100 | 26 | 2,820 | 32 | 2,800 | 80 |
| India | 1,200 | 65 | 640 | 20 | 1,120 | 26 | 3,060 | 33 | 2,800 | 80 |
| European Union | 2,000 | 30 | 990 | 14 | 1,750 | 29 | 3,420 | 50 | 6,600 | 70 |
| Rest of the World* | 1,525 | 45 | 868 | 17 | 1,298 | 31 | 3,340 | 39 | 4,300 | 80 |

* Non-weighted average of metrics from the United States, China, India and the European Union.

*Sources: IEA (2023)*

Fig. G – Capital costs and capacity factor in 2022

*Sources: IEA (2023)*

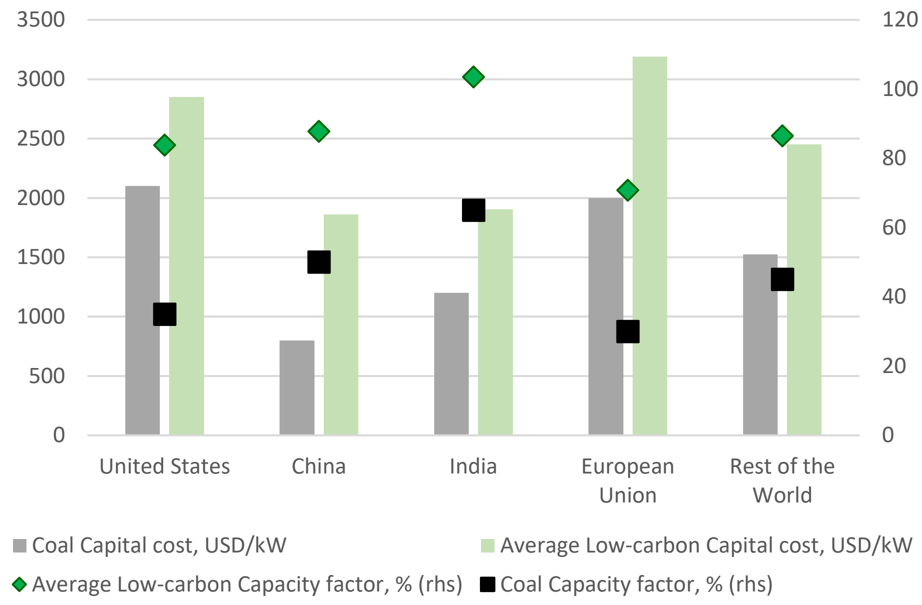



Table C – Stranded assets under the 1.5°C scenario, billion USD

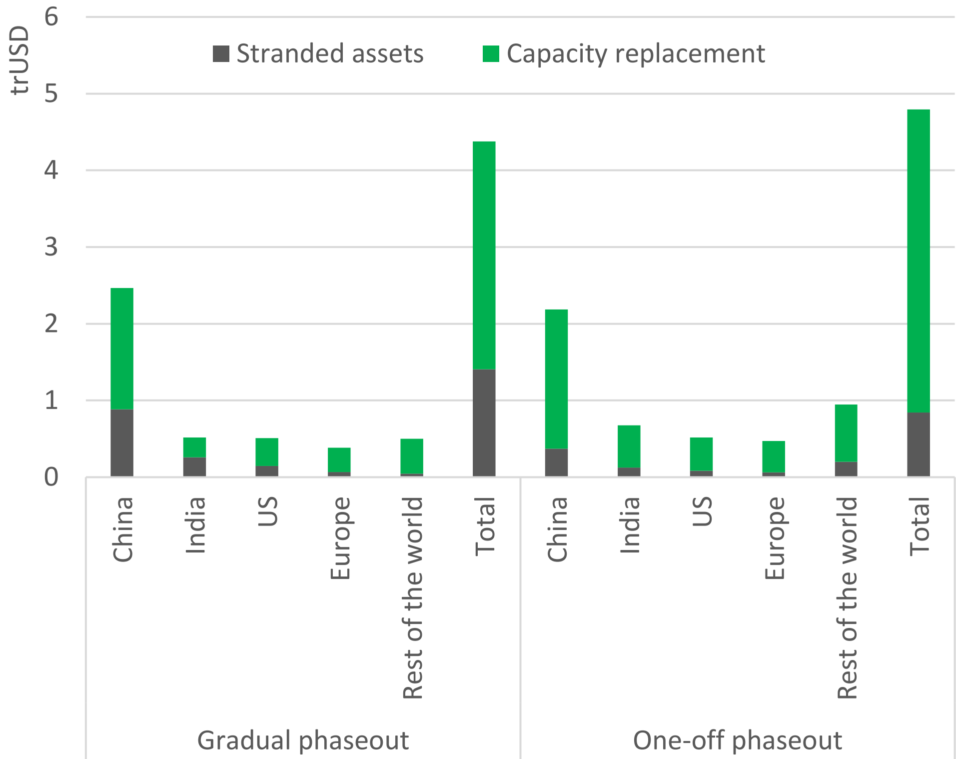
| | | Operating plants, 1.5°C threshold | Future plants (to become stranded if built) |
|---|---|---|---|
| Billion USD | World | 842 | 338 |
| | China | 373 | 200 |
| | India | 124 | 34 |
| | US | 82 | 0 |
| | Europe | 64 | 10 |
| | Rest of the world | 199 | 94 |

Table D – Total upfront costs implied by the 1.5°C pathway, billion USD

| | Stranded assets, early decommissioning of operating coal plants | Cost of low carbon, replacement of operating and planned coal plants | Total |
|---|---|---|---|
| World | 842 | 4,503 | 5,345 |
| China | 373 | 2,229 | 2,602 |
| India | 124 | 608 | 732 |
| US | 82 | 434 | 516 |
| Europe | 64 | 415 | 479 |
| Rest of the world | 199 | 817 | 1,016 |

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

Table E - Total stranded assets and upfront investments for our one-off scenario (scenario 3), and present value of stranded assets and upfront investments for a gradual phase-out plan compatible with the NZE scenario.




*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

Table F – Cost of debt of low-carbon plants

| | Mean of WACC (%) | Cost of low carbon, replacement of operating and planned coal plants, bn USD | Cost of investments per year, bn USD | Average remaining lifetime of coal plants to be decommissioned, years | Accumulated debt costs, present value, bn USD |
|---|---|---|---|---|---|
| World | 6.0* | 4,503 | 269 | 21.9 | 3,135 |
| China | 4.75 | 2,229 | 106 | 27.0 | 1,737 |
| India | 9.75 | 608 | 59 | 23.3 | 539 |
| United States | 4.25 | 434 | 18 | 8.1 | 119 |
| Europe | 4.25 | 415 | 18 | 8.6 | 88 |
| Rest of the World | 8.25* | 817 | 269 | 19.9 | 653 |

Note: We take the indicative weighted average cost of capital of utility-scale solar PV projects as estimated by the IEA (IEA, 2022a). Onshore wind is assumed by IEA to have the same WACC as utility-scale solar PV. We assume that all low-carbon energy have the same WACC. We discount the future flows by the WACC to get the present value.

*For the rest of the world, we take the arithmetic average of all 8 WACC estimates of the IEA report (IEA, 2022a)

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

Table G – Operational costs in 2022, in USD/MWh

| | Coal | | Solar | Wind onshore | Wind offshore | Nuclear | Coal minus low-carbon total operational costs |
|---|---|---|---|---|---|---|---|
| | Fuel, $CO_2$ and O&M by STEPS | Fuel, $CO_2$ and O&M by NZE (2030) | Fuel, $CO_2$ and O&M | Fuel, $CO_2$ and O&M | Fuel, $CO_2$ and O&M | Fuel, $CO_2$ and O&M | |
| United States | 30 | 155 | 10 | 10 | 35 | 30 | -3,772 |
| China | 50 | 120 | 10 | 10 | 25 | 25 | -2,763 |
| India | 40 | 105 | 5 | 15 | 25 | 30 | -208 |
| European Union | 125 | 185 | 10 | 20 | 15 | 35 | -151 |
| Rest of the World* | 61 | 141 | 9, | 14 | 25 | 30 | -127 |

* Non-weighted average of metrics from the United States, China, India and the European Union

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

Table H – CO2 prices for electricity production by region

| | 2030 | 2040 | 2050 |
|---|---|---|---|
| STEPS scenario | | | |
| Canada | 130 | 150 | 155 |
| Chile and Colombia | 13 | 21 | 29 |
| China | 28 | 43 | 53 |
| EU | 120 | 129 | 135 |
| Korea | 42 | 67 | 89 |
| NZE scenario | | | |
| Advanced Economies | 140 | 205 | 250 |
| EMDE w/ net zero pledges | 90 | 160 | 200 |
| EMDE without net zero pledges | 25 | 85 | 180 |
| Other EMDE | 15 | 35 | 55 |

*Source: IEA (2023)*

Table I - Cumulated costs implied by the 1.5°C pathway, billion USD

| | Stranded assets, early decommissioning of operating coal plants | Cost of low carbon, replacement of operating and planned coal plants, bn USD | Financing debt costs (present value) | Net costs on Fuel, $CO_2$ and Operations & Maintenance (present value) | **Net costs** |
|---|---|---|---|---|---|
| World | 842 | 4,503 | 3,135 | -3,772 | **4,708** |
| China | 373 | 2,229 | 1,737 | -2,763 | **1,576** |
| India | 124 | 608 | 539 | -208 | **1063** |
| US | 82 | 434 | 119 | -151 | **484** |
| Europe | 64 | 415 | 88 | -127 | **440** |
| Rest of the world | 199 | 817 | 653 | -524 | **1,145** |

*Sources: Global Coal Plant Tracker (2023), World Economic Forum (2021), IEA (2023), authors*

Table J – Cumulated costs implied by the 1.5°C pathway, with maximum WACC at 4.75%, and carbon pricing in line with the 2030 NZE scenario, billion USD

| | Stranded assets, early decommissioning of operating coal plants | Cost of low carbon, replacement of operating and planned coal plants, bn USD | Financing debt costs (present value, scenario: WACC at 4.75% max) | Net costs on Fuel, $CO_2$ and Operations & Maintenance (present value, scenario: carbon pricing in line with NZE scenario) | **Net costs** |
|---|---|---|---|---|---|
| World | 842 | 4,503 | 2865 | -10,776 | **-2,567** |
| China | 373 | 2,229 | 1737 | -6,663 | **-2,325** |
| India | 124 | 608 | 423 | -843 | **312** |
| US | 82 | 434 | 119 | -561 | **74** |
| Europe | 64 | 415 | 64 | -529 | **14** |
| Rest of the world | 199 | 817 | 522 | -2,179 | **-642** |

*Source: authors*