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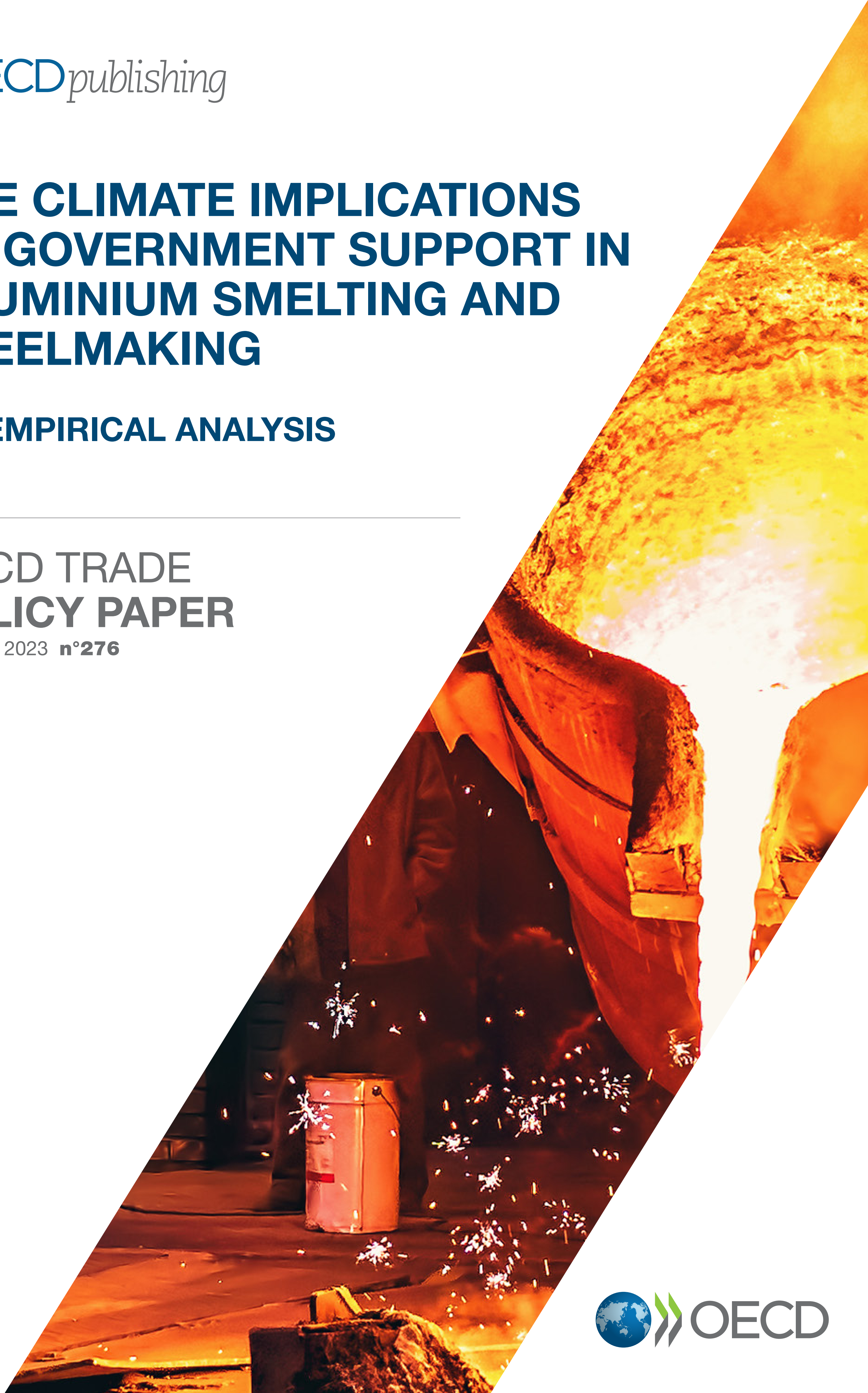
THE CLIMATE IMPLICATIONS OF GOVERNMENT SUPPORT IN ALUMINIUM SMELTING AND STEELMAKING

AN EMPIRICAL ANALYSIS



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The Climate Implications of Government Support in Aluminium Smelting and Steelmaking: An Empirical Analysis

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This report combines multiple novel datasets to provide evidence that government support has contributed to increased carbon emissions from aluminium and steelmaking activities through an increase in production output and by shifting production to more emission intensive plants. While improvements in technology have driven overall emissions downward, there is no evidence that government support in this sector has been targeted at, or has contributed to, developing techniques that improve environmental performance. Removing such support could therefore contribute to a cost-effective decarbonisation strategy. For example, removing government support to aluminium smelting and steel making worldwide would reduce carbon emissions by 75% more than the reduction observed in 2020 resulting from COVID-related restrictions. In addition, the removal of such support would free up scarce public resources for alternative uses.

Key words: Greenhouse gas emissions, emissions-intensive industries

JEL codes: Q5, L61, H24, H32.

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Table of Contents

Figures

Tables

Key messages

What is the problem?

- Large amounts of government support have been provided in the aluminium and steel industries, which are energy intensive activities.
- There is a need to understand whether such government support has contributed to increasing emissions of greenhouse gases from these sectors.

Why is it important?

- Government interventions that result in increased emissions would raise concerns in view of the climate emergency and recent pledges by many countries to reduce greenhouse gas (GHG) emissions to net zero by 2050.
- Efficient and coherent government measures require that policies across programme areas support, rather than undermine, one another.

What are the findings?

- This report combines multiple novel datasets to provide evidence which suggests that:
  - Government support has contributed to increased emissions from aluminium and steelmaking activities, mainly through an increase in production output – that is, a scale effect.
  - Government support has also contributed to shifting production to less efficient plants, which has further increased overall emissions in both sectors beyond that implied from increased production alone.
  - While technology improvements – i.e. reductions in plant emissions intensity – are found to have driven overall emissions downward, there is no evidence that government support in the sector was targeted at, or contributed to, the development of techniques enabling this enhanced environmental performance.
- Using simulations from an Inter-Country Input-Output (ICIO) model, this report also provides evidence that removing government support in aluminium and steelmaking activities would imply large effects beyond these two industries, decreasing global emissions by 1% while reducing global output by 0.3% (in aluminium and steel industries and downstream sectors).
- Removing government support for aluminium smelting and steelmaking activities might therefore be a cost-effective strategy for decarbonisation. For instance, for a comparable decline in output, the emissions reduction from removing government support in aluminium smelting and steelmaking activities is 75% larger than the emissions reduction observed in 2020 resulting from COVID-related restrictions. Additionally, removal of such government support frees up scarce public resources for alternative uses.
- Further analyses could better identify the design features of government support that generate the most adverse effects from a trade and environmental perspective. More research is also needed to better understand the distributional concerns that may arise from phasing out government support to energy-intensive industries.

1. Introduction

Concerns about fair competition in international markets have motivated longstanding OECD efforts to measure government support across a wide range of sectors, including agriculture (OECD, 2020[1]), fisheries (OECD, 2020[2]), and, more recently, key industrial sectors ((OECD, 2019[3]), (OECD, 2019[4]), (OECD, 2021[5])). Many subsidies and other forms of support used by governments can prevent firms from competing on a level playing field, allowing less innovative, efficient or competitive companies to crowd out other firms. When such practices play out in international markets, they can undermine trust in the global trading system and fuel anti-globalisation sentiment (OECD, 2017[6]).

Largely overlooked in this discussion to date are the consequences of government support for climate change.[1] Such consequences could go both ways. On the one hand, well-designed support measures might in some instances be necessary to contribute to the development and adoption of new climate technologies that are needed to reduce emissions in energy-intensive industries. On the other hand, government support might create economic and environmental inefficiencies. For instance, recent analysis shows that government support in the form of financing offered to companies on below market terms is associated with larger investments in fixed tangible assets (OECD, 2021[5]). Such practices may have contributed to allowing inefficient firms to produce industrial output above levels otherwise determined under market conditions, thereby generating excessive emissions. Which of these two effects prevails is an empirical question to which this study contributes by providing new results and insights.

The objective of this report is to estimate the effects of certain types of government support on GHG emissions, the main driver of climate change. This study focuses on aluminium smelting and steelmaking, which are highly energy-intensive industrial activities, to explore the climate implications of government support. There is robust evidence that firms in these sectors have received large amounts of government support (OECD, 2021[5]). Aluminium smelting and steelmaking also account for a large share of global carbon emissions – approximately 2% and 10% respectively (International Aluminium, 2021[7]; IEA, 2020[8]).

The empirical analysis in this report relies on two unique datasets[2] which enable new insights on the climate implications of government support. First, a firm-level dataset provides information on the amount of support that companies receive through grants, tax concessions, and below-market borrowings – i.e. debt financing on terms that are more favourable than those available on the market.[3] Second, a granular database on emissions and production at the plant level enables close tracking of the drivers of changes in sector-wide emissions, such as production moving from more to less efficient plants or improvements in production processes. Matching firms across these two datasets enables analysis of the relationship between the amount of government support received by firms and their environmental performance.

Results show that government support has contributed to increased emissions from aluminium and steelmaking activities, mainly through an increase in production output – that is, a scale effect. Without government support, production would have been lower, reducing potential excess capacities of these emissions-intensive products (OECD, 2021[5]). Consequently, all other things being equal, less greenhouse gases might have been emitted.

Government support has also contributed to shifting production from more to less efficient plants, with the effect of increasing overall emissions in both sectors. Results show that government support was provided relatively more emissions-intensive firms, which subsequently took over market shares at the expense of less emissions-intensive firms – thereby changing the composition of both industries. Without government

[1] One exception is government support for fossil fuels, which has been monitored and measured for many years. Discussions on the climate effects of fossil fuels support can be found in OECD (2021[70]), OECD (2018[72]), and OECD (2015[71]).

[2] See Annex A for a detailed description of data sources.

[3] This database was created to conduct the analysis in OECD (2021[5]). In that report, the authors have also estimated firm-level support of “below-market equity”, which arises when government shareholders tolerate lower returns than private investors. However, because these measures confer less direct benefits than other types of support, their estimations do not lend themselves to an econometric analysis that relies on comparisons across firms and over time. It is therefore decided to exclude this type of government support from the present analysis.

support therefore, a portion of steel and aluminium output would have been produced by more emissions-efficient firms, and less greenhouse gases would have been emitted.

Finally, while at the same time reductions in firms' emissions intensity are also found to be driving sector-wide emissions downward – that is, a technique effect[4] is playing out – this analysis shows that government support did not play a role in this enhanced environmental performance. In other words, while firms received government support, they did not use it to clean up production methods in aluminium and steelmaking activities. Such a result sheds new light on the theoretical argument that support measures for innovation in low-carbon technologies can be justified by the need to promote investments in low-carbon technologies. In practice, empirical data show that government support was not targeted at, and did not contribute to, the development of environmentally friendly technologies.

Next, simulations with an inter-country input-output (ICIO) model calibrated on the aforementioned econometric results are used to estimate the overall emissions reduction if current government support in aluminium and steelmaking activities were removed. Results show that, if no government support were provided to steelmaking and aluminium activities, global CO_2 emissions would decrease 1% while reducing global output 0.3%. Removing government support for aluminium smelting and steelmaking activities might therefore be a cost-effective strategy for decarbonisation. For instance, for a comparable decline in output, the emissions reduction from removing government support in aluminium smelting and steelmaking activities is 75% larger than the emissions reduction observed in 2020 resulting from COVID-related restrictions. Additionally, removal of such government support frees up scarce public resources by an amount of USD 0.71 bln for alternative uses – e.g. support workers and households adversely affected by output loss.

Existing government support to aluminium smelting and steelmaking activities therefore raises concerns in view of climate change and recent pledges by many countries to reduce greenhouse gas (GHG) emissions to net zero by 2050. Current climate policies and actions are putting the world on track for an increase of 2.7°C, well above the 1.5°C target of the Paris Agreement (Climate Action Tracker, 2021[9]); (IPCC, 2021[10])). In a time of fiscal constraints, governments should work to ensure limited resources are effectively targeted at achieving key policy objectives, such as economic recovery and emissions reduction. Instead, existing government support across countries appears to be undermining the achievement of emissions reductions.

This report makes several contributions to the debate on government support. First, it helps to better understand the role that government support plays in sustaining production that both creates trade distortions and hampers climate change mitigation efforts. While the trade-distorting nature of subsidies has long been discussed – see for instance OECD (1998[11]) and WTO (2006[12]) for earlier contributions; OECD (2017[6]) and Evenett and Fritz (2021[13]) for more recent ones – the potential environmental consequences have been overlooked so far. Yet international trade rules and policies are directly and deeply relevant to environmental performance and the achievement of global environmental objectives (Deere-Birkbeck, 2019[14]).

Second, by identifying and documenting the climate implications of government support, this report can also help inform the design of more coherent and comprehensive climate policy packages that may also serve to advance international negotiations on both trade rules and climate policies. This is particularly important in view of the recent Glasgow Climate Pact, whereby countries pledged to "accelerate the development, deployment and dissemination of technologies, and the adoption of policies, to transition towards low-emission energy systems" (UNFCCC, 2021[15]). This goal can only be achieved if trade and climate policies are mutually supportive.

The rest of this report is organised as follows. The next section provides relevant background on the aluminium and steelmaking industries. Section 3 develops a conceptual framework to explore how government support can have both negative and positive effects on emissions in industrial sectors. Section 4 presents and discusses the results of the empirical analysis.

[4] Throughout this report, reductions in firms' emissions intensities, as measured by the emissions-to-production ratio, are considered to be outcomes of (environmentally friendly) technological innovations. For instance, they can result from using a different mix of inputs or relying on new and more efficient equipment. Such a measure for the effects of technological improvements, widely adopted in the environmental economics literature, is called the technique effect. See Levinson (2009[47]) for a discussion.

2. An environmental perspective on aluminium smelting and steelmaking

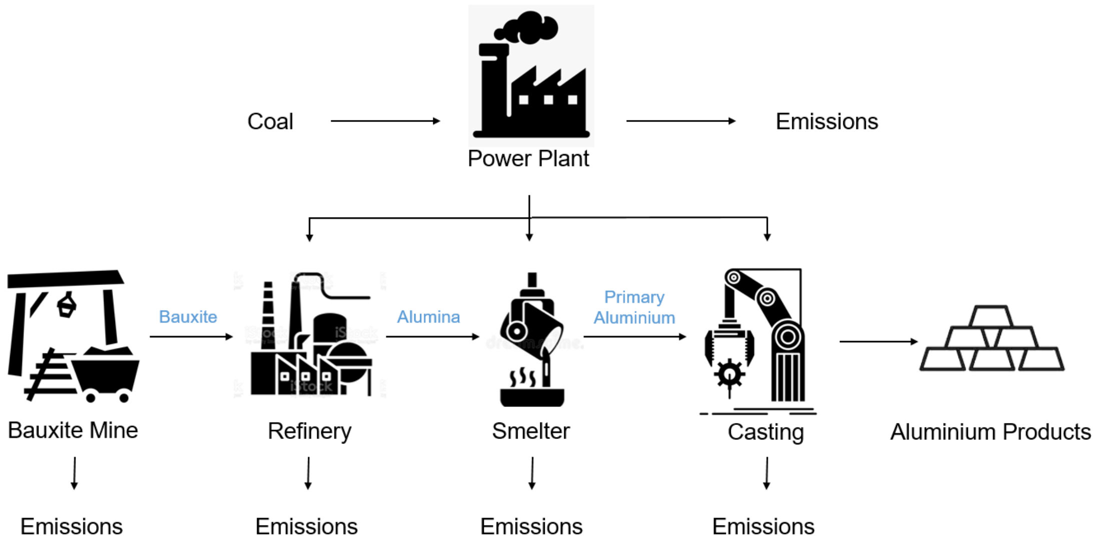
Aluminium and steel play a fundamental role in modern societies. While it was uncommon and very costly to produce in the 19th century, aluminium has now become the second most used metal after iron, with approximately 1.39 billion tonnes produced since 1900 (U.S. Geological Survey, 2021[16]). Today, aluminium is used in food packaging, windows frames, components for aircrafts and vehicles, and construction. Likewise, an astonishing 45 billion tonnes of steel products were produced between 1900 and 2015 (Wang et al., 2021[17]), which have been used in buildings, infrastructure (e.g. bridges, tunnels, rail tracks) and transport networks (e.g. train stations, ports, and airports) (Worldsteel, 2021[18]).

Global aluminium and steel production have a large carbon footprint because both are currently produced via emissions-intensive production methods. This section provides background on the manufacturing processes and on how emissions reductions can be achieved in these sectors.

2.1. Smelting aluminium is one of the most energy-intensive industrial activities

The primary aluminium value chain involves several production stages (Figure 1). Put simply, after bauxite ore is refined into alumina, the latter is converted into primary aluminium through an industrial process called smelting. Finally, primary aluminium is cast into moulds to produce aluminium-alloy parts.

Figure 1. Emissions arising from the aluminium supply chain



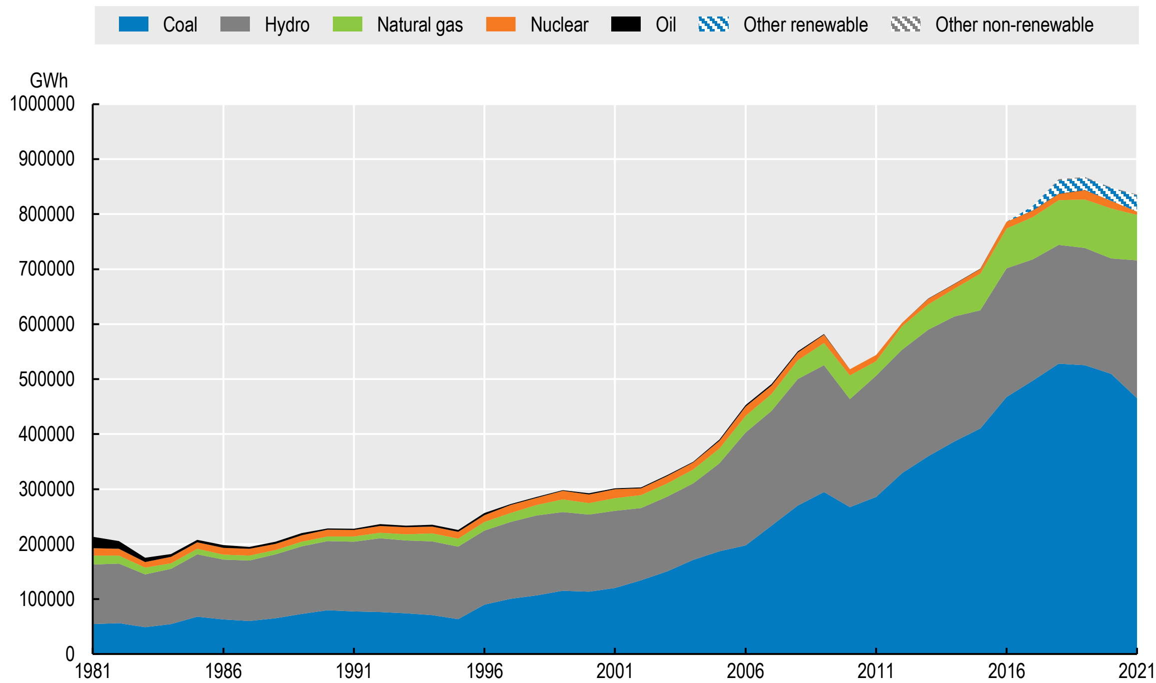
Source: Tan and Khoo (2005[19]).

Smelting aims to extract aluminium from alumina and is a carbon-intensive process for two reasons. First, alumina is dissolved into aluminium and oxygen via an intense electric current that is passed through a bath of electrolyte – i.e. a liquid that contains cryolite, a solvent, and alumina. This process – called electrolysis – requires enormous amounts of electricity. Second, the electric current is sent through anodes that are typically made of carbon. As the aluminium is being dissolved, the anodes are degraded, and CO_2 is released. In 2019, emissions associated with power used in electrolysis and anode consumption accounted for 670.2 million tonnes of CO_2 (tCO_2) and 92.6 million tCO_2 respectively – i.e. 1.82% and 0.25% of global CO_2 emissions (International Aluminium, 2021[7]).[5]

[5] This is considering that global CO_2 emissions (excluding land use change) amounted to 36.71 Gt. See https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

While reducing emissions in the aluminium industry is challenging, solutions exist (WEF, 2020[20]; International Aluminium, 2021[21]; IEA, 2021[22]). First and foremost, electricity used in the smelting process needs to be decarbonised. However, the industry has dramatically increased its reliance on coal as a power source – from 25% of power production in 1980 to 60% in 2020 (Figure 2). Switching to low carbon sources of electricity is nonetheless largely within control of companies, as 55% of power consumed by the industry globally is self-generated rather than purchased from the grid (IEA, 2021[23]). In addition, producing recycled aluminium – i.e. from scrap or end-of-life aluminium – requires just 5% of the energy needed to produce primary aluminium (WEF, 2020[20]). Therefore, increasing the circularity of aluminium production – through improved collection, sorting and recycling processes for secondary materials – is essential to reduce emissions. It is estimated that a fully circular system with maximised recycling rates and without any (collection and process) losses would decrease sector-wide emissions by 20% compared to a business-as-usual scenario (International Aluminium, 2021[21]). Additionally, in the heat- and steam-based thermal processes needed to produce alumina, emissions can be reduced through electrification with renewables, fuel switching to green hydrogen, or carbon capture, utilisation, and storage (CCUS) technologies. Finally, anodes made with carbon could be replaced by inert anodes made from alternative materials that release oxygen rather than carbon emissions. This technology is currently being developed and could be ready for commercialisation as soon as 2024 (IEA, 2021[23]).

Figure 2. Aluminium firms' electricity mix since 1980

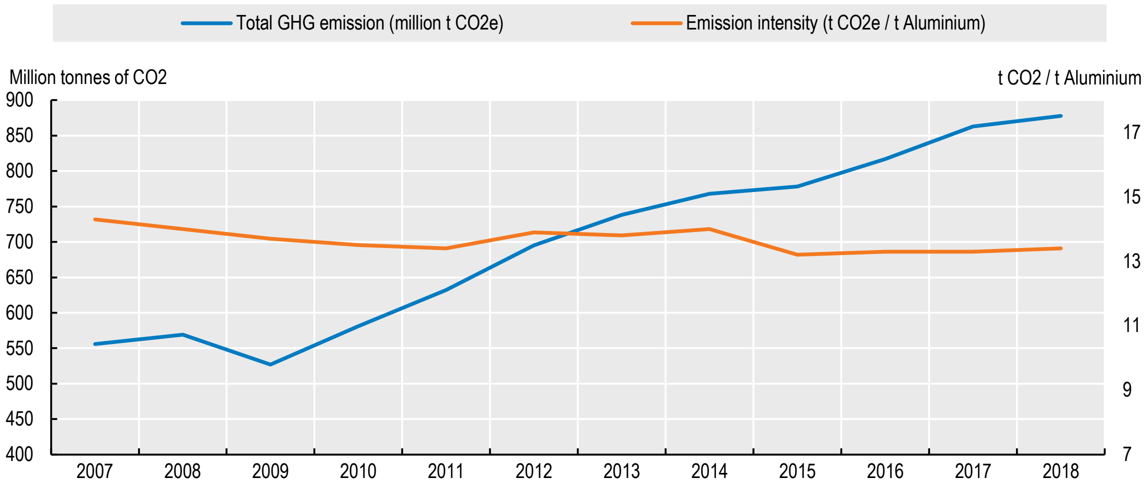


Source: International Aluminium Institute (IAI), https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/.

However, the sector is currently not on track to achieve net zero emissions by 2050 (IEA, 2021[23]). Plants that self-generate fossil-based electricity for their smelters do not always have the opportunity to switch to renewables as they might be located in areas with limited or unreliable grid-power alternatives (WEF, 2020[20]). For such production units, CCUS technologies might offer a pathway to reduce emissions (at least in the short run). Other producers may have better opportunities in ramping up their scrap recycling capacity. All primary aluminium producers will have to reduce their direct – i.e. non-electricity related – emissions through new technologies such as inert anodes and green hydrogen in order to achieve net zero emissions (International Aluminium, 2021[21]). As discussed in the next section, such fundamental technological changes are unlikely to take place without government intervention.

Aluminium smelting accounted for approximately 2% of global carbon emissions in 2020, and for about 1.6% of global industrial energy consumption in 2020 (International Aluminium, 2021[7]) (IEA, 2022[24])). Between 2007 and 2018, (direct and indirect) emissions from aluminium smelting increased by 58%, up to 878 million tCO_2e (International Aluminium, 2021[7]). The carbon intensity of aluminium smelting has slightly decreased over the last 15 years, reflecting the (slow) introduction of cleaner power sources for electrolysis.

Figure 3. Emissions from aluminium smelting activities, 2007-2018



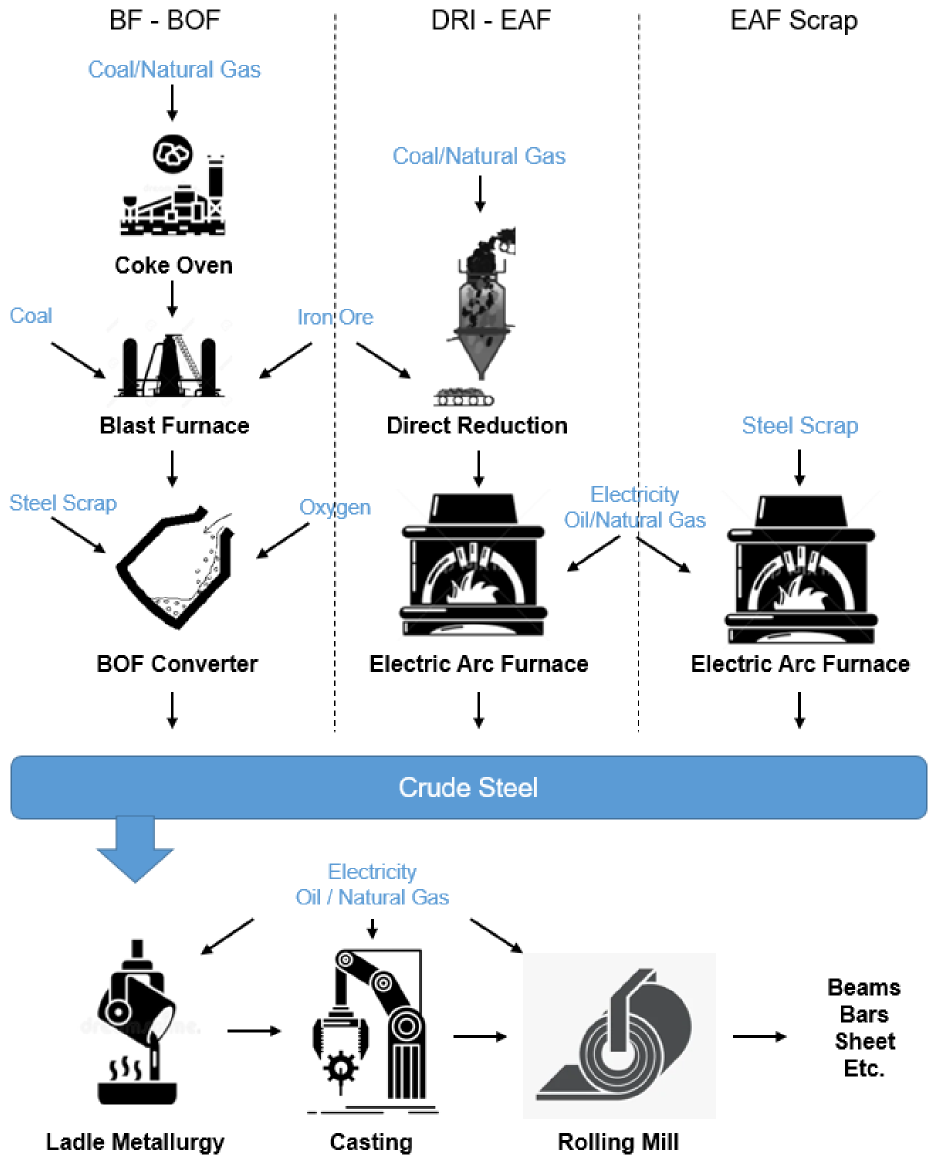
Source: International Aluminium Institute (IAI), https://international-aluminium.org/statistics/primary-aluminium-production/.

2.2. Steel production accounts for a large share of global carbon emissions

There are three main “routes” to produce steel (Figure 4). First, liquid iron can be produced in a blast furnace using coke (made by heating coal) and is then transformed into steel in a basic oxygen furnace (BOF) – also called a converter – with typically 15-20% scrap (IEA, 2020[8]). This commonly known as the BF-BOF route. Second, steel scrap can be re-melted in an electric arc furnace (EAF), which is known as the EAF-scrap route. Third, direct reduced iron (DRI) can be produced, most commonly using natural gas, before melting it (often with scrap) in an EAF. This commonly known as the DRI-EAF route. Each route has a different emissions intensity. Due to its reliance on coal, the BF-BOF route – which accounted for 71% of production in 2019 – emits around 2.2 tCO_2 per tonne of crude steel, against 1.4 tCO_2 for the (natural gas-based) DRI-EAF route and 0.3 tCO_2 for the EAF-scrap route (IEA, 2020[25]).[6]

[6] These numbers include direct and indirect emissions. Direct emissions arise from fuel combustion in the iron and steel sector. Indirect emissions are from electricity generation and imported heat. See IEA (2020[24]) for more details.

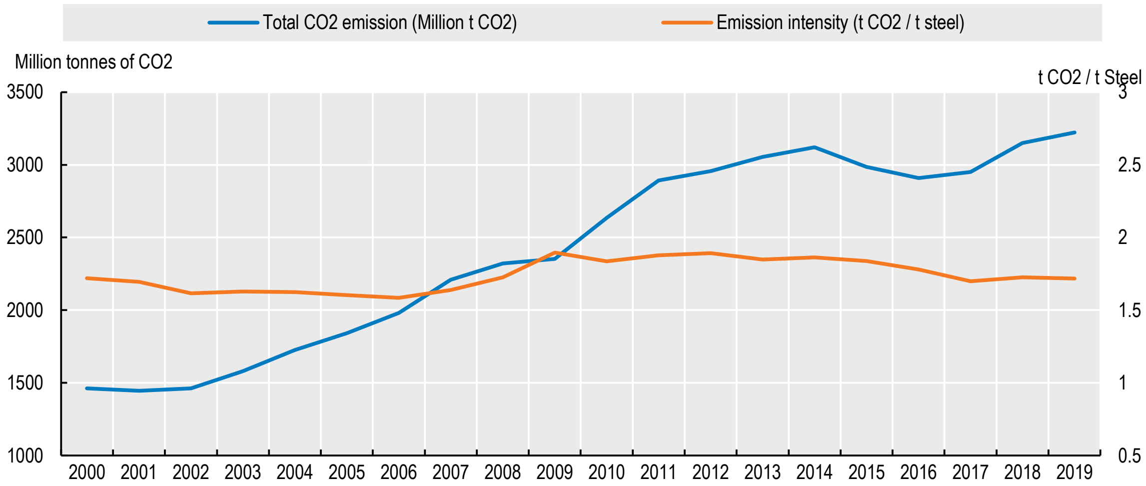
Figure 4. Emissions arising from the steel supply chain



Source: Worldsteel Association (https://www.worldsteel.org/about-steel/steelmaking.html) and Johansson (2014[25]).

In 2019, steelmaking accounted for 20% of global industrial energy use and 8% of total final energy use (IEA, 2020[25]). Between 2000 and 2019, (direct and indirect) emissions from steelmaking increased by 120% (Figure 5). In 2019, they amounted to 3.7 billion tCO_2, accounting for 10% of global carbon emissions from the energy sector (IEA, 2020[25]). At the global level, the carbon intensity of steelmaking was falling significantly until 1995 – due to energy efficiency improvements in the blast furnace and other technological advances – but has subsequently stagnated (Wang et al., 2021[17]) (IEA, 2020[8])). While further improvements to existing technologies are important to start a low-carbon transition, they alone are unlikely to drastically reduce emissions in line with a 1.5°C target. In addition, breakthrough technologies – including production methods utilising CCUS, hydrogen-based solutions, direct electrification (i.e. electrolysis) solutions, and bioenergy-based options – are needed (Wang et al., 2021[17]) (IEA, 2020[25]) (IEA, 2020[8])).

Figure 5. Emissions arising from steelmaking activities, 2000-2019



Source: International Energy Agency (IEA) and Worldsteel Association.

3. Conceptual framework: Is government support an issue for emissions reduction?

This section develops a conceptual framework to explore how government support can have both negative and positive effects on emissions in industrial sectors.

3.1. Firms face incentives to decrease emissions

Ambitious climate policies create strong incentives for firms to reduce emissions. A large number of studies have provided evidence that firms respond to environmental regulation with more environmental innovations, which drive efficiency improvements (especially energy efficiency) that translate into reduced production costs and higher profits (Dechezleprêtre and Sato, 2017[27]) (Popp, 2019[28]) (Dechezleprêtre and Kruse, 2018[29]). Such mechanisms – known as the Porter hypothesis[7] (Porter and Linde, 1995[30]) – implies that environmental policies do not significantly harm firms' competitiveness and that firms can improve their emissions performance without jeopardizing their economic prospects.

In the current context where climate policies are becoming more ambitious, financial markets also create incentives for firms to reduce the environmental impact of their activities. Improved environmental risk management signals a less risky investment over the longer term that should be rewarded through lower interest rates (i.e. lower cost of debt) and higher stock prices for a given expected return (i.e. lower cost of equity) (Sharfman and Fernando, 2008[31]).[8] Empirical studies have shown that investors penalise high-emitting firms. For instance, from a sample of US firms, estimates show that investors would discount between USD 79 and USD 212 in firms' value – i.e. their market capitalisation – for each tonne of

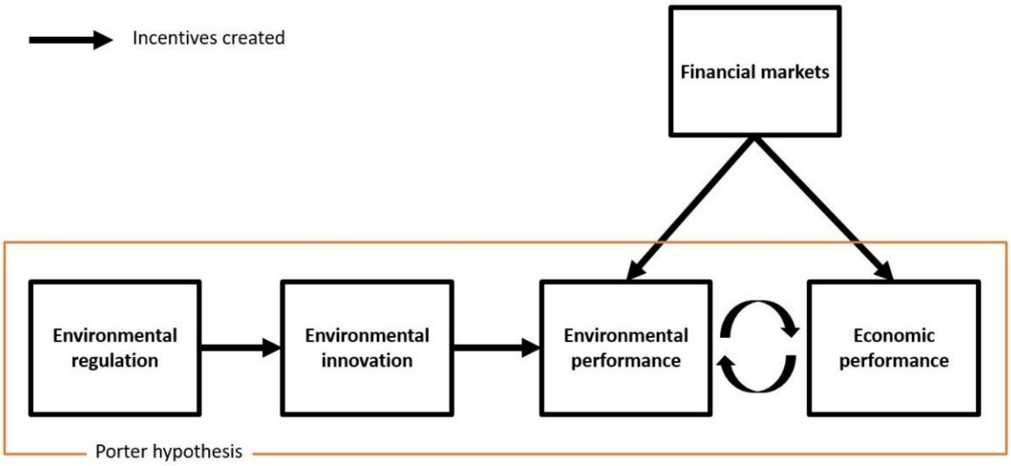
[7] The "weak" version of the Porter hypothesis predicts that environmental regulation will spur innovation to reduce costs associated with (the newly introduced) environmental regulation. The "strong" version of the Porter hypothesis predicts that such innovation will more than offset regulatory costs. That is, environmental regulation can lead to an increase in firm competitiveness (Ambec et al., 2013[58]).

[8] More recently, company boards have been facing growing pressure from shareholders seeking more ambitious environmental, social, and governance (ESG) objectives. Such new shareholder activism has taken place even in major oil producers like ExxonMobil and Shell. For instance, see Temple-West (2021[64]) and Aliaj et al. (2021[65]).

greenhouse gas emissions (Griffin, Lont and Sun, 2017[32]) (Matsumura, Prakash and Vera-Muñoz, 2013[33]) .[9, 10]

Thus, both climate policies and financial markets can create incentives to improve emissions efficiency: the former put a price – explicit or implicit – on emissions, while the latter offer lower capital costs. Such interactions are summarised in Figure 6.

Figure 6. Financial markets can create strong incentives for economic and environmental performance



Source: Authors' elaboration.

3.2. Government support and the low-carbon transition

Support measures for innovation in low-carbon technologies can be justified because climate change is an issue that originates in two market failures. First, GHG emissions generate negative environmental externalities, which, if not internalised, result in a higher-than-socially-desired levels[11] of climate change. Second, climate innovations generate positive "knowledge spillover" externalities that are not fully captured by inventors, which results in a lower-than-socially-desired level of low-carbon technology. That is, firms investing in technologies incur the costs of their innovations (if they cannot all receive intellectual property protection) while other firms can benefit from them. As a result, firms have weaker incentives to increase their investment in technology. These issues can be addressed by two distinct sets of policy instruments: one for increasing market incentives to reduce emissions – e.g. through carbon pricing – and one explicitly designed to foster innovation in low-carbon technologies (Jaffe, Newell and Stavins, 2005[34]).[12]

Furthermore, without government support, developing new technologies when they are substitutes for existing ones can be hampered by path dependency effects. Acemoglu et al. (2012[34]) show that, in the absence of government intervention, research efforts are directed towards old and dirty technologies rather

[9] See also Bui, Moses and Houque (2019[55]) for empirical evidence based on a multi-country sample.

[10] While investors are increasingly concerned by firms' ability to minimise climate-related risks, evidence to date shows that companies' self-reported assessments of these risks are riddled with blind spots, thereby suggesting that companies may not be accurately capturing the magnitude and implications of climate change risks in disclosures to investors (Sullivan and Gouldson, 2012[57]) (Goldstein et al., 2018[56])).

[11] A situation also called the "tragedy of the commons".

[12] In theory, the first-best policy to address climate change would be a single instrument that would set a (very) high price on GHG emissions. However, for political economy reasons, such a single instrument is often not appealing to policy makers who prefer to rely on a combination of (not-too-high) carbon pricing instruments and technology policies (Jaffe, Newell and Stavins, 2005[34]).

than new and clean alternatives. This is because improvements in one type of technology make future advances in the same technology more profitable, thereby spurring researchers to build on previous innovations rather than developing new technologies. In such a context, recent economic modelling also suggests that an optimal government policy relies on a mix of R&D subsidies and carbon taxes (Acemoglu et al., 2016[36]).

Finally, capital market failures can be particularly acute for climate technologies. Uncertainties around the future costs of climate change and the trajectories of climate and energy policies can make technological solutions to climate change a risky investment area, with private investors, when found, demanding very high premiums (Jaffe, Newell and Stavins, 2005[34]). For instance, certain technologies needed for the decarbonisation of industrial activities such as aluminium and steel production are still prototypes and characterised by high capital and operating expenses, which requires government support for long-term R&D until commercialisation and deployment (IEA, 2021[22]) (IEA, 2020[25]) (IEA, 2021[23]).[13]

However, government support can also be an obstacle to a low-carbon transition. In particular, incentives for high economic and environmental performance can be muted by the soft budget constraint phenomenon ((Dewatripont and Maskin, 1995[37]) (Kornai, Maskin and Roland, 2003[38])). The soft budget constraint phenomenon arises when a government is willing to cover the deficit of a company and is unable to credibly commit to ceasing support to inefficient companies (Dewatripont and Maskin, 1995[37]). A government might find itself trapped into continuing to finance inefficient firms because the social costs[14] of ceasing support would be too large, thereby allowing the firm to survive. In addition, the firm's management, knowing that government will provide support in case of financial deficits, is not incentivised to maximise profits, to innovate and develop new technologies and products (Kornai, Maskin and Roland, 2003[38]), and can even adopt rent-seeking behaviour through lobbying practices (Rodrik, 2014[39]).

The environmental implications of the soft budget constraint phenomenon are clear. Inefficient firms – which are likely to have poor emissions performances since economic efficiency and emissions efficiency are correlated (Dechezleprêtre and Kruse, 2018[29]) – are allowed to expand more, or to survive longer, than under market conditions. In emissions-intensive industries like steelmaking or aluminium, they would therefore contribute to increasing overall GHG emissions beyond what would be the case in the absence of support. In addition, such firms face very weak incentives for improving their environmental performance as support from the government helps to cover the costs of poor environmental management. For example, firms may expect that the government will intervene in case of an increase in (global) energy prices that would affect their profitability through higher energy costs.[15]

Various forms of firm-level government support used extensively in several countries – including direct transfers, tax concessions, and favourable credit conditions – have been identified as leading to softening budget constraints.[16] More recently, OECD (2021[5]) provides evidence that significant government support has been provided through the financial system[17] to firms in emissions-intensive industries such as

[13] In fact, developing long-term climate solutions entails investing in a large portfolio of technologies, some of which may fail to be profitable. Private investors will underinvest in such portfolios as their evaluation is based on financial performance – which may bring negative returns – rather than overall social benefits (Rodrik, 2014[39]).

[14] The expression "social costs" here refers to a welfare loss that includes the economic costs but also the social disruptions – e.g. massive layoffs – that would result from the firm's collapse.

[15] In 2021, the *OECD Inventory of Support Measures for Fossil Fuels* reported that USD 56 billion were provided to industries. This amount has recently increased because of high energy prices. Such support can sometimes be justified to shield firms that are essentially competitive but suffering from short-term costs. However, a policy challenge is to distinguish such firms from ones that would have failed anyway. Work in the Trade Committee also explores the issue of below-market energy inputs benefitting industrial producers (OECD, 2023[73]).

[16] See Kornai, Maskin and Roland (Kornai, Maskin and Roland, 2003[38]) for a literature review; Cull and Xu (Cull and Xu, 2000[59]) on China and Schaffer (Schaffer, 1998[60]) on post-socialist economies for early studies. See OECD (OECD, 2021[5]) for more recent evidence on a global scale.

[17] In the theoretical literature, the credit system plays a central role in softening budget constraints. Dewatripont and Maskin (1995[37]) show that a decentralised credit system – i.e. with no central government intervention – could serve as a mechanism to harden budget constraints. Essentially, this is because decentralised (private) banks are more risk averse and face stricter liquidity constraints than governments (or state-owned banks with ties to the government).

aluminium, steelmaking, cement, glass and ceramics, and chemicals. That report sheds light on government practices of financing offered to firms in these sectors through loans with preferential conditions or equity injections with a tolerance for poor returns. It also finds a (firm-level) positive correlation between the amount of government support provided and net investment in tangible assets, thereby suggesting that such government intervention contributes to the excess capacity observed in some of these industries.

3.3. Has government support increased or decreased emissions? An empirical question

Thus, while support measures might be warranted to overcome the costs associated with the development and adoption of new climate technologies, they risk creating soft budget constraint conditions that might lead to economic and environmental inefficiencies. Under such circumstances, incentives created by regulation and financial markets for both high environmental and economic performance – such as those illustrated in Figure 6 – can become muted.

Which of the two effects of government support on emissions prevails remains an unanswered empirical question. Most of the empirical literature on government R&D in climate technologies has focused on its effect on the development of new technologies – not on how such technologies may have helped firms to reduce emissions. Results seem to be inconclusive, with some studies finding positive effects of public R&D spending on patenting in climate-related technologies and others reporting insignificant effects (Popp, 2019[28]). More recently, a number of studies have addressed the role of environmental government support received by Chinese listed firms (Song, Zhang and Su, 2020[40]) (Wang and Zhang, 2020[41]) (Ren, Sun and Zhang, 2021[42]) (Hu et al., 2021[43]). These studies consider a broader environmental concept than climate change and estimate the effect of government support on a wide variety of variables such as sewage treatment fees – a proxy for corporate environmental spending – or investments in environmental protection projects. Their results also appear inconclusive, with some studies finding positive effects on investments in environmental protection ((Wang and Zhang, 2020[41]) (Song, Zhang and Su, 2020[40])) but others reporting insignificant results on patents in environmental technologies (Ren, Sun and Zhang, 2021[42]).

This report aims to address this knowledge gap by developing an empirical analysis, which is presented in the next section.

4. Empirical analysis: How does government support contribute to increased emissions?

The objective of this empirical analysis is to provide evidence on whether government support has contributed to increasing or decreasing emissions in two carbon-intensive industrial activities; namely, aluminium smelting and steelmaking. Based on the firm-level data collected by OECD (2021[5]), three forms of government support are considered:

- Government grants: lump-sum cash transfers provided by governments and disclosed by firms in their financial statements.
- Tax concessions: reductions in income tax offered by governments and disclosed by firms in their financial statements.

As a result, they will refrain from refinancing inefficient firms or projects. However, the authors also show that decentralisation tends to discourage projects that are too slow to pay off, thereby fostering an over-emphasis on short-term profit opportunities.

- Below market borrowings:[18] government support provided through more favourable borrowing conditions than those prevailing in financial markets by state banks or other government-related financial entities.[19]

This analysis examines changes in emissions by adopting the common practice of decomposing changes in emissions into three drivers (Grossman and Krueger, 1991[44]) (Copeland and Taylor, 1994[45]) (Copeland and Taylor, 2004[46]) (Levinson, 2009[47]) (Levinson, 2015[48])):

- A scale effect, which measures changes in emissions if output was simply scaled up, holding constant the composition among production units and their emissions intensities (i.e. their technology).
- A composition effect, which measures changes in emissions due to changes in the composition among production units (i.e. changes in production units' market shares), holding constant their emissions intensities and the scale of the sector.
- A technique effect, which measures changes in emissions due to changes in production unit emissions intensities, holding constant their output and composition.

Trends in emissions from aluminium and steelmaking were estimated from a sample of aluminium smelters and steel mills located in OECD countries and emerging economies and being owned by top companies in these industries – see Annex A for more details. In both activities, the scale effect has been the single strongest driver of the growth of emissions (Figures 7 and 8, respectively). Over 2006-21, emissions from aluminium smelting increased 109.4%, of which 103.6 percentage points (pp) are accounted for by the scale effect, 17.1 pp by the composition effect, and -11.3 pp by the technique effect. Over the same period, emissions from steelmaking increased 20.4%, of which 24 pp are accounted by the scale effect, 3.4 pp by the composition effect, and -7 pp by the technique effect. Technology has therefore had a downward effect on emissions in both sectors, but these environmental gains were more than offset by the scale effect.20 In addition, the composition effect has contributed to increasing total emissions of these industries, implying that output has been (partly) reallocated to more carbon-intensive production units.

The previous section highlighted that government support could play a role in each of these effects. Support can: i) allow firms to grow larger than under market conditions, ii) alter market shares and shift production towards more or less efficient firms; iii) spur firms to improve production technologies and clean up their production processes (or mute incentives to do so). The extent to which government support in these industries has contributed to each of these effects is analysed in the rest of this section.

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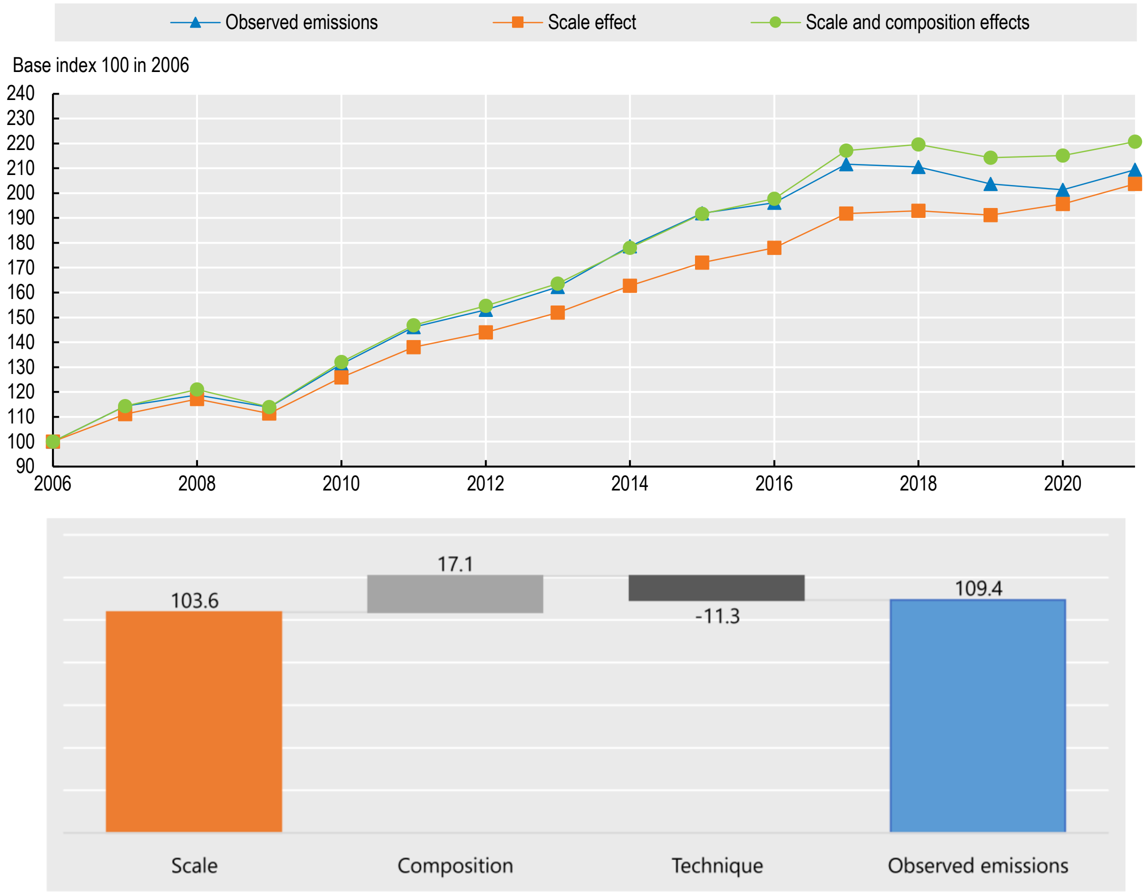
[18] Unlike grants and tax concessions that were directly provided by firms' financial statements, government support through below market borrowings was estimated by OECD (2021[5]). See Annex A for a description of data sources.

[19] Such favourable conditions are, for example, a longer repayment period or preferential interest rates. See OECD (2021[5]) for a full discussion.

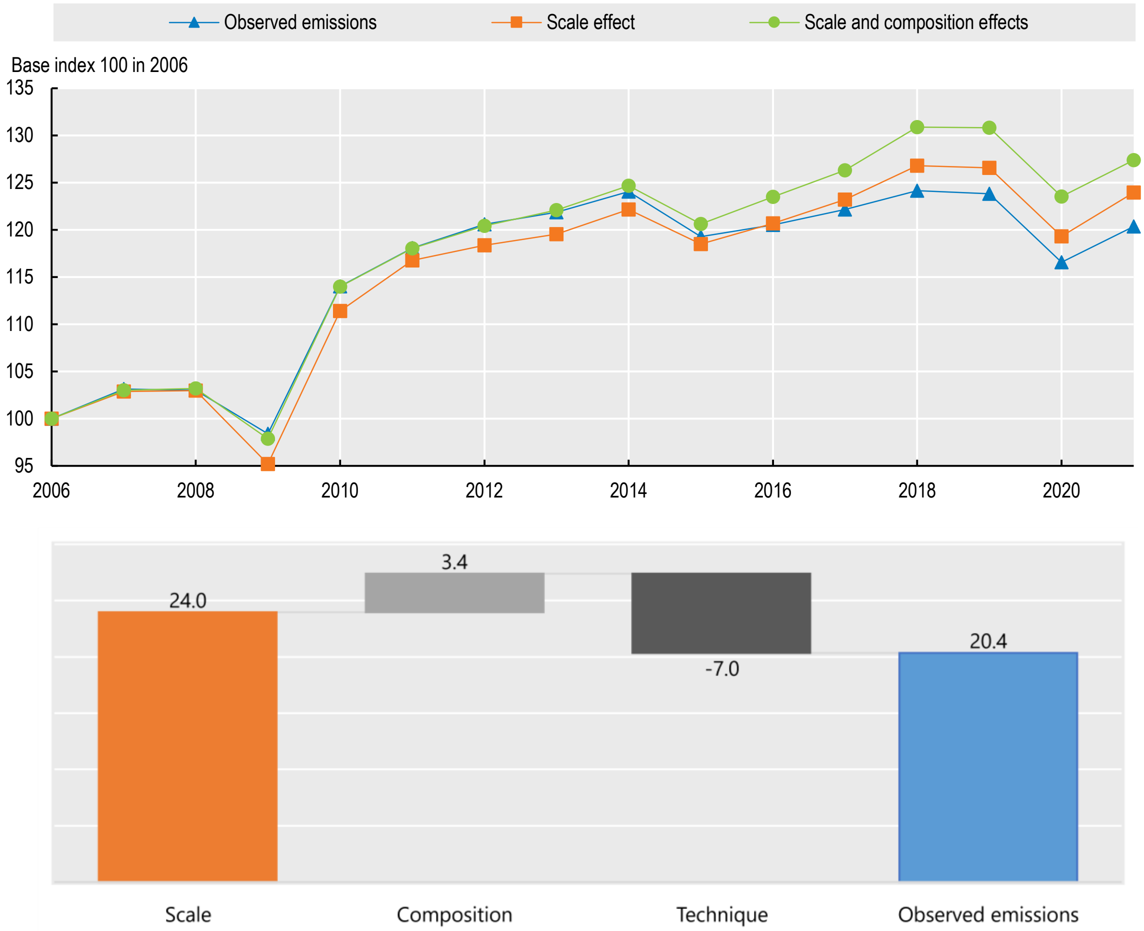
[20] This finding is in line with studies that find that improvements in steelmaking emissions intensity have been largely dwarfed by the increase in the volume of steel production over the 20th century, which has resulted in a failure to achieve an absolute emissions reduction (Wang et al., 2021[17]).

Figure 7. Increased emissions in aluminium smelting are driven mostly by the scale effect



Note 1: Aggregate emissions calculated from 273 production units – i.e. aluminium smelters – representing a global geographical coverage. Emissions are from the production of primary aluminium arising from electrolysis processes and casting processes (scope 1 and 2 emissions); and upstream preparation of anodes (part of scope 3 emissions). Emissions have been standardised for all production units. See Annex A for a complete description of the methodology of the CRU emissions analysis tool.
Note 2: The bottom of the figure provides a decomposition of the observed increase in emissions into a scale, composition, and technique effects. The contribution of each effect is calculated in percentage points of the observed increase in emissions.
Source: Authors' calculations based on CRU emissions analysis tool.

Figure 8. Increased emissions in steelmaking are driven mostly by the scale effect



Note 1: Aggregate emissions calculated from 309 production units – i.e. steel mills – representing a global geographical coverage. Emissions are from the production of crude steel arising from on-site raw materials preparation (sinter and coke), iron making, steelmaking, and casting (scope 1 and 2 emissions); and upstream preparation of coke and pellets (part of scope 3 emissions). Emissions have been standardised for all production units. See Annex A for a complete description of the methodology of the CRU emissions analysis tool.
Note 2: The bottom of the figure provides a decomposition of the observed increase in emissions into a scale, composition, and technique effects. The contribution of each effect is calculated in percentage points of the observed increase in emissions.
Source: Authors' calculations based on CRU emissions analysis tool.

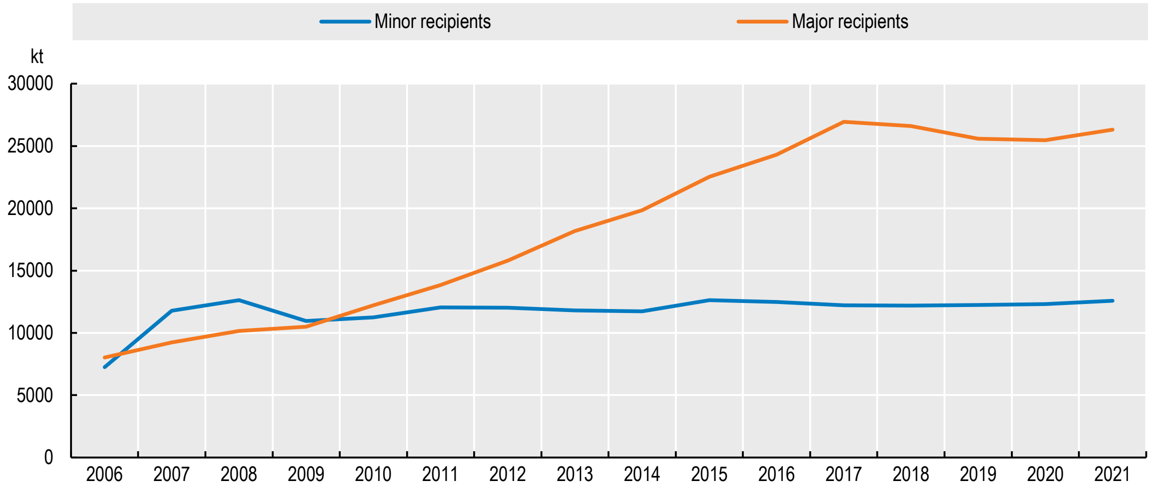
4.1. Does government support increase production?

In both aluminium smelting and steelmaking activities, firms that received most government support have produced substantially more (Figure 9 and Figure 10). For the aluminium sector, major recipients of government support, those that receive more support than the median recipient, accounted for 61% of aggregate primary aluminium production between 2006 and 2021 (295.5 million tonnes of primary aluminium against 188.1 million tonnes produced by minor recipients of government support). For the steel sector, the figure is 63% (6 billion tonnes of crude steel produced by the major recipients of government support against 3.59 billion tonnes produced by those receiving less support).

These findings suggest that government support might have played a role in the emissions' scale effect observed in Figure 7 and Figure 8. To test this hypothesis, a set of regressions is run over a panel of 68 firms (37 firms in steel and 31 firms in aluminium) between 2006 and 2021. The regressions control for firms' income, returns on assets, production site costs and electricity costs and use a robust fixed-effect structure to isolate the effects of government support.[21] Results show that the greater the government support received by a firm (in the form of below market borrowings, government grants, and tax concessions), the larger its output (columns 1-2 in Table 1). Therefore, major recipients have grown proportionally more than minor recipients (after controlling for secular sector-wide growth[22]). Increased total (firm-level) government support by 10% is, on average, associated with an increase of 0.58% in (firm-level) production. Separating by type of government support, tax credits are found to have the most important effect on (firm-level) production (columns 3-5 in Table 1). Returns on assets, production site costs, and power costs have no significant effect on production. As expected, firms with larger income – a variable capturing firm size – have larger production output.

Thus, there is evidence that government support helps drive production, which drives emissions. Therefore, it is likely that, absent government support, steel and aluminium output would have been smaller, leading to less emissions. Higher prices could ensue from such a smaller production, which may incentivise consumers to turn towards alternatives that can be less carbon intensive.[23] These results also raise concerns about potential excess capacity in these sectors. For instance, data show that aluminium smelters have a utilisation ratio (production/capacity) of (only) 85,13% on average, which echoes recent analysis linking the amount of government support received by firms with larger investments in fixed tangible assets (OECD, 2021[5]). Further research could investigate to what extent government support leads to overinvesting in production capacities in both sectors.

Figure 9. Production of aluminium firms (major vs minor recipients of government support)



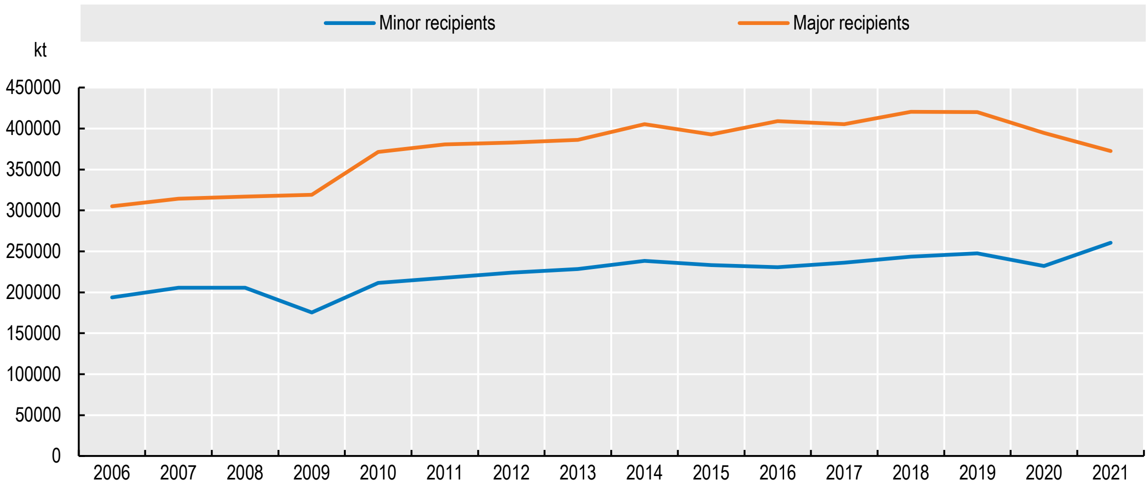
Note: Aggregate production of primary aluminium calculated for 31 firms included in the government support dataset from OECD (2021[5]). Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

[21] See Annex B for a full description of the empirical methodology.

[22] Secular sector-wide growth is controlled by sector-time fixed effects, which are included in all regressions.

[23] This is assuming that demand for aluminium and steel products is not perfectly inelastic, which is a reasonable assumption considering that such products be substituted by other products. In the construction industry for instance, aluminium and steel inputs can be substituted by engineered wood or plastics products, which have a substantially lower carbon footprint ((Alcorn, 2010[63]) (Hajiesmaeili et al., 2019[61]) (Shashi, Leitch and Dia, 2020[62])).

Figure 10. Production of steel firms (major vs minor recipients of government support)



Note: Aggregate production of crude steel calculated for 37 firms included in the government support dataset from OECD (2021[5]). Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

Table 1. Impact of government support on firm-level production

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs)	0.0238				
	(0.297)				
ln(Power Costs)		0.0400	0.0208	0.0283	0.0675
		(0.172)	(0.177)	(0.175)	(0.171)
ln(Returns on Asset)	0.0674	0.0783	0.150	0.0588	0.0600
	(0.587)	(0.606)	(0.641)	(0.633)	(0.586)
ln(Income Before Tax)	0.0111	0.0110	0.0128*	0.0140*	0.00785
	(0.00718)	(0.00713)	(0.00747)	(0.00737)	(0.00726)
ln(Total Government Support)	0.0584***	0.0582***			
	(0.0206)	(0.0208)			
ln(Below Market Borrowing)			0.0320*		
			(0.0164)		
ln(Grants)				0.0387*	
				(0.0210)	
ln(Tax Break)					0.0659***
					(0.0187)
Observations	854	854	854	854	854
R-squared	0.974	0.974	0.973	0.973	0.974

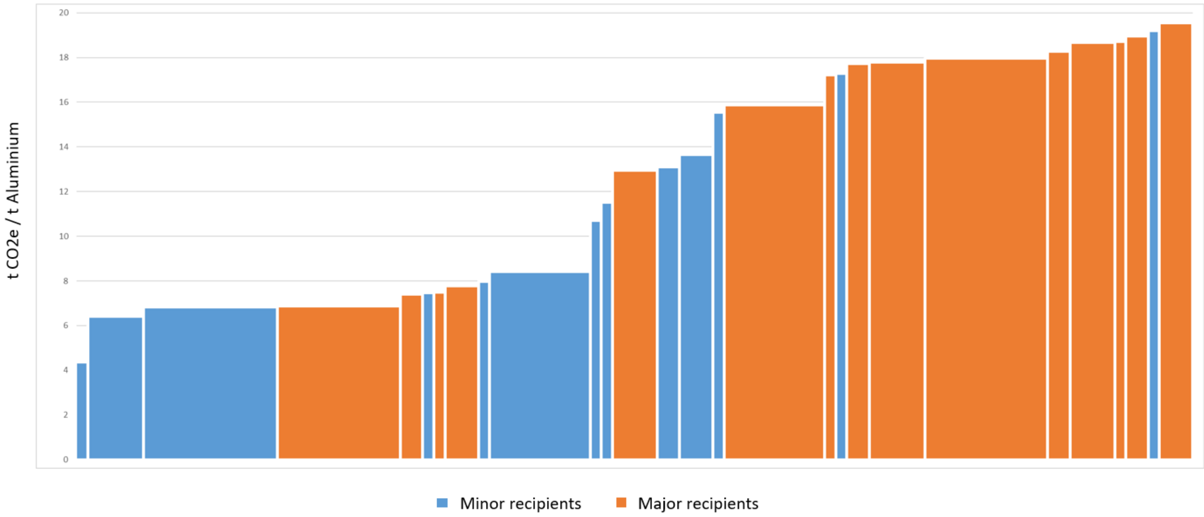
Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

4.2. Does government support alter composition of production?

The composition effect captures changes in sector-wide emissions due to changes in firms' market shares, holding constant their emissions intensities and the scale of the sector. If more emissions-intensive firms take over market shares at the expense of less emissions-intensive firms, sector-wide emissions will increase (if firms' technology and the sector's scale remain constant). Government support might contribute to such a dynamic.

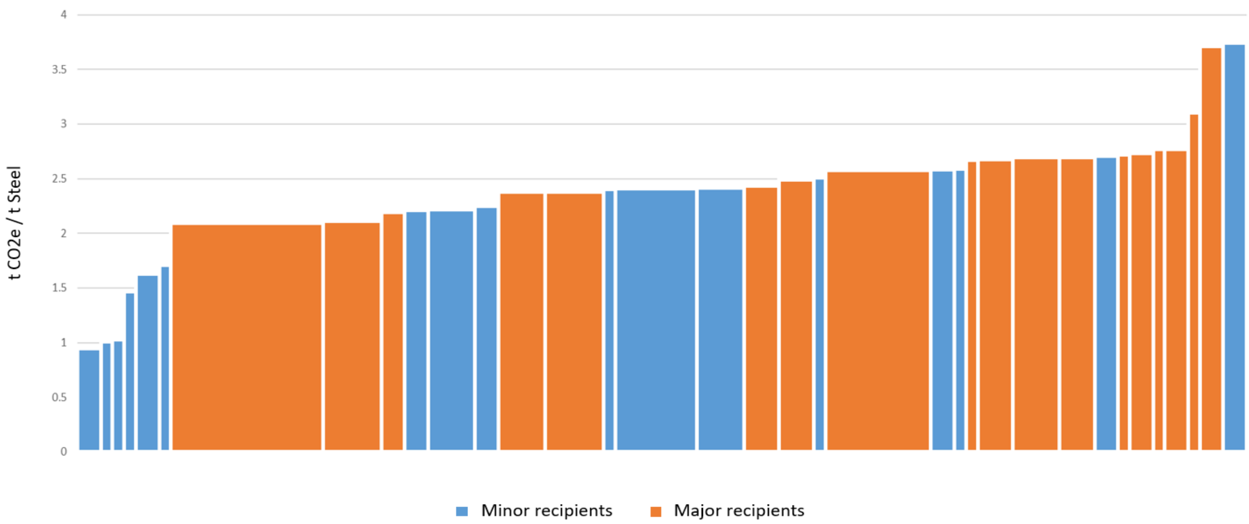
In aluminium smelting, major recipients of government support are amongst the most emissions intensive firms (Figure 11). The picture is more mixed in steelmaking, with major recipients of support being amongst both the most and the least emissions-intensive firms in the sample (Figure 12). Therefore, at least for aluminium smelters, government support may be correlated with firm-level emissions intensities and could play a role in the composition effect observed in Figure 7 and Figure 8.

Figure 11. Emissions intensity of firms in the aluminium industry (major vs minor recipients of government support)



Note: Emissions intensity (emissions-to-production ratio) calculated for 31 firms included in the government support dataset from OECD (2021[5]) based on data from the CRU emissions analysis tool. Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support. The width of the columns represents the production of each firm.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

Figure 12. Emissions intensity of firms in the steel industry (major vs minor recipients of government support)



Note: Emissions intensity (emissions-to-production ratio) calculated for 37 firms included in the government support dataset from OECD (2021[5]) based on data from the CRU emissions analysis tool. Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support. The width of the columns represents the production of each firm.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

To test the hypothesis that government support contributes to the composition effect, the same set of regressions as in Table 1 are run but allowing for a differentiated scale effect between initially most and least emissions-intensive firms in the sample.[24] If the scale effect is stronger for most emissions-intensive firms, the latter will grow more rapidly than least emissions-intensive firms, thereby increasing their market shares and increasing sector-wide emissions through a change in the composition of the sector.

Results in Table 2 show that the scale effect of government support is stronger for initially most emissions-intensive firms. In fact, the impact of government support is not significant and very close to zero for the least emissions-intensive firms but positively significant for the most emissions-intensive firms (columns 1-2 in Table 2 and Figure 13). For emissions-intensive firms, increased total (firm-level) government support by 10% is, on average, associated with an increase of 1.176% in (firm-level) production (column 2 in Table 2 and Figure 13). Separating by type of government support, grants are found to have the most important effect on (firm-level) production of most emission-intensive firms (columns 3-5 in Table 2 and Figure 13).[25]

[24] Most and least emissions-intensive firms are identified based on their initial – i.e. the time they are first observed in the sample – emissions intensity in order to maintain technology constant between the two groups of firms. Some firms may improve technologies over time and become less emissions-intensive – even to a point where they would belong to the group of least emissions-intensive firms. But such an effect, by definition, would be a technique effect, which will be estimated in the next subsection.

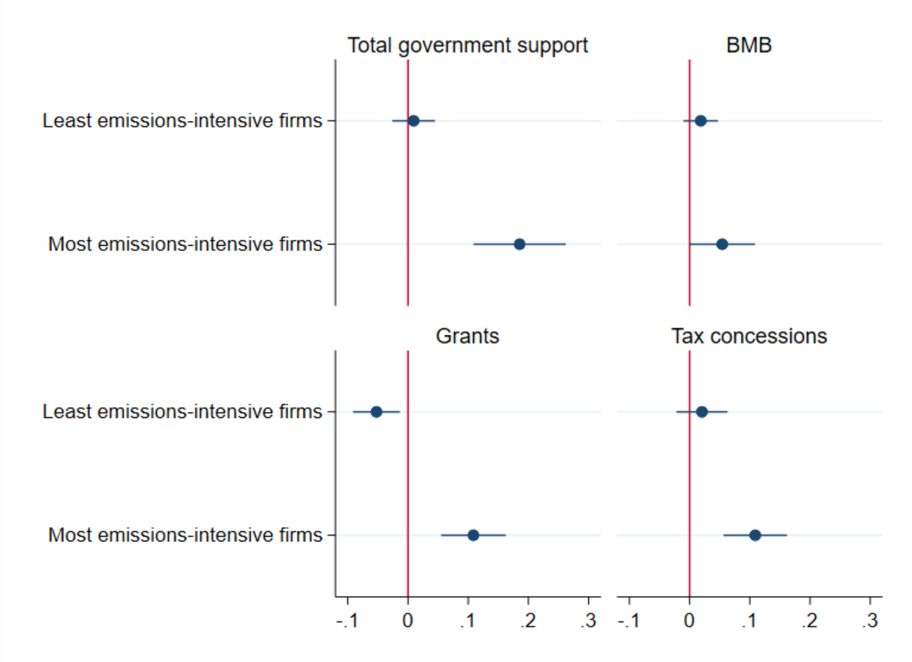
[25] Secular sector-wide growth is controlled by sector-time fixed effects included in all regressions. Therefore, the negative effect of grants for the least emissions-intensive firms means that such firms tend to grow less than the sector average when receiving grants.

Table 2. Impact of government support on firm-level production depending on initial emission intensity

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs)	-0.0703				
	(0.271)				
ln(Power Costs)		-0.00672	0.0132	-0.0801	0.0370
		(0.150)	(0.176)	(0.144)	(0.164)
ln(Returns on Asset)	0.212	0.220	0.252	-0.0615	0.0700
	(0.507)	(0.528)	(0.611)	(0.584)	(0.558)
ln(Income Before Tax)	0.00884	0.00889	0.0116	0.0118*	0.00878
	(0.00649)	(0.00649)	(0.00743)	(0.00681)	(0.00746)
Initial top 50% emissions-intensive firms = o,	-	-	-	-	-
ln(Total Government Support)	0.00928	0.00932			
	(0.0215)	(0.0215)			
Initial top 50% emissions-intensive firms x ln(Total Government Support)	0.177***	0.176***			
	(0.0525)	(0.0518)			
ln(Below Market Borrowing)			0.0185		
			(0.0175)		
Initial top 50% emissions-intensive firms x ln(Below Market Borrowing)			0.0357		
			(0.0366)		
ln(Grants)				-0.0524**	
				(0.0237)	
Initial top 50% emissions-intensive firms x ln(Grants)				0.161***	
				(0.0393)	
ln(Tax Break)					0.0205
					(0.0258)
Initial top 50% emissions-intensive firms x ln(Tax Break)					0.0885*
					(0.0454)
Observations	854	854	854	854	854
R-squared	0.976	0.976	0.973	0.975	0.975

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Figure 13. Marginal effects of government support on firm-level production



Note: Point estimates and confidence intervals of the total marginal effects of government support– for firms with high and low initial emission intensity – on firm-level production. These point estimates are calculated using the "margin" command in the statistical software STATA with the estimation results of Table 2. They report full elasticities.
Source: Authors' calculations based on the panel fixed-effect model specification described in Annex B.

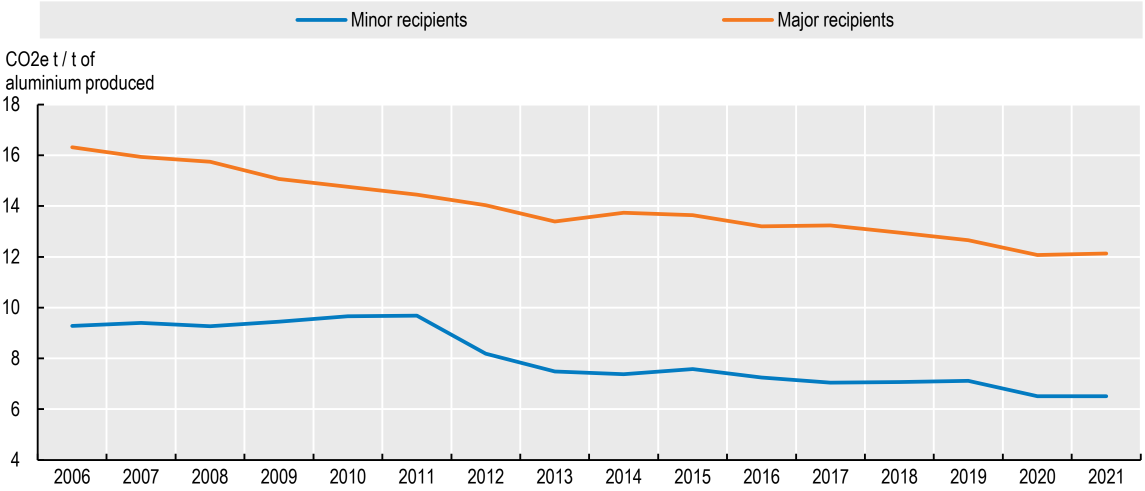
The interpretation of these results is clear. Absent government support, production in the steel and aluminium industries would likely have been more balanced towards less emission-intensive firms. If government support creates soft budget constraint conditions, removing it could mean that the most inefficient firms exit the market in favour of more efficient ones, thereby decreasing emissions because economic efficiency and emissions efficiency are correlated (Dechezleprêtre and Kruse, 2018[29]). Established results in the literature suggest that policy interventions in 1980s – and particularly subsidies – played a role in the composition of the steel industry in Europe. Compared to the United States, the European market lacked dynamism. Large incumbent firms survived longer than they would have done in the absence of government support. After subsidies substantially decreased, newcomers performed strongly and pushed incumbent firms from the market ((Moore, 1998[49]) (Barnett and Crandall, 2011[50])).

4.3. Does government support improve technology?

While firms that are major recipients of government support have (on average) high emissions intensity, they could improve their emissions intensity through technological innovations that make their production processes cleaner, thereby leading to a technique effect that tends to decrease aggregate emissions. As argued in the previous section, government support could be a driver of such innovation. In this case, the emissions intensity of subsidised firms should decrease more rapidly than that of their non-subsidised counterparts.

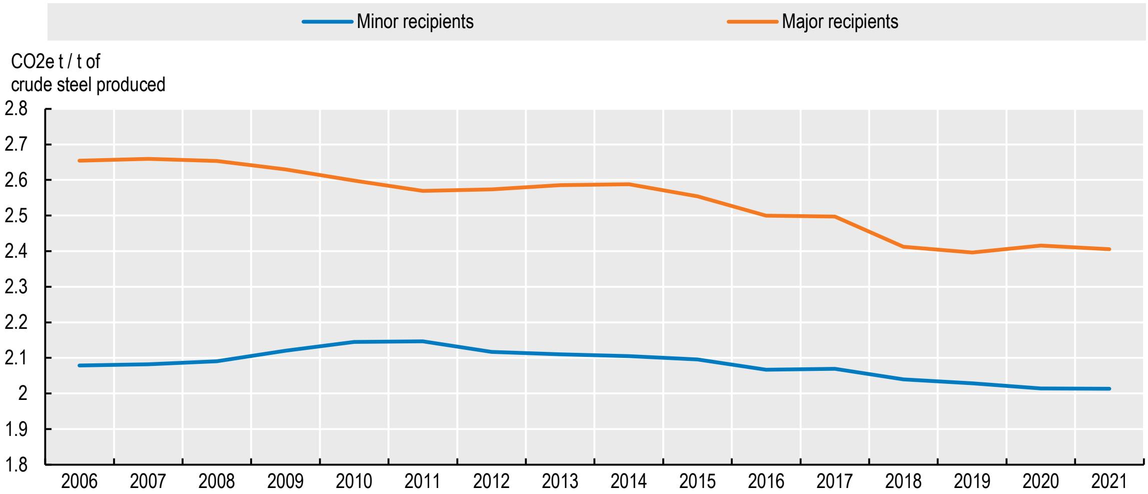
This effect does not appear to be happening. In both aluminium smelting and steelmaking activities, major recipients of government support are substantially more emissions intensive (Figures 14 and 15). In the aluminium sector, major recipients of government support had, on average, an emissions intensity 1.73 times larger than minor recipients between 2006 and 2021 (13.9 tonnes of CO_2e per tonnes of aluminium produced for the major recipients of government support against 8.05 tonnes of CO_2e per tonnes of aluminium produced for those receiving less support). In the steel industry, the figure is 1.22 (2.54 tonnes of CO_2e per tonnes of crude steel produced for the major recipients of government support against 2.08 tonnes of CO_2e per tonnes of crude steel produced for those receiving less support).

Figure 14. Emission intensities of aluminium plants (major vs minor recipients of government support)



Note: Aggregate emissions intensities calculated from 31 firms representing a global coverage. Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support.
Source: Authors' calculations based on (OECD, 2021[5]) and CRU emissions analysis tool.

Figure 15. Emission intensities of steel plants (major vs minor recipients of government support)



Note: Aggregate emissions intensities calculated from 37 firms representing a global coverage. Average annual government support received between 2006 and 2021 is calculated for each firm. The median of obtained values is then used as a threshold to separate major and minor recipients of government support – i.e. major recipients of government support are the half sample of firms with the largest average annual government support.
Source: Authors' calculations based on (OECD, 2021[5]) and CRU emissions analysis tool.

This finding suggests that government support did not drive the technique effects observed in Figure 7 and Figure 8. This hypothesis can be tested by running a set of fixed-effect regressions similar to Table 1 and Table 2 but using firms' emissions as a dependent variable and controlling for firms' output. Therefore, the coefficient of government support captures its effect on firms' emissions holding firms' output constant – i.e. its effect on firms' emissions intensity.

Results show no significant correlation between total government support and emissions intensity (columns 1-2 of Table 3). Importantly, the coefficient of total government support is very close to zero, thereby suggesting that its non-significance is due to its small magnitude[26]. No effect is found when each type of government support is considered separately (columns 3-5 of Table 3). Like findings in Table 1 and Table 2, firms' production site costs and firms' power costs have no significant effect on emissions. However, returns on assets are found to have a negative effect on emissions, thereby suggesting a positive relationship between financial profitability and emissions efficiency.

Thus, observed technological improvements – which tended to drive emissions downward in both aluminium smelting and steelmaking activities – does not appear to have originated from the provision of government support. Robust empirical results show that increasing total (firm-level) government support has not, on average, been associated with a decrease in (firm-level) emissions intensity.

Table 3. Impact of government support on firm-level emissions

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)
ln(Production)	0.908***	0.908***	0.901***	0.904***	0.907***
	(0.0912)	(0.0912)	(0.0914)	(0.0923)	(0.0897)
ln(Production Site Costs)	0.115				
	(0.163)				
ln(Power Costs)		0.0212	0.0115	0.0183	0.0189
		(0.0882)	(0.0902)	(0.0892)	(0.0879)
ln(Returns on Asset)	-0.501**	-0.511**	-0.516**	-0.519**	-0.512**
	(0.195)	(0.208)	(0.198)	(0.213)	(0.202)
ln(Income Before Tax)	-0.000891	-0.000967	-0.00134	-0.00118	-0.000897
	(0.00281)	(0.00282)	(0.00280)	(0.00284)	(0.00273)
ln(Total Government Support)	-0.00575	-0.00563			
	(0.00527)	(0.00532)			
ln(Below Market Borrowing)			0.00617		
			(0.00621)		
ln(Grants)				0.00112	
				(0.00807)	
ln(Tax Break)					-0.00361
					(0.00607)
Observations	854	854	854	854	854
R-squared	0.992	0.992	0.992	0.992	0.992

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

[26] As opposed to a non-significant coefficient that would be large in magnitude but inaccurately estimated.

5. Modelling analysis: How can removing government support reduce emissions?

In this section, simulations of emissions reduction are conducted in a scenario where observed government support is removed from aluminium smelting and steelmaking activities. These simulations are based on the econometric estimates of the relationship between government support and production of aluminium and steel found in the previous section. If government support is removed, output in aluminium smelting and steelmaking activities will decrease, thereby reducing emissions (through a "de-scale" effect).

Because aluminium and steel are key intermediate inputs in many sectors, decreasing their supply implies an impact on emissions beyond these two industries. Firstly, they draw on resources from other potentially emission-intensive sectors, such as electricity generation. Secondly, a lower supply of aluminium and steel can constrain output across downstream industries, which each have their own degree of carbon intensity of production. Finally, this effect can also spill over internationally to industries in other countries via global value chains.

To capture these wide network effects, an economy-wide framework is used that captures up- and downstream linkages. The use of an input-output model with sectoral level detail enables the capture and quantification of many complex cross-country interactions, through production and trade. The modelling analysis can consequently illustrate the large-scale climate implications of removing government support in the aluminium smelting steelmaking activities.

5.1. The modelling framework for a supply-side scenario

Simulations are conducted based on a Ghosh input-output model.[27] The modelling analysis combines five databases: (1) OECD Inter-Country Input-Output tables which underlay TiVA indicators: 2021 edition; (2) the EXIOBASE environmentally extended input-output tables; (3) OECD database on Carbon dioxide emissions embodied in international trade; (4) the CRU emission analysis tool; and (5) Industrial government support dataset (OECD, 2021[5]).[28] The input-output model consists of 67 countries/region and 47 sectors. The Ghosh formulation is supply driven: changes in sectoral output are calculated based on exogenously specified changes in sectoral inputs.[29] This is different from the commonly used demand driven Leontief approach where production levels in each industry are calculated from exogenous changes in final demand. The Ghosh approach is more relevant to the government support removal scenario as it represents a shock due to the reduction of supply of two important commodities, therefore propagating throughout the economy.

Using the supply-side input-output approach implies several assumptions. Firstly, the results represent a short-term impact. The scenario removes government support immediately and is designed to highlight the important features of the impact of such policy on the global economy. Longer-term adjustment mechanisms are therefore not present in the analysis. Secondly, output coefficients are fixed. For instance, if production from steelmaking activities is reduced then purchases of steel by other sectors will be reduce proportionally (Miller and Blair, 2009[51]). As a result, the output of all sectors using steel as an input will decrease as the model assumes perfect demand elasticity to changes in supply (Galbusera and Giannopoulos, 2018[52]). This assumption can be thought of as being most relevant to analyse a supply disruption to a basic commodity and fits with the sectoral analysis in this report. Aluminium and steel are basic commodities that can be difficult or impossible to substitute with other inputs in the short term. [30]

The model results illustrate the downstream impacts of a supply-side shock (namely the removal of government support in aluminium smelting and steelmaking activities). Because there can be important CO_2 implications in industries upstream of aluminium smelting and steelmaking, the changes in production

[27] See Annex D for a description of the modelling strategy.

[28] See Annex A for a description of data sources.

[29] This methodology has found recent application to analysis of the COVID-19 pandemic which was characterised by severe supply-side shocks. For a discussion, see Pichler and Farmer (2022[69]).

[30] See Miller and Blair (2009[51]) for a discussion.

and in CO_2 emissions stemming from inputs in aluminium smelting – i.e. electricity generation – are also calculated and added to the overall results.

5.2. Removing government support leads to substantial emissions reduction

Simulations show that removing government support in aluminium smelting and steelmaking activities would decrease global emissions by 1%, while reducing global output by 0.3%. Such a cut to global emissions is sizeable considering that the analysis is confined to government support provided in two industries only. Such an effect is driven by China and India, which account for 96% and 89% of the emissions and output reductions, respectively. By comparison, OECD countries only account for less than 2% and 7% of the emissions and output reductions, respectively.

Most of the government support in aluminium and steelmaking activities is provided in a small subset of countries, which also tend to have a comparatively large share of global aluminium and steel output. China and India account for 49% of both global primary aluminium and crude steel production while they have a ratio of support to output between 1.8 and 7 times the world average. Some OECD countries also provide significant government support relative to production, but their industrial output is much lower, which limits the effect on emissions reduction. For instance, Germany and Norway provide comparatively high support to aluminium smelting but produce a relatively low share of global output.[31] Therefore, the effect of removing government support globally will overall be larger for China and India because, among other things, the amount of government support removed is larger and it applies to a larger production base.

China and India are also characterised by high emission intensities in aluminium smelting and steelmaking activities. Their emission intensity of aluminium smelting and steelmaking are respectively one and a half and three times larger than OECD economies. As a result, steel accounts for 2.5% of total output but 17% of CO_2 emissions in China and India. In addition, aluminium production is particularly carbon intensive because it draws on an electricity supply that is the most carbon intensive across regions.[32] The aluminium industry uses 4.4% of the total electricity generated in China and India and it is the most electricity intensive industry per unit of output.

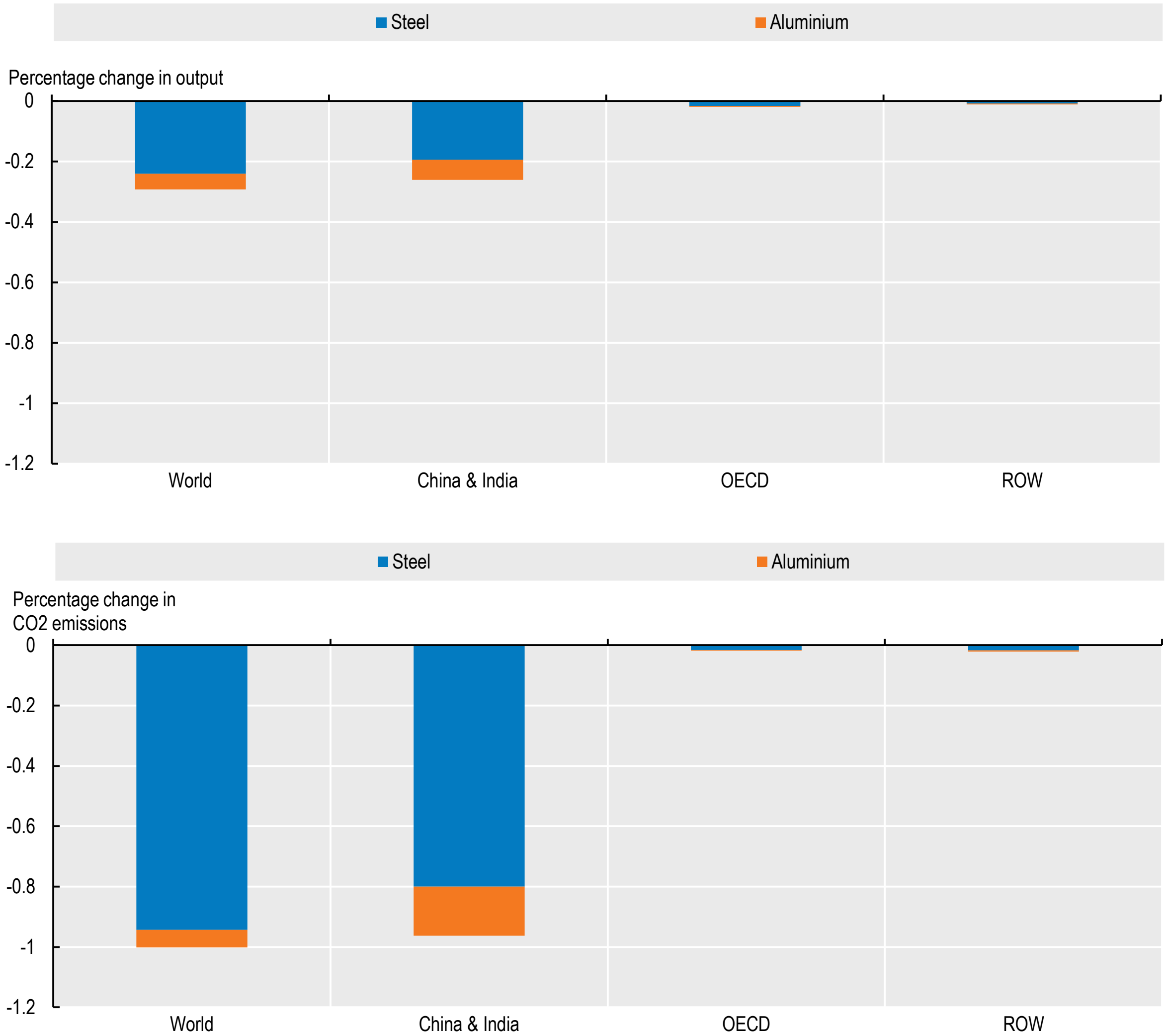
From a country perspective, China would have the largest emissions reduction and output decline as government support is removed. By contrast, OECD economies have much smaller reductions in both emissions and output. While emissions and output reductions arise both in aluminium smelting and steelmaking activities, downstream users of aluminium and steel also play an important role in driving emissions down. In China, users tend to be larger and more carbon intensive than in OECD countries. Moreover, construction is the largest user of steel – using 25% of total domestic output – while being the largest of all economic sector – accounting for 10% of total output. In OECD countries, the largest user of steel is the fabricated metals sector, which only accounts for 1.4% of total output. Removing government support therefore affects a (much) larger downstream industry in China: the contraction in the construction industry accounts for 12% of the total loss in output in China. In addition, construction also has a higher carbon intensity than fabricated metals (by a factor of 1.7), thereby significantly driving emissions down when contracting.

Over time, the shortfall in aluminium and steel inputs could be offset through imports from other producers, which may have a lower carbon intensity of production. Therefore, while construction and other heavy industries in China and India are affected through a supply shock of key commodities, such output reductions should be thought of as a short-term upper-bound on the economic costs of the support reduction. This dynamic reorientation of supply chains is not captured in the model.

[31] However, the United States and Korea are important steel producers – accounting for 6% and 4% of global production respectively – and provide relatively high support.

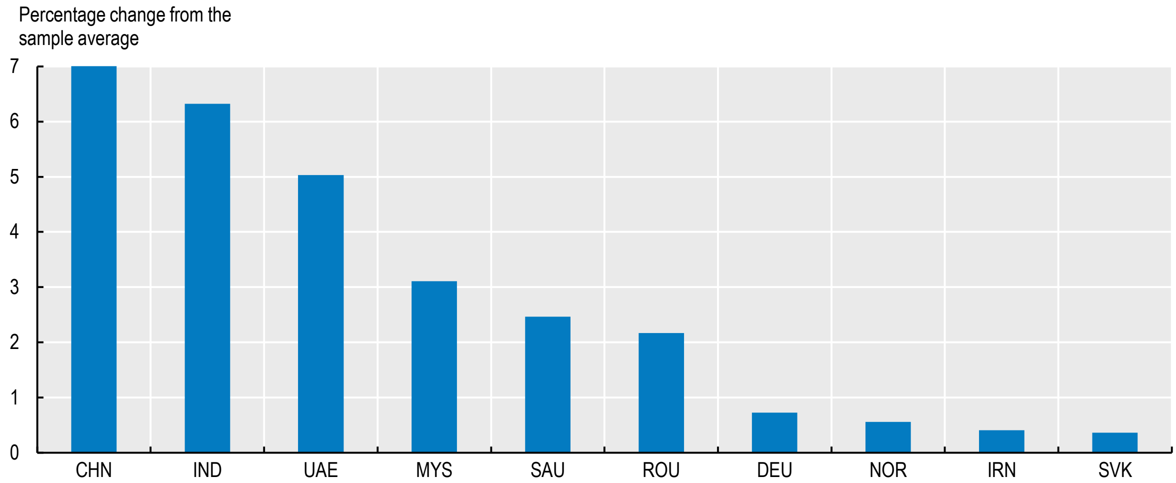
[32] Electricity generation accounts for 50% of CO_2 emissions in China and India (combined) and 42% in both the OECD and ROW (rest of the world).

Figure 16. Decrease in output and CO_2 emissions from a removal of government support



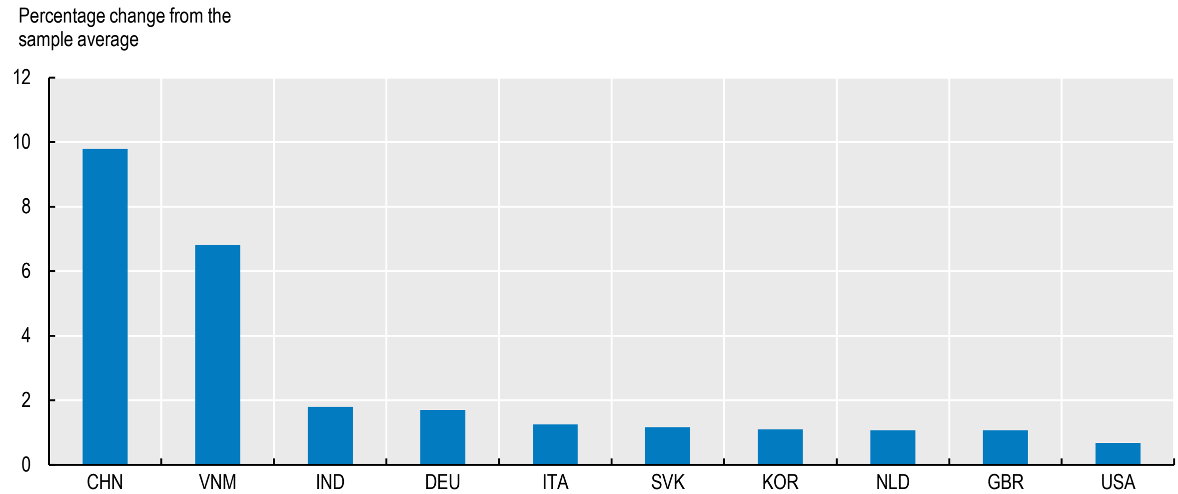
Note: Simulations of removing government support are run separately for steel and aluminium. Output changes are calculated by region for all sectors. Regional output changes are calculated as their proportion of the world output decline. CO_2 changes are calculated by taking the output changes and mapping them to emissions by sector and region using the emission intensity data. Regional figures are calculated from their relative contribution to the world emissions decline.
Source: Authors' calculations based on OECD (2021[5]), CRU emission analysis tool, OECD TiVA indicators: 2021 edition, EXIOBASE, and the OECD Carbon dioxide emissions embodied in international trade dataset.

Figure 17. Government support relative to production by country in aluminium smelting — top 10 producers



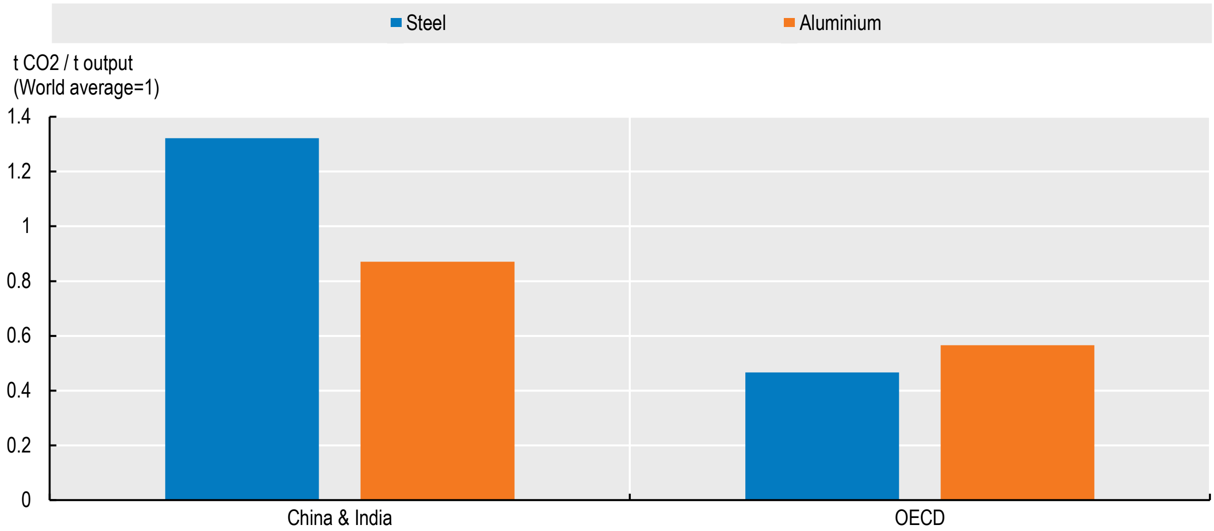
Note: Government support received by (parent) company is allocated to its smelters based on their relative production. Amounts of government support per smelter are then summed by country. Government support by country is then divided by total production of aluminium per country. The figure shows percentage change of this ratio relative to the sample average. For instance, aluminium subsidies in India and China are over six times the sample average ratio.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

Figure 18. Government support relative to production by country in steelmaking, top 10 producers



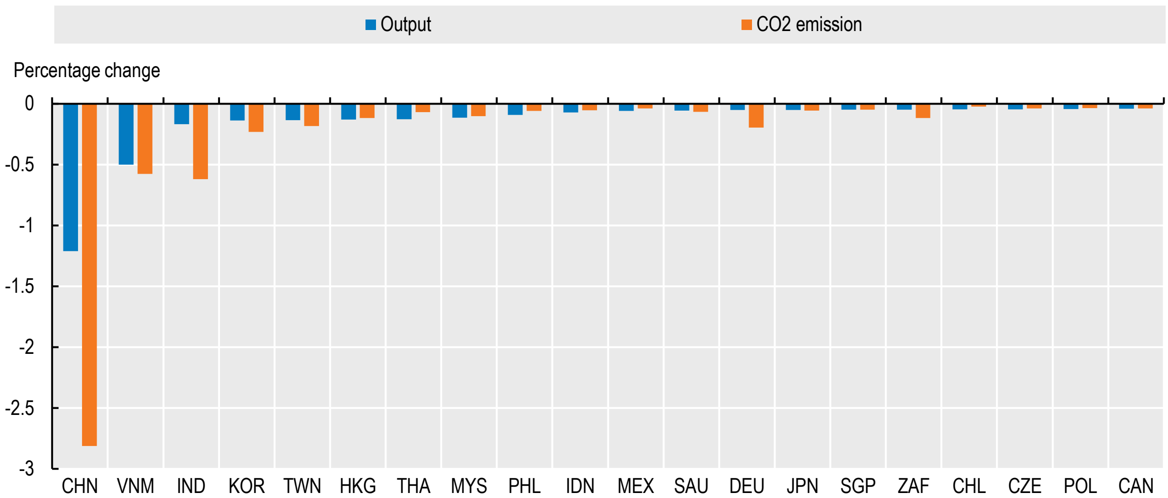
Note: Government support received by (parent) company is allocated to its steelmills based on their relative production. Amounts of government support per steelmills are then summed by country. Government support by country is then divided by total production of steel per country. The figure shows percentage change of this ratio relative to the sample average. For instance, steel subsidies in China and Vietnam are over six times the sample average ratio of subsidies to production.
Source: Authors' calculations based on OECD (2021[5]) and CRU emissions analysis tool.

Figure 19. Relative CO_2 intensity of output in steel and aluminium



Note: World average is set to one. Figures are taken as a percentage relative to the world average, i.e. OECD countries have an emission intensity of about 40% of the world average for steel.
Source: Authors' calculations based on OECD TiVA indicators: 2021 edition, EXIOBASE, and the OECD Carbon dioxide emissions embodied in international trade dataset.

Figure 20. Output and CO_2 emissions reduction by country



Note: Output decline by country (in percentage changes) for the top 20 most impacted countries. Output changes are calculated by country for all sectors. CO_2 emissions changes are calculated by taking the output changes and mapping them to emission intensity data (by country sector).
Source: Authors' calculations based on OECD (2021[5]), CRU emission analysis tool, OECD TiVA indicators: 2021 edition, EXIOBASE, and the OECD Carbon dioxide emissions embodied in international trade dataset.

5.3. Removing government support might be a cost-effective strategy to reduce emissions

Importantly, the emissions reduction is in proportion larger than the output reduction for most countries: a reduction in global emissions of 1% is associated with a reduction in output of 0.3%. By comparison, in 2020, emissions fell by 5.7% while COVID-related restrictions on economic activity reduced global output by 3% (Le Quéré et al., 2020[53]). Thus, for a global output reduction of 0.3%, all COVID-related restrictions would have led to an emissions reduction of 0.57% (5.7%/10) – as opposed to 1% when considering the removal of government support. In other words, for a comparable decline in output, the emissions reduction from removing government support in aluminium smelting and steelmaking activities is 75% larger than the one observed in 2020 with all COVID-related restrictions.

In addition, removing government support in aluminium smelting and steelmaking activities will also induce fiscal savings estimated USD 0.71 bln globally – or an equivalent of USD 2 per tonne of CO_2 abated. These fiscal gains could be used for purposes such as retraining and other social programs for workers in activities experiencing an output loss.

These results point to the large potential environmental benefits compared to the economic costs of removing government support. In the longer-term, a reorientation of resources (i.e. labour and capital) to non-subsidised and less carbon-intensive activities suggests that such economic costs could be even lower. Therefore, these results suggest that removing government support could be a cost-effective strategy for emissions reduction – and one that would help level the trade level playing field.

6. Policy implications and concluding remarks

Government support can have both positive and negative effects on firms' emissions performance. On the one hand, well-designed government support may be warranted in some cases to overcome market failures associated with the development and adoption of new climate technologies. On the other hand, government support risks creating conditions that lead to economic and environmental inefficiencies.

The objective of this report is to estimate empirically which of these two effects has prevailed in the aluminium and steel industries. Based on a representative sample of firms, the main results of this analysis can be summarised as follows.

- *Ex post* empirical evidence shows that on average:
    - Government support has had an effect on firm production, thereby contributing to the scale effect on emissions.
    - Government support's effect on firm production is heterogeneous among firms depending on their emissions intensity, thereby contributing to the composition effect on emissions.
    - Government support is found to have no effect on firms' emissions intensity, thereby suggesting that it has not been used by recipient firms to adopt technologies that would decrease emissions.
- *Ex ante* modelling simulations show that:
    - Removing current government support for aluminium smelting and steelmaking activities would decrease global emissions by 1% while reducing global output 0.3%.
    - Removing government support for aluminium smelting and steelmaking activities might be a cost-effective strategy for decarbonisation. For instance, for a comparable decline in output, the emissions reduction from removing government support in aluminium smelting and steelmaking activities is 75% larger than the emissions reduction observed in 2020 resulting from COVID-related restrictions. In the long run, the economic costs of phasing out government support could even be lower thanks the reorientation of economic resources (i.e. labour and capital) to non-subsidised and less carbon-intensive activities.
    - Additionally, the removal of such government support frees up scarce fiscal resources by an amount of USD 0.71 bln for alternative uses – e.g. support workers and households adversely affected by output loss.
    - Emissions reductions through removing government support would be heterogeneous among regions, with China and India accounting for the bulk of the decrease.

These findings raise environmental issues on top of already well-documented adverse effects of government support on international competition (OECD, 2017[6]) (OECD, 2021[5]). They show that government support provided to firms in this study's sample has, on average, inflated industrial output and consequently increased emissions. They therefore suggest that subsidies provided to firms in the aluminium and steel industries have caused both market distortions and increased global emissions, thereby undermining the functioning of the global trading system and the achievement of emissions reduction objectives.

Policy implications are manifold. First, policy makers should address government support provided to industrial activities in international discussions that focus on both trade and environment issues. Decarbonising emissions-intensive industries likely requires government policies to foster the adoption of new, cleaner, technologies. As this study shows however, existing support measures to those industries have so far run counter to this objective, while they also have contributed to create market distortions. Reforming government support provided to emissions-intensive industries therefore appears to be one opportunity to both strengthen the global trading system and to support a (global) low carbon transition.

Second and relatedly, trade negotiations and climate negotiations can no longer take place in isolation as their outcomes spill over to one another. International climate negotiations will be hampered if the rules-based trading system is unable to tackle issues related to environmentally harmful subsidies. Likewise, fragmented climate policies could challenge the rules-based trading system. Exploiting existing synergies between trade and environment policies would therefore ensure not only that the multilateral trading system keeps delivering substantial economic benefits but also that the chances of achieving a low-carbon transition are increased.

This report is one of the first pieces of evidence shedding light on the climate implications of industrial subsidies. It opens several avenues for future research relevant for the design of policies that aim to support a low-carbon transition.

First, further analyses on the design features of support measures could better identify which types of government support generate the most adverse effects from a trade and environmental perspective. Certain types of support measures likely generate more emissions and create more market distortions than others. Reforming or redesigning such support measures – e.g. by removing discrimination and including conditions for firms to achieve high environmental performance – might improve environmental outcomes, facilitate climate negotiations, and ease trade distortions on international markets.

Second, further research is needed to better understand the distributional concerns that may arise from phasing out government support to energy-intensive industries. As this report shows, removing government support in aluminium smelting and steelmaking achieve a significant emissions reduction for a moderate decline of output in the subsidised industries, but with heterogenous effects across firms and their workers. Future studies could address such labour market effects and discuss how best to redirect freed up fiscal resources towards households and firms most affected by the reforms.

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Annex A. Data sources

Firm-level dataset on government support

Firm-level data on government support are provided by OECD (2021[5]) (updated 2023). In that study, the amount received by individual firms in the aluminium and steelmaking industries was estimated for three types of government support:

- Government grants: lump-sum cash transfers provided by governments and disclosed by firms in their financial statements.
- Tax concessions: reductions on income tax offered by governments and disclosed by firms in their financial statements.
- Below market borrowings: government support provided through more favourable borrowing conditions than the ones prevailing on financial markets and offered by state banks or other government-related financial entities.[33]

Information on *grants* and *tax concessions* received by firms was collected from the non-operating income section and the income tax section of firms' financial statements, which generally provide monetary values for these types of government support. Whenever possible, the data collection process also relied on complementary (external) sources such as government databases and press reports for verification and quality checks. While there is no assurance that the data collected include every possible grant and tax concession that was provided to firms, OECD (2021[5]) arguably provides the best available firm-level information on such type of government support.

The estimation of government support received through *below-market borrowings* requires to compare actual interest rates paid by firms against hypothetical rates that would have been charged on private markets – i.e. benchmark interest rates. Such estimation was conducted as follows.

First, OECD (2021[5]) calculates the actual interest rate charged to a firm by dividing its interest payments by its outstanding debt, which is an information available from a firm's financial statements.[34] Next, benchmark interest rates are constructed by combining a (local) risk-free base rate[35] with a spread that captures the credit risk of a firm. Such a risk-adjusted spread is estimated for each credit rating as the average spread between corporate bonds and (risk-free) government bonds.[36] Therefore, given a company's credit rating, its benchmark rate can be established.[37] Finally, the amount of firm-level government support is calculated by multiplying its outstanding debt with the difference between a firm's benchmark rate and its actual interest rate.

[33] Such favourable conditions are, for example, a longer repayment period or preferential interest rates. See OECD (2021[5]) for a full discussion.

[34] To smooth yearly fluctuations, OECD (2021[5]) divides interest payments in a given year (t) by the average debt outstanding in the same year (t) and the previous year (t-1).

[35] Depending on their availability and on each country's practice, risk-free base rates are chosen from: six-month interbank rates (e.g. the US London Inter-Bank Offered rates [USLIBOR], Euro Interbank Offered Rate [EURIBOR], Tokyo Interbank Offered Rate [TIBOR]); one-year government bond yields; or other commonly used base rates (one year), such as the base rates published by the People's Bank of China. As the currency of benchmark rates should ideally match that of the corporate debt being analysed, the study takes into account a company's funding currency.

[36] In addition, government guarantees that typically improve official companies' credit rating were also considered. That is, if a credit rating was favourably adjusted because of the guarantee of government support in case of financial distress, the original rating absent government support – which is also provided by credit-rating agencies – is considered.

[37] For firms with no official credit rating, the latter is estimated based on financial data and the coefficients of an econometric model that were estimated with the sample of available firms' ratings – see OECD (2021[5]) for a detailed explanation.

Data on risk-free rates were extracted from FactSet – a firm-level financial information database – and the website of the People's Bank of China (for Chinese firms). Spreads on corporate bonds were obtained from FactSet. Firms' credit ratings were obtained from both FactSet and the websites of credit-rating agencies such as Moody's, Fitch, and Standard & Poor's.

Overall, the dataset constructed by OECD (2021[5]) and updated in 2023 provides estimations of government support for 31 firms in the aluminium industry (accounting for approximately 57% of global production) and 37 firms in the steelmaking industry (accounting for approximately 68% of global production). While the dataset covers mainly top companies in each sector, a geographical diversity is also achieved and firms from emerging economies are well represented. The time coverage of the dataset extends from 2005 to 2021.

Table A A.1. List of firms

Industrial activity	Firm name	Other firm names	Home economy
Aluminium -- ALUM	AMAG	AMAG Austria Metall AG; AMAG-Gruppe; AMAG Group	AUT
Aluminium -- ALUM	Alba	Aluminium Bahrain B.S.C	BHR
Aluminium -- ALUM	Alcoa	Alcoa, Inc.	USA
Aluminium -- ALUM	Aluar	Aluar Aluminio Argentino S.A.I.C.	ARG
Aluminium -- ALUM	Century Aluminum	Century Aluminum Company	USA
Aluminium -- ALUM	Chalco	Aluminum Corporation of China Limited; 中国铝业股份有限公司	CHN
Aluminium -- ALUM	China Hongqiao	China Hongqiao Group Ltd.; Shandong Weiqiao Aluminum & Power; 中国宏桥集团有限公司	CHN
Aluminium -- ALUM	China Zhongwang	China Zhongwang Holdings Ltd.	CHN
Aluminium -- ALUM	East Hope	East Hope Management; 东方希望企业管理有限公司	CHN
Aluminium -- ALUM	Henan Shenhuo	Henan Shen Huo Coal Industry and Electricity Power Co., Ltd.; 河南神火煤电股份有限公司	CHN
Aluminium -- ALUM	Henan Zhongfu Industrial	河南中孚实业股份有限公司	CHN
Aluminium -- ALUM	Hindalco	Hindalco Industries Ltd.	IND
Aluminium -- ALUM	Hydro	Norsk Hydro ASA	NOR
Aluminium -- ALUM	IMIDRO	Iranian Mines and Mining Industries Development & Renovation Organization; سازمان توسعه و نوسازی معادن و صنایع معدنی ایران	IRN
Aluminium -- ALUM	JISCO	Jiuquan Iron and Steel Co. Ltd.; Jiuquan Iron and Steel (Group) Co., Ltd. ; 酒泉钢铁（集团）有限责任公司; 酒钢集团	CHN
Aluminium -- ALUM	Kaiser Aluminium	Kaiser Aluminium Corporation; KALU	USA
Aluminium -- ALUM	Maaden	Ma'aden; معادن	SAU
Aluminium -- ALUM	Mamoura Diversified	Mamoura Diversified Global Holding PJSC; Mubadala; Emirates Global Aluminium PJSC	ARE
Aluminium -- ALUM	Mytilineos	Μυτιληναίος A.E.	GRC
Aluminium -- ALUM	NALCO	National Aluminium Company Limited; नेशनल एल्यूमिनियम कंपनी लिमिटेड	IND
Aluminium -- ALUM	Press Metal	Press Metal Aluminium Holdings Berhad	MYS
Aluminium -- ALUM	QPIG	Qinghai Provincial Investment Group; 青海省投资集团有限公司	CHN
Aluminium -- ALUM	Rio Tinto	Rio Tinto plc; Rio Tinto Ltd.	AUS
Aluminium -- ALUM	Rusal	UC Rusal; United Co. RUSAL Plc; РУСАЛ	RUS

Industrial activity	Firm name	Other firm names	Home economy
Aluminium -- ALUM	SPIC	State Power Investment Group; 国家电力投资集团有限公司; 国家电投	CHN
Aluminium -- ALUM	Shandong Nanshan	Nanshan Aluminium; 山东南山铝业股份有限公司	CHN
Aluminium -- ALUM	South32	South32 Limited	AUS
Aluminium -- ALUM	Trimet	TRIMET Aluminium SE	DEU
Aluminium -- ALUM	Vedanta Resources	Vedanta Resources Ltd.	IND
Aluminium -- ALUM	Vimetco	Vimetco N.V.	NLD
Aluminium -- ALUM	Yunnan Aluminium	Yunnan Aluminium Co. ; 云南铝业股份有限公司	CHN
Steel -- STEE	Ansteel Group	Anshan Iron and Steel Group Corporation; Angang Group; 鞍山钢铁集团公司	CHN
Steel -- STEE	Anyang Steel	Anyang Iron and Steel Co., Ltd.; AYIS; 安阳钢铁股份有限公司	CHN
Steel -- STEE	ArcelorMittal	ArcelorMittal S.A.	LUX
Steel -- STEE	Baoshan	Baosteel; Baoshan Iron and Steel; 宝山钢铁股份有限公司	CHN
Steel -- STEE	Baotou Steel Union	Inner Mongolia Baotou Steel Union Co., Ltd.; 内蒙古包钢钢联股份有限公司	CHN
Steel -- STEE	Benxi Steel	Benxi Steel Group; 本钢集团有限公司	CHN
Steel -- STEE	CITIC Steel	CITIC Pacific Special Steel Group Co., Ltd.; Daye Special Steel; 中信泰富特钢集团股份有限公司	CHN
Steel -- STEE	China Baowu Steel	Baosteel Group; 中国宝武钢铁集团有限公司; 中國寶武鋼鉄集團有限公司	CHN
Steel -- STEE	EVRAZ	EVRAZ plc; Евраз	RUS
Steel -- STEE	Fangda Special Steel	Fangda Special Steel Technology Co., Ltd.; 方大特钢科技股份有限公司	CHN
Steel -- STEE	Gerdau	Gerdau S.A.	BRA
Steel -- STEE	HBIS	Hesteel Group Company Limited; Hegang; Hebei Iron and Steel Group Co., Ltd.; 河钢集团有限公司; 河鋼集團有限公司 (formerly: 河北钢铁集团有限公	CHN
Steel -- STEE	Hoa Phat	Hoa Phat Group; HPG; Tập đoàn Hòa Phát; Hoa Phat Steel Joint Stock Company	VNM
Steel -- STEE	Hyundai Steel	Hyundai Steel Co., Ltd.; 현대제철	KOR
Steel -- STEE	IMIDRO	Iranian Mines and Mining Industries Development & Renovation Organization; سازمان توسعه و نوسازی معادن و صنایع معدنی ایران	IRN
Steel -- STEE	JFE Steel	JFE Holdings, Inc.; JFE Group; JFEホールディングス	JPN
Steel -- STEE	JISCO	Jiuquan Iron and Steel Co. Ltd.; Jiuquan Iron and Steel (Group) Co., Ltd. ; 酒泉钢铁（集团）有限责任公司; 酒钢集团	CHN
Steel -- STEE	JSW Steel	JSW Steel Limited	IND
Steel -- STEE	Liuzhou Steel	Guangxi Liuzhou Iron and Steel Group; 广西柳州钢铁集团有限公司	CHN
Steel -- STEE	MMK	PJSC Magnitogorsk Iron and Steel Works; ПАО Магнитогорский металлургический комбинат	RUS
Steel -- STEE	NLMK	OJSC Novolipetsk Steel; NLMK Group; ОАО Новолипецкий металлургический комбинат	RUS
Steel -- STEE	Nanjing Steel	Nanjing Iron & Steel Co., Ltd., 南京钢铁股份有限公司, 南钢股份	CHN
Steel -- STEE	Nippon Steel	Nippon Steel Corporation; 日本製鉄株式会社; NSSMC; Nippon Steel & Sumitomo Metal Corporation	JPN
Steel -- STEE	Nucor	Nucor Corporation	USA

Industrial activity	Firm name	Other firm names	Home economy
Steel -- STEE	POSCO	Pohang Iron and Steel Co., Ltd.; 주식회사 포스코	KOR
Steel -- STEE	SAIL	Steel Authority of India Limited; Hindustan Steel Limited; भारतीय इस्पात प्राधिकरण	IND
Steel -- STEE	Shagang Group	Jiangsu Shagang Group; 江苏沙钢集团有限公司; 江蘇沙鋼集團有限公司	CHN
Steel -- STEE	Shandong Steel Group	Shandong Iron and Steel Group Co., Ltd.; SISG; 山东钢铁集团; 山东钢铁集团有限公司	CHN
Steel -- STEE	Shougang Group	Shougang Group Co., Ltd.; 首钢集团有限公司	CHN
Steel -- STEE	Steel Dynamics	Steel Dynamics, Inc.	USA
Steel -- STEE	Tata Steel	Tata Steel Limited	IND
Steel -- STEE	Ternium	Ternium S.A.	ARG
Steel -- STEE	Thyssenkrupp	Thyssenkrupp AG	DEU
Steel -- STEE	US Steel	United States Steel Corporation	USA
Steel -- STEE	Valin Steel	Hunan Valin Steel Co., Ltd.; 湖南华菱钢铁股份有限公司	CHN
Steel -- STEE	WISCO	Wuhan Iron & Steel Corporation; Wugang; 武钢集团有限公司	CHN
Steel -- STEE	Zenith Steel	Zhongtian Steel Group Co., Ltd.; 中天钢铁集团有限公司	CHN

Firm-level dataset on emissions

Data on firm-level greenhouse gas (GHG) emissions are constructed from the CRU emissions analysis tool (https://cruonline.crugroup.com/). The CRU group is a private firm collecting business intelligence in the mining, metals, and fertiliser industries. Their emissions analysis tool is a dataset that provides unique estimations of emissions at the production-unit level, covering all stages of the value chains in these industries. Their calculations are both in line with international standards and granular enough to be useful for an empirical analysis.

The CRU emissions analysis tool has an excellent coverage of the aluminium and steel production units. It provides emissions data for aluminium smelters and steelmills. Such data are built-up for like-for-like comparisons by considering emissions associated with specific standardised products. For aluminium smelters, such product is primary aluminium. For steelmills, it is crude steel.

Importantly, boundaries to measure the emissions arising along the manufacturing processes of these products are also standardised. Precisely, the following types of emissions are covered:

- **Scope 1 GHG emissions,** which arise on site – i.e. directly from smelters and steelmills activities. Such emissions include direct emissions from industrial processes – e.g. emissions from anodes dissolution in the smelting process or from combustion of fossil fuels in steelmills – or from electricity generation if the latter takes place on site.
- **Scope 2 GHG emissions,** which arise off site from the electricity generation and other types of energy purchased by smelters or steelmills for their industrial activities. Scope 2 emissions also include purchased heat streams, such as purchased steam.
- **Scope 3 GHG emissions**, which arise off site and are included for standardisation purposes. They cover emissions associated with the manufacturing of third-party inputs that are typically but not always produced on site. For instance, some BOF steelmills produce their own metallurgical coke while others purchase it from suppliers. To allow for meaningful comparisons, GHG emissions from the production of such third-party inputs are therefore included in steemills' emissions. Not all third-party input purchases need to be covered, only those that help make a like-for-like comparison. Therefore, scope 3 emissions included in the CRU database are those associated with inputs

necessary to the production of primary aluminium or liquid steel – i.e. coke, pellet, direct reduced iron and pig iron for liquid steel, and anode for aluminium.

CRU's data collection process follows the standard GHG Protocol methodology, which provides guidance to companies in quantifying and reporting their GHG emissions (The Greenhouse Gas Protocol, 2004[54]). All GHG emissions estimations are reported in tonnes of carbon dioxide equivalents (tCO_2e).

Overall, the database covers 281 aluminium smelters and 309 steelmills for the time period 2000-22. Ownership information of these production units – also provided in the CRU database – allows to construct firm-level emissions data points. The emissions of a firm (in the aluminium or the steelmaking industry) is calculated as the sum of emissions of the production units it owns (weighted by its share of ownership).[38] Production is constructed following the same approach. The emission intensity of a firm is calculated as the ratio of its emissions to its production.

Two variables of production costs are also constructed at the firm level from production units data points provided in the CRU database: production site costs and power costs. Production costs' variables of a firm are calculated as the ratio of its costs to its production (measured in USD/t of primary aluminium or crude steel).

Production site costs

- *Aluminium smelters*: Production site costs account for all costs incurred to produce primary aluminium. They include costs related to alumina purchasing, anode purchasing, power use, labour costs, maintenance costs – i.e. capital investment to maintain a production site current capacity – and any other relevant costs.
- *Steelmills*: Production site costs account for all costs incurred at the operating facility. They include raw material purchasing (e.g. iron ore and coal), power use, labour costs, maintenance costs – i.e. capital investment to maintain a production site current capacity. They do not include costs beyond the 'plant/mine gate' such as products transportation.

Power costs

- *Aluminium smelters*: Power costs account for all costs related to power generation and power purchase at the operating facility. The estimates are produced based on the local power price (including wheeling charges, distribution costs, and taxes, plus adjustments for state aid (e.g. EU ETS free permits) multiplied by power consumption at each production unit.
- *Steelmills*: Power costs account for all costs related to power generation and power purchase at the operating facility. The estimates are produced based on the local power price (including wheeling charges, distribution costs, and taxes, plus adjustments for state aid (e.g. EU ETS free permits)) multiplied by power consumption at each production unit. It also includes the costs of solid, liquid, and gaseous fuels used to produce power onsite (i.e. by-process gases produced in the BF-BOF and reused onsite).

Table A A.2 and Table A A.3 provide descriptive statistics and pairwise correlation for the variables of the constructed dataset. Table A A.2 shows the high standard deviation of government support variables relative to their means, highlighting the important heterogeneity in support distribution across firms. Table A A.3 highlights a strong correlation between production and power costs variables and between grants and BMB with total government support.

[38] For instance, if a firm owns 25% of a smelter, only 25% of this smelter's emissions will be attributed to this firm.

Table A A.2. Descriptive statistics

Variable	Observation	Mean	Standard deviation	Min	Max
ln(Emission)	882	9.58712	1.379878	3.109135	12.19819
ln(Production)	882	8.197777	1.790875	2.378858	11.45953
ln(Production Site Costs)	882	6.576769	0.8055108	5.365359	7.942384
ln(Power Costs)	882	5.513881	0.7632691	3.724668	7.086348
ln(Income Before Tax)	881	5.005695	2.598959	0	9.92779
ln(Returns on Asset)	857	0.03999	0.047231	0	0.294665
ln(Below Market Borrowing)	882	2.809219	2.701457	0	8.745638
ln(Grants)	882	1.78192	1.792465	0	6.533522
ln(Tax Break)	882	1.375369	1.729101	0	6.86787
ln(Total Government Support)	882	3.900488	2.178678	0	8.808323

Note: Reported values correspond to means, standard deviations, minimum and maximum of each variable of interest specified in the empirical strategy described in Annex B.
Source: Authors' calculations based on (OECD, 2021[5]) and CRU emissions analysis tool.

Table A A.3. Pairwise correlation table

	ln(Emission)	ln(Production)	ln(Site Cost)	ln(Power Cost)	ln(Income Before Tax)	ln(Returns on Asset)	ln(Below Market Borrowing)	ln(Grants)	ln(Tax Break)	ln(Total Government Support)
ln(Emission)	1									
ln(Production)	0.8878	1								
ln(Production Site Costs)	-0.5466	-0.7958	1							
ln(Power Costs)	-0.3842	-0.6956	0.8894	1						
ln(Income Before Tax)	0.2028	0.1944	-0.1104	-0.1356	1					
ln(Returns on Asset)	-0.1402	-0.0696	-0.0634	-0.1546	0.5057	1				
ln(Below Market Borrowing)	0.2942	0.1682	-0.0622	0.138	-0.0323	-0.2593	1			
ln(Grants)	0.2727	0.1574	-0.0046	0.1649	-0.0059	-0.2496	0.4844	1		
ln(Tax Break)	0.16	0.1407	0.001	-0.0685	0.2415	0.1253	-0.0264	0.0772	1	
ln(Total Government Support)	0.3663	0.2435	-0.0766	0.0742	0.043	-0.2439	0.8123	0.6689	0.3253	1

Note: Reported values correspond to correlation coefficients between each variable of interest specified in the empirical strategy described in Annex B.
Source: Authors' calculations based on (OECD, 2021[5]) and CRU emissions analysis tool.

Modelling analysis data

TiVA dataset

TiVA input-output tables forms the base of the analysis providing indicators for 66 economies including all OECD, EU and G20 countries, and a selection of East and Southeast Asian economies and South American countries. For each country and region TiVA covers 45 unique industrial sectors.[39] The data captures detailed sectoral and bilateral trade relationships and goods' and services' production chains, allowing to quantify the global impact of removing government support. Within the 45 sectors in TiVA steel and aluminium are aggregated into the ISIC Rev.4 industrial classification "basic metals". For this analysis this sector is split into three, basis metals, steel and aluminium. As steel and aluminium are important intermediate inputs in a range of sectors it is important to preserve this value chain detail for the

[39] For a guide to the TiVA database see Martins Guilhot, Webb and Yamano (2022[66]).

quantification of impacts. To split the TiVA data while preserving the value chain information the EXIOBASE input-output table is used.

EXIOBASE dataset

EXIOBASE is a global, detailed Multi-Regional Environmentally Extended and input-output table which is constructed for the analysis of environmental impacts associated with consumption of product groups.[40] EXIOBASE is older than TiVA with data from 2013 but it has more detail with 163 industries.[41] Importantly for this analysis this applies to the basic metals industry where steel and aluminium are each reported separately.[42] For each country/region and industry for intermediate and final goods the shares of steel and aluminium in basic metals are calculated in EXIOBASE and these shares are then used to split the rows and columns of the basic metals industry in TiVA. Though this use of two input-output tables the advantage of the more up to date data on production and trade volumes for a wider array of countries/regions in TIVA can be used for an analysis of steel and aluminium. EXIOBASE allows this split to be performed right the way through the value chain in TiVA.[43]

OECD carbon dioxide emissions embodied in international trade dataset

The data on CO_2 emissions by industry are taken as CO_2 emissions based on production from the OECD database on Carbon dioxide emissions embodied in international trade.[44] This database combines the OECD inter-country input-output database with statistics on CO_2 emissions from fuel combustion and other industry statistics to estimate demand-based carbon dioxide emissions. It provides a measure of the distribution across economies of final demand for embodied carbon that has been emitted anywhere in the world, along global production chains. This database has the same industry detail and timeframe as TiVA and so can be used to quantify the emission changes that could result from a change in production in the subsidies removal scenario.

As with production and trade, emissions of iron and steel are not reported separately. They are amalgamated in basic metals and EXIOBASE is used to recover the emissions shares of steel and aluminium. EXIOBASE contains extensive environmental data with 417 emission categories for 163 industries. Six categories of CO_2 emissions are combined by country/region and industry and aggregated to TiVA sectors.[45] This emission and industry level detail is used to split both steel and aluminium emissions out from basic metals for each country/region and industry in TiVA.

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[40] For a guide to EXIOBASE see Tukker et al. (2014[67]). EXIOBASE contains 44 countries, 5 Rest of World regions.

[41] Industries in EXIOBASE are classified by NACE codes, in TiVA the classification is by ISIC codes. The industries in EXIOBASE are aggregated into TiVA industries using correspondence tables.

[42] For details on the basic metals industry in EXIOBASE and the split of the basic metals industry, see Table A D.1 in Annex D. TiVA contains more countries/region than EXIOBASE, for those not present in EXIOBASE the TIVA split is based on that of a regional aggregate in EXIOBASE. See Table A D.2 in Annex D.

[43] This split assumes that the share of steel and aluminium in basic metals and its use in each industry, in different industry and countries/regions, is constant over the different time points in TiVA and EXIOBASE. In TiVA the time point is 2018, in EXIOBASE it is 2013.

[44] For more detail on the database, see Yamano and Guilhoto (2020[68]).

[45] The six categories are, CO_2 - combustion, non-combustion - Cement production, non-combustion - Lime production, agriculture - peat decay, waste – biogenic and waste – fossil. This split assumes that the share of CO_2 emissions from steel and aluminium in basic metals in different sectors and countries/regions is constant over the different time points in TiVA and EXIOBASE.

Annex B. Empirical strategy

Estimating the effect of government support on production (scale effect)

To estimate the effect of received government support on firms' production, the following equation is regressed:

$$\begin{aligned} Production_{ist} = {} & \alpha + \beta\, Support_{ist} + \gamma\, Income_{ist} + \delta\, ROA_{ist} \\ & + \nu\, Costs_{ist} + \mu_i + \lambda_{st} + \varepsilon_{ist} \end{aligned} \quad (1)$$

where $Production_{ist}$ denotes production (in kt of crude steel or aluminium) of firm *i* in sector *s* and year *t*; $Support_{ist}$ is the government support received by that same firm (in million USD), which can be in the form of tax concessions, grants or below-market borrowings, included separately or summed as total government support depending on the specification; $Income_{ist}$ is the income before tax (in million USD) of firm *i* in sector *s* at year *t*; ROA_{ist} is the return on assets ratio of firm *i* in sector *s* at year *t*; $Costs_{ist}$ is either the production site costs or power costs (in USD/t of primary aluminium or crude steel) depending on the regression specification – faced by firm *i* in sector *s* and year *t*; μ_i and λ_{st} are firm and paired sector-year dummies, respectively; and ε_{ist} is an error term. As these regressions include firm-level and paired sector-year-level fixed effects, all time invariant unobservable characteristics at the firm and sector-year level are controlled. Standard errors are clustered by firm.

The inclusion of $Income_{ist}$ and ROA_{ist} allow to respectively control for firms' size and profitability, which are likely correlated with firms' production. Firms' production site costs and firms' power costs (measured in USD/t of primary aluminium or crude steel) are also included in regressions because these two variables are potentially correlated with firms' production output. In addition, firms' power costs partly capture the environmental policy stringency faced by firms as power prices are accounted for by taxes. Hence the importance to control for all these variables to limit the influence of confounding factors in regressions results.

The estimated parameter β consequently captures the effect of government support on production holding the size, the profitability, and the production efficiency of firms constant.

Robustness checks were conducted using lagged values of government support in t-1 and in t-2. Results are found to be similar to those reported in Table 1 – Table A C.1 and Table A C.2 in Annex C.

Estimating the effect of government support on production depending on initial emission intensity (composition effect)

To estimate the effect of received government support on firms' production depending on initial emission intensity, the following equation is regressed:

$$\begin{aligned} Production_{ist} = {} & \alpha + \beta\, Support_{ist} + \delta\, IEI_{is} + \theta\, IEI_{is}\, Support_{ist} \\ & + \gamma\, Income_{ist} + \delta\, ROA_{ist} + \nu\, Costs_{ist} + \mu_i + \lambda_{st} + \varepsilon_{ist} \end{aligned} \quad (2)$$

where each variable is the same as above and IEI_{is} is a dummy variable indicating that the initial emission intensity (in tCO_2e/t of production (primary aluminium or crude steel)) of firm i in sector s and year 2006 is higher than the median emission intensity of all firms in sector s and year 2006. Standard errors are clustered by firm.

Robustness checks were conducted using lagged values of government support in t-1 and in t-2. Results are found to be similar to those reported in Table 2 – Table A C.3 and Table A C.4 in Annex C.

Estimating the effect of government support on emissions intensity (technique effect)

To estimate the effect of received government support on firms' emissions intensity, the following equation is regressed:

$$Emissions_{ist} = \alpha + \beta\ Support_{ist} + \gamma\ Production_{ist} + \gamma\ Income_{ist} + \delta\ ROA_{ist} + \nu\ Costs_{ist} + \mu_i + \lambda_{st} + \varepsilon_{ist} \quad (3)$$

where each variable is the same as above and $Emissions_{ist}$ denotes emissions (in tCO_2e) of firm *i* in sector *s* and year *t*. Standard errors are clustered by firm.

The inclusion of $Production_{ist}$ allows to control for the output of the firm and to estimate the effect of government support on emissions disentangled from its effect through $Production_{ist}$ estimated by equation (1) (and reported in Table 1). The estimated parameter β consequently captures the effect of government support on emissions holding the output of firms constant. In other words, β captures the effect of government support on emissions intensity as measured by the emissions-to-production ratio.

Robustness checks were conducted using lagged values of government support in t-1 and in t-2. Results are found to be similar to those reported in Table 3– Table A C.5 and Table A C.6 in Annex C.

Annex C. Robustness checks

Scale effect

Table A C.1. Impact of government support in t-1 on firm-level production in t

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs) *t-1*	0.240				
	(0.304)				
ln(Power Costs) *t-1*		0.0497	0.0245	0.0473	0.0731
		(0.149)	(0.151)	(0.148)	(0.150)
ln(Returns on Asset) *t-1*	-0.362	-0.374	-0.295	-0.376	-0.363
	(0.483)	(0.495)	(0.517)	(0.521)	(0.482)
ln(Income Before Tax) *t-1*	0.0105*	0.0104*	0.0117*	0.0128**	0.00833
	(0.00586)	(0.00585)	(0.00617)	(0.00611)	(0.00626)
ln(Total Government Support) *t-1*	0.0447**	0.0445**			
	(0.0185)	(0.0187)			
ln(Below Market Borrowing) *t-1*			0.0279*		
			(0.0149)		
ln(Grants) *t-1*				0.0270	
				(0.0175)	
ln(Tax Break) *t-1*					0.0477**
					(0.0189)
Observations	783	783	783	783	783
R-squared	0.980	0.980	0.980	0.980	0.980

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Table A C.2. Impact of government support in t-2 on firm-level production in t

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs) *t-2*	0.273				
	(0.287)				
ln(Power Costs) *t-2*		0.0258	-0.00240	0.0283	0.0566
		(0.117)	(0.116)	(0.114)	(0.118)
ln(Returns on Asset) *t-2*	-0.275	-0.284	-0.172	-0.321	-0.317
	(0.454)	(0.461)	(0.476)	(0.504)	(0.466)
ln(Income Before Tax) *t-2*	0.00730	0.00702	0.00743	0.00999*	0.00724
	(0.00517)	(0.00519)	(0.00552)	(0.00566)	(0.00574)
ln(Total Government Support) *t-2*	0.0423**	0.0421**			
	(0.0168)	(0.0170)			
ln(Below Market Borrowing) *t-2*			0.0278**		
			(0.0132)		
ln(Grants) *t-2*				0.0214	
				(0.0155)	
ln(Tax Break) *t-2*					0.0344**
					(0.0164)
Observations	719	719	719	719	719
R-squared	0.984	0.984	0.984	0.983	0.984

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Composition effect

Table A C.3. Impact of government support in t-1 on firm-level production in t depending on initial emission intensity

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs) *t-1*	0.164				
	(0.269)				
ln(Power Costs) *t-1*		0.0146	0.0187	-0.0562	0.0515
		(0.134)	(0.150)	(0.128)	(0.146)
ln(Returns on Asset) *t-1*	-0.196	-0.207	-0.202	-0.426	-0.354
	(0.435)	(0.440)	(0.499)	(0.480)	(0.451)
ln(Income Before Tax) *t-1*	0.00874	0.00863	0.0107*	0.0108*	0.00936
	(0.00549)	(0.00549)	(0.00617)	(0.00587)	(0.00636)
Initial top 50% emissions-intensive firms = o,	0	0	0	0	0
	(0)	(0)	(0)	(0)	(0)
ln(Total Government Support) *t-1*	0.00227	0.00189			
	(0.0192)	(0.0193)			
Initial top 50% emissions-intensive firms x ln(Total Government Support) *t-1*	0.150***	0.151***			
	(0.0432)	(0.0430)			
ln(Below Market Borrowing) *t-1*			0.0167		
			(0.0164)		
Initial top 50% emissions-intensive firms x ln(Below Market Borrowing) *t-1*			0.0300		
			(0.0343)		
ln(Grants) *t-1*				-0.0551**	
				(0.0218)	
Initial top 50% emissions-intensive firms x ln(Grants) *t-1*				0.142***	
				(0.0311)	
ln(Tax Break) *t-1*					0.00515
					(0.0233)
Initial top 50% emissions-intensive firms x ln(Tax Break) *t-1*					0.0861**
					(0.0420)
Observations	783	783	783	783	783
R-squared	0.982	0.982	0.980	0.981	0.981

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Table A C.4. Impact of government support in t-2 on firm-level production in t depending on initial emission intensity

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Production)	ln(Production)	ln(Production)	ln(Production)	ln(Production)
ln(Production Site Costs) *t-2*	0.192				
	(0.256)				
ln(Power Costs) *t-2*		-0.00480	-0.00379	-0.0660	0.0378
		(0.110)	(0.117)	(0.105)	(0.118)
ln(Returns on Asset) *t-2*	-0.178	-0.185	-0.154	-0.416	-0.302
	(0.423)	(0.422)	(0.466)	(0.474)	(0.442)
ln(Income Before Tax) *t-2*	0.00654	0.00634	0.00719	0.00915	0.00857
	(0.00503)	(0.00502)	(0.00550)	(0.00574)	(0.00586)
Initial top 50% emissions-intensive firms = o,	0	0	0	0	0
	(0)	(0)	(0)	(0)	(0)
ln(Total Government Support) *t-2*	0.00723	0.00663			
	(0.0158)	(0.0157)			
Initial top 50% emissions-intensive firms x ln(Total Government Support) *t-2*	0.125***	0.127***			
	(0.0393)	(0.0394)			
ln(Below Market Borrowing) *t-2*			0.0250		
			(0.0153)		
Initial top 50% emissions-intensive firms x ln(Below Market Borrowing) *t-2*			0.00767		
			(0.0304)		
ln(Grants) *t-2*				-0.0508***	
				(0.0191)	
Initial top 50% emissions-intensive firms x ln(Grants) *t-2*				0.126***	
				(0.0291)	
ln(Tax Break) *t-2*					-0.00247
					(0.0216)
Initial top 50% emissions-intensive firms x ln(Tax Break) *t-2*					0.0760**
					(0.0362)
Observations	719	719	719	719	719
R-squared	0.985	0.985	0.984	0.985	0.984

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Technique effect

Table A C.5. Impact of government support in t-1 on firm-level emissions in t

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)
ln(Production) *t-1*	0.627***	0.627***	0.620***	0.623***	0.627***
	(0.0881)	(0.0889)	(0.0882)	(0.0897)	(0.0880)
ln(Production Site Costs) *t-1*	0.368*				
	(0.207)				
ln(Power Costs) *t-1*		0.0480	0.0381	0.0458	0.0460
		(0.0983)	(0.100)	(0.0980)	(0.0986)
ln(Returns on Asset) *t-1*	-0.851***	-0.875***	-0.880***	-0.889***	-0.877***
	(0.262)	(0.271)	(0.260)	(0.281)	(0.265)
ln(Income Before Tax) *t-1*	0.00399	0.00376	0.00338	0.00360	0.00389
	(0.00309)	(0.00300)	(0.00301)	(0.00299)	(0.00324)
ln(Total Government Support) *t-1*	-0.00385	-0.00410			
	(0.00817)	(0.00839)			
ln(Below Market Borrowing) *t-1*			0.00703		
			(0.00773)		
ln(Grants) *t-1*				0.00247	
				(0.00961)	
ln(Tax Break) *t-1*					-0.00384
					(0.0108)
Observations	783	783	783	783	783
R-squared	0.984	0.984	0.984	0.984	0.984

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Table A C.6. Impact of government support in t-2 on firm-level emissions in t

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)	ln(Emission)
ln(Production) *t-2*	0.461***	0.462***	0.458***	0.460***	0.461***
	(0.0823)	(0.0830)	(0.0826)	(0.0833)	(0.0841)
ln(Production Site Costs) *t-2*	0.330				
	(0.216)				
ln(Power Costs) *t-2*		0.0165	0.00811	0.0129	0.0169
		(0.101)	(0.103)	(0.0992)	(0.103)
ln(Returns on Asset) *t-2*	-0.828***	-0.840***	-0.822***	-0.857***	-0.842***
	(0.294)	(0.296)	(0.288)	(0.309)	(0.292)
ln(Income Before Tax) *t-2*	0.00445	0.00411	0.00373	0.00425	0.00404
	(0.00339)	(0.00337)	(0.00341)	(0.00331)	(0.00346)
ln(Total Government Support) *t-2*	0.000117	-0.000125			
	(0.0102)	(0.0103)			
ln(Below Market Borrowing) *t-2*			0.00536		
			(0.00836)		
ln(Grants) *t-2*				0.00595	
				(0.0133)	
ln(Tax Break) *t-2*					0.00104
					(0.0112)
Observations	719	719	719	719	719
R-squared	0.982	0.982	0.982	0.982	0.982

Note 1: All results are from the panel fixed-effect model specification described in Annex B, conducted on a panel of 68 firms - 37 in steel and 31 in aluminium - between 2006 and 2021. All regressions include firm and paired sector-year fixed effects.
Note 2: Robust standard errors in parentheses clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1.

Annex D. Modelling analysis framework

The Ghosh model

To estimate the counterfactual amounts of production and emissions without government support, the following Ghosh model formula is used:

$$\mathrm{Z} = \begin{pmatrix} \mathrm{z}_{11} & \cdots & \mathrm{z}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{z}_{n1} & \cdots & \mathrm{z}_{nn} \end{pmatrix}, \ \mathrm{x} = \begin{pmatrix} \mathrm{x} \\ \vdots \\ \mathrm{x}_{n} \end{pmatrix}, \ \mathrm{S} = \begin{pmatrix} \mathrm{s}_{1} \\ \vdots \\ \mathrm{s}_{n} \end{pmatrix}, \ \mathrm{C} = \begin{pmatrix} \mathrm{c}_{1} \\ \vdots \\ \mathrm{c}_{n} \end{pmatrix}$$

where Z is a square matrix with n rows and n columns, n corresponding to the number of countries/regions multiplied by the number of sectors ($n = 3149$ in this model, as there are 67 countries/regions and 47 sectors); x is a vector of output for each sector in each country/region; S is a shock vector of output reductions to implement the subsidy reduction scenario; and C is a vector of CO_2 emissions for each sector in each region/country; following the notation in (Miller and Blair, 2009[51]).

To compute the output in the scenario without government support, the following expression is used:

$$B = \hat{x}^{-1}\mathrm{Z}$$

where B is the direct-output coefficient matrix.

The subsidy scenario is then calculated as:

$$\Delta x = G'S$$

where, $G = (I - B)^{-1}$, is the output inverse.

Once the output changes are calculated, C is used to calculate the CO_2 implications.

The firm-level combination of datasets on government support and on emissions yields estimate of the elasticity of production in steel and aluminium with respect to government support. This estimate is converted to level changes at the point of the means to calibrate the illustrative support reduction scenario. Each country in the database will have a different level of government support, and so the reduction in output will vary.[46] This will enter the input-output model as a shock to the level of production.

[46] See Figures 17 and 18 for a country comparison.

Matching TiVA and EXIOBASE data

Table A D.1. Basic metals in EXIOBASE

Manufacture of basic iron and steel and of ferro-alloys and first products thereof
Re-processing of secondary steel into new steel
Precious metals production
Re-processing of secondary precious metals into new precious metals
Aluminum production
Re-processing of secondary aluminum into new aluminum
Lead, zinc and tin production
Re-processing of secondary lead into new lead, zinc and tin
Copper production
Re-processing of secondary copper into new copper
Other non-ferrous metal production
Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
Casting of metals

Note: For steel, manufacture of basic iron and steel and of ferro-alloys and first products thereof and re-processing of secondary steel into new steel are combined. For Aluminium, aluminium production is used. These are taken as shares of basic metals which included all sectors listed.
Source: Exiobase.

Table A D.2. Regional aggregates applied to TiVA countries

TiVA	EXIOBASE
Chile	America
Colombia	America
Costa Rica	America
Iceland	Europe
Israel	Middle East
New Zealand	Asia Pacific
Argentina	America
Brunei Darussalam	Africa
Cambodia	Africa
Hong Kong, China	Asia Pacific
Kazakhstan	Middle East
Lao People's Democratic Rep	Asia Pacific
Malaysia	Asia Pacific
Morocco	Africa
Myanmar	Africa
Peru	America
Philippines	Asia Pacific
Saudi Arabia	Middle east
Singapore	Asia Pacific
Thailand	Asia Pacific
Tunisia	Africa
Viet Nam	Asia Pacific

Note: For the rest of the world region in TiVA aggregate shares are constructed from the regions in EXIOBASE. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities or third party. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.
Source: TiVA and Exiobase.

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Comments are welcome and can be sent to tad.contact@oecd.org.