Energy Policy 198 (2025) 114507

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Competition and climate policy in the steel transition: Comparing costs and subsidies in the US and the EU

Jonas Algers [a,*], Jindan Gong [b], Björn Nykvist [c], Max Åhman [a]

[a] Environmental and Energy Systems Studies, Lund University, Klas Anshelms väg 14, 22363, Lund, Sweden
[b] Stockholm Environment Institute, Linnégatan 87D, 104 51, Sweden
[c] Stockholm Environment Institute, Linnégatan 87D, 104 51, Sweden

ABSTRACT

The nexus of climate policy and "competitiveness"—how to transition to clean energy while ensuring a competitive economy—is a concern on both sides of the Atlantic. In the United States and the European Union, there has been an attempt to resolve the issue by turning towards green industrial policy and subsidies for low-carbon production, sparking a debate on the merits and risks of a 'subsidy race'. In this paper, we conduct a transparent and quantified study of how subsidies affect the cost of low-carbon steelmaking as a case of industrial policy in a low-carbon transition. We first map subsidy intervention points across the steel supply chain in the US and the EU, showing how subsidies can cumulate over several segments. Afterwards, we use a bottom-up techno-economic model to quantify and compare subsidies with cost components including raw materials, energy, and labour costs in four hypothetical cases in Ohio, West Virginia, Germany, and Spain. We discuss the subsidy regimes and conclude that there is a dilemma between an equal policy playing field and rapid action on climate change.

## 1. Introduction: the nexus of climate and competition policy

The nexus of climate policy and economic 'competitiveness' is at the centre of political and academic debate. The passage of Inflation Reduction Act (IRA), with its subsidies for green tech in the United States, and the introduction of the Carbon Border Adjustment Mechanism (CBAM) to price carbon imports in the EU has raised concerns of both geopolitical rivalry and potential industrial relocation as a consequence of the low-carbon transition. This nexus is an important issue in both the 2024 US and EU elections, as parties on both sides of the Atlantic position themselves for or against climate policy based on how they perceive it to affect their respective countries' international competitiveness.

The nexus is also an academic point of contention. While earlier studies have focused on how carbon pricing negatively affects competitiveness (see, for example, Bassi et al., 2009; Okereke and McDaniels, 2012), there has recently been an increasing interest in whether green industrial policy can support emission reductions and boost competitiveness (see, for example, Rodrik, 2015; Veugelers et al., 2024). Meanwhile, the energy systems literature has studied how low-cost renewable energy will provide cost advantages for energy-intensive industries located in renewable-rich regions. Samadi et al. (2023) write: "due to the increasing competitiveness of renewables, regional differences in both the availability and marginal costs of green energy sources could become an important factor in the decisions made by companies about where to locate or relocate their businesses". However, the combined effect of the recent increase in industrial policy and difference in renewable energy costs on cost-competitiveness has not been empirically studied.

In this article, we provide the first such empirical study of the relationship of contemporary green industrial policy, renewable energy, and international cost-competitiveness in the US and the EU. We use the steel industry as a case, due to its energy intensity and importance for downstream sectors. The steel industry is very carbon-intensive. Today, the industry produces about 7–10 percent of total global carbon emissions—second only to the petrochemical industry among heavy industry sectors (International Energy Agency, 2019). Due to long investment cycles, a strong and rapid push away from the current emission-intensive blast furnace production route is needed (Wesseling et al., 2017; Vogl et al., 2021). Scrap-based steelmaking is much less carbon-intensive and is widely used in both the US and the EU, but due to scrap availability and quality requirements for key steel segments such as automotive parts and machinery, decarbonised primary steelmaking is necessary. The alternative low-carbon primary steelmaking technology that has seen the most interest from steelmakers and analysts alike is hydrogen direct reduction (H-DR) (Bataille et al., 2018; Swalec and Grigsby-Schulte, 2023; Vogl et al., 2018, 2023). This technology uses hydrogen produced from clean energy to reduce iron ore, which is then

* Corresponding author.
E-mail address: jonas.algers@miljo.lth.se (J. Algers).

https://doi.org/10.1016/j.enpol.2025.114507
Received 22 July 2024; Received in revised form 17 January 2025; Accepted 17 January 2025
Available online 27 January 2025

melted, usually in an Electric Arc Furnace (EAF), and this steelmaking route is accordingly called H-DR-EAF. However, the process requires large amounts of hydrogen produced from clean energy sources, and therefore several recent studies have analysed how renewable energy cost differentials across geographic space will provide competitive advantages in the low-carbon era, giving rise to the so-called "renewables-pull hypothesis" (Devlin and Yang, 2022; Samadi et al., 2023; Verpoort et al., 2023).

Green industrial policies have been introduced in the US and the EU, in part with the explicit aim of improving the competitiveness of domestic industries. Proponents of green industrial policy argue that provisions for domestic green industrial development have been 'critical'; both to drive investment in new, low-carbon tech, and for the political feasibility of climate policy (Kaufman et al., 2023). By supporting domestic low-carbon industries, climate policy can create a political feedback loop that strengthens political coalitions in favour of stronger climate policy (Breetz et al., 2018; Meckling et al., 2015; Stokes and Warshaw, 2017). However, previous studies have not quantified and compared the relative role of industrial policy—such as the subsidies provided for low-carbon steel production in the US and the EU—with other cost components such as renewable energy. The renewables-pull literature has studied how natural endowments and value chain optimisation will create new comparative advantages and lead to the relocation of steelmaking in a low-carbon transition. But while access to renewables may attract investment in low-carbon steelmaking, the literature has not accounted for how incumbent steelmaking countries may introduce various forms of industrial policy to countervail this tendency.

In this study, we outline the first comparison between the role of such natural endowments and the contribution of subsidies to the cost of future steelmaking. With this as a background, we discuss how industrial path dependence may lead to persistent patterns of industrial location when initial subsidies are phased out, granting long-term advantages to countries with the fiscal capacity for industrial subsidies in the early development of the green steel industry. We do not study profitability or firm-level competition, and therefore make no claim on what location will have more competitive steel firms.

The article is structured as follows: we first review the literature on competitiveness and industrial policy, and renewables-driven industrial relocation. Second, we map and compare the subsidy regimes of the United States and the European Union across the supply chain of low-carbon steel. Third, we use a transparent, bottom-up techno-economic model to study the interplay of renewable energy, subsidies, and other cost components on the costs of low-carbon steelmaking. Finally, we discuss the results, the limitations of our study, and avenues for future research.

## 2. Theoretical background

In the following section, we discuss the nexus of climate policy and competitiveness by reviewing and making connections between the bodies of literature on industrial relocation, competitiveness, and green industrial policy.

Industrial competitiveness is affected to a high degree by the cost of inputs. The renewables-pull hypothesis states that cost advantages will lead to sites with good renewable electricity potentials, increasingly pulling investment in industrial production. As coking coal is replaced with hydrogen in the iron- and steelmaking process, steel companies will be incentivised to relocate to sites where they can access large amounts of hydrogen (Verpoort et al., 2023). The falling cost of renewable electricity generation has raised expectations that hydrogen-based steelmaking will soon become cost-competitive, with conventional steelmaking in ideal locations and worldwide by 2050 (Devlin et al., 2023). These studies use bottom-up models, optimising industrial location based on natural endowments; primarily renewable energy. However, these studies do not always transparently present the composition of cost components. Labour costs remain a key cost differential across countries but its impact is understudied, energy costs assumptions, that often drive results differ greatly across studies, and system boundaries and technology choices differ, making comparisons across regions difficult or partial.

Policy will also play an important role in the low-carbon transition. As the switch from fossil to renewable energy entail a deep, structural change in selected industries, recent years has seen a surge of interest in green industrial policy (Aiginger and Rodrik, 2019; Criscuolo and Lalanne, 2024; Juhász et al., 2024; Meckling and Allan, 2020; Meckling et al., 2015; Nilsson et al., 2021; Rodrik, 2015). The definition of industrial policy differs in the literature. On the one side, Juhász et al., 2024 define industrial policy as "government policies that explicitly target the transformation of the structure of economic activity in pursuit of some public goal. (…) Since industrial policy targets structural change, a key characteristic is the exercise of choice and discretion by public authorities: 'we promote X but not Y,' although the later part of this statement is typically left implicit" (Juhász et al., 2024, p. 4); i.e., interventions targeting the *transformation* of *select* industries. In contrast, industrial policy can also be defined broadly. As Rodrik and Stiglitz (Rodrik and Stiglitz, 2024, p. 16) write: "all government policies, either by commission or omission, shape the economy and affect economic growth. In that sense, every country has an industrial policy—it's just that some don't know it". A broad definition allows for a separation between transformation-oriented industrial policy on the one hand, which aims to change industrial structures, and protectionist industrial policy, which aims to retain and protect existing industries (Aiginger and Rodrik, 2019; Nilsson et al., 2021). In this paper, we define 'industrial policy' as any policy intervention that alters the cost of steelmaking in a defined jurisdiction, no matter whether the aim is protectionist or transformational. The instruments used to implement industrial policy also can take many forms, and we choose to focus on subsidies in the model. Subsidies have a direct and quantifiable effect on production costs, making them easier to model. Subsidies have also been the most controversial element of the recent green industrial policy push.

Through industrial policy, policymakers can 'construct' comparative advantages in specific industries and shape competitiveness beyond what is given by natural endowments (Auty, 1991; Evans, 1995). As Peter Evans wrote in his classic piece, *Embedded Autonomy,* "[i]n a globalised economy where most value is added at several removes from natural resources, the global division of labour presents itself as an opportunity for agency, not just an exogenous constraint" (Evans, 1995, p. 8). The steel industry is associated with long investment cycles and strong lock-in effects (Algers and Åhman, 2024; Wesseling et al., 2017). Related infrastructure in the form of power lines, rail tracks, and ports, established upstream and downstream supply chains, and a trained labour force creates benefits for existing steel plants. The large capital costs in the industry create both barriers to entry and barriers to exit (Algers and Åhman, 2024). Green industrial policy can thus break with carbon lock-in by setting a new sustainable direction for industrial development (Mazzucato, 2016; Nilsson et al., 2021; Unruh, 2000). Strong but temporary support may therefore provide permanent benefits for low-carbon steelmakers in given jurisdictions over latecomers.

Previous studies have shown how subsidies in the IRA lower the cost of power production and increase growth (Arkolakis and Walsh, 2023), but there has not been any peer-reviewed study on the role of subsidies in lowering the cost of steel. Analyses by Rethink Energy and BNEF have indicated that these interventions significantly improve the competitiveness of the US domestic steel industry by lowering the costs of (low-carbon) steelmaking (Collins, 2023a,b-a).

Another important element of green industrial policy is political sustainability. By supporting domestic industrial development, industrial policies can create political constituencies and coalitions in favour of more climate action (Meckling et al., 2015). Green industrial policy can also be part of 'green bargains', in which carrots for politically popular industrial development are coordinated with corresponding and politically costly sticks (Meckling et al., 2017; Meckling and Strecker, 2022; Algers and Åhman, 2024). According to the US Bureau of Labor Statistics, wages in the solar and wind industries are lower than they are in comparable jobs in fossil and nuclear industries, which may undermine political support for a green energy transition (McCormick, 2022). To boost the political sustainability of climate action, the IRA includes conditionalities to demand that recipients of subsidies meet certain conditions, such as providing opportunities for communities currently dependent on fossil fuels called 'energy communities' and paying so-called 'prevailing wages'; i.e. wages that are not lower than the industry standard for a region (Reynolds, 2024).

However, while labour remuneration can be important for the political sustainability of industrial transitions (Burgess et al., 2024; Greco, 2022; Grubert and Hastings-Simon, 2022; Meckling et al., 2015; Stokes and Warshaw, 2017), labour costs are also an important factor for both the cost of industrial production and industrial location (Auty, 1991; D'Costa, 1994; Milberg and Houston, 2005; Moore, 1987; Walker and Storper, 1981). Historically, increasing labour productivity or repressing wages have been forms of industrial policy intended to increase industries' competitiveness (Milberg and Houston, 2005), and lower the costs of transformational technologies (Breetz et al., 2018). Japan is a classic example, where state-ensured investment in certain technologies and innovation is intended to increase productivity (Lynn, 1981), but also supresses wages (Moore, 1987). As formulated by political economist Robert Wade, "the [Japanese] state dominated in state–capital relations, and the state helped capital to dominate in capital–labour relations" (Wade, 2018, p. 529).

Ensuring positive labour outcomes can be important for the political sustainability of climate policy, but such provisions could lead to higher labour costs. The role of labour provisions on total costs has previously been studied in relation to renewable energy (Mayfield et al., 2023), but the relationship has not been studied in the steel sector. This study is the first in which labour provisions are analysed as part of a green industrial policy for the energy-intensive industry.

## 3. Methodology

In the following empirical section, we first review the relevant policy landscapes in the US and the EU. We have first mapped the subsidy regimes by consulting websites and press releases from the White House, the Department of Energy, and the European Commission. We selected four hypothetical cases to illustrate and analyse cost differentials across different subsidy regimes, renewable energy endowments, and labour costs. We also wanted to build our cases on the available information on subsidies. We therefore chose Ohio (case 1) and West Virginia (case 2) in the US in order to compare two contexts with the same subsidy regime but different labour costs reflecting costs in a unionised plant in Ohio versus costs in the right-to-work state of West Virginia. We chose Germany (case 3) and Spain (case 4) as our European cases, as the two countries have very different renewable energy endowments and labour costs, but both have granted state aid for low-carbon steelmaking.

We use a bottom-up techno-economic model to estimate the levelised cost of steelmaking (LCOS) across selected jurisdictions. Our supply chain specification for the different cases is the same for the US and EU, assuming integrated production of molten steel in all cases. We estimate labour costs based on the average steelworker wage in each case. The modelled wages in Case 1 stem from a labour agreement between USW and Cleveland-Cliffs (United Steelworkers, 2022). The modelled wages in Case 2 represent annual mean wages for metal-refining furnace operators and tenders in West Virginia, a right-to-work state with a non-union Nucor steel plant (Global Energy Monitor, 2024). For cases 3 and 4, data on wages and salaries paid to employees, and number of employees in the basic iron and steel sector were obtained from UNIDO (2024). Energy costs are estimated according to case-specific electricity rates. Our modelled rates are based on the work of Fasihi and Breyer (2020) and their region-specific 2030 projections of levelized costs of baseload electricity (LCOBLEL). In our analysis, we assume that this baseload electricity is primarily sourced from large-scale, grid-connected renewable energy systems. The specific locations used for retrieving baseload LCOBLEL data represent the location of H-DRI project and existing steel plants. For a more thorough review of the methodology, please see the appendix.

We assumed that a new steel plant of the same capacity is built in the four cases, and model costs such as resources, renewable energy, and labour, as well as subsidies based on existing announcements for existing projects in the relevant jurisdictions.

## 4. Mapping of subsidy regimes

The American and European steel subsidy systems are different, reflecting the sovereignty of European member states collaborating within the European Union compared to the centralised structure of the federal US government.

The current United States subsidy system is comprehensive.[1] The Inflation Reduction Act (IRA) of 2022 provides an array of subsidies and incentives for key steps of the low-carbon steel supply chain, primarily in the form of 'tax credits', as it was passed as a budgetary reconciliation bill to allow it to pass with only 51 votes in the US senate, not the 60 votes required for normal bills. It provides a Clean Electricity Investment Tax Credit (CEITC) of 6% of the investment, which increases to 30% if it meets prevailing wage and apprenticeship requirements. Right-to-work legislation does not preclude meeting prevailing wage conditionalities in the IRA. An additional 10 percentage points are added if it meets domestic content requirements and another 10 percentage points are added if it is located in an "energy community". Second, the IRA provides a Renewable Energy Production Tax Credit (REPTC) of up to ¢ 2.75/KWh for renewable energy. Third, there is an Advanced Energy Project Credit of up to 30% of the investment, as well as a Hydrogen Production Tax Credit of up to $3/kg hydrogen, in which the full subsidy requires prevailing wage and apprenticeship requirements be met. And finally, the IRA funds the Industrial Demonstrations Program, which has provided $500 million for one hydrogen-based steelmaking facility (Office of clean energy demonstrations, 2024). In our modelling, we include this project funding to show how important this contribution is to the cost of steelmaking, though we are aware that it is unlikely that all steelmakers will receive the same level of funding. The subsidies are 'stackable'; i.e., they can be added on top of each other—aside from the investment and production tax credits for clean energy and the AEPC and HPTC for hydrogen. We only model the production tax credits, as these lead to larger cost reductions than the investment tax credits.

The European Union—which notably was established as the European Coal and Steel Community (ECSC) in 1952—has grown into an organisation that is increasingly responsible for the coordination of strategic industrial development across sectors (Veugelers et al., 2024); that is, a horizontal approach to industrial policy based on strengthening the internal market and ensuring fair competition across and within the EU (Zurstrassen, 2022). Targeted state aid has therefore not been allowed, as it would unfairly benefit some actors over others and risk leading to an internal subsidy race. However, due to the ambition for a low-carbon transition in the EU, the European Commission has opened up exemptions to this rule through the 2021 Guidelines on State aid for Climate, Environmental Protection, and Energy (European Commission, 2021). EU member states can therefore provide state aid directly, and have done so in both Spain and Germany. Both countries have provided national state aid for the construction of low-carbon iron and steel

[1] Please note that while this compilation focuses on federal funding, there are several additional state and local-level subsidy schemes. We have chosen to exclude these, as they differ across states and/or are not available *ex ante* to all applicants.

facilities. The EU also has the Innovation Fund, which funds innovative flagship projects. So far, this mechanism has funded low-carbon steel demonstration projects, but not in the countries we study, and its mandate is limited to early projects. We do not therefore include support from the Innovation Fund in the compilation.

Hydrogen is a key input in low-carbon steelmaking, and national state aid has also been provided in EU member states, approved through a project coordination system called the Important Project of Common European Interest (IPCEI). In addition to these CAPEX and investment subsidies, a third intervention available in the EU is OPEX support through a Hydrogen Bank for hydrogen in a competitive bidding process for a fixed premium in €/kg hydrogen produced. In the first auction, €0.48/kg hydrogen was made available, and we assume this in our study. The EU targets an annual production of 10 million tonnes plus another 10 million to be imported. However, support under the Hydrogen Bank cannot be combined with national state aid from member states; at least not in the first bidding process (Collins, 2023a, b-b), and most of the EU subsidies are therefore not 'stackable'. The relationship between EU-level support and national state aid is a major tension in the EU, as an EU-level industrial policy would require centralising both funding and political power to Brussels. National state aid, on the other hand, risks fragmenting the EU single market, where larger member states are able to provide more funding (Kleimann et al., 2023; Veugelers et al., 2024).

EU member states also provide substantial subsidies for renewable energy, which reached €80 bn or about 0.57% of total EU GDP in 2020 (Kleimann et al., 2023). The EU and its member states have provided and are providing a variety of subsidies and interventions for low-carbon electricity, including feed-in-tariffs and contracts-for-difference for offshore wind, and these are some of the most substantial green industrial policies in EU member states (Criscuolo and Lalanne, 2024). However, power pricing in the EU is granted via marginal pricing, and therefore these volume-based subsidies have an indirect effect on power prices. There is also evidence that the effect of such subsidies on power prices remains low (Trujillo-Baute et al., 2018). It is forbidden to give a direct subsidy per kWh to industries in the EU, as this would be a violation of the level playing field of the single market. We therefore cannot assume a given subsidy per kWh of renewable energy in Spain nor in Germany, and we therefore do not consider the effects of subsidies for renewable energy production on either of these cases in our model, although we acknowledge such subsidies are provided in the EU. In Table 1, we have compiled the subsidies and the values we include in our model. In Fig. 1, we have compiled the relevant subsidies along the supply chain for hydrogen-based steelmaking in the EU and the US. In contrast to the US subsidy regime, the EU does not attach conditionalities for labour standards, energy communities, or domestic content to subsidies for low-carbon steel.

**Table 1**
Input data to model US subsidies explored in Case 1 and 2.

| Subsidy | | Value | Unit | Reference |
|---|---|---|---|---|
| REPTC Base rate | Utility-Scale Solar | 24 | % reduction of LCOBLEL | Min et al. (2023) |
| | Land-Based Wind | 16 | % reduction of LCOBLEL | Min et al. (2023) |
| REPTC Prevailing wages | Utility-Scale Solar | 71 | % reduction of LCOBLEL | Min et al. (2023) |
| | Land-Based Wind | 70 | % reduction of LCOBLEL | Min et al. (2023) |
| REPTC Domestic content & Energy community | Utility-Scale Solar | 82 | % reduction of LCOBLEL | Min et al. (2023) |
| | Land-Based Wind | 84 | % reduction of LCOBLEL | Min et al. (2023) |
| HPTC Base rate | | 0.6 | US$/kg $H_2$ | Sadler (2023) |
| HPTC Bonus rate | | 3 | US$/kg $H_2$ | (US Department of Energy, n.d.-a) |
| IDP | Federal cost share | 500 | m US$ | (US Department of Energy, n.d.-b) |
| | Capacity | 3 | Mt/year | (Cleveland-Cliffs Inc, 2024) |

A significant difference between the EU and the US regimes is that the US is based on tax credits while a larger part of the EU system is application-based. This means that companies developing low-carbon steelmaking can plan ahead more easily for future cost structures in the US, while in the EU this is subject to processes relating to policymakers. The US system therefore is more open to new entrants, which can increase competition (Reynolds, 2024). In the European system, on the other hand, incumbents have a significant advantage over start-ups, and new entrants through existing contacts and relationships to local and national policymakers, potentially limiting the policy's effectiveness (Criscuolo and Lalanne, 2024).

The US Industrial Demonstration Program and the national state in EU aid are similar, in that subsidies are granted on an application basis. The motivation for the programmes is to demonstrate the technology in first-of-its-kind plants and therefore lower risk, allowing other companies to follow. In the EU, it is unclear whether the German and Spanish measures are also intended as demonstrations, and whether following projects can go ahead without subsidies. But as the ArcelorMittal project in Spain will use natural gas rather than hydrogen (European Commission, 2023), the demonstration effect is limited, and the German government has given state aid to several different projects (European Commission, 2024). It is unclear whether these initial subsidies will unlock further non-subsidised projects.

The differences in the subsidy regimes of the US and the EU can be explained with institutional and political path dependency. In addition to ambitions on climate and competitiveness, the design of the Inflation Reduction Act in the US is a factor in the requirements for a reconciliation bill and the need to entrench political support for climate policy. The design of the subsidy regime in the EU, on the other hand, is the result of the compromises between national and Union-level decision-making (see Fig. 1).

## 5. Quantification of subsidy regimes

To compare the contribution of natural resources, labour, and subsidies to the cost of low-carbon steelmaking across the four cases, we have constructed Fig. 2 below, showing costs and cost components per tonne of steel across our four cases. The stacked bar to the left in each subplot shows the unsubsidised cost components of H-DR-EAF steel, while the blue bars in the waterfall show the cost reductions from various subsidies resulting in final subsidised cost on the right-hand side. Due to the structure of subsidies targeting hydrogen production, we have separated hydrogen into its own cost component. The dark blue field shows the cost reductions from base rate subsidies; i.e., the subsidies paid without the steelmaker having to meet any additional conditionalities. The medium blue shows the cost reduction from the subsidy conditioned on meeting prevailing wage requirements. The light blue shows the cost reduction from the subsidy conditioned on meeting domestic content requirements and being located in locations defined as energy communities. The bar furthest to the right shows the post-subsidy cost composition per tonne of steel.

The figure shows that without subsidies, Spain is the lowest-cost case at $652/t steel, while West Virginia is the highest-cost case at $728/t steel, driven mainly by differences in hydrogen and energy costs, giving rise to a renewables-pull effect. Germany and Ohio have similar costs at $679 and $673, respectively. However, the US subsidy regime is much more ambitious, and the final cost per tonne of steel in West Virginia and Ohio falls to $454 and $419, respectively, far below the $575 and $542 for Germany and Spain. The cost differentials in the EU remain at similar

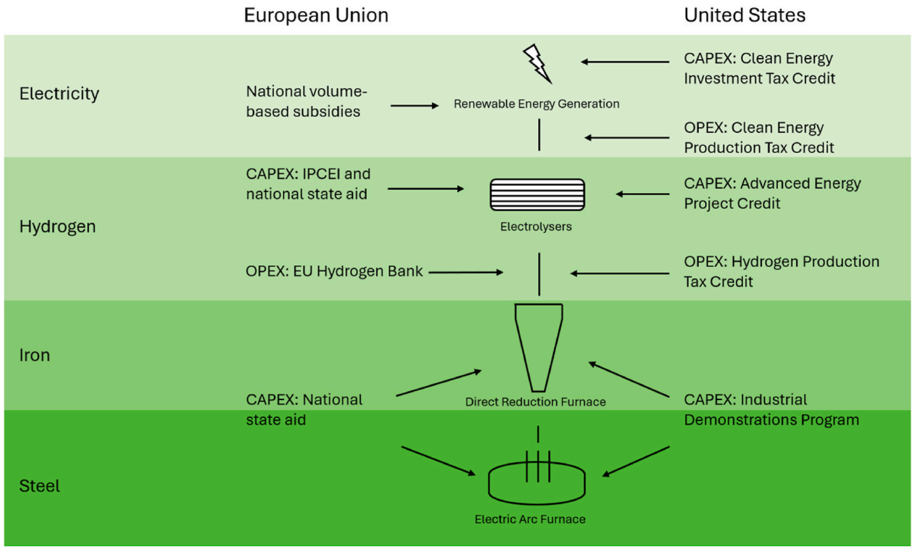


**Fig. 1.** Subsidy intervention points for low-carbon steelmaking in the European Union and United States.

levels before and after subsidies (from $27 to $33), while the cost differentials within the US are reduced (from $55 to $35). The subsidies wipe out the renewables-pull effect, which is at $74 between West Virginia and Spain. The result is based on the assumption that a low-carbon steel facility can get the full available subsidy, meeting conditionalities for low-carbon hydrogen, prevailing wages, domestic content requirements, being defined as an 'energy community', as well as getting the discretionary Industrial Demonstrations Program (IDP) subsidy. Few projects will meet all these criteria, and the IDP will not be replicated for all projects. However, we have included all these subsidies to show what the total cost effect would be.

The largest cost reduction in the US is provided by the hydrogen PTC at $31/t steel, which grows substantially to a total of $154/t steel when projects meet standards for low-carbon hydrogen and prevailing wages. The benefit of meeting prevailing wages in clean energy is also substantially larger than the difference in labour costs between high-labour cost states such as Ohio, and low-labour cost states such as West Virginia.

The EU subsidy regime is less generous, where the national state aid reduces steelmaking costs per tonne steel by $31–$38, and the total EU subsidy regimes would reduce the cost of low-carbon steelmaking by about $100 if all subsidies could be stacked. However, the discretionary national state aid is larger than the US IDP (at $31–$38 compared to $13), and the EU-approved state aid under the IPCEI for electrolysers is larger than the support provided under the Hydrogen Bank per kg hydrogen, suggesting that the EU is 'front-loading' its subsidy regimes for low-carbon steel projects. This could support a more rapid start of deployment in the EU, while in the US, the subsidy regime provides larger incentives over the long term. It could also reflect that the EU will approach long-term costs or increase the subsidies paid via the EU Hydrogen Bank at a later stage, while the US subsidy regime is developed by attempting to lock-in profitability over shifting political administrations. However, future studies should analyse the effects of the EU's indirect and volumetric renewable energy subsidies on LCOS.

Subsidies have a large impact on the cost of low-carbon steelmaking in the EU, and even more so in the US. The impact is larger than either the cost differentials for energy or for labour in the selected cases. Labour cost differentials contribute little to the cost differentials across the four cases. The benefit of steelmakers in the US to relocate to a state with low labour costs is therefore small.

The post-subsidy costs are low compared to cost of conventional emission-intensive steelmaking, ranging between $332 and $701 per tonne steel globally (IEA, 2023). The post-subsidy cost of steelmaking in the US is about $87 away from the lower bound of the conventional cost range, assuming all subsidies are stacked. These results do not show the final price of a tonne of steel, as we do not include rolling to finished goods, and there are additional cost components such as employer, energy, and emission taxes, pensions, and labour protection costs which will increase the cost of steelmaking and can potentially alter cost relations. The above exercise shows, however, how the key cost differentiators related to subsidy regimes, labour costs, energy costs, and the cost of other resources measured against each other.

## 6. Conclusions and policy implications

The energy-intensive steel sector is currently shifting away from coal towards green hydrogen, supported by the falling cost of renewables and strict climate policy including various subsidies. In this study, we have empirically examined the nexus of climate policy and 'competitiveness' by mapping the US and EU subsidy regimes for low-carbon steel and quantifying the effect of subsidies compared to resource costs in four hypothetical cases across the US and the EU.

We find that the US subsidy regime is both stronger and more transparent compared to the European regime, making it easier for steelmakers to predict costs and profitability and thus plan investments. Subsidies have a large impact on the cost of low-carbon steelmaking, and US subsidies are large enough to make steel production in the US cost less than in the EU, despite generally higher pre-subsidy costs. Three qualitative differences stand out between the US and EU regimes: 1) while the capex subsidies awarded at the beginning of a project are larger in the EU than in the US, the American regime is much more generous on opex support, particularly when it comes to hydrogen. While this may contribute to getting projects started quickly in the EU, long-term profitability is stronger in the US. 2) The US regime is associated with conditionalities providing strong incentives on labour standards, location and domestic content while the EU system has no similar coherent structure. 3) The US regime is explicitly 'stackable', where multiple subsidies can be stacked on top of each other, while the EU regime so far is not, weakening the EU regime relative to the one in the US.

The US and the EU are two of the jurisdictions with the largest fiscal capacity to support the development of new low-carbon steelmaking technologies, and if all the subsidies available in US can be combined for a new project, the impact on cost-competitiveness is significant. The

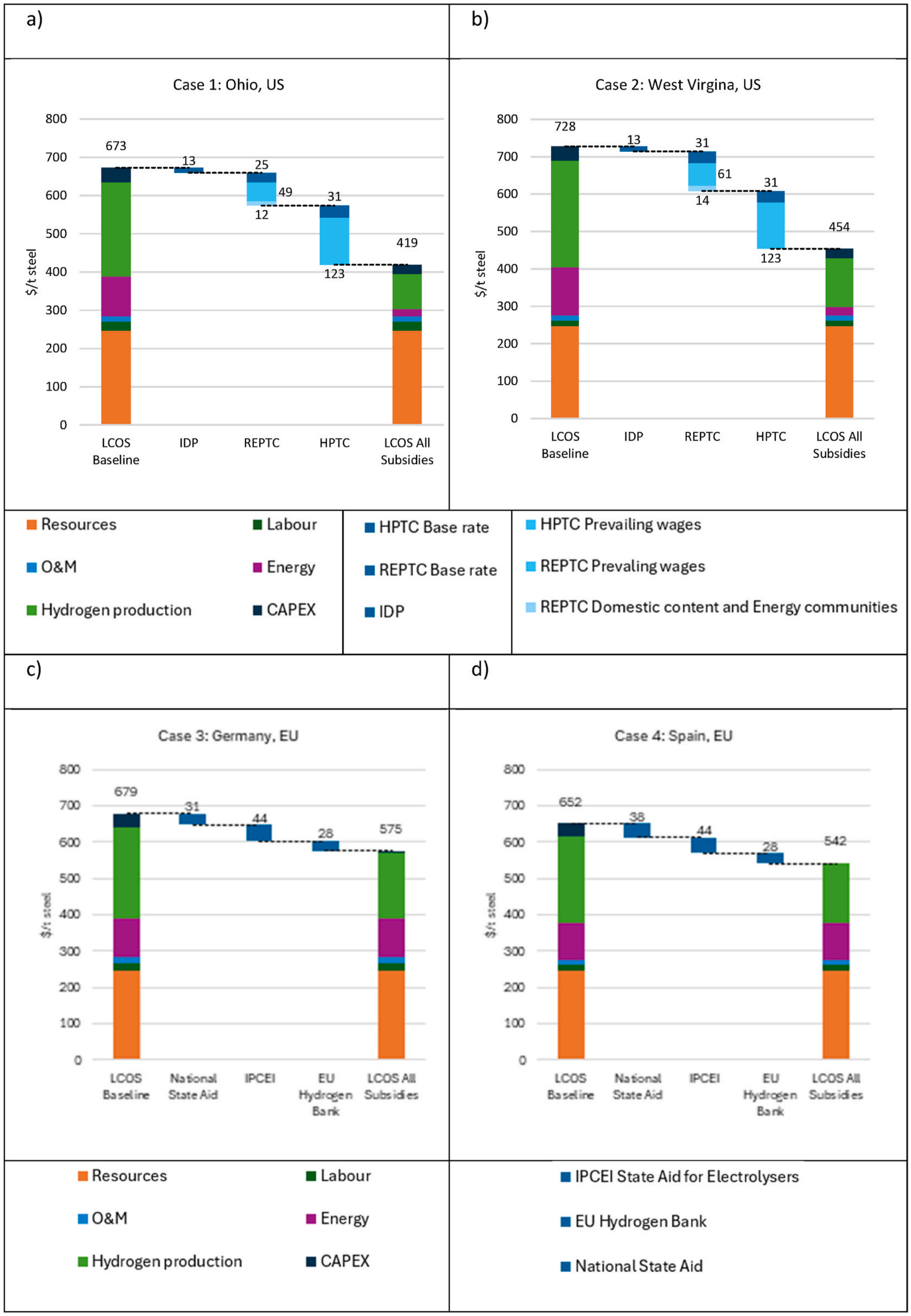


**Fig. 2.** US subsidies and their effect on the LCOS in case 1: Ohio, US 1a; US subsidies and their effect on the LCOS in case 2: West Virginia, US 1b; EU subsidies and their effect on the LCOS in case 3: Germany, EU 1c; and the EU subsidies and their effect on the LCOS in case 4: Spain, EU 1d.

subsidies have a larger effect on total steelmaking costs than labour and energy cost differentials within the US. The significant size of the cost reductions is likely to attract investments in low-carbon steelmaking, enabling these jurisdictions to take a market share in the low-carbon steel market early on, discouraging a large-scale relocation of the steelmaking industry.

The subsidies provided in the US and the EU are not permanent but are used to drive initial investment in low-carbon steelmaking and will disappear over time. Some, such as the Industrial Demonstrations Program and national state aid, are only given for initial projects. However, while these polices will be phased out and their effects will subside, they may give a strong enough push for a path-dependent development of

**Table 2**
Input data to model EU subsidies explored in cases 3 and 4.

| Case | Subsidy | | Value | Unit | Reference |
|---|---|---|---|---|---|
| Case 3: Germany, EU | National State Aid | Measure | 1.3 | bn EUR | (European Commission, 2024-a) |
| | | Capacity | 3.8 | Mt/year | (European Commission, 2024-a) |
| Case 4: Spain, EU | National State Aid | Measure | 460 | m EUR | European Commission (2023) |
| | | Capacity | 1.1 | Mt/year | Vogl et al. (2023) |
| Case 3: Germany, EU | IPCEI | Measure | 220 | m EUR | European Commission (2022) |
| Case 4: Spain, EU | | Capacity | 205 | MW | European Commission (2022) |
| Case 3: Germany, EU<br>Case 4: Spain, EU | EU Hydrogen Bank | Bid price | 0.48 | EUR/kg $H_2$ | European Commission (2024b) |

**Table 3**
Energy cost input data (Fasihi and Breyer, 2020).

| | Location | Baseload LCOE | PV to hybrid PV-wind ratio |
|---|---|---|---|
| | | [US$/MWh] | % |
| Case 1: Ohio, US | Middletown, Ohio | 63 | 85 |
| Case 2: West Virginia, US | Mason county, West Virginia | 78 | 94 |
| Case 3: Germany, EU | Duisburg, North Rhine-Westphalia | 66 | – |
| Case 4: Spain, EU | Puertollano, Ciudad Real | 62 | – |

low-carbon steelmaking in these jurisdictions, leading to further investment without subsidies supported by agglomeration effects, despite high energy costs compared to what can be found in parts of the Global South.

This certainly contributes to a less level global playing field. However, by incentivising low-carbon steel projects and thus deploying and demonstrating new technologies at scale, these subsidies will be instrumental for increasing the speed of the global low carbon transition for steel. If the two jurisdictions with fiscal capacity incentivise the deployment of low-carbon steelmaking technology, this may prove the technology, enable learning, and reduce risk and associated capital costs, encouraging other countries to eventually follow, as in the technology and policy developed in the solar PV industry across Germany and China (Meckling, 2021). Although countries with better energy resources but less fiscal capacity may not capture as large a market share within low-carbon steelmaking as may otherwise be the case, they may be able to progress through the transition to low-carbon steelmaking more quickly. Such spillover effects do not, however, preclude the need for international cooperation on trade and policies for steel decarbonisation for a just and inclusive transition. The steel sector is, for example, currently under significant pressure relating to overcapacity of conventional emission-intensive steelmaking, which is distorting the market and will require cooperation on trade and new definitions of green steel to support a healthier industry (Algers and Åhman, 2024).

There are historical precedents for ‘unfair’ policy interventions leading to long-run positive spillovers. Japanese industrial policy supported an efficient and low-cost Japanese steel industry in the 1970s and 1980s, increasing the Japanese market share in the steel sector. However, the Japanese push led to the development of technology and methods that spilled over to steelmakers in the United States with Japanese investment (Florida and Kenney, 1992). In this way, while favouring domestic industry, such policy interventions can induce innovation and lead to spillovers in the industry across the globe.

The implication for policy is that if fiscal capacity is a larger potential cost differential than renewable energy across countries, the speed of global deployment may be determined more by the willingness to use that fiscal capacity through industrial policy, rather than simple natural endowments. Therefore, such policies will contribute both to lowering of emissions and enabling in a more rapid transition to low-carbon steelmaking in other parts of the world. This suggests a trade-off between the speed of the global low-carbon transition and the degree of industrial relocation. We can call this a ‘fairness-vs-speed-dilemma’. Refraining from subsidies may be ‘fairer’—as richer countries do not leverage their greater fiscal capacity. However, if lowering of low-carbon steelmaking costs leads to a more rapid deployment and demonstration at scale, this may increase the overall speed of the global transition.

## CRediT authorship contribution statement

**Jonas Algers:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jindan Gong:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Björn Nykvist:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Max Åhman:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jonas Algers reports financial support was provided by Swedish Energy Agency. Max Ahman reports financial support was provided by Swedish Energy Agency. Jindan Gong reports financial support was provided by Swedish Energy Agency. Bjorn Nykvist reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.114507.

## Appendix

We use a bottom-up techno-economic model to estimate the levelized cost of steelmaking (LCOS) across selected jurisdictions. We have chosen the US and the EU as these jurisdictions are major steelmakers that all have formulated a strategic aim for low-cost green hydrogen, and low-carbon steelmaking. More specifically, we divide each jurisdiction into two cases, exemplifying high- and low cases in terms of renewable energy endowments and labour costs. For Case 1: we explore Ohio, US, estimating labour costs based on the United Steelworkers-Cleveland-Cliffs bargaining agreement of 2022. We contrast this with Case 2: West Virginia, US, basing labour cost estimates on the Bureau of Labor Statistics data for West Virginia, a right-to-work state with a non-union Nucor steel plant. For Case 3 and Case 4, we select Germany and Spain respectively. While both countries have unionised workforces in the steel sector, Spanish workers have lower salaries than their German counterparts. Our value chain specification for the different cases is the same for the US and EU assuming integrated production in all cases.

In the model, we use 2030 as the project installation year and assuming 0% scrap charge. Our model purposely does not include upstream (such as iron ore processing and beneficiation), or downstream (such as casting and rolling) processes as we aim to analyse the wider implications of subsidy regimes on the LCOS. It rather described the production of green hydrogen, reduction of iron ore pellets, and production of molten steel through electrolysers, DRI shaft furnaces, and EAFs. At core, our model employs mass and energy balances based on Vogl et al. (2018), considering the basic chemical reactions in the electrolysis and iron ore pellet reduction. It further builds in energy balance revisions, in the shape of calculating specific heat and enthalpies using the Shomate equation, accounting for auxiliary power requirements in the DRI shaft furnace, and adding electric heating efficiencies at 85%, derived from Bhaskar et al. (2022). The LCOS is calculated through equation (1), as the annualised cost of the steel plant.

$$LCOS = C_{Resources} + C_{Labour} + C_{O\&M} + C_{Energy} + C_{Hydrogen\ production} + C_{CAPEX} \tag{1}$$

**Where $C_{Resources}$ denotes the annual costs of iron ore pellets, lime fluxes graphite electrodes and alloys; $C_{Labour}$ denotes the annual labour costs; $C_{O\&M}$ denotes the annual operational and maintenance costs (O&M) of the DRI shaft an the EAF; $C_{Energy}$ denotes the annual cost for energy used in the pre-heating of iron ore pellets before its fed into the shaft, and the energy use in the DRI shaft furnace and EAF; $C_{Hydrogen\ production}$ denotes the annualised capital expenditures (CAPEX), resource, energy, O&M, and labour costs associated with green hydrogen production via electrolysers; and lastly, $C_{CAPEX}$ denotes the annualised CAPEX of the DRI shaft furnace and the EAF. CAPEX is annualised using equation (2).**

$$ACC = r / \left(1 - (1 + r)^{-n}\right) \tag{2}$$

**Where $ACC$ denotes the annualization factor; $r$ denotes the discount rate; and $n$ denotes the lifetime. The main economic assumptions, relevant for all cases are specified in Table 1.**

**Table 1**
Main inputs for economic calculations.

| Parameter | Value | Unit | Reference |
|---|---|---|---|
| Exchange rate | 1.1434 | $/€ | (European Central Bank, n.d.) |
| Production capacity | 2.5 | Mt steel/y | Vogl et al. (2018) |
| CAPEX electrolyser | 0.675 | $/kW installed capacity | Vogl et al. (2018) |
| CAPEX DRI shaft furnace | 262.98 | $/t capacity | Vogl et al. (2018) |
| CAPEX EAF | 210.386 | $/t capacity | Vogl et al. (2018) |
| O&M | 3 | % of CAPEX | Vogl et al. (2018) |
| Iron ore pellets | 140 | $/t | Nykvist et al. (preprint) |
| Lime fluxes | 102.90 | $/t | Vogl et al. (2018) |
| Graphite electrodes | 4573.60 | $/t | Vogl et al. (2018) |
| Graphite electrode consumption | 2 | kg/t steel | Vogl et al. (2018) |
| Alloys | 2031.82 | $/t | Vogl et al. (2018) |
| Alloy consumption | 11 | kg/t steel | (Vogl et al., 2018) |
| Labour intensity electrolyser | 2 | h/kW installed electrolyser | Devlin et al. (2023) |
| Labour intensity DRI shaft | 0.18 | h/t DRI | (Global Energy Monitor, 2024) |
| Labour intensity EAF | 0.492 | h/t steel | (Global Energy Monitor, 2024; personal communication) |
| Discount rate | 5 | % | Vogl et al. (2018) |
| Lifetime DRI shaft and EAF | 20 | y | Vogl et al. (2018) |
| Lifetime electrolyser | 10 | y | Vogl et al. (2018) |
| Working year | 2080 | h | (U.S. Bureau of labor U.SBureau of labor statistics, 2023) |

We estimate labour costs based on the average steelworker wage in each case. These are detailed in Table 2. The modelled wages in Case 1 stem from a labour agreement between USW and Cleveland-Cliffs, where we use the average of the tentatively agreed wages for 2025 across all labour grades (United Steelworkers, 2022). The modelled wages in Case 2 represent annual mean wage for Metal-refining furnace operators and tenders in West Virginia, where only one steel plant is currently located (Global Energy Monitor, 2024). For cases 3 and 4, data on wages and salaries paid to employees, and number of employees in the basic iron and steel sector were obtained from (UNIDO, 2024) for the years 2017–2019. Our final assumption on the wages for each case represent the average of the annual mean wages per person over the three years (see Table 3).

**Table 2**
Labour cost input data.

| | Average steelworker wages | | Reference |
|---|---|---|---|
| | $/person/year | $/person/h | |
| Case 1: Ohio, US | – | 33.71 | United Steelworkers (2022) |
| Case 2: West Virginia, US | 42700.00 | – | (U.S. Bureau of labor U.SBureau of labor statistics, 2023) |
| Case 3: Germany, EU | 59190.23 | – | UNIDO (2024) |
| Case 4: Spain, EU | 42851.13 | – | UNIDO (2024) |

Energy costs are estimated by case-specific electricity rates. Our modelled rates are based on the work of Fasihi and Breyer (2020) and their regionally varying 2030 projections of baseload levelized costs of electricity (LCOE) for large-scale, on-site hybrid PV-wind systems. The specific locations used for retrieving baseload LCOE data represent the location of a project selected for award negotiations under the Industrial Demonstrations Program (IDP) for case 1 (Office of clean energy demonstrations, 2024); of the only steel plant in West Virginia for case 2 (Global Energy Monitor, 2023); of a direct reduction plant announced in Puertollano, Spain for case 3 (Global Energy Monitor, 2023); and of a green-field green steel plant announced in Duisberg, Germany for case 4 (Global Energy Monitor, 2023).

## Data availability

Data will be made available on request.

## References


Aiginger, K., Rodrik, D., 2019. Rebirth of industrial policy and an agenda for the twenty-first century. Journal of industry. Competition and Trade 20 (2), 189–207. https://doi.org/10.1007/s10842-019-00322-3.

Algers, J., Åhman, M., 2024. Phase-in and phase-out policies in the global steel transition. Clim. Pol. 1–14. https://doi.org/10.1080/14693062.2024.2353127.

Arkolakis, C., Walsh, C., 2023. Clean Growth. NBER Working Paper Series (No. 31615).

Auty, R.M., 1991. Creating competitive advantage: South Korean steel and petrochemicals. Tijdschr. Econ. Soc. Geogr. 82 (1), 15–29. https://doi.org/10.1111/j.1467-9663.1991.tb01792.x.

Bassi, A.M., Yudken, J.S., Ruth, M., 2009. Climate policy impacts on the competitiveness of energy-intensive manufacturing sectors. Energy Pol. 37 (8), 3052–3060. https://doi.org/10.1016/j.enpol.2009.03.055.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., Rahbar, S., 2018. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. J. Clean. Prod. 187, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107.

Bhaskar, A., Abhishek, R., Assadi, M., Somehesaraei, H.N., 2022. Decarbonizing primary steel production: techno-economic assessment of a hydrogen based green steel production plant in Norway. J. Clean. Prod. 350. https://doi.org/10.1016/j.jclepro.2022.131339.

Breetz, H., Mildenberger, M., Stokes, L., 2018. The political logics of clean energy transitions. Bus. Polit. 20 (4), 492–522. https://doi.org/10.1017/bap.2018.14.

Burgess, M.G., Van Boven, L., Wagner, G., Wong-Parodi, G., Baker, K., Boykoff, M., Converse, B.A., Dilling, L., Gilligan, J.M., Inbar, Y., Markowitz, E., Moyer, J.D., Newton, P., Raimi, K.T., Shrum, T., Vandenbergh, M.P., 2024. Supply, demand and polarization challenges facing US climate policies. Nat. Clim. Change. https://doi.org/10.1038/s41558-023-01906-y.

Cleveland-Cliffs Inc, 2024. Cleveland-Cliffs selected to receive $575 million in US Department of Energy investments for two projects to accelerate industrial decarbonization technologies. Cleveland-Cliffs. March 25. https://www.clevelandcliffs.com/news/news-releases/detail/629/cleveland-cliffs-selected-to-receive-575-million-in-us.

Collins, L., 2023a. 'Green Steel Will Become Cheaper than Grey in US as Soon as Hydrogen Tax Credits Kick in': Analyst. Hydrogen Insight.

Collins, L., 2023b. The €800m for EU's first green hydrogen auction is 'peanuts' compared to what's needed, says top EU official. Hydrogen insight.

Criscuolo, C., Lalanne, G., 2024. A new approach for better industrial strategies. Journal of industry,. Competition and Trade 24 (1). https://doi.org/10.1007/s10842-024-00416-7.

D'Costa, A., 1994. State, steel and strength: structural competitiveness and development in South Korea. J. Dev. Stud. 31 (1), 44–81.

Devlin, A., Yang, A., 2022. Regional supply chains for decarbonising steel: energy efficiency and green premium mitigation. Energy Convers. Manag. 254. https://doi.org/10.1016/j.enconman.2022.115268.

Devlin, A., Kossen, J., Goldie-Jones, H., Yang, A., 2023. Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits. Nat. Commun. 14 (1), 2578. https://doi.org/10.1038/s41467-023-38123-2.

European Central Bank. (n.d.). Euro exchange rates charts. European Central Bank. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

European Commission, 2021. State Aid: Commission Endorses the New Guidelines on State Aid for Climate, Environmental Protection and Energy.

European Commission, 2022. State Aid: Commission Approves €220 Million Spanish Measure to Support COBRA in Production of Renewable Hydrogen.

European Commission, 2023. State Aid: Commission Approves €460 Million Spanish Measure to Support ArcelorMittal Decarbonise its Steel Production.

European Commission, 2024a. Commission Approves €1.3 Billion German State Aid Measure Funded under Recovery and Resilience Facility to Support ArcelorMittal Decarbonise its Steel Production.

European Commission, 2024b. European Hydrogen Bank Auction Provides €720 Million for Renewable Hydrogen Production in Europe.

Evans, P., 1995. Embedded Autonomy. Princeton University Press.

Fasihi, M., Breyer, C., 2020. Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. J. Clean. Prod. 243. https://doi.org/10.1016/j.jclepro.2019.118466.

Florida, R., Kenney, M., 1992. Restructuring in place: Japanese investment, production organization, and the geography of steel. Indust. Geogr. 68 (2), 146–173.

Global Energy Monitor, 2024. Global Steel Plant Tracker.

Greco, L., 2022. A just transition: insights from the labour unions of a steel locality (Taranto, Italy). Econ. Ind. Democr. 44 (4), 1127–1148. https://doi.org/10.1177/0143831x221111417.

Grubert, E., Hastings-Simon, S., 2022. Designing the mid-transition: a review of medium-term challenges for coordinated decarbonization in the United States. WIREs Climate Change 13 (3). https://doi.org/10.1002/wcc.768.

International Energy Agency, 2019. Iron and Steel Technology Roadmap.

International Energy Agency, 2023. Indicative production costs for crude steel via electrolytic hydrogen-based DRI in selected regions compared to current references, IEA. Paris. https://www.iea.org/data-and-statistics/charts/indicative-production-costs-for-crude-steel-via-electrolytic-hydrogen-based-dri-in-selected-regions-compared-to-current-references. Licence: CC BY 4.0.

Juhász, R., Lane, N., Rodrik, D., 2024. The New Economics of Industrial Policy. Annual Review of Economics 16 (1), 213–242. https://doi.org/10.1146/annurev-economics-081023-024638.

Kaufman, N., Saha, S., Bataille, C., 2023. Green Industrial Policy Will Drive Decarbonization, but at what Cost to Trade? Finance & Development.

Kleimann, D., Poitiers, N., Sapir, A., Simone, Tagliapietra, Véron, N., Veugelers, R., Zettelmeyer, J., 2023. How europe should answer the inflation reduction Act (policy contribution, issue 04/2023). https://www.bruegel.org/sites/default/files/2023-02/PB%2004%202023_0_1.pdf.

Lynn, L., 1981. New data on the diffusion of the basic oxygen furnace in the U. S. And Japan. J. Ind. Econ. 30 (2), 123–135. https://doi.org/10.2307/2098198.

Mayfield, E., Jenkins, J., Larson, E., Greig, C., 2023. Labor pathways to achieve net-zero emissions in the United States by mid-century. Energy Pol. 177. https://doi.org/10.1016/j.enpol.2023.113516.

Mazzucato, M., 2016. From market fixing to market-creating: a new framework for innovation policy. Ind. Innovat. 23 (2), 140–156. https://doi.org/10.1080/13662716.2016.1146124.

McCormick, M., 2022. America's green revolution comes to coal country. Financ. Times. https://www.ft.com/content/70920b90-57ee-4bf1-834f-d584a9b360cf.

Meckling, J., 2021. Making industrial policy work for decarbonization. Global Environ. Polit. 21 (4), 134–147. https://doi.org/10.1162/glep_a_00624.

Meckling, J., Allan, B.B., 2020. The evolution of ideas in global climate policy. Nat. Clim. Change 10 (5), 434–438. https://doi.org/10.1038/s41558-020-0739-7.

Meckling, J., Strecker, J., 2022. Green bargains: leveraging public investment to advance climate regulation. Clim. Pol. 23 (4), 418–429. https://doi.org/10.1080/14693062.2022.2149452.

Meckling, J., Kelsey, N., Biber, E., Zysman, J., 2015. Winning coalitions for climate policy. Science 349 (6253), 1170–1171. https://doi.org/10.1126/science.aab1336.

Meckling, J., Sterner, T., Wagner, G., 2017. Policy sequencing toward decarbonization. Nat. Energy 2 (12), 918–922. https://doi.org/10.1038/s41560-017-0025-8.

Milberg, W., Houston, E., 2005. The high road and the low road to international competitiveness: extending the neo-Schumpeterian trade model beyond technology. Int. Rev. Appl. Econ. 19 (2), 137–162. https://doi.org/10.1080/02692170500031646.

Min, Y., Brinkerink, M., Jenkins, J., Mayfield, E., 2023. Effects of renewable energy provisions of the Inflation Reduction Act on technology costs, material demand and labor. BlueGreen Alliance (Working Paper) 1–18.
Moore, J.B., 1987. Japanese industrial relations. Lab. Ind. 1 (1), 140–155. https://doi.org/10.1080/10301763.1987.11673891.
Nilsson, L.J., Bauer, F., Åhman, M., Andersson, F.N.G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., van Sluisveld, M., Vogl, V., 2021. An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. Clim. Pol. 21 (8), 1053–1065. https://doi.org/10.1080/14693062.2021.1957665.
Office of clean energy demonstrations, 2024. Industrial demonstrations program selections for award negotiations. Department of energy. Retrieved April 30 from. https://www.energy.gov/oced/industrial-demonstrations-program-selections-award-negotiations.
Okereke, C., McDaniels, D., 2012. To what extent are EU steel companies susceptible to competitive loss due to climate policy? Energy Pol. 46, 203–215. https://doi.org/10.1016/j.enpol.2012.03.052.
Reynolds, E.B., 2024. U.S. Industrial transformation and the "how" of 21st century industrial strategy. Journal of industry. Competition and Trade 24 (1). https://doi.org/10.1007/s10842-024-00420-x.
Rodrik, D., 2015. Green industrial policy. Oxf. Rev. Econ. Pol. 30 (3), 469–491. https://doi.org/10.1093/oxrep/gru025.
Rodrik, D., Stiglitz, J., 2024. A New Growth Strategy for Developing Nations. Harvard University,1-16.
Sadler, J., 2023. Stacking rules, bonus credits, and the future industrial markets the IRA aims to create. RMI. September 28. https://rmi.org/stacking-rules-bonus-credits-and-the-future-industrial-markets-the-ira-aims-to-create/.
Samadi, S., Fischer, A., Lechtenböhmer, S., 2023. The renewables pull effect: how regional differences in renewable energy costs could influence where industrial production is located in the future. Energy Res. Social Sci. 104. https://doi.org/10.1016/j.erss.2023.103257.
Stokes, L.C., Warshaw, C., 2017. Renewable energy policy design and framing influence public support in the United States. Nat. Energy 2 (8). https://doi.org/10.1038/nenergy.2017.107.
Swalec, C., Grigsby-Schulte, A., 2023. 2023 Pedal to the Metal. G. E. Monitor.
Trujillo-Baute, E., del Río, P., Mir-Artigues, P., 2018. Analysing the impact of renewable energy regulation on retail electricity prices. Energy Pol. 114, 153–164. https://doi.org/10.1016/j.enpol.2017.11.042.
UNIDO, 2024. INDSTAT Revision 4.
United Steelworkers, 2022. Summary of the Proposed Agreement between the United Steelworkers and Cleveland-Cliffs.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Pol. 28, 817–830.
U.S. Bureau of labor statistics, 2023. Metal-refining Furnace Operators and Tenders U.S. Bureau of Labor Statistics, 51–4051.
Verpoort, P.C., Gast, L., Hofmann, A., Ueckerdt, F., 2023. Estimating the renewables pull in future global green value chains. Nature (under review). https://doi.org/10.21203/rs.3.rs-2743794/v1.
Veugelers, R., Tagliapietra, S., Trasi, C., 2024. Green industrial policy in europe: past, present, and prospects. Journal of industry. Competition and Trade 24 (1). https://doi.org/10.1007/s10842-024-00418-5.
Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. J. Clean. Prod. 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279.
Vogl, V., Olsson, O., Nykvist, B., 2021. Phasing out the blast furnace to meet global climate targets. Joule 5 (10), 2646–2662. https://doi.org/10.1016/j.joule.2021.09.007.
Vogl, V., Sanchez, F., Morales, E.T., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., Witecka, W., Olsson, O., Rootzén, J., 2023. Green Steel Tracker.
Wade, R.H., 2018. The developmental state: dead or alive? Dev. Change 49 (2), 518–546. https://doi.org/10.1111/dech.12381.
Walker, R., Storper, M., 1981. Capital and industrial location. Prog. Hum. Geogr. 5 (4), 473–509. https://doi.org/10.1177/030913258100500401.
Wesseling, J.H., Lechtenböhmer, S., Åhman, M., Nilsson, L.J., Worrell, E., Coenen, L., 2017. The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. Renew. Sustain. Energy Rev. 79, 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156.
Zurstrassen, D., 2022. EU industrial policy in the steel industry: historical background and current challenges. In: Defraigne, J.-C., Traversa, Edoardo, Wouters, J., Zurstrassen, D. (Eds.), EU Industrial Policy in the Multipolar Economy. Edward Elgar Publishing, pp. 269–303.