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The renewables pull effect: How regional differences in renewable energy costs could influence where industrial production is located in the future

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ABSTRACT

To combat climate change, it is anticipated that in the coming years countries around the world will adopt more stringent policies to reduce greenhouse gas emissions and increase the use of clean energy sources. These policies will also affect the industry sector, which means that industrial production is likely to progressively shift from CO_2-emitting fossil fuel sources to renewable energy sources. As a result, a region's renewable energy resources could become an increasingly important factor in determining where energy-intensive industries locate their production. We refer to this pull factor as the "renewables pull" effect. Renewables pull could lead to the relocation of some industrial production as a consequence of regional differences in the marginal cost of renewable energy sources. In this paper, we introduce the concept of renewables pull and explain why its importance is likely to increase in the future. Using the examples of direct reduced iron (DRI) and ammonia production, we find that the future costs of climate-neutral production of certain products is likely to vary considerably between regions with different renewable energy resources. However, we also identify the fact that many other factors in addition to energy costs determine the decisions that companies make in term of location, leaving room for further research to better understand the future relevance of renewables pull.

1. Introduction

Limiting the increase in the global average temperature to "*well below* 2°C" above pre-industrial levels, as stipulated by the Paris Agreement, will require significant reductions in emissions in the forthcoming years and decades [1]. It is anticipated that countries around the world – in their efforts to contribute to climate change mitigation – will implement more stringent policies to reduce greenhouse gas emissions and increase the use of clean energy sources. This will undoubtedly affect the industrial sector, which accounted for roughly 24 % of the world's total net greenhouse gas emissions in 2019, according to IPCC estimates [2]. This share increases to 34 % – the highest share of all sectors – when indirect emissions from electricity and heat generation are included [2]. As a consequence of climate change mitigation efforts, industrial production is likely to progressively switch from CO_2-emitting fossil fuel sources to renewable energy sources [3]. Recent initiatives in countries around the world, such as the Inflation Reduction Act [4] in the US and the REPowerEU plan [5] and the Net Zero Industry Act [6,7] in the EU, aim to accelerate the increased use of renewable energy sources in industry. This could lead to a region's renewable energy resources becoming an increasingly important factor in determining where energy-intensive industries locate their production.

We define "renewables pull" as the pull factor for industrial production triggered by exceptional renewable energy conditions in certain regions of the world. Renewables pull may lead to regional changes in industrial production, either through the relocation of existing production capacities or through changes in investment patterns in regard to new production facilities. If this shift from one region to another region results primarily from a variation in the marginal costs of renewable energy (or secondary energy or feedstocks based on renewable energy), we refer to this phenomenon as "green relocation", following Verpoort et al. [8]. To date, such relocations are a hypothetical phenomenon, but they may be empirically verified in the future.

Industrial relocation induced by renewables pull has some

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similarities with the concept of "carbon leakage", as the latter also refers to the relocation of industrial activity from one region to another.[1] However, the causes of relocation due to carbon leakage and renewables pull differ. In the case of carbon leakage, regions with comparatively weak climate protection regulations and low CO_2 prices attract fossil fuel-based industrial production, as production based on fossil fuels in these regions can be cheaper and therefore more competitive than similar production in regions with more ambitious climate policies and higher CO_2 prices. The theoretical framework and practical relevance of carbon leakage have been discussed extensively in the scientific literature since the 1990s [12–14]. Recent literature [15,16] suggests that some carbon leakage may have occurred in the past but it has, so far, been limited.

The renewables pull effect, on the other hand, has rarely been discussed or quantified in the scientific literature to date. One explanation could be that even in regions with exceptional renewable energy conditions, the production of energy-intensive products or materials using fossil fuels has generally been cheaper than the renewables-based production of these products. However, as electricity and hydrogen generation costs from renewable energy sources continue to decrease [17] and CO_2 costs are expected to increase in the future [3], some authors have recently discussed the possibility of industrial relocations induced by renewables pull – although usually without using this term.

Gielen et al. [18] point out that the relocation of energy-intensive industries to countries with exceptional wind and solar conditions could enable climate-neutral industrial production to become cost-competitive with conventional production in the future. The authors focus on hydrogen-based steel production and suggest that the energy-intensive process of reducing iron ore could, in the future, be based in countries such as Australia, which holds iron ore deposits and also benefits from favourable wind and solar conditions. The direct reduced iron (DRI) could then be exported to other countries, where it would be further processed into steel. If locations with cheap renewables-based hydrogen are used, the authors suggest that hydrogen-based steelmaking could become competitive at moderate CO_2 prices. Similarly, Trollip et al. [19] also expect that, over time the hydrogen-based production of DRI in certain locations will be able to compete with conventionally-produced iron and suggest that South Africa, with its iron ore deposits and low-cost solar PV electricity, could become an exporter of hydrogen-based DRI. Lopez et al. [20] develop global scenarios for the transition of primary steelmaking to hydrogen-based and electricity-based routes and identify the need for further research on potential future changes in the locations of steel manufacturing due to production cost differences.

Some of the recent literature has also discussed the possibility of producing ammonia in regions with very good solar and wind conditions. While natural gas is currently the main feedstock for ammonia production, it is anticipated that future climate-neutral ammonia production will use hydrogen instead. Fasihi et al. [21] predict that green ammonia production will become cost-competitive with conventional ammonia production in niche markets by 2030 and more widely by 2040. In their paper, the authors estimate the future production costs for green ammonia globally, indicating that regions with very good solar and wind conditions could become key locations for ammonia production. Armijo and Philibert [22] examine the production of green hydrogen and green ammonia from wind and solar PV specifically in Chile and Argentina and suggest that the exceptional renewable energy conditions in these countries could help the production costs for green ammonia to reach a breakeven point compared to conventional ammonia production, raising the possibility of future ammonia exports to other countries. Several other recent studies also focus on the costs and locations for green ammonia production and on available transportation options, partially assuming that green ammonia will be used as a transport medium for green hydrogen [23–25].

A recent paper by Egerer et al. [11] analyses how the transformation in the industry sector from fossil fuels to hydrogen may reorganise the value chains of different industries. They derive region-specific cost estimates for the hydrogen-based production of steel, ethylene and urea and conclude that for some processes, such as ammonia production, relocations to favourable regions "may occur due to substantial comparative cost advantages". A preprint by Verpoort et al. [8] refers specifically to the renewables pull effect and also quantifies the potential relative cost savings that can be achieved by relocating the renewable-based production of steel, ethylene and urea from a renewable-poor region to a renewable-rich region. The authors conclude that in the absence of policy intervention, the renewables pull effect "is likely to incentivise green relocation". Finally, a study by Day [26] argues that high transport costs for non-fossil energy sources (i.e. biomass, electricity and hydrogen) will significantly increase the relevance of energy costs in industrial location decisions as compared to the current situation where transport costs for fossil fuels are generally very low, and that this could lead to the relocation of energy-intensive forms of production.

The potential future relevance of differences in the cost of renewable energy is also suggested by existing empirical studies, which have found a demonstrable impact of both, fossil fuel energy endowments and general energy prices on the location decisions of energy-intensive industries [27–30]. A study by Panhans et al. [30] on the response of European firms to changes in electricity prices shows that domestic electricity price reductions can have a significant impact on the location decisions of foreign firms already considering relocation. However, the study also finds that domestic firms that did not expect to relocate in the first place are much less responsive to increases in domestic electricity prices.

Despite some of the aforementioned literature sources discussing the potential for regions with favourable renewable energy conditions to attract certain types of industrial production, to our knowledge there is no peer-reviewed literature that provides a framework for the theoretical concept of the underlying renewables pull effect. This article aims to provide such a concept. It builds on a project report [31] published in 2021 that first introduced the concept.[2]

The remainder of this article is composed of four main sections. Section 2 describes the theory of the renewables pull effect while Section 3 focuses on the practical examples of DRI and ammonia as two industrial products that are likely to be affected by renewables pull in the near future. Section 4 provides a comparison between Germany and Morocco in terms of the potential future production costs of DRI and ammonia and also discusses the relevance of additional, difficult-to-quantify location factors. Finally, Section 5 concludes and identifies further research needs.

[1] Because of this similarity to the carbon leakage concept, recently the term "green leakage" was used by some authors [9–11] to describe relocations induced by renewables pull. We refrain from using this term and prefer the term "green relocation" [8], as new investments induced by renewables pull are likely to replace or complement existing *fossil fuel*-based production processes but not "green" production processes. Therefore, the term "leakage" in connection with "green" seems inappropriate for describing industrial relocation effects that may be associated with the renewables pull effect. In addition, the term "leakage" has a negative connotation, which we believe is not appropriate for a phenomenon which offers promising opportunities for industrial development in many regions of the world and for cost-effective global climate protection.

[2] The present article goes significantly beyond that report, mainly by identifying characteristics of industrial production that increase the likelihood of a strong renewables pull effect and by specifically discussing the potential relevance of the renewables pull effect for DRI and ammonia production.

2. Theory of the renewables pull effect

This section describes the theory of the renewables pull effect by distinguishing three potential causes of the effect (Subsection 2.1) and using a simple two-country model to illustrate how these causes could lead to the relocation of industrial production (Subsection 2.2). Subsequently, it identifies production process characteristics that make it more or less likely for a product to be affected by renewables pull (Subsection 2.3).

2.1. Potential causes of the renewables pull effect

The following three developments may cause the renewables pull effect to become relevant. These developments have been observed in the past and are likely to become increasingly relevant in the future:

- *Rising cost of using fossil fuels:* for example, as a result of stricter climate policy and related instruments, such as the introduction of (or increase in) CO_2 prices [3,32]. The associated increase in the cost of fossil-based industrial production could lead to industrial production based on renewable energy sources becoming cost-competitive in regions with good renewable energy conditions.
- *Reduced cost of using renewable energy sources:* for example, through technical advances, subsidies for using renewable energy sources or other policy-induced incentives.[3] This could make renewable energy sources more economical than fossil fuels in certain industrial applications, even without (additional) climate policy instruments [33,34].
- Emergence in the markets of an *explicit demand for "green" materials or products:* for example, "green" products with a low carbon footprint could become a unique selling point in growing market segments [35].

It should be noted that while any one of these developments could lead to renewables pull becoming more significant, it may well be that all three developments work in combination to increase the future relevance of renewables pull.

Due to the typically long lifetimes of industrial plants (especially in the basic materials industry), it should be kept in mind that in addition to *current* fossil fuel costs, renewable energy costs and consumer preferences affecting the occurrence of renewables pull, their *future development* as projected by investors is also relevant.

2.2. Illustration of the renewables pull effect using a simple two-country model

This section provides an explanation of the renewables pull effect using a simple two-country model. The following model assumptions are made:

- In the baseline situation, industrial production based on fossil energy sources costs the same in country A and country B and is cheaper than industrial production based on green energy sources.
- The marginal costs of green energy sources are lower in country B than in country A.
- While the transportation costs of industrial products and of fossil fuels between the two countries are negligible,[4] this does not apply to the transportation costs of green energy sources such as green electricity, green hydrogen or biomass [26,36,37].[5]
- In the baseline situation, there is some exchange of industrial production between the two countries. (Although production costs are assumed to be identical, trade still occurs due to differences in product characteristics, i.e. the products are not completely homogeneous.)

Fig. 1 a) and b) illustrate how the rising costs of using fossil fuels can lead to changes in production costs and why, as a consequence, the relocation of industrial production from country A to country B is possible.

Fig. 1 a) illustrates the case of an identical or similar increase in the cost of using fossil fuels in countries A and B. The cost increase is assumed to be triggered by the strengthening of policy measures in both countries, e.g., caused by an international climate protection treaty. These policy measures explicitly or implicitly[6] lead to an increase in CO_2 costs and, consequently, to an increase in the cost of using fossil energy sources and fossil feedstocks (see shaded areas in Fig. 1 a)).

As a consequence of the price increase for fossil fuels, the economic viability of green energy sources improves in both countries in terms of both renewable energy sources used directly in industrial processes (e.g. biomass and solar thermal energy) and those energy sources or feedstocks produced from renewable energy sources (e.g. green electricity, green hydrogen or green methanol). 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 taken by companies about where to locate or relocate their businesses. Such differences in marginal costs can stem from differences in geographical and climatic conditions or differences in the procurement costs of green energy sources from regions with more favourable production costs. It should be noted that there can also be differences between locations within the same country. For example, locations in inland Germany may be disadvantaged in terms of both the marginal costs of harnessing wind energy and access to seaports (with their relatively low procurement costs for imported energy sources) compared to coastal locations in northern Germany.

Due to favourable natural and climatic conditions in country B,[7] the rising costs of fossil fuel energy sources triggered by a more stringent climate policy can be partially compensated by the relatively favourable marginal costs of green energy sources. However, country A does not enjoy the same advantage. Here, production based on green energy sources remains more expensive than production based on fossil energy sources even after the increase in CO_2 costs. The high cost of transporting renewable energy means that country A cannot benefit from

[3] In the US, for example, the Inflation Reduction Act provides tax credits for renewable energy and hydrogen production. Such support schemes can compensate for existing cost differences between fossil fuels and renewable energy sources, thereby encouraging the use of climate-friendly energy sources [4].

[4] This assumption is only made in the model for the sake of simplicity. The renewables pull effect can in principle also occur when the transportation costs of products are relevant, although in this case to a lesser extent or only when there is a greater difference in the costs of using renewable energy sources between regions.

[5] DeSantis et al. [37] find that the cost per kWh of transmitting electricity 1000 miles in the United States is higher than the cost per kWh of generating electricity from onshore wind [37]. Similarly, transporting hydrogen over long distances is very expensive, especially if pipeline transport is not an option. For example, the IEA [36] estimates that the cost of transporting hydrogen from Australia to Japan could be between 30 % and 45 % of the full cost of hydrogen.

[6] An explicit increase in the CO_2 price would be brought about by introducing or increasing a CO_2 tax. Implicitly, the CO_2 price would be increased, among other things, by reducing the quantity of certificates made available in an emissions trading system. Regulatory climate protection measures (such as targets for product-specific or plant-specific CO_2 emissions) can also be understood as an implicit increase in the price of CO_2.

[7] In this two-country illustrative model, the assumption is made that country B has a clear advantage over country A in terms of its own natural and climatic conditions. This could lead to very low production costs for electricity from solar and/or wind power plants in country B. Country A cannot compensate for this relative disadvantage through imports because (for example) it is located far away from regions with favourable generation costs and/or has no coastline and thus no maritime transport connections. Alternatively, country B's advantage could also be based on exclusive and low-cost import options.

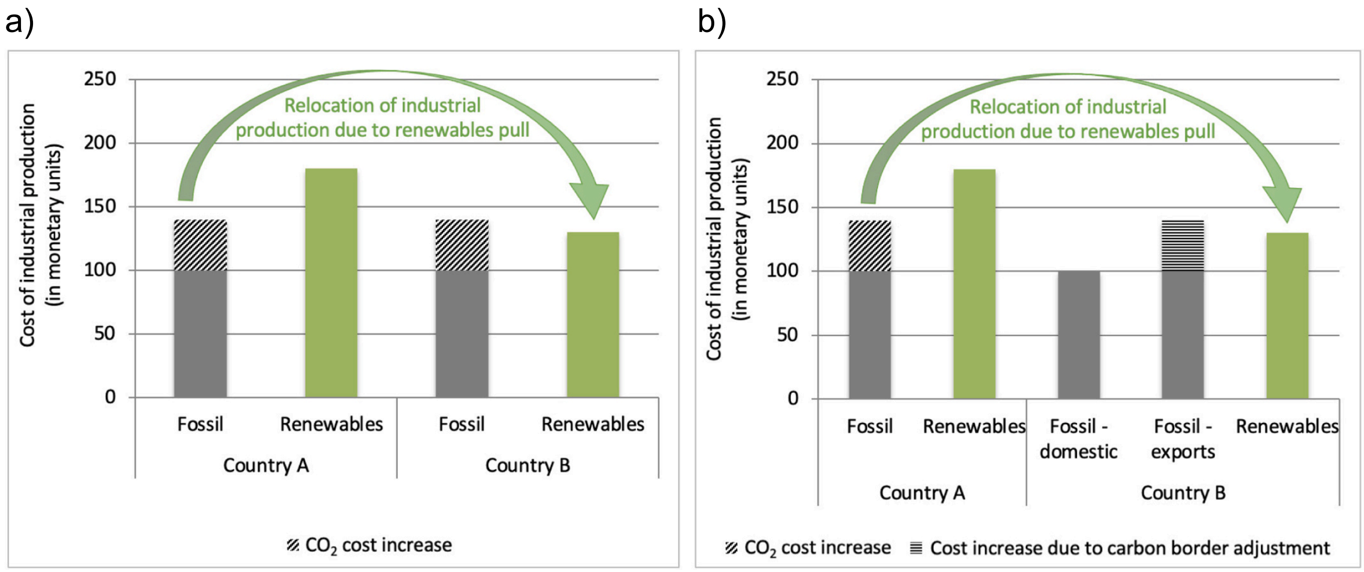

Fig. 1. Schematic representation of the renewables pull effect due to rising costs of fossil fuel use as a consequence of a) tighter climate policy in both countries and b) unilateral tightening of climate policy in country A in combination with the introduction of a carbon border adjustment mechanism.

low-cost green energy imports from abroad. All other things being equal, the lower increase in energy costs in country B strengthens the competitive position of country B vis-à-vis country A. Consequently, the renewables pull effect occurs and the relocation of industrial production from country A to country B may become attractive, particularly for companies in energy-intensive industries, both to meet demand in country B and to export to country A.

While the assumption is made in Fig. 1 a) that climate policy tightens to a similar extent in both countries, renewables pull can in principle also occur if only *one* country pursues a more stringent climate protection policy. If such policy tightening is implemented in country A, for example, and at the same time a carbon border adjustment mechanism (CBAM)[8] is set up to avoid or minimise carbon leakage, country A could be faced with the relocation of parts of its industrial production due to renewables pull (see Fig. 1 b)). This would be the case if it became profitable for individual companies to set up climate-friendly production based on green energy sources in country B and to export the products to country A. This way, companies could benefit from the relatively low cost of climate-friendly production in country B and – due to the low CO_2 footprint of their production – would not be faced with a (significant) border adjustment price.[9]

Likewise, the unilateral tightening of climate policy in country B could also lead to renewables pull. This is explained in more detail in [31].

It should be noted that the simple two-country model presented only allows for the conclusion to be drawn that there is a general *possibility* of green relocations. Whether or to what extent such relocations *actually* occur depends on many factors – not least on the relevance of energy costs compared to other location factors – and cannot be answered without empirical analysis.

In principle, the renewables pull effect could also occur without an increase in the cost of fossil fuels – for example, if industrial production benefits from cost reductions for green energy. Such reductions could originate from lower costs in wind or photovoltaic plants, but could also be triggered or reinforced by cost reductions in the specific processes necessary for the use of green energy sources (e.g., in hydrogen-based direct reduction plants for primary steel production). In such a case, industrial production based on green energy sources in country B (with its good conditions for renewable energy sources) could become cheaper than industrial production based on fossil energy sources. As a result, it is conceivable that parts of the industrial production previously located in country A would relocate to country B.

Finally, another conceivable cause for renewables pull is not connected to changes in production costs but is driven by demand-side preferences. Although consumers may initially see an industrial product (e.g., a tonne of crude steel) as a homogeneous product regardless of the production process, this could change over time as a result of increased environmental or climate change awareness. Consequently, some consumers might start to distinguish between an industrial product produced using fossil fuels and that produced using green energy.[10] It is also conceivable that existing social awareness could be harnessed by corporate initiatives to distinguish their products from other similar products.

If such a distinction is accompanied by a greater willingness to pay for the climate-friendly or climate-neutral industrial product, this could lead to falling demand for fossil-based industrial production in both countries and to growing demand for industrial production based on

[8] A CBAM aims to compensate for potential international competitive disadvantages faced by domestic companies resulting from stricter domestic climate protection policy. This can be done by making imports from countries or regions in which companies bear no or lower CO_2 costs more expensive in line with their CO_2 intensity and by reimbursing the CO_2 costs (or parts thereof) for exports to these countries.

[9] In reality, it is possible that a country with abundant renewable energy sources is already today using low-cost renewable energy sources (such as hydropower) to a certain extent for the production of industrial goods. In the case of another country enacting more stringent climate policies in combination with a CBAM, producers in the renewable-rich country may have an incentive to use existing renewable energy sources to produce goods for this particular export market, while using fossil fuels for the production of goods for the domestic market or other export markets. Such "resource shuffling" could negate or minimise the policy's climate mitigation effects. The likely scale of this resource shuffling effect and potential regulatory steps to limit the effect have been discussed extensively in regard to the planned CBAM of the European Union [38–40].

[10] Such a distinction can also be stimulated by the government, e.g., by imposing a quota that obliges certain processing sectors (e.g., the car industry) to purchase a minimum share of "green" raw materials. However, we consider such a policy to be imposing an indirect cost on CO_2 emissions so we would rather categorise this under the "rising costs of using fossil fuels" discussed above.

green energy sources. Due to the lower marginal costs of production based on green energy sources in country B, it can be assumed that in this case there would be a shift in industrial production from country A to country B due to the renewables pull effect. The relocated business could then export "green" industrial production to country A or replace exports from country A to country B, meeting environmentally-conscious demand in country B.

It should be noted that even as CO_2 prices increase, industrial companies using fossil fuels may remain competitive for some time by purchasing renewable energy certificates or carbon offsets. This, however, will only work if future regulation allows companies to compensate for their CO_2 emissions or verify potential future renewable energy obligations in such a way.[11] Furthermore, any such compensation needs to be available at sufficiently low costs to enable industrial production using fossil fuels to remain competitive with industrial production in regions with abundant and cheap renewable energy. As the world is ultimately aiming for carbon neutrality, we believe it is likely that the costs faced by manufacturers to offset their CO_2 emissions will eventually become prohibitively high. Therefore, at best, such offsetting schemes are likely to only temporarily reduce the impacts of the renewables pull effect.

2.3. Production process characteristics that determine the relevance of renewables pull

We have identified the following seven key characteristics that increase the likelihood of renewables pull becoming relevant for any given production process:

- *Energy costs account for a high share in total production costs:*
  If this share is high, it is more likely that regional differences in energy costs play a key role in the locational decisions made by any given industry, which increases the relevance of renewables pull [8,27].
- *Low transportation costs per value of product:*
  Low transportation costs make it more likely that production will shift to regions with exceptional renewable energy conditions, as it will be relatively cheap to ship the products to industrial customers or end users around the world. High transportation costs, on the other hand, tend to lead to more distributed production sites that are closer to the selling markets [45].
- *Concurrence of significant renewables potential and the availability of key input materials:*
  In such cases, relocating to a region with favourable renewable energy conditions can decrease both energy costs and the costs and risks associated with obtaining key input materials [18].
- *Low value of existing assets for climate-neutral production:*
  Industries requiring entirely new production processes in order to become climate neutral are – all other things being equal – more likely to be affected by renewables pull than industries that can use many of their existing assets even after switching to renewable energy sources [46].[12]
- *Lack of existing synergies of vertically-integrated production:*
  If such synergies exist, the relocation of (only) a certain process leads to the loss of these synergies, reducing incentives to relocate [47]. While the simultaneous relocation of several steps of a value creation chain is – in principle – possible, this is likely to be much more difficult to achieve as it will typically involve a number of different companies and not every part of the chain may benefit from relocation.
- *Low level of product heterogeneity:*
  A low level of product heterogeneity means that producers at existing locations are unable to provide products with unique characteristics. This makes it more difficult for existing producers to compete with low production costs elsewhere [48].
- *Domestic production is not considered important for the given country:*
  Industrial production that is not considered to be particularly important for a given country is less likely to receive financial and other means of support, making it more likely that the companies responsible for producing the goods will (fully) relocated to other parts of the world. Industries may be considered significant by their country when they play key roles in economically important value chains or when their products are deemed to be essential, for example for maintaining key technological capabilities [49].[13]

3. Analysing the potential future relevance of the renewables pull effect using the examples of DRI and ammonia production

While it is outside the scope of this paper to systematically evaluate the potential future relevance of the renewables pull effect for different industries, this paper will focus on the climate-friendly production of direct reduced iron (DRI) and ammonia as two exemplary production processes with characteristics that make it relatively likely for them to be affected by renewables pull in the future. These two basic materials have been selected because previous literature [18,19,21,22] has already discussed the potential benefits of producing these materials in regions with abundant renewable energy sources (see Section 1 above).[14]

This section will first discuss the characteristics that make DRI and ammonia production likely to be affected by the renewables pull effect (Subsection 3.1). Subsection 3.2 then provides evidence that the renewables pull effect may already be active in these two industries by highlighting company announcements, government plans and industry survey results.

3.1. Production process characteristics that make DRI and ammonia production likely to be affected by the renewables pull effect

Table 1 provides an overview of how we assess the seven characteristics identified in Subsection 2.3 as crucial for determining the future relevance of renewables pull for DRI and ammonia production respectively.

Both DRI and ammonia production are very energy-intensive processes associated with high energy costs. When produced using renewable energy sources, energy costs are expected to account for up to around 50 % (DRI) and even around 90 % (ammonia) of total production costs in 2035 (see Fig. 2).

[11] There are indications that in the past such compensation mechanisms did not fully deliver the amount of emission reductions that were intended [41,42]. Governments may, therefore, be cautious about allowing such mechanisms to be used in the future. Indeed, concerns about the effectiveness of offsetting schemes have recently led the UK Advertising Standards Authority to restrict how companies can refer to the use of such schemes in their advertising [43], while in Germany, courts have ruled that the use of certain labels claiming carbon neutrality through offsetting schemes was misleading to consumers and had to be removed from products [44].

[12] It should be noted that even if valuable assets exist and can be used for climate-neutral industrial production, these assets have a limited technological lifetime and renewables pull may thus still occur when the end of lifetime of the key assets is reached or when major reinvestments are needed to prolong their lifetime.

[13] A government's ability to provide subsidies to key industries may be limited by international agreements, such as the WTO Agreement on Subsidies and Countervailing Measures or EU state aid rules [50,51].

[14] The direct reduction of iron using hydrogen is widely regarded as a key climate-friendly primary steel-making alternative to the currently dominant CO_2-intensive blast furnace route. The production of ammonia, which is mainly used for fertilisers, is also expected to shift in the future from using mainly natural gas as a feedstock to using green hydrogen. Additionally, ammonia is a potential transportation medium for future hydrogen imports.

Compared to energy costs, transportation costs are relatively low for both DRI and ammonia [18,19,21], even though the technical infrastructure required for exports via shipping (particularly in the case of ammonia) is associated with high investment costs [52].[15]

In the case of DRI production, there are some regions in the world with very good renewable energy conditions where the key input material, iron ore, is also found. These regions include South Africa, Canada, Brazil and Northern Sweden, which are currently the four main countries supplying iron ore for the German steel industry [54]. This concurrence in some regions of the world increases the likelihood of green relocations. Ammonia production, on the other hand, does not require input materials with region-specific occurences.

In the cases of DRI, renewable energy-based production processes will require new direct reduction plants. This means that assets at existing sites (such as blast furnaces) are of limited value for climate-neutral production of DRI. However, some general advantages relating to existing brownfield locations of primary steel producers (such as a skilled labour force or a well-developed energy and transport infrastructure) are likely to remain relevant even when new production processes are introduced. In the case of ammonia, existing ammonia synthesis plants can, in principle, continue to be used when green hydrogen replaces fossil fuels as a feedstock [6]. However, the existing ammonia plants were originally optimised to be used alongside upstream synthesis gas generation plants – most commonly steam methane reforming – which would be replaced by the use of green hydrogen as a feedstock. Therefore, for green ammonia production an adapted plant concept would be required, including an external steam and nitrogen supply. This aspect, combined with the expectation that future green ammonia production plants will be smaller in size than current plants [55], leads us to believe that the economic advantages of existing sites will be limited.

In the case of DRI, there are some synergies (albeit limited) of vertically integrated production, meaning DRI production at existing sites can benefit to some extent from available downstream assets such as basic oxygen furnaces (BOFs), rolling mills and continuous casting lines. For example, a synergy of vertically integrated production may be achieved through the application of “hot charging”, meaning the heat contained in the DRI following the reduction process can be used in the subsequent smelting process to increase energy efficiency [56]. In the case of ammonia, synergies at current ammonia production sites are limited.

Regarding the level of product heterogeneity, ammonia does not have significant differences in product characteristics depending on the manufacturer. On the other hand, DRI does vary to a certain extent according to the producer. However, as these differences mainly stem from the types of iron ore used in the reduction process, this heterogeneity is only likely to limit renewables pull effects if existing producers can retain or obtain exclusive or cheap access to high-quality iron ore deposits. In terms of the general iron and steel industries and their products, higher levels of heterogeneity, for example through significant differences in quality, may occur to a greater extent at later stages in the value chain (such as steel processing).

Both domestic DRI and ammonia production can be seen to be relatively significant for their countries of production, potentially triggering protectionist actions should domestic production come under economic pressure. In the case of DRI production, the downstream value chain for iron (i.e., steel-making and further downstream industries such as car manufacturing, plant engineering and machinery) is often economically important for any given country and its economy, and this value chain could be assessed as being at risk of relocation if iron production is relocated. In the case of ammonia, countries are also likely to have an interest in retaining some domestic production, as ammonia is a key input for fertiliser which may be essential for domestic food production.

3.2. Evidence of the renewables pull effect already being relevant in the iron and steel and ammonia industries

In the past few years, a number of announcements were made by companies highlighting the fact that the renewables pull effect may indeed already be playing a role in influencing the short to medium term investment plans of companies in both the iron and steel and ammonia industries. Table 2 provides examples of such announcements.

While there could be many specific reasons for investing in these locations, the companies listed in Table 2 probably anticipate more stringent climate policies in the coming years. In such a scenario, the production of green basic materials protects against increasing CO_2 prices and acts as a safeguard should “green” quotas for certain products in individual countries or world regions be introduced. Recent cost reductions for renewable energy technologies [17], as well as higher fossil fuel prices following the Russian invasion of Ukraine in early 2022, are likely to provide additional incentives for avoiding the use of fossil fuels and investing in climate-friendly production processes. The investments listed in Table 2 are also likely to aim to capitalise on the “green” characteristics of the produced DRI and ammonia, as demand for such intermediate products grows to accommodate the increasing demand from end users for products with low CO_2 footprints. Consequently, we believe that all three potential causes of renewables pull, as identified in Section 2.1, work together to explain recent decisions taken by companies to invest in green industrial production.

The national hydrogen strategies of several countries with exceptional renewable energy conditions, such as Australia [66], Chile [67] and Morocco [68], also suggest that at least some of these countries are already exploring the option of not only exporting green hydrogen in the future, but also exporting ammonia or iron and steel products. Australia’s national hydrogen strategy, for example, proposes investigating “new opportunities for clean hydrogen such as clean ammonia exports, clean fertiliser exports, industrial heating, iron ore processing and steel making”, while Chile “aims to export [...] renewable energy to the world in the form of green liquid hydrogen, green ammonia and clean synthetic fuels.”

The results of a 2021 survey of 1278 German companies[16] [69] support the idea that renewables pull is becoming relevant in the location decisions made by companies for both DRI and ammonia production. The results indicate that the chemical and metal industries are particularly exposed to potential increases in energy costs and the possibility of green relocations. They anticipated that it will be impossible to pass on increasing costs (resulting from a switch to climate-friendly products and processes) in the same way as other industries. Additionally, of all the manufacturing industries the metal industry reported the highest share of energy expenditure – accounting for 11 % of total costs – even at a time of generally low energy prices. When asked if they expected competitors, suppliers or customers to relocate as a result of the renewables pull effect, 32 % of metal production and processing companies and 24 % of companies in the chemical industry assumed that a large proportion of energy-intensive intermediate products would be imported in the future due to this effect. In other areas of manufacturing, an average of only 20 % of companies expect relocations due to the

[15] As fertiliser production accounts for nearly 70 % of the current ammonia demand worldwide [53], it is expected that much of the future green ammonia will also be used to produce fertilisers. Therefore, it is conceivable that fertilisers based on green ammonia will be traded globally in the future to a much larger extent than green ammonia itself. Nevertheless, green ammonia may also be used as a transportation medium for green hydrogen.

[16] The “IW Future-Panel” is a company survey conducted by the German Economic Institute twice a year and includes up to 1500 companies, mainly from the manufacturing industry but also from industry-related services and other sectors.

Table 1
Assessment of characteristics for DRI and ammonia production that are crucial for the relevance of renewables pull.

Characteristics of industrial production	DRI production	Ammonia production
Share of energy costs in total production costs	*High*	*Very high*
Transportation costs per value of product	*Low to medium*	*Low*
Concurrence of significant renewables potential and the availability of key input materials	*Yes (iron ore)*	*Not relevant*
Value of existing assets for climate-neutral production	*Low*	*Low to medium*
Existing synergies of vertically integrated production	*Limited*	*Limited*
Level of product heterogeneity	*Low to medium*	*Low*
Relevance of domestic production for the given countries	*Medium to high*	*Medium to high*

Dark green: Characteristic strongly indicates a relevant renewables pull effect.
Light green: Characteristic indicates a relevant renewables pull effect.
Grey: Characteristic is neutral regarding a relevant renewables pull effect.
Orange: Characteristic is contra-indicative of a renewables pull effect becoming relevant.

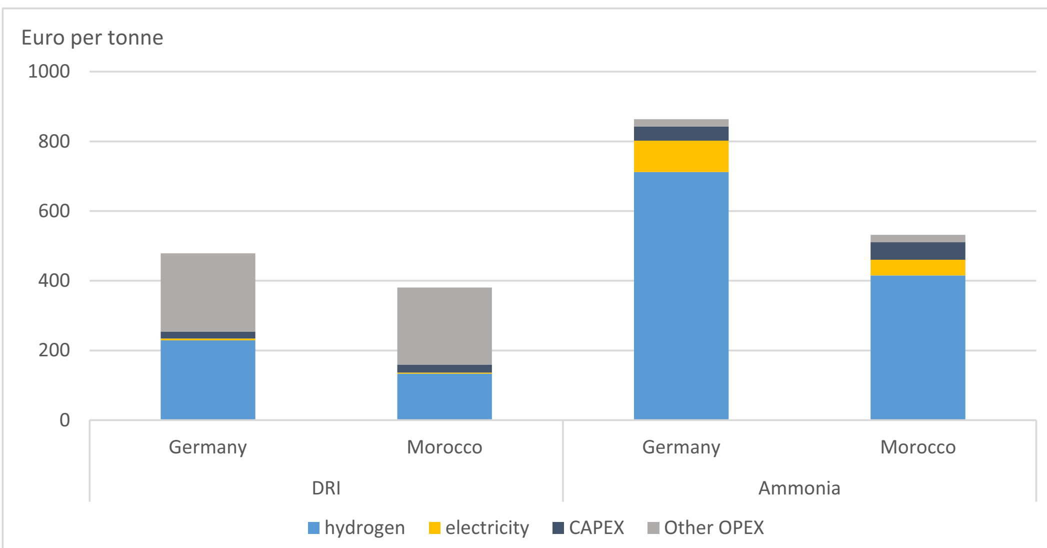

Fig. 2. Estimated production costs of green basic materials in 2035 in Euro per tonne for DRI and ammonia* (Own calculations based on [70–72]).
*CAPEX costs include investment costs for shaft furnaces (DRI production) and the Haber-Bosch process (ammonia production), including ASU units. Other OPEX costs entail fixed operating and maintenance costs. Additionally, in the case of DRI, specific costs for natural gas and iron pellets are also included.

renewables pull effect. While the companies surveyed did not generally feel that businesses in their own industry sectors would migrate as a consequence of renewables pull, in the metal and chemical sectors a higher proportion of companies were less certain. In these sectors, 6 % of companies predicted significant levels of relocation among their competitors in the future due to renewables pull. In all other industry sectors, only 2 % of companies held this view.

4. Comparison of production cost differences and other location factors between Germany and Morocco

Due to the specific characteristics of ammonia and DRI production as described in Subsection 3.1, as well as the company announcements highlighted in Subsection 3.2, the occurrence of a strong future renewables pull effect seems possible for these two products. To further examine this possibility, this section provides a comparison of potential future production costs and additional location factors between Germany and Morocco. These two countries were chosen as Germany has a large energy-intensive industry but only moderate renewable energy resources, while Morocco has excellent solar and wind conditions and is also in relatively close proximity to the large European markets for industrial goods. Therefore, exporting energy-intensive materials from Morocco to Germany or the EU is likely to involve relatively low transportation costs. It could even be feasible to export ammonia via pipeline to the EU from Morocco.

Subsection 4.1 presents estimated cost differences for the climate-friendly production of DRI and ammonia in both countries. Subsquently, for a broader assessment of the future likelihood of green relocations, Subsection 4.2 compares additional location factors, which are typically also of high importance for the choice of new industrial sites.

4.1. Estimates of regional production cost differences for green DRI and green ammonia production

Fig. 2 compares the expected production costs for green DRI and green ammonia for Germany and Morocco for the year 2035, using the parameters given in Table 3. In both cases, the production process is based on the use of green hydrogen. Hence, electricity from renewable energy sources is mainly used to generate the necessary hydrogen. The differences between the electricity and hydrogen costs stem from different natural potentials for renewable energy generation. For

Table 2
Recent company announcements indicating possible renewables pull effects in the iron and steel and in the ammonia industries.

Industry	Source	Company announcement	Renewables pull relevance
Iron and steel	ArcelorMittal [57]	ArcelorMittal is planning to transport part of the sponge iron produced at its Hamburg plant via direct reduction to its steel plant in Duisburg for further processing.	It is expected that green hydrogen, which will be used at the Hamburg plant, will be available at lower cost there (with its proximity to offshore wind farms in the North Sea) compared to the inland location of Duisburg.
	H2 Green Steel [58]	Swedish start-up H2 Green Steel aims to build a large-scale greenfield hydrogen-powered direct reduction plant in the northern Swedish region of Norrbotten.	H2 Green Steel stresses that the Swedish region has “access to abundant energy from renewable energy sources”. This includes wind and hydropower resources. Iron ore deposits are also located nearby.
	Iberdrola [59]	Iberdrola and H2 Green Steel plan to build a large-scale renewable hydrogen plant and a DRI plant on the Iberian Peninsula.	Iberdrola stresses that the future location on the Iberian Peninsula will have access to “low-cost renewable energy supplies”.
	SSAB [60]	SSAB, LKAB and Vattenfall plan to build a demonstration plant for the hydrogen-based production of sponge iron in the Northern Swedish town of Gällivare.	Two significant reasons why Gällivare in Northern Sweden was chosen as the site for the demonstration plant: it has an existing iron ore mine and Northern Sweden possesses very good wind and hydropower conditions.
	ArcelorMittal [61]	ArcelorMittal signed an MoU with SNIM to evaluate the opportunity to jointly develop a pelletisation plant and a DRI plant in Mauritania.	Mauritania has both excellent solar and wind conditions and large iron ore deposits.
	Zawya [62]	Jindal Shadeed intends to set up an integrated steel mill in Duqm (Oman) to produce green steel using renewable energy sources.	The new steel mill will be powered predominantly by green energy and will be connected to a 600 MW solar plant in a country with excellent solar energy potential.
Ammonia	NEOM [63]	Air Products, ACWA Power and NEOM signed an agreement for a large-scale green ammonia production facility in Saudi Arabia for export to global markets.	The project partners aim to harness the “unique profile” of Saudi Arabia’s sun and wind resources.
	AustriaEnergy [64]	AustriaEnergy and Ökowind formed a joint venture in 2020 to develop a green ammonia plant in southern Chile’s Magallanes region.	AustriaEnergy points out that the production site’s excellent renewable energy conditions give it a “superior competitive advantage”.
	Yara [65]	Yara, Aker Clean Hydrogen and Statkraft launched the company HEGRA, which is planning to build a new green ammonia plant in Norway.	Yara states that Norway has “a competitive advantage within renewable energy and hydrogen” and possesses “renewable energy in abundance”.

Germany, the electricity is assumed to be generated by nearby onshore and offshore wind plants. In the case of Morocco, hybrid solar and wind power plants provide electricity on site for the potential industrial locations [70].

For DRI, hydrogen costs account for 48 % of total production costs in Germany and 35 % in Morocco. In the case of ammonia, hydrogen costs account for 82 % in Germany and 78 % in Morocco. Electricity costs, mainly for compression and air separation, account for significantly lower shares of the total cost. Cheaper green electricity and hydrogen mean that DRI production is about 26 % cheaper in Morocco and ammonia production is about 62 % cheaper than in Germany – even after accounting for the higher weighted average cost of capital (WACC) in Morocco (see Table 3). These results confirm the overall findings from other recent studies into estimated ammonia production costs at different locations. Fasihi et al. [21], for example, estimated that green ammonia production in the MENA region could be between 11 % and 31 % cheaper than in Europe in 2030, depending on the specific production location. By 2050, the authors expect considerable decreases in production costs, but the price gap between Europe and the MENA region is still estimated to remain between 10 % and 30 %. Arnaiz and Cloete [23] also predict significant cost differences between production locations for green ammonia by 2050. They estimate that production costs in Germany will exceed costs in Spain and Saudi Arabia by 36 % and 59 % respectively.

It should be noted that these cost estimates include elements of uncertainty since future cost developments for the technologies and energy sources considered cannot be projected with certainty. For example, estimates of future green hydrogen costs vary significantly between different literature sources. In terms of the total cost of green DRI and ammonia, estimates may also vary because of differences in the way the costs are calculated. For instance, some cost comparisons cover costs of investments, resources and energy sources, whereas others may also include labour costs, costs of production-related services, maintenance costs or taxes and further levies.

4.2. *Impact of “soft” location factors on location and relocation decisions*

In addition to the quantifiable production costs compared in Subsection 4.1, other location factors also affect the overall attractiveness of potential production sites. Many of these factors and their monetary values are difficult or even impossible to quantify. In some cases, tools such as criteria-based assessments or rankings need to be used to measure differences between certain location-specific characteristics. For example, investment risks due to a lack of legal certainty may not be perfectly reflected by observable interest rates. Furthermore, even some tangible location factors – such as market access, availability of skilled workers and the quality of the transport infrastructure – cannot be reflected straightforwardly in a comparison of production costs. Nonetheless, we know through surveys that such factors can be of high relevance for industrial companies, particularly for the metal and chemical industries [73]. The survey referenced previously [69] also confirms the significance of a well-developed transport infrastructure and geographical proximity to suppliers and customers to safeguard transport quality. Overall, 42 % of responding companies valued geographical proximity as an “important” or “rather important” factor when choosing suppliers. The companies’ responses underlined the significance of logistical advantages relating to the close proximity of suppliers or customers. They highlighted the advantages of quick, flexible and less expensive delivery as relevant factors when choosing suppliers in close geographical proximity. Therefore, even if total transport costs are quite low, spatial proximity to customer markets could be

Table 3
Underlying location-specific and product-specific cost parameters.

		Germany	Morocco	Source
Energy costs (Euro per MWh)	Electricity	60	30	[70]
	Hydrogen	120	70	
	Natural gas[a]	20	12	
Specific investment costs	Shaft furnace (Euro per tonne of DRI)	230		[71]
	Haber-Bosch process (Euro per kW ammonia)	835		[72]
Depreciation period (years)	Shaft furnace	18		[71]
	Haber-Bosch process	25		[72]
Capacity utilization (%)		90		[71]
WACC (%)		4.88	7.15	[72]

[a] A relatively small amount of natural gas (roughly 0.57 MWh per tonne of DRI) is assumed to be used in the DRI process to account for gas temperature control and carbon content [70].

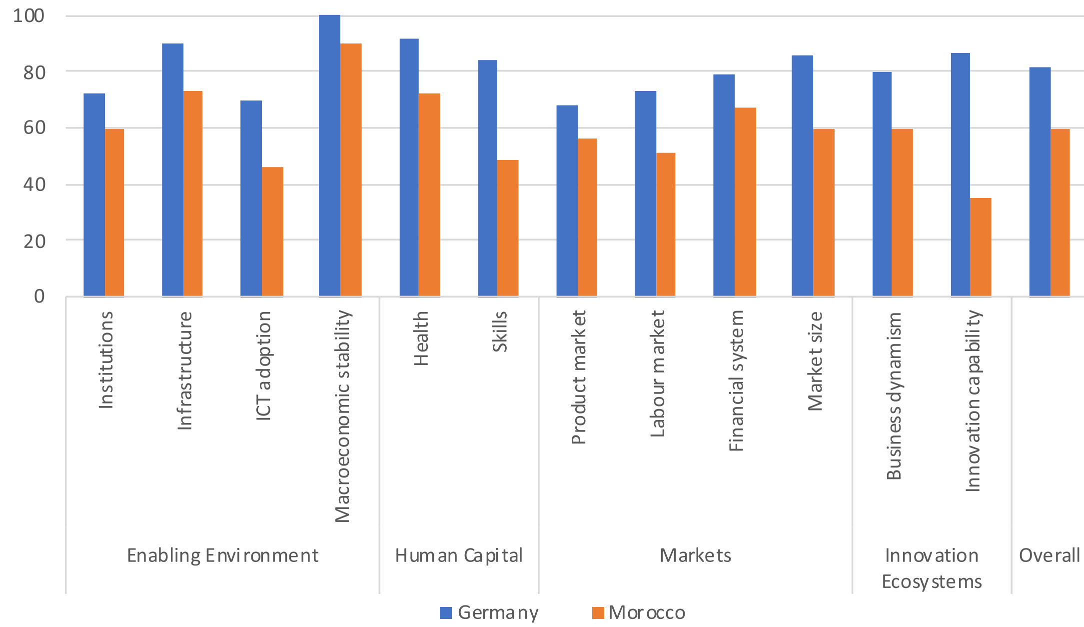

Fig. 3. Evaluations for Germany and Morocco, taken from the Competitiveness Index 2019 [76]; Score: 0–100, Rank: 1–141.

highly relevant when taking location decisions.

For Germany, energy costs, taxes and labour costs all constitute location disadvantages in comparison to many other countries. For example, the average wages in the industrial sector in Morocco are only 9 % of the respective wages in Germany [74,75]. However, according to several comparisons and rankings of business locations, Germany also has significant location advantages. For example, the Competitiveness Index, conducted by the World Economic Forum [76], ranks Germany as the seventh most competitive region, whereas Morocco is ranked seventy-fifth. The Competitiveness Index confirms the advantages of qualified labour, market access and a well-developed transport infrastructure (see Fig. 3), which are highly valued assets for industrial sectors such as the metal and chemical industries. In terms of macroeconomic stability (which mainly includes inflation risks and debt dynamics) and innovation capability, Germany is number one in this ranking. Morocco, on the other hand, ranks in the bottom half in many of these categories. In terms of the crucial aspect of the labour market and the availability of skilled labour, Morocco ranks in the lowest quartile.

An alternative comparison and ranking of 45 industrial and emerging countries in terms of their appeal as industrial and company locations, undertaken by the German Economic Institute (IW) [77], also confirms the assessment of Germany as a country that provides many location-specific advantages but also faces high production costs. This study lists Germany as the fourth best choice overall, only behind Switzerland, the US and the Netherlands. It ranks Germany in the Top 10 in all of the six underlying categories except costs, where it is near the bottom (placed at 41 of 45). However, in the two categories of infrastructure and markets, Germany is in second and first place, respectively.

These rankings do not yet include location-specific advantages associated with a high potential for cost-efficient renewable energy generation. However, as previously mentioned, many location factors increase the attractiveness of location sites in stable, high-income countries such as Germany or other highly industrialised countries. Additionally, the preference generally expressed by companies for nearby suppliers and customers could decrease the likelihood of the spatial expansion of supply chains and, consequently, of green relocations. On the other hand, this preference for the close proximity of suppliers could lead to relocations of additional parts of value chains once green relocations do occur in energy-intensive basic materials production.

Some locations may, of course, combine both aspects by providing excellent renewable energy conditions and simultaneously fulfilling other important location qualities such as a highly qualified work force and well-developed transport infrastructures. This probably holds true, for example, for some regions of the United States. The United States also provides competitive prices for fossil fuels, which could continue to be used by companies during a transition period before they eventually switch to fully renewables-based industrial production. It is reasonable to expect that DRI and ammonia production could undergo this type of gradual transformation. In newly constructed direct reduction plants, for example, natural gas may be used initially, before a gradual shift to green hydrogen occurs as the latter becomes increasingly available and cost-competitive. Consequently, the combined availability of renewable energy sources and natural gas at competitive prices could provide a significant location advantage for new industrial production facilities. In view of the fact that the United States is ranked second best in both the WEC Competitiveness Index [76], and the German Economic Institute rankings [77], it could provide a multitude of location advantages for new industrial production facilities.[17]

5. Conclusions and further research needs

Theoretical considerations, together with recent announcements by several companies in energy-intensive industries, suggest that differences in renewable energy conditions between countries or regions may play an increasingly important role in business location decisions. We use the term “renewables pull” to refer to this effect, which could lead to a loss of industrial production or a lack of investment in new industrial capacity in certain countries or regions because of superior renewable energy conditions in other countries or regions and high transportation costs of the respective energy carriers. This paper provides a conceptual illustration of how and under what circumstances industrial relocation may occur as a result of the renewables pull effect. It also discusses which product characteristics make it more likely that production will be affected by this effect. Due to their characteristics, the energy-

[17] The attractiveness of the United States for new investments was further substantiated by the adoption of the Inflation Reduction Act (IRA) in August 2022, which offers significant tax credits particularly for the expansion of low carbon energy sources.

intensive production of DRI and ammonia are identified as two products with a relatively high likelihood of being affected by renewables pull in the future. At the same time, the paper stresses that, even for companies in energy-intensive industries there are numerous relevant location factors in addition to energy costs, making it difficult to predict how much industrial production will relocate due to the renewables pull effect.

To gain a better understanding of the renewables pull effect, we identify the need for more research in the following three areas:

- Future relevance of the renewables pull effect
- Implications of the renewables pull effect for economies
- Potential of governments to influence the occurrence of green relocations

A better understanding of the future relevance of the renewables pull effect requires first and foremost an analysis of the importance of energy costs in comparison to other location factors for different industries and products. Other location factors are often more difficult to quantify in monetary terms than energy costs, and there is a lack of comprehensive studies into location qualities, including the availability and cost of renewable energy sources. Statistical analysis of past business location decisions and exploratory interviews with corporate decision-makers could help to gain a better understanding of the most relevant location factors for individual industries. Another way to better understand the relevance of the renewables pull effect would be to conduct case studies that explore the complex reasoning of individual companies when deciding where to locate future investments. The knowledge gained from such analysis can be incorporated into models of global economic trade. These models could then be used to quantitatively assess under what circumstances (e.g. what CO_2 prices or renewable energy penetration levels) the relocation of various industrial activities due to the renewables pull effect can be expected.

We believe it is important to gain a better understanding of the renewables pull effect on business location decisions, as this could have a profound impact on the increasingly relevant interplay between climate change and industrial policies. From a climate change perspective, the decarbonisation of highly-emitting heavy industries (including iron and steel and ammonia, but also others) could be accelerated if the new renewables-based production processes were located in regions with cheap renewable energy sources. This scenario could be likely as the transportation of basic materials is typically cheaper than the alternative of transporting electricity or green hydrogen from renewable resource-rich locations to current heavy industry centres, which are often located in regions with less favourable renewable energy conditions.

An important question for governments around the world is whether, and to what extent, the loss of production facilities caused by renewables pull could affect the international competitiveness of the remaining production within a particular country by impacting other parts of the corresponding value chains. This is an important question because the energy-intensive production of basic materials, for example, typically represents only a limited part of an economy, particularly in terms of added value or employment – but the economic impact of any relocation of basic materials production could be much higher because of the dependencies of a number of sectors on these materials (e.g., the automotive industry). The competitiveness of the remaining companies in downstream supply chains could be affected by increased transportation costs for their inputs and the loss of potential networking benefits associated with the proximity of suppliers. A better understanding of the likely extent to which downstream production could be affected might be gained by analysing past geographical dynamics within supply chains and examining the relevance of supplier proximity for the potentially affected industries.

Finally, another area for further research into the renewables pull phenomenon is the identification and evaluation of policy options. For example, governments of countries with significant energy-intensive industries but limited renewable energy potential could pursue policies to prevent or mitigate green relocations. Such policies could include support for the rapid and cost-effective expansion of domestic renewable energy generation, even if the country's renewable energy potential is limited compared to other countries. Policies could also facilitate the targeted and coordinated expansion of transport infrastructure for electricity, hydrogen and other sustainable energy carriers, partly for imports from abroad. In addition, policies in these countries could seek to focus on maintaining or developing other locational advantages, for example by funding research capacity, improving education or expanding transport infrastructure. On the other hand, governments in countries with exceptional renewable energy potential could create conditions to help their countries benefit from the renewables pull effect and attract new industrial production. Further research could explore the potential and limitations of such policy options for both types of countries, which could provide them with new opportunities for economic development in line with the global need to drastically reduce CO_2 emissions.

A combination of international climate policy and joint industrial development strategies could provide opportunities for a "win-win" situation for both types of countries and regions through the renewables pull effect. A joint approach across world regions could lead to faster climate mitigation and strong global green growth. Strategies allowing developed countries to decarbonise their industries faster and at lower cost should be designed and become an important part of international climate policy. Such strategies should also allow for economic development in the Global South. International sectoral climate policies, such as those currently emerging in the context of climate clubs [78], should therefore take account of the renewables pull effect and seek to turn it into a powerful lever for sustainable development by accelerating decarbonisation and green growth.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data we use and all data sources are provided in Table 3 and in Figure 3.

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