

# Estimating the renewables pull in future global green value chains

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## Article

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# Estimating the renewables pull in future global green value chains

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## Abstract

On the path to climate neutrality, global patterns of industrial production and trade might change due to the heterogeneous distribution of renewable energy resources. Here we estimate the “renewables pull”, i.e. the cost savings when relocating low-carbon production from a renewable-scarce region and instead importing energy-intensive basic materials from renewable-rich regions. For an electricity-price difference of 50 EUR/MWh, these relocation savings are roughly  $-20\%$  for imported steel and  $-50\%$  for urea and ethylene. Conserving production patterns by importing green hydrogen via ship is substantially costlier. A middle way could be a relocation of only the most energy-intensive parts of industrial production, while keeping substantial value creation in importing regions. Despite inhibiting factors such as benefits of short and integrated supply chains, the renewables pull is likely to incentivise green relocation without policy interventions. A societal debate on macroeconomic, industrial and geopolitical implications is needed, potentially resulting in selective policies of green-relocation protection.

**Keywords:** Renewables pull, green relocation, techno-economic analysis, industry transformation, hydrogen, steel, chemicals

## Main

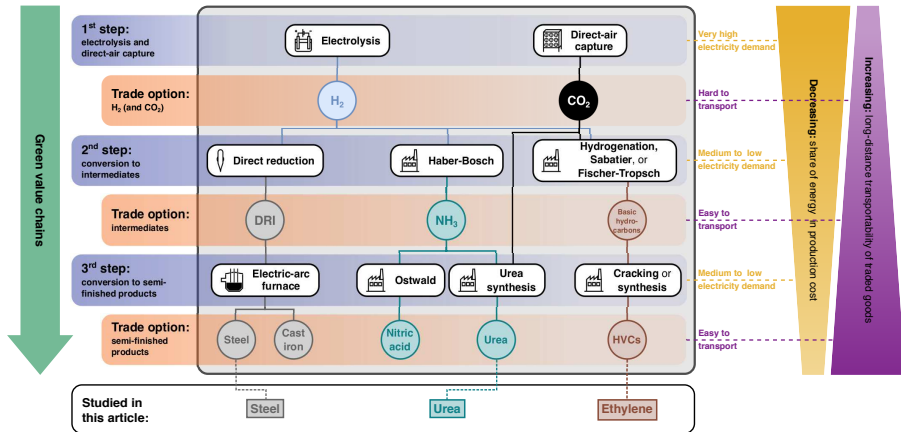
The transition to net-zero greenhouse-gas (GHG) emissions necessitates a deep transformation of the production of energy-intensive basic materials. The steel and chemical subsectors, which together were responsible for 44 % of all industrial GHG emissions in 2020 (Ritchie et al, 2020), are particularly hard to abate because they require energy carriers as feedstocks and cannot be decarbonised through direct electrification (Madeddu et al, 2020; Luderer et al, 2021).

Power-to-X (PtX) technologies based on renewable electricity (RE) are a promising option for a carbon-neutral production of these feedstocks (Ueckerdt et al, 2021). Plans to scale-up PtX technologies have consequently been announced by several industrial stakeholders (IEA, 2022b; Wulf et al, 2020) and governments (EUH, 2020; Krupnick and Bergman, 2022) across the globe. Despite the early stage of their deployment and some remaining uncertainties, it has become clear that certain basic green feedstocks, such as hydrogen (H<sub>2</sub>), atmospheric carbon-dioxide (CO<sub>2</sub>), ammonia (NH<sub>3</sub>), methanol (MeOH), and other synthetic hydrocarbons will become core elements of emerging green value chains (Fig. 1).

Energy prices are a major factor for production cost of basic materials already today (Boulamanti and Moya, 2017) and will continue to be for these future green value chains. While global variations of the abundance of primary energy led to trade with fossil energy carriers in the past, it is significantly less efficient and more costly to transport electricity and H<sub>2</sub> over long distances compared to coal, oil, and natural gas. As a result, substantial geographical differences in RE costs can create an incentive to relocate future production due to the associated energy-cost savings (Devlin and Yang, 2022), which is referred to as renewables pull (Samadi et al, 2021). The electricity-price difference between RE-scarce industrialised countries producing today's basic materials and some potential future RE-rich producers can be huge in some cases, such that this effect has the potential to shape future production patterns and trade flows of energy-intensive basic materials.

Prominent candidates for the RE-scarce importer are the European Union, which has already declared ambitious goals for imports of 10Mt of green H<sub>2</sub> (33 TW h, assuming LHV) by 2030 (REP, 2022), as well as Japan, a densely populated island with limited RE potentials that imports 96 % of its today's domestic energy demand (Zhu et al, 2020). Obvious candidates for green energy-intensive exports are most regions in the global south, primarily Africa, the Middle East, Australia, and Latin America. A renewables pull within a region is also conceivable, such as within the European Union (e.g. Germany to Spain) or within the US (e.g. north to south). The analysis in this article is kept generic, as we estimate the renewables pull purely based on electricity-price differences and other techno-economic parameters.

We provide quantitative insights into the renewables pull from a techno-economic and energy perspective by estimating the energy-cost savings and competing effects (transport and financing penalties) for the green value chains of three major basic materials: steel, urea and ethylene. We conduct our



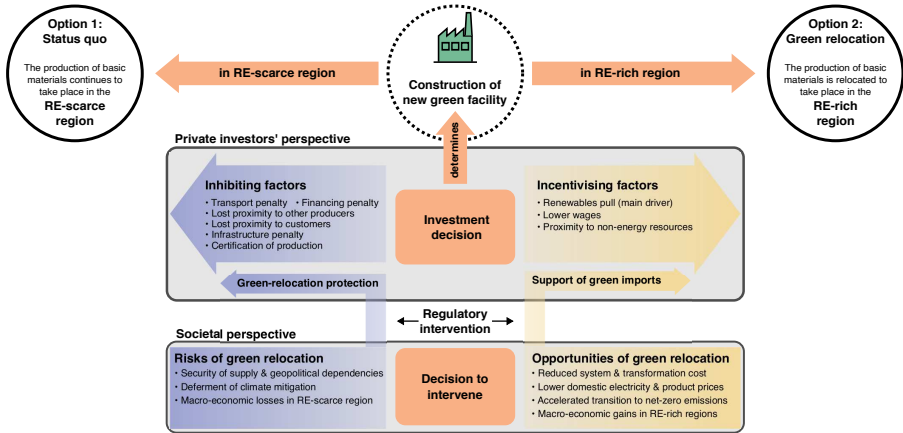
**Fig. 1 Emerging green value chains and the associated production steps, feedstock flows, and trade options.** Defossilising the value chains of energy-intensive basic materials, in particular in the steel and chemical sectors, necessitates the emergence of new green value chains that rely on the provision of low-carbon PtX feedstocks produced from renewable electricity (RE). All value chains commence with water electrolysis and, in the cases of urea and ethylene, with direct-air capture (DAC), which yields the basic building blocks green hydrogen (H<sub>2</sub>) and atmospheric carbon-dioxide (CO<sub>2</sub>). Combining these two together with iron and nitrogen yields directly reduced iron (DRI), ammonia (NH<sub>3</sub>), and basic hydrocarbons, which we refer to as intermediates. These are finally converted into (semi-)finished products that are widely used in industry, such as semi-finished steel, cast iron, fertiliser, and higher-value chemicals (HVCs). While the share of energy in the production cost decreases along the value chain, the long-distance transportability of intermediate products increases. In this article, we estimate the renewables pull for the green value chains of three commodities: steel, urea, ethylene.

analysis for a varying degree of production relocation and thereby study the relevance of each individual production step in the respective value chain.

In the next section, we first embed the renewables pull into a broader conceptual framework and discuss other driving factors, before presenting our quantitative estimates in the proceeding section.

## A broader picture of the renewables pull and green relocation

The effect we ultimately aim to understand is green relocation, which we define as the relocation of industrial production incentivised by the renewables pull (i.e. the energy-cost savings). We note that our definition is slightly adjusted compared to the one by [Samadi et al \(2021\)](#), who refer to the renewables pull and the resulting green relocation both using the term renewables pull only. The illustration in [Fig. 2](#) is intended to guide the reader, as we introduce the framework we use to structure all major factors that can influence the occurrence of green relocation. Further notes on terminology can be found in [Methods](#).



**Fig. 2 Broader picture of green relocation and the renewables pull.** Investments into new green production facilities can occur in two ways. Option 1: Plants are constructed in RE-scarce regions, where (grey) industrial production is located today, hence reinforcing the status quo (left circle). Option 2: Plants are constructed in new RE-rich regions, where no or little industrial production takes place today, hence resulting in green relocation (right circle). The construction of such facilities is determined by private investment decisions, which are influenced by a number of incentivising and inhibiting factors. The renewables pull is only one of these factors, and we estimate it quantitatively together with transport and financing penalties. Other hard-to-quantify factors are briefly listed in this figure and explained in further detail in the Supplementary Information. Green leakage also comes with societal risks and opportunities, which however require regulatory intervention in order to translate into further factors influencing private investment decisions. A comprehensive list of risks and opportunities is also provided in the Supplementary Information.

The occurrence of green relocation depends on the investment decision of private investors, which is influenced by incentivising or inhibiting factors, of which the renewables pull is only one. These factors can broadly be split up into hard factors, i.e. those that are easy to express as changes in the production cost, and soft factors, i.e. those that are not. Those hard factors that our generic study is able to capture can be summarised in the following simple relation,

$$\begin{aligned} \text{Relocation savings} &= \text{Renewables pull} \\ &\quad - \text{Transport penalty} \\ &\quad - \text{Financing penalty} \end{aligned}$$

where we define the term relocation savings to refer to the overall production-cost savings resulting from production relocation. We note that our conceptual framework and our estimations assume electricity and heat supply from renewable sources, where the residual GHG intensity in both regions is the same, such that no competitive advantage emerges from cleaner production in one or the other region. Other soft factors that are hard to quantify and need further analysis beyond the scope of this article are the proximity to customers (short value chains), the proximity to other producing facilities (effects of integration,

clustering, joint industrial infrastructure, and economies of scope), the availability of general infrastructure (roads, ports, water, etc.), and availability and cost of skilled labour, where a detailed list can be found in the Supplementary Information.

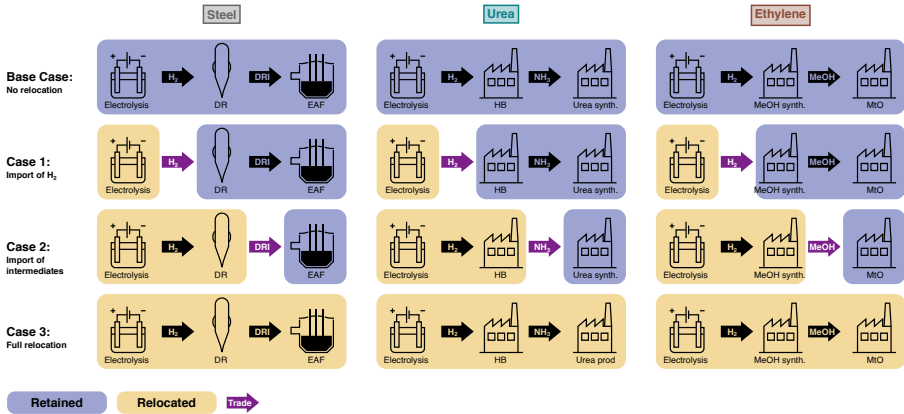
From a societal perspective, the occurrence of green relocation is associated with risks and opportunities for both RE-scarce and RE-rich countries. On the RE-scarce side, opportunities are low-cost imports of basic materials, reduced system and transformation cost, lower domestic energy prices, and an accelerated transition to net-zero emissions. Risks include security of supply and geopolitical dependencies, a potential deferment of climate mitigation, as well as macroeconomic losses due to lost employment, value creation, and GDP. The last of these risks, i.e. the value creation relocated, is the greatest opportunity of the RE-rich region, while the risks lie in introducing neocolonial structures in developing countries and using RE potentials only for exports and not for domestic decarbonisation (so-called resource shuffling) and energy-system development. A comprehensive list of risks and opportunities is again placed in the Supplementary Information.

Policy makers may decide to try to influence future production patterns and potential relocation based on these societal risks and opportunities. Regulatory intervention could either support green imports (e.g. development aid (BMWK, 2022)) or protect against green relocation (e.g. subsidies or trade tariffs), which translates into additional incentivising and inhibiting factors and thus influence private investment decisions.

## Quantifying the renewables pull for key energy-intensive value chains

We estimate the renewables pull for the green value chains of three commodities, which are chosen to be broadly representative for key emerging green value chains (compare Fig. 1):

1. Liquid steel as an intermediate product of the steel industry and a precursor to (semi-)finished steel products (cast steel slabs, rolled strips) – produced from directly reduced iron (DRI) with green H<sub>2</sub> in a direct-reduction (DR) shaft and melted in an electric-arc furnace (EAF)
2. Urea as both an intermediate and final product of the chemical industry and key component of nitrogen fertilisers (pure urea, urea mixed with nitrate fertilisers) with approx. 50% global market share in 2018 (Fer, 2022) — produced from green H<sub>2</sub> converted to NH<sub>3</sub> via the Haber-Bosch process and combined with atmospheric CO<sub>2</sub>
3. Ethylene as an intermediate product of the chemical industry and precursor to polymer plastics (polyethylene, polyethylene-terephthalate) — produced from green H<sub>2</sub> used for the hydrogenation of CO<sub>2</sub> to yield MeOH, which is then reacted into ethylene via the Methanol-to-Olefin (MtO) process (note that the output of MtO is actually a mixture of ethylene, propylene, and other by-products, but for simplicity we refer to it by just ethylene)

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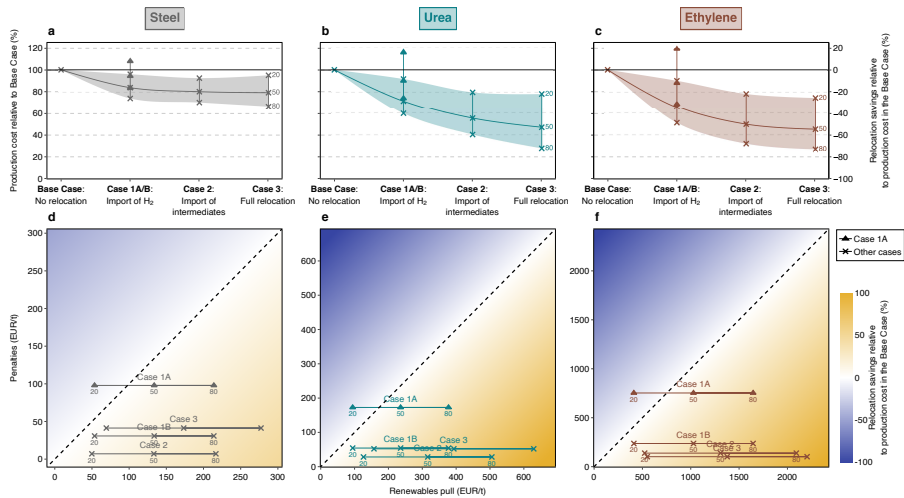
**Fig. 3** Processing steps and resulting import cases for the green value chains of the three studied commodities (left-to-right: steel, urea, ethylene). Each of the value chains commences with 1) the production of green H<sub>2</sub> via water electrolysis, continues with 2) the conversion to the secondary feedstocks DRI, NH<sub>3</sub>, and MeOH, and finishes with 3) the conversion step into the (semi-)finished industrial products steel, urea, and ethylene. We associate the winning of CO<sub>2</sub> from DAC to the process step consuming this as a feedstock, i.e. the final step in the urea and the second step in the ethylene value chain. Trade may occur in between these three production steps, resulting in four import cases: a Base Case, where all production steps are retained in the RE-scarce region, and Cases 1–3, in which respectively one additional production step is relocated to the RE-rich region. Hence, in Case 3, all production takes place in the RE-rich region, and only the final good is imported by the RE-scarce region.

For each basic material, we define four relocation cases that subdivide green value chains according to their three main processing steps, such that we can capture cases of partial relocation (Fig. 3).

We estimate the production cost for the three commodities for each of the four relocation cases, with results presented in Fig. 4, Fig. 5, and Tab. 1 with the assumed variation of regional electricity prices also listed in Tab. 1. Moreover, we distinguish Case 1 into Case 1A, showing high H<sub>2</sub> transportation cost of 50 EUR/MWh, and Case 1B, showing moderate cost of 15 EUR/MWh, corresponding to, respectively, shipping-based and pipeline-based transport modes.

Technology parameters are chosen to represent the year 2040, such that they include learning effects that result from a wide deployment of those technologies with a low readiness level today. Moreover, the cost estimates are intended to be generic and provide a framework for further analysis, hence we do not assume specific regional cases. We choose a relocation-induced increase of the weighted average cost of capital (WACC) from 5% to 8% to account for the financing penalty, whose magnitude appears to be small, as visible in Fig. 5. Further details on assumptions and how the techno-economic data was curated can be found in the Methods section.

Production costs of the studied basic materials decrease with every process step relocated to the RE-rich region, except for Case 1A when the transport and financing penalties exceed the renewables pull (Fig. 4a–c). The resulting



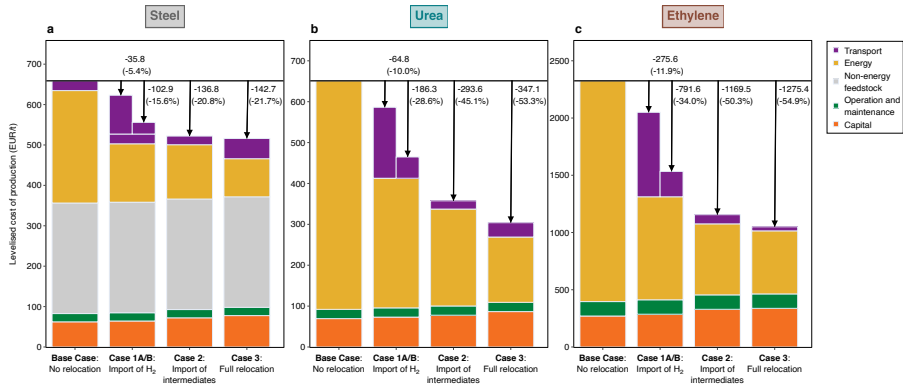
**Fig. 4 Relocation savings for the different import and electricity-price cases for the three studied commodities (left-to-right: steel, urea, ethylene).** Top row: Relocation savings, i.e. overall production-cost savings, relative to the Base Case production cost, shown for the import cases outlined in Fig. 3 and electricity-price cases in Tab. 1. Bottom row: Comparison between the renewables pull, i.e. energy-cost savings, on the lower axis and transport and financing penalties on the upper axis with the heatmap showing the resulting relocation savings relative to the Base Case for the medium-pull electricity-price case. Case 1A is displayed separately from the other cases and not included in the corridor of values on the top row to highlight its saliency and contrast it to the otherwise monotonous decrease of production cost with increasing degree of relocation. The bottom row shows how the penalties cause Case 1A to have higher production cost compared to the Base Case for an electricity-price difference below approx. 35 EUR/MWh.

**Table 1 Electricity prices assumed and resulting relocation savings for Case 3.** The electricity prices were used in our estimates with results presented in Fig. 4 and Fig. 5.

Price case	Electricity price (EUR/MWh)			Relocation savings in Case 3 relative to production cost in the Base Case (%)		
	In RE-rich region	In RE-scarce region	Difference	Steel	Urea	Ethylene
<b>Strong pull</b>	10	90	80	-5.5	-21.9	-25.3
<b>Medium pull</b>	20	70	50	-21.7	-53.3	-54.9
<b>Weak pull</b>	30	50	20	-34.6	-72.4	-73.1

full relocation savings (from Base Case to Case 3) spread across a broad range of  $-5.5\%$  to  $-73.1\%$  and strongly depend on the electricity-price difference case and the respective value chain. The relocation savings are considerably lower for steel, where non-energy feedstock costs (especially iron ore and alloys) are high and CAPEX in relation to energy cost are larger compared to urea and ethylene. Yet, a plausible electricity-price difference of 50 EUR/MWh





**Fig. 5** Levelised cost of production for the three studied value chains (left-to-right: steel, urea, ethylene). These estimates are shown for the four relocation cases defined in Fig. 3 and assume the medium-pull case from Tab. 1. The levelised cost visualise how the high feedstock cost in the steel value chain diminish the relocation savings compared to those for urea and ethylene, which have a much higher share of energy in the total production cost. Moreover, the higher WACC of 8% in the RE-rich region compared to 5% in the RE-scarce region results in higher capital cost, yet this effect appears to be small compared to the renewables pull.

(medium-pull case) yields substantial relocation savings of  $-21\%$  for steel. In contrast, the production cost of urea and ethylene is even more strongly determined by its energy cost, hence resulting in huge relocation savings of  $-53\%$  and  $-55\%$ , respectively. In the strong pull case, relocation savings reach  $-34\%$ ,  $-72\%$ , and  $-73\%$  for steel, urea, and ethylene, respectively.

The penalties, which are dominated by the transport component, vary between relocation cases, but are typically overcompensated by the renewables pull (Fig. 4d–f). An exception is Case 1A, i.e. the shipping-based import of H<sub>2</sub>, where a large transport penalty is driven by high conversion losses of different H<sub>2</sub> shipping options, which can only be compensated by an electricity-price difference of at least approximately 35 EUR/MWh. Above this price difference, the relocation savings yielded by Case 1A remain small, causing further relocation savings of Cases 2 and 3 compared to Case 1A to be large, as is also apparent in Fig. 5. Therefore, in the absence of cheap pipeline-based H<sub>2</sub>-imports, there is a strong overall cost incentive to import secondary feedstocks (DRI, NH<sub>3</sub>, MeOH) or (semi-)finished goods instead of H<sub>2</sub>.

## Discussion and conclusions

Access to cheap energy has always shaped the production locations of energy-intensive industries. On the path to climate neutrality and an increasingly renewable-based energy system, the heterogeneous distribution of renewable energy resources might change global patterns of industrial production and trade.

Here we estimate the “renewables pull”, which describes the cost savings when relocating low-carbon industrial production from a RE-scarce region and instead importing energy-intensive basic materials from RE-rich regions. We find that green relocation can create overall savings of roughly  $-20\%$  for steel and  $-50\%$  for urea and ethylene, assuming an electricity-price difference of 50 EUR/MWh and a full relocation of the green value chains considered.

Moreover, we analyse a partial relocation of only the most energy-intensive parts of production. This leads to different divisions of green value chains between RE-scarce and RE-rich regions.

Only relocating green H<sub>2</sub> production, which accounts for the highest share of energy demand for the studied basic materials, and importing shipping-based H<sub>2</sub> implies only small relocation savings ( $\sim -5\%$  for steel and  $\sim -10\%$  for urea and ethylene), as the energy-cost savings are compensated by high H<sub>2</sub> transport costs. A substantial renewables pull would remain for relocating further energy-intensive production steps and importing industrial products that are easier to transport.

Hence, trying to conserve production patterns by importing green H<sub>2</sub> via ship would be substantially costlier than relocating more parts of the green value chains. This finding challenges the H<sub>2</sub> import strategies of some renewable-scarce regions, such as the EU or Japan. While importing H<sub>2</sub> could retain much of the value creation and capital-intensive employment of further downstream production steps, relying on the emergence of a global and reliable H<sub>2</sub> shipping market entails risks. It is uncertain whether H<sub>2</sub> will be shipped in substantial volumes as the shipping and trade of H<sub>2</sub>-based derivatives and industrial products is more cost competitive. H<sub>2</sub> imports via pipelines can be cheaper and thus substantially dampen the renewables pull; yet, there also remain incentives to relocate more of the energy-intensive downstream production steps, as our analysis demonstrates.

A middle way could be a relocation of only the most energy-intensive parts of industrial production, while keeping substantial value creation in importing regions. This would include imports of DRI, NH<sub>3</sub>, MeOH, or other (semi-)finished products, which are further processed and refined in the importing regions. However, relocating the production of intermediate or (semi-)finished goods could stimulate a full relocation of basic material production away from renewable-scarce regions, even though the additional energy cost savings are low.

More research is needed on factors that might counteract relocation. This includes understanding the effect of a partial relocation on downstream production steps and the wider economy. Such locational factors are proximity to customers (short and secure supply chains), proximity to other producing facilities (production and supply chain integration), the availability of general infrastructure (roads, ports, water, etc.), and skilled labour. Yet, given the magnitude of the renewables pull estimates reported by our study, these factors might only have a dampening effect, such that a strong relocation incentive remains without policy interventions.

From a societal and macroeconomic perspective, there are opportunities and risks for both RE-rich exporting and RE-scarce importing regions. Renewable-rich regions could create or expand their energy-intensive industry and secure a higher share of the value creation, which could become part of development cooperation strategies. For RE-scarce regions, relocating energy-intensive parts of their production would reduce tension due to RE scarcity in their energy systems, leading to reduced energy prices and an eased energy transition overall. On the other hand, relocation might reduce value creation and employment in RE-scarce countries, and can create import dependencies that are subject to geopolitical and security considerations. In particular, the dependencies increase with every production step relocated along the value chain, as upstream intermediates are more versatile and easier to replace than downstream products.

Governments in renewables-scarce countries are tasked with shaping the low-carbon transformation of their basic materials industry against a background of deteriorating economic competitiveness. Governments could interfere with schemes of “green relocation protection”; however, given the size of basic material production and renewables pull, this could become very costly.

Hence, governments will likely have to be selective with respect to the sectors and extent of protection. There might be sweet spots in cutting green value chains such that only the most energy-intensive parts are relocated, while much of the value creation could be kept in the importing country. Being selective with sectors and process steps has the potential to reduce electricity prices and hence weaken the renewables pull for the selected industrial production.

Circular economy approaches are an alternative opportunity to reduce material and energy intensities and thus the renewables pull. Increasing the recycling rates would reduce the dependence on energy-intensive primary materials. This includes mechanical and chemical recycling of plastics or secondary steel from scrap, as further discussed in the Supplementary Information.

Many public decisions today already are explicit or implicit choices about future locations of industrial production. Examples are policies and strategies with respect to compensation of industry in the energy crisis, emission reduction in industry (e.g. CCfDs), imports of green fuels (e.g. choice of fuels and feedstocks in H<sub>2</sub>Global (BMWK, 2022)), or infrastructure such as H<sub>2</sub> or CO<sub>2</sub> infrastructure.

Conscious decisions based on a long-term strategy with a consistent set of policy instruments can avoid path dependencies, frictions between individual instruments, and costly disruptive changes. This likely requires a political and broader societal debate on the role of a country in global industrial production. Such a debate should start in the near future and be informed by scientific assessments such that the trade offs associated with green relocations can be estimated. A resulting strategy could include policies of selective green-relocation protection that balance the complex issues of cost savings, security of supply, and wider societal interests.

## Methods

**Terminology.** Tab. 2 contains an overview of terms used within this article. We stress again that we use the term renewables pull to refer to the pure energy-cost savings, while green relocation is the resulting effect, i.e. relocation of industrial production due to the energy-cost incentive.

Another term sometimes used for green relocation is green leakage, in analogy to the term carbon leakage, in which case relocation is incentivised by the evasion of climate-abatement cost. While carbon leakage is predominantly considered as undesirable, as it undermines climate-mitigation efforts, green leakage comes with both risks and opportunities. We therefore prefer the term green relocation to enable an open and balanced debate.

**Technology data from literature review.** A total of 31 original data sources (Al-Qahtani et al, 2021; Arnaiz del Pozo and Cloete, 2022; Bazzanella and Ausfelder, 2017; Devlin and Yang, 2022; ECORYS, 2008; Commission, 2007; Fasihi et al, 2019; Fiamelda et al, 2020; Hauser et al, 2021; Hegemann and Guder, 2020; Hölling et al, 2017; Holst et al, 2021; IEA, 2021a, 2022c, 2021b; IRENA, 2022; Jarvis and Samsatli, 2018; Keith et al, 2018; Kent, 1974; Madhu et al, 2021; Matzen et al, 2015; Oliveira, 2021; Otto et al, 2017; Ozkan et al, 2022; Pérez-Fortes et al, 2016; Rechberger et al, 2020; Sasiain et al, 2020; Vartiainen et al, 2021; Vogl et al, 2018; Worrell et al, 2007; Wörtler et al, 2013) were used to collect 173 individual entries of techno-economic data referring to the following 9 processes: water electrolysis (Alkaline and PEM), low-temperature aq. DAC, low-temperature heat pumps (for delivering heat for DAC at 80–120°C), direct reduction furnaces, electric-arc furnaces, ammonia synthesis via the Haber-Bosch process using nitrogen from an air-separation unit (ASU), urea synthesis, methanol synthesis via the hydrogenation of CO<sub>2</sub>, and methanol-to-olefins.

The following data types were curated: capital expenditure (CAPEX), demands of energy and non-energy feedstock, non-energy non-feedstock operational expenditure (OPEX), and prices of non-energy feedstocks. While the curation of this database is done with great care across all technologies and data types, extra care is taken with respect to the energy intensity of processes, which is of particular interest to this work. Interpretation or adjustment of data is kept minimal. The resulting database of collected entries is published as a spreadsheet file (see section Data availability below).

**Adaptation of collected data for estimations.** Based on the collected literature data, secondary data was adapted for the presented estimations. Where multiple sources are available for one entry type, we either take the average value or proceed with the more conservative assumption. Conservative in this case means assuming the set of parameters least supporting a renewables pull (high CAPEX, low energy demand). The main technology parameters resulting from this literature review are reported in Tab. 3.

**Table 2** Terminology used within this article.

Category	Term	Explanation
<b>Cost changes</b> associated with production relocation from the RE-scarce to the RE-rich region	<b>Renewables pull</b> or energy-cost savings	Production-cost savings due to reduced energy cost.
	<b>Transport penalty</b>	Production-cost surplus due to increased transport cost of traded goods.
	<b>Financing penalty</b>	Production-cost surplus due to increased financing cost (higher WACC)
	<b>Relocation savings</b>	The total production-cost savings that results from the above three components
<b>Effects</b>		
related to production relocation due to reduced energy cost	<b>Renewables pull</b>	The incentive for production relocation arising from the energy-cost savings. It is one factor among several others that can serve to incentivise or inhibit green relocation.
	<b>Green relocation</b> or green leakage	The actual occurrence of production relocation due to the renewables pull. Note that we prefer the term green relocation over the term green leakage, due to the negative connotation hidden in the analogy to the term carbon leakage.
<b>RE availability</b>		
and its difference between the RE-rich and RE-scarce regions	<b>Electricity-price difference</b>	The difference in effective electricity prices between the RE-scarce and the RE-rich region. The renewables pull depends linearly on the electricity-price difference.
<b>Regions</b>		
considered in this work for generic relocation analysis	<b>RE-scarce region</b>	A region (potentially a specific country) whose availability of renewable electricity (RE) is low and therefore its resulting electricity prices are comparatively high, which incentivises the import of energy or energy-intensive goods from a RE-rich region.
	<b>RE-rich region</b>	A region (potentially a specific country) whose availability of renewable electricity is high and therefore its resulting electricity prices are comparatively low, which incentivises the export of energy or energy-intensive goods to a RE-scarce region.

The heat demand of processes was converted into an electricity demand as follows: the heat for DAC, which requires  $T \sim 80\text{--}120\text{ }^\circ\text{C}$ , can be provided by low-temperature industrial heat pumps with a coefficient of performance (COP) of around 3–3.5, the heat required by all other processes, which requires  $T \gtrsim 200\text{ }^\circ\text{C}$ , is assumed to be provided by resistive (Ohmic), radiative, microwave, or inductive heating, for which we assume a constant efficiency of 100 %. These assumptions are feasible, as such electrified heating of industrial processes is piloted and the technology is straight-forward and available, while industrial heat pumps for  $T \gtrsim 200\text{ }^\circ\text{C}$  are still in early development (TRL 4–5 (IEA, 2022a)) and the efficiency and feasibility of heat pumps for  $T \gtrsim 400\text{ }^\circ\text{C}$  (for most chemical processes) and  $T \gtrsim 800\text{ }^\circ\text{C}$  (for steel processes) is unclear.

**Transport cost.** In principle, transport costs are dependent on distance, yet in practice we can assume case-independent generic values. This is particularly the case for shipping, where harbour dues, terminal cost, and liquefaction (esp.  $\text{H}_2$ ) make up a large share of the total transport cost.

For shipping-based  $\text{H}_2$  transport, specific costs are in the range of 2.0–2.6 USD/kg $\text{H}_2$  in 2030, depending on distance and transport medium used ( $\text{LH}_2$ , LOHC, ammonia) (Glo, 2022). This corresponds to 55–72 EUR/MWh, hence we assume 50 EUR/MWh, which includes learning effects achieved by 2040. Pipeline-based imports are only feasible for short-distance transportation of approximately 1000 km, which gives 0.5–1.0 USD/kg $\text{H}_2$  of transport cost, depending mainly on whether new pipelines are built or old ones are repurposed (Glo, 2022). This corresponds to 14–28 EUR/MWh, hence we choose 15 EUR/MWh.

Moreover, we assume transport of ammonia in LPG tankers and of all other liquids in oil tankers at 35 EUR/t (Perner and Unteutsch, 2021). Based on analysis of the data from 2016 published by UNCTADstat<sup>1</sup> together with press releases of the past three months stating today’s levels, we assume transport cost of 15 EUR/t, 20 EUR/t, and 50 EUR/t for, respectively, iron ore, HBI, and semi-finished steel products.

**Levelised cost of production.** This is calculated from the curated techno-economic data and yields our quantitative estimations of the relocation savings. We assume

$$LCOP = \frac{(FCR + RFOPEX) \times CAPEX}{OCF} + \sum_k d_k \times p_k + \sum_g d_g \times tc_g, \quad (1)$$

where  $LCOP$  is the levelised cost of production,  $FCR$  is the fixed-charge rate given as  $(i \times (1 + i)^n) / ((1 + i)^n - 1)$  with interest rate  $i \in [0, 1]$  and lifetime  $n$  in years,  $CAPEX$  is the capital expenditure in units of annual production capacity,  $RFOPEX$  are the fixed operational expenditures relative to  $CAPEX$ ,  $OCF \in [0, 1]$  is the operational capacity factor,  $d_k$  and  $p_k$  are the demand and price for feedstock or energy carrier  $k$ , and  $d_g$  is the demand of

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<sup>1</sup> Accessible via <https://unctadstat.unctad.org/>

**Table 3 Main technology assumptions derived from literature review.** For a full list of literature values, check the Supplementary Information. The caloric heat content of H<sub>2</sub> assumes the lower heating value (LHV). Annotations: <sup>(1)</sup>Only covering the primary feedstocks of the respective production steps, i.e. HBI, NH<sub>3</sub>, and MeOH. <sup>(2)</sup>Of which 0.43 MWh are provided as natural gas to provide the carbon content for steel. <sup>(3)</sup>For all relocation cases, except for Case 2, where an additional 0.159 MWh/t are needed to reheat the imported HBI. <sup>(4)</sup>Mixed output of Ethylene, Propylene, and other by-products.

Process	Unit of output	CAPEX per annual capacity (EUR)	Fixed OPEX rel. to CAPEX (%)	Elec. demand (MW h)	Heat demand (MW h)	H <sub>2</sub> demand (MW h)	Primary <sup>(1)</sup> feed-stock demand (t)
Electrolysis	MW h	25	3	1.4			
DAC	t	199	4	0.3	1.3		
Heat pump for DAC	MW h	61	2	0.285			
Direct reduction	t	350	3	0.1	0.73 <sup>(2)</sup>	1.8	
Electric-arc furnace	t	260	3	0.58 <sup>(3)</sup>			1.07
Haber-Bosch with ASU	t	379	3	0.723	2.06	6.03	
Urea synth.	t	214	3	0.133	0.914		0.575
MeOH synth.	t	497	5	1.5		6.466	
MtO	t <sup>(4)</sup>	395	7	1.39			2.28

transported intermediate good  $g$ , and  $tc_g$  is the transport cost of transported good  $g$ .

We assume the OCF to be 100% for all plants except for the electrolyser, which we assume to have an OCF of 50%. A detailed discussion of flexible operation of plants is provided in the Supplementary Information.

In the case of steel, we only add transport cost for iron ore in the Base Case and Case 1, as we assume the exporting country of HBI to be a producer of iron ore. This assumption is justified since the largest three iron-ore exporting countries (Australia, Brazil, and South Africa) also have ample RE potentials. Moreover, we assume that DRI is charged into the EAF without allowing it to lose substantial amounts of heat in all import cases, except for Case 2 (where HBI is imported and shipped), where we increase the electricity demand by 0.159 MWh/t (Vogl et al, 2018).

**Financing assumptions.** Many of the RE-rich exporting regions implicitly considered in this article have higher financing cost compared to the RE-scarce importing regions. This effect is captured by a higher WACC assumed to determine the fixed-charge rate in the calculation of the *LCOP* above. Clearly, such an increase in WACC is not universal, as e.g. Australia is a country

with a high potential to become a RE-rich exporter, while profiting from an established economy with a low WACC. Nonetheless, we assume 5% for the RE-scarce and 8% for the RE-rich region in the results presented in Figs. 4 and 5, and we provide sensitivity analysis in Extended Data Figures.

For simplicity and to demonstrate the minor effect of capital and financing cost, we assume a low value of 18 years for the lifetime of new green facilities independent of the technical lifetime of plants.

## Data availability

The collected data on technologies will be made publicly available as a spreadsheet file and is attached for the review of this manuscript. The adapted data used in calculations is listed in Methods and published alongside the code as an input file.

The results of our study can be reproduced under different electricity-price assumptions via a webapp available under <https://interactive.pik-potsdam.de/green-value-chains/> (access during review via username ‘preview’, password ‘preview’).

## Code availability

The Python code used for calculations and plotting is available on GitHub: <https://github.com/PhilippVerpoort/green-value-chains/>.

## References

- (2020) A hydrogen strategy for a climate-neutral europe URL [https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen\\_en](https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en)
- (2022) Fertilizer industry facts & figures. Tech. rep., URL <https://www.fertilizerseurope.com/publications/industry-facts-and-figures-2022/>
- (2022a) The future of heat pumps. Tech. rep., URL <https://www.iea.org/reports/the-future-of-heat-pumps>
- (2022) Global hydrogen review. Tech. rep., URL <https://www.iea.org/reports/global-hydrogen-review-2022>
- (2022b) Hydrogen projects database. Tech. rep., URL <https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database>
- (2022) Repowereu: A plan to rapidly reduce dependence on russian fossil fuels and fast forward the green transition. Tech. rep., URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483>



- Al-Qahtani A, Parkinson B, Hellgardt K, et al (2021) Uncovering the true cost of hydrogen production routes using life cycle monetisation. *Applied Energy* 281:115,958. <https://doi.org/10.1016/j.apenergy.2020.115958>, URL <http://dx.doi.org/10.1016/j.apenergy.2020.115958>
- Arnaiz del Pozo C, Cloete S (2022) Techno-economic assessment of blue and green ammonia as energy carriers in a low-carbon future. *Energy Conversion and Management* 255:115,312. <https://doi.org/10.1016/j.enconman.2022.115312>, URL <http://dx.doi.org/10.1016/j.enconman.2022.115312>
- Bazzanella AM, Ausfelder F (2017) Low carbon energy and feedstock for the european chemical industry. Tech. rep., German Society for Chemical Engineering and Biotechnology (DECHEMA) and released by the European Chemical Industry Council (Cefic), URL [https://dechema.de/en/Low-carbon\\_chemical\\_industry-path-123212,124930.html](https://dechema.de/en/Low-carbon_chemical_industry-path-123212,124930.html)
- Boulamanti A, Moya JA (2017) Production costs of the chemical industry in the eu and other countries: Ammonia, methanol and light olefins. *Renewable and Sustainable Energy Reviews* 68:1205–1212. <https://doi.org/10.1016/j.rser.2016.02.021>, URL <http://dx.doi.org/10.1016/j.rser.2016.02.021>
- Commission E (2007) Reference document on best available techniques for the manufacture of large volume inorganic chemicals — ammonia, acids and fertilisers. Tech. rep., European Commission, URL <https://eippcb.jrc.ec.europa.eu/reference/large-volume-inorganic-chemicals-ammonia-acids-and-fertilisers>
- Daehn KE, Cabrera Serrenho A, Allwood JM (2017) How will copper contamination constrain future global steel recycling? *Environmental Science & Technology* 51(11):6599–6606. <https://doi.org/10.1021/acs.est.7b00997>, URL <http://dx.doi.org/10.1021/acs.est.7b00997>
- Devlin A, Yang A (2022) Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation. *Energy Conversion and Management* 254:115,268. <https://doi.org/10.1016/j.enconman.2022.115268>, URL <http://dx.doi.org/10.1016/j.enconman.2022.115268>
- ECORYS (2008) Study on the competitiveness of the european steel sector. Tech. rep., ECORYS, Danish Technological Institute, Cambridge Econometrics, CES IFO, and IDEA Consult, URL <https://op.europa.eu/en/publication-detail/-/publication/7b6df831-0266-40a1-9ca2-13992d526bf7>
- Fasihi M, Efimova O, Breyer C (2019) Techno-economic assessment of co2 direct air capture plants. *Journal of Cleaner Production* 224:957–980. <https://doi.org/10.1016/j.jclepro.2019.03.086>, URL <http://dx.doi.org/10.1016/j.jclepro.2019.03.086>

- Fiamelda L, Suprihatin, Purwoko (2020) Analysis of water and electricity consumption of urea fertilizer industry: case study pt. x. IOP Conference Series: Earth and Environmental Science 472(1):012,034. <https://doi.org/10.1088/1755-1315/472/1/012034>, URL <http://dx.doi.org/10.1088/1755-1315/472/1/012034>
- Gao Y, Cabrera Serrenho A (2023) Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nature Food* 4(2):170–178. <https://doi.org/10.1038/s43016-023-00698-w>, URL <http://dx.doi.org/10.1038/s43016-023-00698-w>
- German Federal Ministry for Economic Affairs and Climate Action (2022) Press release: Federal ministry for economic affairs and climate action launches first auction procedure for h2global – €900 million for the purchase of green hydrogen derivatives. URL <https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2022/12/20221208-federal-ministry-for-economic-affairs-and-climate-action-launches-first-auction-procedure-for-h2global.html>
- Golmohamadi H (2022) Demand-side management in industrial sector: A review of heavy industries. *Renewable and Sustainable Energy Reviews* 156:111,963. <https://doi.org/10.1016/j.rser.2021.111963>, URL <https://www.sciencedirect.com/science/article/pii/S1364032121012284>
- Hauser PD, Burmeister H, Münnich PJ, et al (2021) Klimaschutzverträge für die industrietransformation. analyse zur stahlbranche. Tech. rep., Agora Energiewende
- Hegemann KR, Guder R (2020) *Stahlerzeugung*. Springer Fachmedien Wiesbaden, <https://doi.org/10.1007/978-3-658-29091-7>, URL <http://dx.doi.org/10.1007/978-3-658-29091-7>
- Hölling M, Weng M, Gellert S (2017) Bewertung der herstellung von eisen-schwamm unter verwendung von wasserstoff. *Stahl und Eisen* 137(6):47–53
- Holst M, Aschbrenner S, Smolinka T, et al (2021) Cost forecast for low temperature electrolysis – technology driven bottom-up prognosis for pem and alkaline water electrolysis systems. Tech. rep., Fraunhofer Institute for Solar Energy Systems ISE, URL <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cost-forecast-for-low-temperature-electrolysis.pdf>
- IEA (2021a) Ammonia technology roadmap – towards more sustainable nitrogen fertiliser production. Tech. rep., International Energy Agency, URL <https://www.iea.org/reports/ammonia-technology-roadmap>

- IEA (2021b) Global hydrogen review. Tech. rep., International Energy Agency, URL <https://www.iea.org/reports/global-hydrogen-review-2021>
- IEA (2022c) Direct air capture – a key technology for net zero. Tech. rep., International Energy Agency, URL <https://www.iea.org/reports/direct-air-capture-2022>
- IRENA (2022) Global hydrogen trade to meet the 1.5°C climate goal: Part iii – green hydrogen cost and potential. Tech. rep., International Renewable Energy Agency, URL <https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost>
- Jarvis SM, Samsatli S (2018) Technologies and infrastructures underpinning future CO<sub>2</sub> value chains: A comprehensive review and comparative analysis. *Renewable and Sustainable Energy Reviews* 85:46–68. <https://doi.org/10.1016/j.rser.2018.01.007>, URL <http://dx.doi.org/10.1016/j.rser.2018.01.007>
- Keith DW, Holmes G, St. Angelo D, et al (2018) A process for capturing CO<sub>2</sub> from the atmosphere. *Joule* 2(8):1573–1594. <https://doi.org/10.1016/j.joule.2018.05.006>, URL <http://dx.doi.org/10.1016/j.joule.2018.05.006>
- Kent JA (1974) *Riegel's handbook of industrial chemistry*. Springer
- Krupnick A, Bergman A (2022) Incentives for clean hydrogen production in the inflation reduction act: incentives for clean hydrogen production in the inflation reduction act. Tech. rep., URL <https://www.rff.org/publications/reports/incentives-for-clean-hydrogen-production-in-the-inflation-reduction-act/>
- Luderer G, Madeddu S, Merfort L, et al (2021) Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nature Energy* 7(1):32–42. <https://doi.org/10.1038/s41560-021-00937-z>, URL <https://doi.org/10.1038/s41560-021-00937-z>
- Madeddu S, Ueckerdt F, Pehl M, et al (2020) The CO<sub>2</sub> reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters* 15(12):124,004. <https://doi.org/10.1088/1748-9326/abb02>, URL <https://dx.doi.org/10.1088/1748-9326/abb02>
- Madhu K, Pauliuk S, Dhathri S, et al (2021) Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. *Nature Energy* 6(11):1035–1044. <https://doi.org/10.1038/s41560-021-00922-6>, URL <http://dx.doi.org/10.1038/s41560-021-00922-6>

- Matzen MJ, Alhajji MH, Demirel Y (2015) Technoeconomics and sustainability of renewable methanol and ammonia productions using wind power-based hydrogen. *Journal of Advanced Chemical Engineering* 5(3). <https://doi.org/10.4172/2090-4568.1000128>, URL <http://dx.doi.org/10.4172/2090-4568.1000128>
- Oliveira C (2021) Tno's technology factsheet: Advanced methanol to olefines process. Tech. rep., TNO EnergieTransitie, URL <https://energy.nl/media/data/Technology-Factsheet-Advanced-methanol-to-olefins.pdf>
- Otto A, Robinius M, Grube T, et al (2017) Power-to-steel: Reducing co2 through the integration of renewable energy and hydrogen into the german steel industry. *Energies* 10(4):451. <https://doi.org/10.3390/en10040451>, URL <http://dx.doi.org/10.3390/en10040451>
- Ozkan M, Nayak SP, Ruiz AD, et al (2022) Current status and pillars of direct air capture technologies. *iScience* 25(4):103,990. <https://doi.org/10.1016/j.isci.2022.103990>, URL <https://www.sciencedirect.com/science/article/pii/S2589004222002607>
- Pauliuk S, Milford RL, Müller DB, et al (2013) The steel scrap age. *Environmental Science & Technology* 47(7):3448–3454. <https://doi.org/10.1021/es303149z>, URL <https://doi.org/10.1021/es303149z>, PMID: 23442209, <https://arxiv.org/abs/https://doi.org/10.1021/es303149z>
- Pérez-Fortes M, Schöneberger JC, Boulamanti A, et al (2016) Methanol synthesis using captured co2 as raw material: Techno-economic and environmental assessment. *Applied Energy* 161:718–732. <https://doi.org/10.1016/j.apenergy.2015.07.067>, URL <http://dx.doi.org/10.1016/j.apenergy.2015.07.067>
- Perner J, Unteutsch M (2021) Wirtschaftlichkeit von ptx-produkten aus nordafrika — business case analysen, URL [https://www.frontier-economics.com/media/4979/frontier-ptx-business-cases-studie\\_teil-1-hauptstudie.pdf](https://www.frontier-economics.com/media/4979/frontier-ptx-business-cases-studie_teil-1-hauptstudie.pdf)
- Rechberger K, Spanlang A, Sasiain Conde A, et al (2020) Green hydrogen?based direct reduction for low?carbon steelmaking. *steel research international* 91(11):2000,110. <https://doi.org/10.1002/srin.202000110>, URL <http://dx.doi.org/10.1002/srin.202000110>
- Ritchie H, Roser M, Rosado P (2020) CO<sub>2</sub> and greenhouse gas emissions. *Our World in Data* URL <https://ourworldindata.org/emissions-by-sector>
- Samadi S, Lechtenböhmer S, Viebahn P, et al (2021) Renewables pull - verlagerung industrieller produktion aufgrund unterschiedlicher kosten erneuerbarer energien. *Energiewirtschaftliche Tagesfragen* 71(7-8):10 – 13. URL <http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77936>

- Sasiain A, Rechberger K, Spanlang A, et al (2020) Green hydrogen as decarbonization element for the steel industry. *BHM Berg- und Hüttenmännische Monatshefte* 165(5):232–236. <https://doi.org/10.1007/s00501-020-00968-1>, URL <http://dx.doi.org/10.1007/s00501-020-00968-1>
- Toktarova A, Göransson L, Thunman H, et al (2022a) Thermochemical recycling of plastics – modeling the implications for the electricity system. *Journal of Cleaner Production* 374:133,891. <https://doi.org/10.1016/j.jclepro.2022.133891>, URL <https://www.sciencedirect.com/science/article/pii/S0959652622034643>
- Toktarova A, Walter V, Göransson L, et al (2022b) Interaction between electrified steel production and the north european electricity system. *Applied Energy* 310:118,584. <https://doi.org/10.1016/j.apenergy.2022.118584>, URL <https://www.sciencedirect.com/science/article/pii/S0306261922000654>
- Ueckerdt F, Bauer C, Dirnaichner A, et al (2021) Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change* 11(5):384–393. <https://doi.org/10.1038/s41558-021-01032-7>, URL <http://dx.doi.org/10.1038/s41558-021-01032-7>
- Vartiainen E, Breyer C, Moser D, et al (2021) True cost of solar hydrogen. *Solar RRL* 6(5):2100,487. <https://doi.org/10.1002/solr.202100487>, URL <http://dx.doi.org/10.1002/solr.202100487>
- Vogl V, Åhman M, Nilsson LJ (2018) Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production* 203:736–745. <https://doi.org/10.1016/j.jclepro.2018.08.279>, URL <http://dx.doi.org/10.1016/j.jclepro.2018.08.279>
- Wang P, Ryberg M, Yang Y, et al (2021) Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nature Communications* 12(1). <https://doi.org/10.1038/s41467-021-22245-6>, URL <http://dx.doi.org/10.1038/s41467-021-22245-6>
- Worrell E, Price L, Neelis M, et al (2007) World best practice energy intensity values for selected industrial sectors. Tech. rep., Lawrence Berkeley National Laboratory, URL <https://escholarship.org/uc/item/77n9d4sp>
- Wörtler M, Schuler F, Voigt N, et al (2013) Steel’s contribution to a low-carbon europe 2050. Tech. rep., The Boston Consulting Group, URL <https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050>
- Wulf C, Zapp P, Schreiber A (2020) Review of power-to-x demonstration projects in europe. *Frontiers in Energy Research* 8. <https://doi.org/10.3389/fenrg.2020.00191>, URL <https://www.frontiersin.org/articles/10.3389/fenrg>

2020.00191

Zhu D, Mortazavi SM, Maleki A, et al (2020) Analysis of the robustness of energy supply in japan: Role of renewable energy. *Energy Reports* 6:378–391. <https://doi.org/10.1016/j.egy.2020.01.011>, URL <https://www.sciencedirect.com/science/article/pii/S2352484718302671>

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## Author contributions

F.U. and P.C.V. suggested the research question. P.C.V. and F.U. jointly conceived and designed the study in consultation with A.H. and L.G. P.C.V., A.H., and L.G. curated the techno-economic data. P.C.V. wrote the code for performing the calculations, and designed and created the figures. P.C.V. and F.U. wrote the manuscript with contributions from L.G.

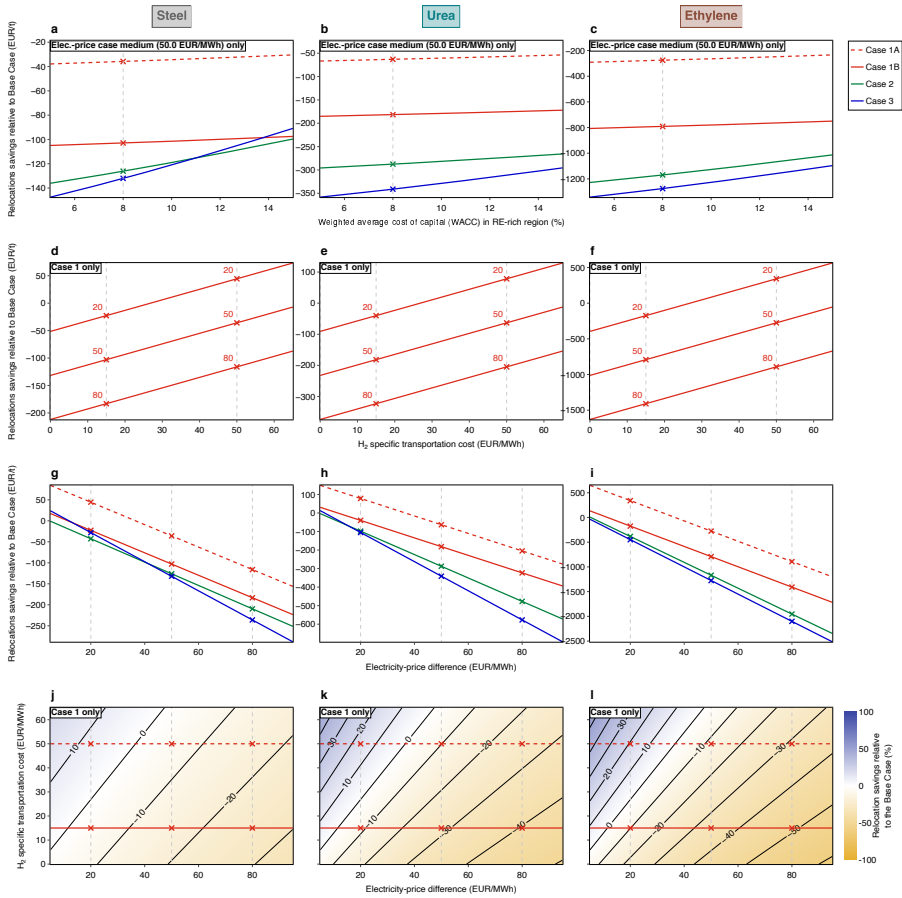
## Competing interests

The authors declare no competing interests.

## Ethics approval / Consent to participate / Consent for publication

Not applicable.

## Extended data figures



**Extended Data Fig. 1 Sensitivity analysis for the three studied commodities (left-to-right: steel, urea, ethylene).** The estimations of the relocation savings shown in Figs. 4 and 5 are analysed with respect to alternative assumptions for the electricity price, specific H<sub>2</sub> transport cost, and weighted-average cost of capital (WACC). First row: relocation savings as a function of WACC in the RE-rich region for the ‘medium pull’ electricity-price case from Tab. 1. Second row: relocation savings as a function of specific H<sub>2</sub> transport cost for Case 1 from Fig. 3. Third row: relocation savings as a function of electricity-price difference. Fourth row: relocation savings as a function of both electricity-price difference and specific H<sub>2</sub> transport cost.

## Supplementary information

### Extended list of incentivising and inhibiting factors and risks and opportunities

**Table S1 Incentivising and inhibiting factors of green relocation that can influence investment decisions of private investors and determine the construction location of new green production facilities.** Those marked with an asterisk (\*) are accounted for in the quantitative estimations presented in this article.

Incentivising factors	Inhibiting factors
<p><b>Renewables pull*</b> (hard), i.e. energy-cost savings due to lower electricity prices in the RE-rich compared to the RE-scarce region.</p>	<p><b>Transport penalty</b> (hard)*, i.e. additional transport cost associated with the trade of intermediate goods. The magnitude of this cost penalty is particularly relevant for trading H<sub>2</sub>.</p>
<p><b>Lower wages</b> (hard), i.e. a decrease in labour cost and hence operation cost in developing countries. We note that the labour cost is a small component in the production cost, as visible in Fig. 5, such that this factor plays a minor role. Moreover, it can be offset by the challenge to find skilled workers in a developing country, which is why we do not consider it in our quantitative estimations.</p>	<p><b>Financing penalty*</b> (hard), i.e. increased cost of financing capital investments, which can be associated with an increased weighted average cost of capital (WACC). This number is typically higher in developing economies. In our quantitative estimations, we use a generic assumption of 5% for the RE-scarce and 8% for the RE-rich region.</p>
<p><b>Potentially gained proximity to non-energy resources</b> (soft), resulting in cost reductions and efficiency gains (esp. iron ore in steel).</p>	<p><b>Lost proximity to other producers</b> (soft), i.e. clustering synergies and economies of scope (soft). This includes lost opportunities of co-production, heat recovery (esp. steel), and waste recovery (esp. chemicals).</p>
	<p><b>Lost proximity to customers</b> (soft), which leads to issues with supply-chain reliability, quality requirements (esp. steel), and easy and fast coordination. The supply-chain reliability issue may be weaker in cases where some degree of dependence on global imports is unavoidable, e.g. iron-ore imports. Moreover, even in the case of fully reliable supply chains, global imports will require additional storage capacity, which incurs additional cost. The potential loss of proximity to customers may lead to a higher readiness to pay by consumers and hence counteract the renewables pull.</p>
	<p><b>Infrastructure penalty</b> (soft). This includes more general infrastructure not included in the clustering synergies, such as access to road, rail, marine, or air transport, as well as to fresh water, electricity, and other basic services. This may pose a particular challenge in developing countries.</p>
	<p><b>Certification of production</b> (soft), proving it is low-carbon and satisfies other regulatory requirements (environmental aspects beyond climate, ethical working conditions, etc). This would be easier to demonstrate and certify for local production compared to complex supply chains abroad.</p>



**Table S2** Extended list of risks and opportunities of green relocation from a societal perspective.

Category	Risks	Opportunities
<b>Overall cost</b>	Overestimation of cost benefit leading to higher transformation cost	Reduction of total transformation cost due to renewables pull; significant cost reductions of green production of bulk materials
<b>Energy prices</b>	Higher energy prices in RE-rich region due to opportunity cost arising from exports	Cheaper energy prices in importing region
<b>Energy transition &amp; climate mitigation</b>	Transition in RE-scarce region slowed down due to false reliance on imports; newly installed RE capacity in RE-rich region only used for exports and not domestic decarbonisation or providing power to local communities	Transition in RE-scarce region made possible due to cheap and available green imports; transition in RE-rich region aided by renewables deployment for exports
<b>Development</b> (economic, infrastructure, desalinated water)	Introducing neo-colonial structures	Accelerated through foreign investments
<b>Jobs &amp; value creation</b>	Jobs and value creation lost in RE-scarce region; key technologies built up elsewhere	Jobs and value creation added in RE-rich region; key technologies (e.g. electrolysers) continue to be supplied by RE-scarce region
<b>Geopolitical</b>	Concerns over geopolitical interdependencies	Strengthening of international relations/cooperation
<b>Investments</b>	Stranded assets if business case is not secure or trade may cease at a later stage	Avoiding stranded assets that become uncompetitive due to the renewables pull
<b>Policy</b>	Need to deal with other downsides of green leakage	No need to create a green-leakage protection mechanism
<b>Supply chain</b>	Remote production jeopardises supply chain reliability	With some products (iron ore for steel) there already is a dependency, so relocation of production has little effect

## Flexible operation, circularity, and demand reduction

We discuss two further factors that can increase energy and material efficiency, reduce the share of energy in the production cost, and hence diminish the magnitude of the renewables pull: 1) flexible operation and 2) circularity. Moreover, we discuss the role of demand reduction and material substitution in the context of the renewables pull.

While it would be desirable to maximise the usage of these efficiency-gaining and cost-saving modes of operation, their employment is limited and their feasibility is, in some cases, uncertain. Therefore, we do not include these in our default assumptions and only briefly describe their potential impact on our main results.

**Flexible operation.** Our results show that the renewables pull crucially depends on the electricity-price difference assumed. Therefore, it is important to understand what factors could have a significant impact on the effective electricity price seen on the RE-scarce and RE-rich side. Clearly, the most important factor determining electricity prices is the availability of RE in the specific regions, which however requires case-specific analysis. However, the effective electricity prices also depend on the time when plants are operated and the electricity prices during those hours.

Plants along the value chain can be operated either at (almost) full load or at reduced load. The latter can, in some cases significantly, reduce the effective electricity price, albeit at the expense of underutilising production capacity and hence increasing capital and fixed cost. While this principle holds true for both the RE-scarce and the RE-rich region, the potential to reduce the electricity price on the RE-scarce side might be substantially higher due to large curtailed RE and grid infrastructure in industrialised economies. Estimating the potential of this mechanism to reduce the renewables pull is challenging since it is case-specific and depends on many assumptions, most importantly the price-duration curve, which in turn depends on electricity demand from the industry sector during low-price hours.

Load flexibilisation could be applied to different process steps along the value chain as well as on different timescales. Short-term flexibilisation, i.e. ramping up and down on an hourly variation or even faster, is suitable only to batch processes, such as EAFs, or to some suitable continuous production processes, such as electrolyzers. With electrolysis being one of the biggest energy consumers, straight-forward to operate intermittently, and most advanced regarding technological development of its flexibilisation, this option is discussed the most. Due to its high energy demand, the same logic could apply to DAC, once the investment cost has decreased sufficiently. Moreover, a flexible operation of further continuous-production processes, such as DR shafts or chemical synthesis plants, is perceivable, yet rather on a weekly or seasonal timescale. Ramping down production in weeks and months of the year when RE availability is low could avoid paying extremely high electricity prices in those weeks and hence cut down the effective average electricity price paid. Flexible

operation can be further incentivised by dropping certain grid-infrastructure cost to be paid on top of wholesale electricity prices, as flexible operation could be considered as a means to stabilise the grid. In addition to increased capital and fixed cost, flexible operation also may add additional demand for storage capacity, whose cost may vary greatly between locations in the case of H<sub>2</sub> storage. Despite various challenges, flexible operation of plants could be an efficient way for industrialised economies to lower effective electricity prices and hence weaken the magnitude of the renewables pull, yet determining an optimal mode of operation (i.e. balancing capital and energy cost) (Toktarova et al, 2022b,a) and assessing the potentials of individual technologies (Golmohamadi, 2022) is beyond the scope of this work.

**Circularity.** A second factor that has the potential to weaken the renewables pull is the degree of implementation of different strategies for circular material flows employed in green value chains. In the particular value chains studied, the use of steel scrap instead of DRI in the EAF could greatly reduce the H<sub>2</sub> and hence electricity demand for steel. Similarly, the use of captured CO<sub>2</sub> from a point source (PS) instead of from DAC could reduce the associated energy demand significantly. Again, while this could be done by both the RE-scarce and the RE-rich region, an industrialised economy will have more steel scrap and PSs available and the cost reduction compared to DAC will be much greater. The usage of steel scrap and captured CO<sub>2</sub> is associated with a number of limitations, some of which might result in high prices for these feedstocks.

Capturing CO<sub>2</sub> from a PS requires investment into appropriate infrastructure that can separate CO<sub>2</sub> from other exhaust fumes and purify it to the required degree and transport it to the consumer, such that the pure winning and transportation of CO<sub>2</sub> is not for free. Moreover, a carbon price may need to be paid for CO<sub>2</sub> released from a PS, depending on whether the CO<sub>2</sub> is of fossil or atmospheric origin and how soon the CO<sub>2</sub> will be released back into the atmosphere, and at least some share of that carbon price will have to be paid by the process utilising the CO<sub>2</sub> as a feedstock, further contributing to its cost on top of the capturing itself. With the alternative option of having the carbon captured and stored (CCS), a carbon price should always be paid to disincentivise a release of CO<sub>2</sub> emissions from fossil PSs into the atmosphere, even from “unavoidable” ones, such as waste or cement. While the carbon contained in biomass is atmospheric and hence its release into the atmosphere is “free” from paying a carbon price, the availability of biomass as a by-product is limited, and the production of purposefully grown biomass remains unadvisable due to land-use issues, while being also subject to the opportunity cost of potential carbon credits received for carbon-dioxide removal (CDR).

In the case of steel, there exists a high degree of uncertainty concerning the potential future role of secondary steel, as it remains unclear to what extent scrap availability may increase in coming decades (Pauliuk et al, 2013) and to what extent the quality of secondary steel may come closer to that of primary steel (Daehn et al, 2017).

**Demand reduction.** Strategies for material demand reduction could reduce the final demand for basic materials and hence the need to produce them in green value chains. Demand-side mitigation strategies for steel include less material for the same service, more intensive use, lifespan extension, fabrication scrap diversion, reuse of end-of-life scrap, and yield improvement (Wang et al, 2021). For ammonia, demand could be reduced by up to 48% N and GHG emissions to 20% of current levels by 2050 if different strategies are applied simultaneously. These strategies include water electrolysis for H<sub>2</sub> (the focus of our study), demand reduction, and fertiliser substitution (Gao and Cabrera Serrenho, 2023).

## Supplementary Files

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