Impact of global heterogeneity of renewable-energy supply on heavy industrial production and green value chains

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Abstract

On the path to climate neutrality, global production locations and trade patterns of basic materials might change due to the heterogeneous availability of renewable electricity. Here we estimate the “renewables pull”, i.e. the energy-cost savings, for varying depths of relocation for three key tradable energy-intensive industrial commodities: steel, urea, and ethylene. For an electricity-price difference of 40 EUR/MWh, we find respective relocation savings of 18 %, 32 %, and 38 %, which might, despite soft factors in the private sector, lead to green relocation. Conserving today’s production patterns by shipping hydrogen is substantially costlier, whereas trading intermediate products could save costs, while keeping substantial value creation in renewable-scarce importing regions. In renewable-scarce regions, 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

A promising option for the climate-change mitigation of the production of energy-intensive basic materials, such as steel and chemicals, is a switch to renewable electricity (RE) and green hydrogen (H_2) [1, 2]. Due to varying RE availability and cost across the globe, the transition to net-zero greenhouse-gas (GHG) emissions might result in a relocation of industrial production and hence a shift of trade patterns for the respective emerging green value chains (Fig. 1).

Energy prices are a major factor for production costs of basic materials [3] and will likely continue to be so for future green value chains. While trade with fossils has so far dampened effects of the heterogeneous availability of primary energy, long-distance transport of electricity and H_2 is much costlier. Thus, energy-cost savings resulting from substantial geographical differences in RE prices will create an incentive (so-called "renewables pull" [4, 5]), which may lead to a relocation of low-carbon production (so-called "green relocation").

Prominent candidates for RE-scarce importers are the European Union (EU), South Korea, or Japan, which respectively import 55 % [6], 84 % [7], and 96 % [8] of their current energy demand. Producing sufficient RE to replace these mostly fossil imports will be challenging, as land and RE potentials are rather limited. While these countries have declared ambitious H_2 import strategies, their openness regarding basic-material imports is unclear, especially given current global trends towards protecting critical supply chains. This work aims to inform both strategies: those seeking to protect against green relocation and those seeking to exploit energy-cost savings through relocation.

Obvious candidates for RE-rich exporters include industrialised countries, such as Australia, the US, and Canada, but also countries located in Africa, the Middle East, and Latin America, most of which are classified as low-income economies. Intraregional effects are also conceivable, such as within the EU (e.g. Germany to Spain) or the US (e.g. north to south). While the renewables pull is a region-specific effect, our work presents a generic framework based on electricity-price assumptions.

Previous works include case studies of steel exports from Australia [9] and South Africa [10], searches for globally optimal steel-production sites [11, 12], as well as studies of global trade with ammonia [13, 14], e-fuels, and e-chemicals [15], which all conclude to varying extent that exporting basic materials from regions with high RE availability can be desirable due to improved cost-competitiveness with fossils and with alternative green production sites. [5] analysed announcements from the private sector, showcasing how the renewables pull influences investment decisions today (see also Tab. S5).

While many public and academic debates rightfully focus on the green-vs-fossil competitiveness [2, 16–18], our assessment looks at the understudied green-vs-green regional competitiveness for basic materials. Also note that there exist several other basic materials not considered in this work, such as aluminium, copper, cement, glass, paper, or silicon. While many aspects discussed here also apply to these products, their green value chains do not

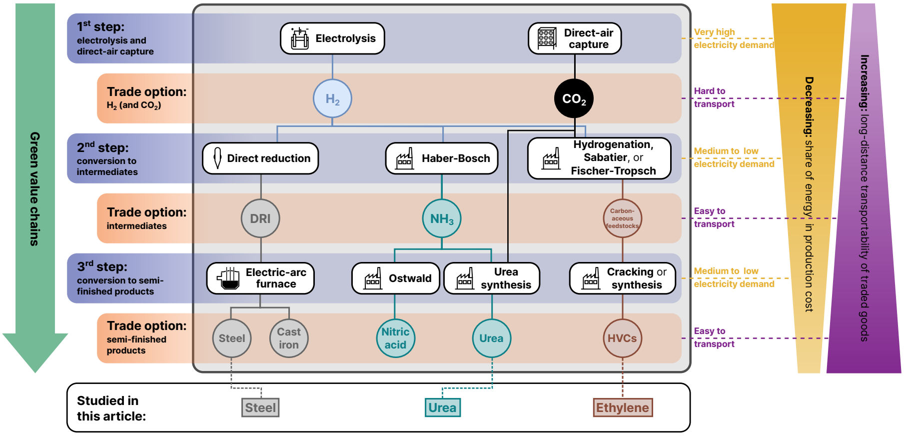

Fig. 1 Emerging green value chains and the associated production steps, feedstock flows, and trade options. Defossilising the value chains of energy-intensive basic materials necessitates the emergence of new green value chains that rely on low-carbon feedstocks produced from renewable electricity (RE). The displayed 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_2) and atmospheric carbon-dioxide (CO_2). Combining these two together (with iron and nitrogen) yields directly reduced iron (DRI), ammonia (NH_3), and basic carbonaceous feedstocks, 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.

rely on H_2, contain fewer intermediate steps, and are responsible for a smaller share of industrial GHG emissions.

Here, we present quantitative insights into the renewables pull by estimating the energy-cost savings and competing effects (transport and financing penalties) for the green value chains of three primary basic materials: steel, urea, and ethylene. We conduct our techno-economic analysis for varying depth of relocation and thereby study the role of individual production steps in these value chains. This approach allows comparisons of competing options for splitting value chains between the importer and exporter side across industrial subsectors. Moreover, we integrate the renewables pull into a holistic perspective that includes difficult-to-quantify private factors, societal implications, and optional regulatory intervention. Finally, we apply our generic approach to a case study of energy-intensive imports to Germany and estimate potential “green-relocation protection”, which we define as the public subsidies required to avoid relocation.

A broader picture of the renewables pull and green relocation

The effect we ultimately aim to study is green relocation, which we define as the relocation of industrial production incentivised by the renewables pull

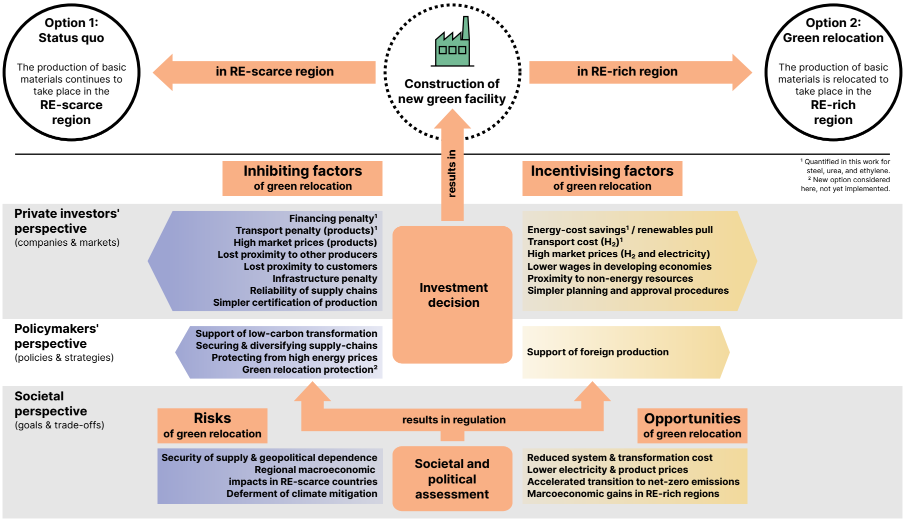

Fig. 2 Broader picture of green relocation, the renewables pull, and competing factors. Investments into new green production facilities can occur in two ways. Option 1: Plants are constructed in RE-scarce regions, where (grey) industrial production is located today, hence reinforcing the status quo (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 soft and hard factors. The renewables pull is only one of these factors, and we estimate it quantitatively together with transport and financing penalties. Green relocation also comes with societal risks and opportunities, which however only translate into factors influencing private investment decisions via regulatory intervention.

(i.e. energy-cost savings). The renewables pull is only one of many factors determining private investment decisions, which jointly may or may not lead to green relocation. We therefore start our work by embedding the renewables pull into a broader conceptual framework, which will allow a structured analysis, before we present quantitative estimates in the next two sections.

We arrange competing factors that influence green relocation in three layers corresponding to different perspectives (Fig. 2): 1.) a private investors' perspective, 2.) a policymakers' perspective, and 3.) a societal perspective. As a result, our analysis is structured along the following three questions: First, when considering companies in free markets, will the renewables pull and other factors from the private sector alone result in green relocation? Second, are there existing, announced, or conceivable forms of policymaking that could influence private investment decisions in addition to factors from the private sector? And finally, what future policymaking can be expected to arise from conflicting societal goals and how these are weighed up by socities and policymakers?

First, the occurrence of green relocation is determined by investment decisions of the private sector, which are influenced by incentivising or inhibiting factors. 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. Hard factors that our generic study is able to capture can be summarised in the following simple relation,

$$\begin{aligned}\text{Relocation savings} \quad = \quad & \text{Energy-cost savings (due to renewables pull)} \\ & - \text{Transport penalty} \\ & - \text{Financing penalty}\end{aligned}$$

where we define the term "relocation savings" to refer to the overall production-cost savings resulting from production relocation. Financing penalty here refers to higher financing cost due to higher WACC in RE-rich exporting countries.

Soft factors may additionally influence production cost, increase consumers' readiness-to-pay for short and reliable supply-chains, otherwise affect private revenues, or strictly prohibit production. Such soft factors may be rather inhibiting, rather incentivising, or with undecided/case-specific influence of green relocation. Rather inhibiting factors include proximity to customers (benefits of short supply chains, just-in-time production, lean manufacturing, close customer relationships, reliability of supply), proximity to other producers (benefits of heat integration, process integration, co-production, joint industrial infrastructure, economies of scope), infrastructure availability in established locations of current industrial production (e.g. roads, ports, electricity grids, water supply), general know-how (i.e. industry expertise), political and economic stability of countries with established industrial production, and certification (which can be easier to obtain when producing in the country where products are demanded). Rather incentivising factors include the availability of space for construction (often ample in RE-rich regions), the complexity of plant integration (challenging in complex arrangements of existing industrial sites), reduced labour cost, and proximity to non-energy resources (e.g. iron ore). Factors that are undecided or case-specific include the market structure and resulting prices of future green products, the complexity of planning and approval procedures, and the availability and cost of skilled labour.

In summary, conserving current production patterns allows utilising many advantages of established production sites in RE-scarce regions, which can only partly be compensated for by the absence of obstructing brownfield integration and potentially lower wages. Moreover, revenues will ultimately depend on future supply and demand curves and hence market prices of energy carriers, feedstocks, intermediates, and products, which are all uncertain. Whether soft factors will suffice to compensate the renewables pull will be highly case specific and constitute an own subject of research. (See Tab. S1 for a comprehensive list of private-sector factors.)

Second in our list of perspectives to account for is the one of policymakers. Many of today's existing or announced policies targeting energy-intensive industries will influence private investment decisions connected to green relocation, as discussed in more detail in the Conclusions. Moreover, policymakers could try to introduce additional regulatory interventions specifically targeted at steering green relocation, such as subsidies (e.g. a potential green-relocation protection scheme) or trade tariffs.

Finally, whether such interventions are necessary or how these should be designed will depend on the perception of risks and opportunities of green relocation in the respective 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 reduced security of supply and geopolitical dependencies, a potential deferment of climate mitigation, and losses of employment and productivity. The latter, i.e. value creation relocated, is the greatest opportunity of RE-rich regions alongside energy-system development, while risks could be introducing neocolonial structures and using RE potentials only for exports instead of domestic climate mitigation (so-called resource shuffling). (See Tab. S2 for a comprehensive list of risks and opportunities.) All risks and opportunities need to be assessed and weighed up by affected countries, potentially resulting in new policies aiming to steer green relocation in one way or the other.

Analysing each layer and answering each question will be the topic of future research and societal debate, especially across regional cases and industrial sectors. In the next section, we start off by addressing the first question through a generic quantification of the renewables pull.

Quantifying the renewables pull for key energy-intensive value chains

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

1. Hot rolled coil (HRC) – the most traded semi-finished steel product at a share of 18 % in 2022 [19]
2. Urea – an intermediate product of the chemical industry and a key component of N-fertilisers with ∼50 % global market share in 2018 [20]
3. Ethylene – an precursor to polymer plastics (polyethylene, polyethylene-terephthalate)

All are produced using green H_2, and their value chains consist of three main processing steps, resulting in four possible import cases of varying degrees of relocation (Fig. 3). Notably, today's value chains in resource-constrained countries best compare with Case 1, given that these value chains rely on imports of fossil primary energy (coal, oil, gas). Therefore, the Base Case may even be considered a case of onshoring, since fossil imports are replaced by

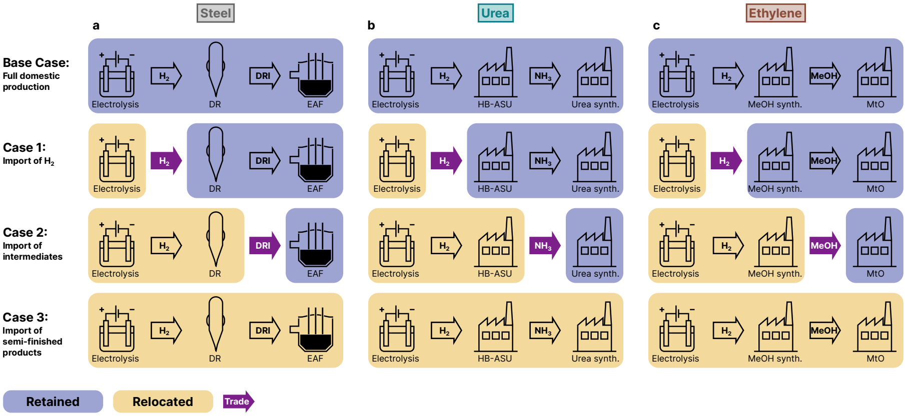

Fig. 3 Processing steps and resulting import cases. All studied value chains commence with producing green hydrogen (H_2) via water electrolysis (a–c). They use this H_2 as a feedstock to produce intermediate products: directly reduced iron (DRI) from direct reduction (DR) of iron ore (a), ammonia (NH_3) from Haber-Bosch synthesis with nitrogen from an air-separation unit (HB-ASU) (b), and methanol (MeOH) from synthesis of H_2 with carbon-dioxide (CO_2) from direct-air capture (DAC) (c). They convert these intermediate products into (semi-)finished industrial products: semi-finished steel from an electric-arc furnace (EAF) (a), urea from the synthesis of NH_3 and CO_2 (b), and ethylene from a methanol-to-olefine (MtO) process (c). Trade may occur in between these three production steps, resulting in four import cases (Base Case and Cases 1–3).

domestic RE generation. When in the following discussing the role of green relocation, we mainly refer to the industrial processes part of the studied value chains and not their energy supply.

We estimate the production cost for these commodities for each import case, with results presented in Fig. 4, Fig. 5, and Tab. 1 with the assumed electricity prices also listed in Tab. 1. We distinguish Case 1 into Case 1A, showing high H_2 transportation cost of 50 EUR/MWh, and Case 1B, showing moderate cost of 15 EUR/MWh, corresponding to, respectively, shipping-based and pipeline-based imports.

Naturally, the magnitude of the renewables pull is most strongly influenced by regional differences in electricity prices, which are inherently uncertain, complex, and dependent on regional context. Here we aim to provide a generic framework and thus vary electricity-price differences between 20 EUR/MWh and 70 EUR/MWh without assuming specific regional cases. While LCOE estimates indicate only price differences of 20 EUR/MWh between RE-rich and RE-scarce regions, we identify five more layers of complexity that can drive differences up to 40–70 EUR/MWh: marginal renewables costs, temporal price profiles, the role of electricity grids, barriers for high renewables deployment, and general infrastructure availability (see section on future electricity prices in the Supplementary Information for an in-depth discussion).

Technology parameters are chosen to represent the year 2040, hence including learning effects resulting from wide deployment of technologies with a low readiness level today. We choose a relocation-induced increase of the WACC

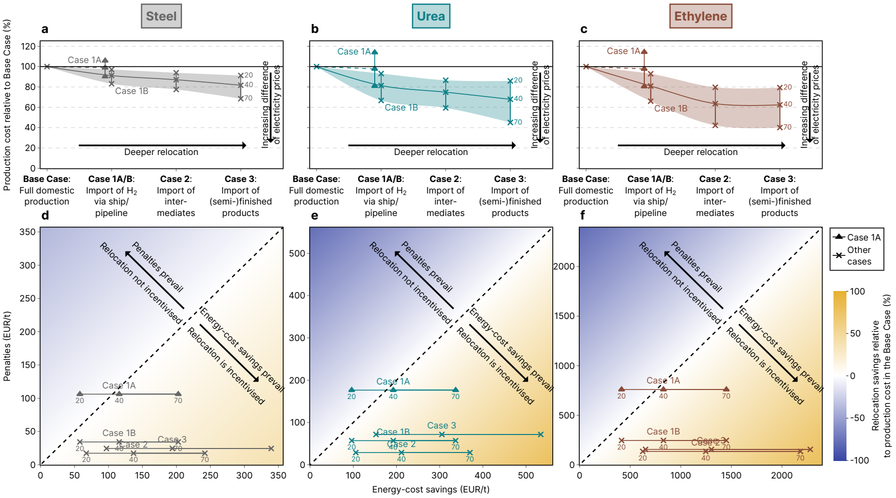

Fig. 4 Relocation savings for the different import and electricity-price cases. Panels left-to-right: Low-carbon production of steel, urea, and ethylene. Results are reported for different electricity-price differences (20, 40, and 70 EUR/MWh) according to Tab. 1. Top row (a–c): Production cost relative to Base Case for the import cases from Fig. 3 (including subcases A/B for Case 1). Bottom row (d–f): 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. 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 with the otherwise monotonous decrease of production cost with increasing depth of relocation. Markers for the same case represent different electricity-price cases, and the shaded band on the top row is a simple spline interpolation serving as visual support.

from 5 % to 8 %, which affects results only lightly (Fig. 5). Note that we choose optimistic assumptions for the energy demand of DAC, for which we present sensitivity analysis below.

The full relocation savings (from Base Case to Case 3) spread across a broad range of 9–60 % and vary strongly depending on assumed electricity-price differences and between commodities (Tab. 1). Savings are lower for steel, where raw-material costs (iron ore etc.) are high. An electricity-price difference of 40 EUR/MWh (medium-pull case) yields substantial relocation savings of 18 %, 32 %, and 38 % for, respectively, steel, urea, and ethylene, whereas savings reach up to 32 %, 55 %, and 60 % for 70 EUR/MWh (strong-pull case).

By splitting up the value chains into three steps and considering the resulting four import cases, we can demonstrate how production costs decrease with every step relocated (except Case 1A and electricity-price difference $\lesssim 35$ EUR/MWh) and which share of savings occurs with the relocation of each step. A large share of energy-cost savings is associated with relocating electrolysis, the most energy-intensive process. Yet, in Case 1A the energy-cost savings translate into only minor relocation savings of respectively 1 %, 2 %, and 2 %

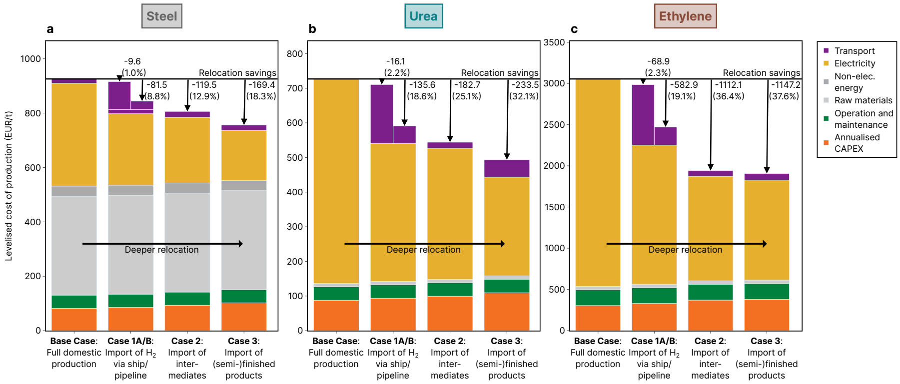

Fig. 5 Levelised cost of production. Panels left-to-right (a–c): Low-carbon production of steel, urea, and ethylene. Results are again shown for the four import cases illustrated in Fig. 3 and assume an electricity-price difference of 40 EUR/MWh (medium-pull case from Tab. 1). The levelised cost visualise how the relocation savings in the steel value chain are smaller in comparison to the other value chains due to the high feedstock cost. Moreover, annualised CAPEX assumes a higher WACC of 8 % in the RE-rich region compared to 5 % in the RE-scarce region over a lifetime of 18 years, resulting in higher levelised capital cost, yet this effect appears to be small compared to the renewables pull. For a detailed composition, we encourage readers to view this figure in the online webapp or download the accompanying spreadsheet file (see Data availability).

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

		Electricity price (EUR/MWh)			**Relocation savings in Case 3 relative to production cost in the Base Case** (%)		
Price case	**Process type**	RE-rich region	RE-scarce region	Difference	Steel	Urea	Ethylene
Weak pull	Electrolysis	30	50	20	8.7	14.1	20.6
	Baseload	50	70				
Medium pull	Electrolysis	30	70	40	18.3	32.1	37.6
	Baseload	50	90				
Strong pull	Electrolysis	15	85	70	31.5	55.0	60.0
	Baseload	35	105				

(medium-pull case), due to high transport costs of different H_2 shipping technologies. Lower H_2 transport cost in Case 1B significantly increase the gained relocation savings to 9 %, 19 %, and 19 %. Moreover, resorting to imports of intermediates (DRI, NH_3, MeOH) would cover almost all relocation savings at 13 %, 25 %, and 37 %. Therefore, there is comparably little cost incentive for further relocation beyond import of intermediates across the studied commodities, which is because the energy demand of the third step is comparably low and transport costs for (semi-)finished products are similar or even higher than for intermediates.

Table 2 Scenario assumptions for case study on German green-relocation protection.

		Base Case full domestic production	**Case 1A** Import of H_2 via shipping	**Case 1B** Import of H_2 via pipeline	**Case 2** Import of inter-mediates	**Case 3** Import of (semi-)finished products
Scenario		**Share of import case**				
Scen 1		33 %	33 %	33 %	–	–
Scen 2		15 %	15 %	–	50 %	20 %
Commodity	**Demand** (Mt/a)	**Potential exporting countries**				
Steel	40	(none)	Chile Australia	Norway Morocco	Sweden, Brazil	
Urea	4				Canada, Saudi-Arabia	
Ethylene	5				USA, Iceland	

Sensitivity analysis shows that our results are mostly robust, yet relocation savings shrink significantly for drastic increases in the WACC on the RE-rich exporter side, in the overall CAPEX, or in specific H_2 transport cost (Fig. 1).

Before applying these results to a specific case study and concluding with interpretation and policy recommendations, it is important to once more understand the meaning of these estimates, appreciate their limitations, and connect them to the wider framework from the previous section. It should be noted that we have so far only estimated quantifiable hard factors and neglected difficult-to-quantify soft factors, such as the readiness to pay for short and reliable supply chains, various advantages of reusing established production sites, and the role of market prices. In summary, our estimations are only able to provide insights based on technologies and RE prices, yet analyses of soft factors and political implications remain an important subject of further research.

Estimating potential green-relocation protection for Germany

We proceed by applying our generic framework to a specific case study on future German imports of H_2 and basic materials, which will allow us to estimate potential policy cost of regulatory intervention aiming to prevent green relocation. Specifically, we estimate the total potential relocation savings for the annual German demand of the considered products (steel, urea, ethylene), which may also be interpreted as the annual subsidy required to protect these industrial subsectors against green relocation. As argued before, there are limitations to our approach and the actual subsidy needed could deviate from our estimations either way, depending on the magnitude of the soft factors. Yet, our estimates are helpful for gaining a first impression on the societal impact of green relocation and implications for regulatory intervention.

We assume two scenarios of varying degree of green relocation, corresponding to policy interventions following competing strategies (Tab. 2).

Scenario 1 – focus H_2
Producing basic materials domestically with a mix of domestic (Base Case) and imported H_2 (via pipeline and ship; Cases 1A/B) at an equal share.

Scenario 2 – focus intermediates
Reducing full domestic production (Base Case) and shipping-based H_2 imports (Case 1A) to 15 % each and replacing pipeline-based H_2 imports (Case 1B) with 50 % imported intermediates (Case 2) and 20 % imported (semi-)finished products (Case 3).

This means we can take the perspective of the German government aiming to 1) conserve industrial production patterns as today (while reducing the share of imported energy through domestic RE expansion) or 2) establish a mixed solution, in which security of supply is realised by retaining a third of industrial production, while for the remaining share relying on imports of intermediates from global markets (and/or selected exporters). Potential exporting countries listed in Tab. 2 are selected based on RE potentials, existing fossil production, green project announcements, and availability of raw materials.

Projections for the German basic-material demand in 2040 are taken from two studies on German industry decarbonisation [21, 22]. Projections for NH_3 demand of ∼3 Mt would translate into ∼5 Mt of urea demand if all NH_3 were to be convert into urea only. For reasons of simplicity, we assume a urea demand of 4 Mt to represent the full fertiliser sector and other industrial NH_3 uses (excluding potential future applications as a fuel). For steel, the share of retained industry production in Scenario 2 corresponds roughly to the steel production capacity that private companies and policymakers envisage to transform until ∼2030 (based on instruments such as EU IPCEIs and CCfDs).

Depending on the strength of the renewables pull (i.e. electricity-price differences), the total potential annual relocation savings (compared to direct imports of the final good) and hence required green-relocation protection span a range of 6–18 bn EUR/a for Scenario 1 and 3–9 bn EUR/a for Scenario 2 (Fig. 6). These numbers can be interpreted as an indication for subsidies or other policy costs that Germany would have to pay as a green-relocation protection to prevent private companies from relocating the production of the considered commodities. It is worth comparing these subsidies to the planned spending from the provisional German federal budget for 2023 [23] and the federal Climate and Transition Fund [24], which indicates that such subsidies would result in a substantial additional expense.

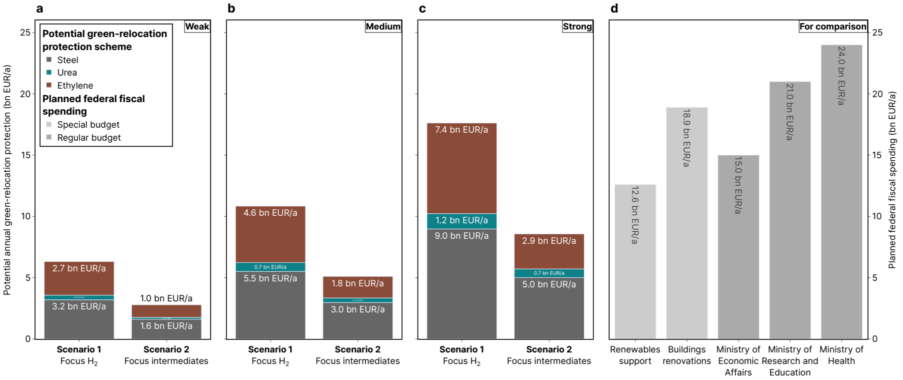

Fig. 6 Estimates of annual green-relocation protection for Germany. Columns a–c present annual volumes for a potential green-relocation scheme for two scenarios defined in Tab. 2: Scenario 1 focussing on imported and domestically produced H_2 and Scenario 2 focussing on importing intermediate industrial products. The presented numbers are derived based on our generic framework for production-cost estimates outlined in the previous section and assume the three electricity-price differences cases (weak, medium, and strong pull) defined in Tab. 1. Column d compares these numbers against planned federal fiscal spending, represented by the regular budgets of selected federal ministries in the provisional German budget for 2023 [23] and the two main special budgets from the federal Climate and Transition Fund [24].

Discussion and conclusions

Access to cheap energy has always shaped the locations of energy-intensive industries. On the path to climate neutrality, the heterogeneous distribution of renewable energy resources might change global patterns of industrial production and trade of basic materials. More specifically, relocating low-carbon industrial production away from RE-scarce and towards RE-rich regions would result in energy-cost savings that provide an incentive (so-called "renewables pull" [4, 5]) for such relocation (so-called "green relocation").

Here we find substantial overall relocation savings of roughly 18 %, 32 %, and 38 % for steel, urea, and ethylene for a full relocation of the considered production steps. These estimates assume an electricity-price difference of 40 EUR/MWh in 2040, which we find conceivable based on estimations of renewable LCOEs, infrastructure cost, and barriers arising for high deployment rates for renewables in RE-scarce regions (with details in a section on future electricity prices in the Supplementary Information), although we also vary this crucial assumption across 20–70 EUR/MWh in our analysis.

Soft factors counteracting the renewables pull will likely only have a dampening effect, given the magnitude of energy-cost savings derived here, and thus will be insufficient to prevent green relocation entirely. However, further sector-specific research is needed to understand locational factors, such as proximity to customers, proximity to other producers, infrastructure, general know-how, skilled labour, certification and approval schemes, and market prices.

By analysing cases of varying "depth" of relocation, we assess different options of splitting value chains between the importer and exporter side and estimate associated relocation savings. This yields two main conclusions: First, while locating only electrolysis (i.e. the first step in each considered value chain) in RE-rich regions and importing green H_2 could shift a large share of energy demand to where it is cheap, the resulting overall relocation savings are small for shipping-based imports (1–2 %) due to high H_2 transportation cost. Therefore, trying to conserve production patterns through H_2 imports is a potentially expensive and risky strategy. Importing H_2 via pipeline instead could weaken the renewables pull, yet they may be infeasible (Japan, South Korea) or take time to construct (Europe). These findings challenge the H_2 import strategies of some RE-scarce regions, in which basic-material production is considered a domestic no-regret H_2 application and hence a key component of future H_2 demand. Second, importing intermediate products (DRI, NH_3, and MeOH) effectively harnesses a large share of the relocation savings (13 %, 25 %, and 37 %), while potentially retaining a significant share of value creation. Since these intermediate products are rather homogeneous goods, security of supply in RE-scarce regions could be established via diverse global markets. This suggests the import of these intermediate goods as a "sweet spot" of relocation.

Policymakers across the globe are tasked with shaping the transition of their basic-material industries against the backdrop of geopolitical tensions, protectionist trends, and – as we establish here – decreasing competitiveness of energy-intensive industries in RE-scarce countries due to the renewables pull. However, policymakers have thus far not addressed the renewables pull but instead focussed on a range of other goals. Specifically, existing policies and strategies aim to: 1) Stimulate domestic industry decarbonisation through investments into new infrastructure (especially H_2 and CO_2) and low-carbon industrial processes, however without considering the future competitiveness of these industries. Examples are the Important Projects of Common European Interest (IPCEIs) on hydrogen and industry, the Net-Zero Industry Act (NZIA) in the EU, the European Hydrogen Backbone (EHB) project, or the German Carbon Contracts for Difference (CCfDs). 2) Secure supply chains of green technologies, however focussing only on critical minerals (such as lithium, cobalt) or technological supply chains (such as mineral refining, manufacturing, batteries, electrolysers) and not on basic materials. Examples are the Critical Raw Materials Act (CRMA) in the EU or the Inflation Reduction Act (IRA) in the US. 3) Compensate for high energy prices during the transition but without considering the need for sustained long-term subsidies to counteract the renewables pull (so-called "green-relocation protection"). An example is the recently proposed German industrial electricity-price subsidy, which is however only considered as a transitional measure. 4) Foster global imports of H_2 and derivatives but without considering the trade of energy-intensive basic materials. Examples are the H_2 import strategies announced by Japan in 2020 and by the EU in 2022, including respective H_2 import targets for 2030 of 10 TW h [25] and 333 TW h [26] (assuming LHV), as well as the German H2Global project [27].

This mix of policies and strategies represents a set of explicit or implicit choices on future locations of industrial production. The result will likely be both domestic production of and global trade with low-carbon basic materials. Contradictions between individual policy instruments across these two opposing goals are conceivable. For example, the German H2Global project tries to stimulate imports of green ammonia, whereas the German CCfDs may contribute to the domestic transformation of the German fertiliser industry. Such contradicting approaches can be interpreted as the outcome of a mindset that seeks to conserve industrial production and trade patterns. This mindset is characterised by the expectation that fossil imports can be replaced with H_2 imports in basic-material value chains and that derivatives (especially NH_3) will be imported via ships, cracked into H_2 at harbours, and distributed inland via pipelines. Such a strategy is challenged by high costs. As soon as RE-rich exporting countries seek to secure more parts of future basic-material value chains, diminishing competitiveness in RE-scarce regions would lead to green relocation and stranded assets or require expensive public compensation schemes. In public debates, it is sometimes raised that green relocation might result in a widespread deindustrialisation. Again, this belief may be challenged given that intermediate products (especially NH_3 or MeOH) will likely become basic energy carriers in future decarbonised energy systems and that the greatest share of industrial value creation is associated with production steps much further downstream from basic-material production. In conclusion, a long-term strategy accounting for the renewables pull and a consistent short-term policy mix can avoid frictions between individual instruments and path dependencies that otherwise would lead to disruptive changes and high costs.

To arrive at such a harmonised strategy, RE-scarce countries first need to assess how they would be impacted by green relocation and how this would align with overarching societal goals. Three considerations appear to be key: i) Security of supply is typically easier to establish for energy carriers and, more generally, for rather homogeneous goods with high supplier substitutability that can be produced low-tech, with a global market likely to emerge. Notably, this is particularly true for shipping-based trade, whereas pipelines might induce strong bilateral dependencies. This suggests that security of supply will generally be possible to achieve through importing hydrogen or intermediates, however this has to be assessed case by case across sectors and depth of relocation. For DRI, the emergence of a global market is unclear, yet existent dependencies on iron-ore imports raise the question whether switching to DRI imports would create much difference. For green NH_3, the emergence of a liquid and diversified market seems likely, given 1) today's global trade volumes for grey NH_3 and 2) announcements of green NH_3 production and terminal capacity [28]. Markets for green carbonaceous feedstocks such as MeOH are currently more uncertain than for green ammonia, hence relying on imports in the short to mid term might also entail supply risks, while fossil methanol can serve as a backup during the transition. Finally, trade dependencies need to be determined on a country-specific level, as e.g. relocation within the EU entails less risk than relocation from the EU to other global regions. ii) Economic productivity and jobs are concerns often raised in public debates. Typically, the number of jobs and added value directly affected by relocation of basic-materials production is comparably low in industrialised countries, yet more research is needed to understand potential knock-on effects for downstream industries (e.g. machinery produced from steel, plastics produced from ethylene). Generally, structural change may allow for more efficient use of production factors, such as human capital and scarce renewable energy, however this may be met by strong opposition among affected societal groups and actors with vested interests. iii) Every energy-intensive process relocated away from RE-scarce regions will also reduce domestic electricity demand, likely resulting in reduced prices for electricity for all consumers. Allowing some energy-intensive processes to relocate to locations with more favourable RE availability could ease pressure on RE expansion targets in RE-scarce countries.

Based on the impact assessment above, policymakers need to decide if and how to intervene in potential relocation of industrial production. The following approaches may be employed to address green relocation: a) In spite of current global onshoring and nearshoring trends, future supply of energy-intensive basic materials could be secured via global imports. Strategies pursuing this solution would aim to foster liquid and diverse markets through collaboration with and technology diffusion across a broad range of potential exporting countries. This may be accompanied by retaining a small level of domestic production capacity and building up strategic reserves (e.g. fertilisers). b) Subsidy-based schemes of “green-relocation protection” are possible but could become costly and are not economically efficient. However, some policymakers have recently voiced their willingness to secure domestic supply chains through subsidies despite the high cost, albeit only as a temporary measure during the transition (e.g. the proposed German industrial electricity-price subsidy [29]). Such a proposal must be informed about the necessity of sustained policy support beyond early stages of the green transition needed to avoid future green relocation due to the renewables pull. If governments decide to protect against green relocation via subsidies, they likely need to strike a balance between affordability and securing value chains by being selective regarding industrial sectors, the share of production retained domestically, and the depth of relocation allowed. Specifically, subsidies could be used to steer towards the above-mentioned sweet spots of relocation, resulting in green value chains being split such that only the most energy-intensive parts are located in RE-rich regions. c) Another complementing strategy for dampening the renewables pull might be a focus on an efficient use of scarce energy resources through material efficiency, circularity, and demand-side flexibility (see also the section on flexibility, circularity, and demand reduction in the Supplementary Information). Increased mechanical and chemical recycling of plastics or secondary steel from scrap would reduce the dependence on energy-intensive primary materials. Designing industrial plants capable of load-following the hourly availability of RE could reduce energy cost [30–32].

There is an urgent need for a broad societal debate on the role of a country in global industrial production informed by scientific assessments of pros, cons, and trade-offs. The scientific community can support this debate in RE-scarce countries with further research on future market structures of green products, difficult-to-quantify soft factors determining private investment decisions, macroeconomic impacts, sector-specific details, and policy assessment. Moreover, the assessment of green relocation presented here rather takes the perspective of RE-scarce countries. For a more comprehensive scientific debate, research on green relocation needs to include a diversity of perspectives in light of existing power dynamics between RE-scarce and RE-rich countries. Exporting and importing countries that occupy different positions might arrive at different evaluations of green relocation.

To better inform societal and policy debates on the energy transition, integrated-assessment and energy-system modelling may account for the renewables pull, green relocation, and the associated geopolitical dimensions. Specifically, models may need to go beyond the trade of energy carriers (such as H_2) and also model the trade of energy-intensive goods such as steel, fertiliser, and higher-value chemicals. Scenario analysis and energy-system modelling will allow for an improved understanding of the impacts of green relocation on the overall energy system and the net-zero transition.

Methods

Terminology

Tab. S6 contains an overview of terminology used within this article. We stress again that we use the term renewables pull to refer to the energy-cost incentive, while green relocation is the potentially resulting effect, i.e. relocation of industrial production as a consequence of energy-cost incentives. We note that our definition of the renewables pull is slightly adjusted from an earlier one given by [4], where the two concepts were both referred to as by the term renewables pull only, which the authors however updated in a more recent publication [5].

Moreover, 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 unbiased debate.

Quantitative estimations

An overview of how quantitative results are compiled is presented in Fig. S4. Details on the individual steps and associated assumptions are presented below.

Technology data from literature review. Technology data required for the calculation of the levelised cost of production (LCOP) outlined below (i.e. CAPEX, FOPEX, VOPEX, and specific energy/feedstock demands) is obtained from POSTED, the Potsdam Open-Source Techno-Economic Database, using release v0.2.3 [33]. In doing so, we used 181 individual entries of techno-economic data from a total of 33 original data sources [1, 11, 28, 34–63] to represent the following 9 processes: Alkaline water electrolysis, low-temperature DAC, industrial 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_2, and methanol-to-olefins (MtO). 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. S7.

Technology assumptions. For our estimations, we consider green value chains based on RE for the three products steel, urea, and ethylene. All three value chains commence with the production of H_2 via Alkaline electrolysis. In the case of steel, H_2 is used to reduce iron ore in a direct-reduction shaft to produce DRI, which is then melted in an electric-arc furnace, cast, and hot rolled into HRC. In the case of urea, H_2 and atmospheric nitrogen from an air-separation unit (ASU) are reacted via the Haber-Bosch process to yield NH_3, which is then combined with atmospheric CO_2 from DAC to synthesise urea. In the case of ethylene, H_2 and CO_2 from DAC constitute the synthesis gas for MeOH production, which is then reacted to ethylene in an 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 hereafter). When splitting these value chains into their three main processing steps, we associate the winning of CO_2 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.

The heat for DAC can be provided by low-temperature industrial heat pumps with a coefficient of performance (COP) of around 3–3.5. This assumption is justified, as the required temperature for low-temperature DAC is only $T \approx 80$–$120\,°\mathrm{C}$ and waste heat should typically be available from the processes consuming the CO_2 (i.e. MeOH and urea synthesis). This means that, the heat demand of DAC of ∼1.68 MWh/t translates into only ∼0.51 MWh/t of electricity demand for the heat pump, while adding CAPEX for the heat pump.

The heat required by all other processes, which require $T \gtrsim 200\,^{\circ}\mathrm{C}$, is assumed to be provided by resistive (Ohmic), radiative, microwave, or inductive heating [64], for which we assume a constant efficiency of 100 %. These assumptions are valid, as such electrified heating of industrial processes is piloted and the technology is straight-forward and available, whereas high-temperature industrial heat pumps for $T \gtrsim 200\,^{\circ}\mathrm{C}$ are still in early development (TRL 4-5 [65]) and the efficiency and feasability of heat pumps for $T \gtrsim 400\,^{\circ}\mathrm{C}$ (for most chemical processes) and $T \gtrsim 800\,^{\circ}\mathrm{C}$ (for steel processes) is unclear.

Importing intermediates (DRI, MeOH, and NH_3 in the specific cases estimated here) can reduce the potential for heat integration and hence increase energy demand. In the case of DRI, we account for this in electricity demand by adding 0.159 MWh/t [1]. In the cases of urea and ethylene, we neglect this, mainly due to poor data availability. Most literature from the past assumes waste heat availability from upstream fossil processes such as steam methane reforming (SMR; needed to produce the required grey H_2). That said, there are other ways to make use of waste heat and potential electricity generated from it, such as 1) selling electricity to the grid, 2) feeding heat into urban district heating, 3) recycling heat and electricity internally for preheating of precursors and operating the plant, or 4) using waste heat for on-site DAC or high-temperature solid-oxide electrolysis (water to H_2 or CO_2 to CO). While options 1) and 2) are likely more relevant for RE-scarce importers with good grid infrastructure and remote urban areas, options 3) and 4) can be applied for both RE-scarce importers and RE-rich exporters.

The fresh-water demand for the production of green H_2 can be a relevant factor for some RE-rich exporters with water scarcity. Our assumed price for water includes cost of water desalination, yet this leads only to a minor contribution to the overall production cost across all value chains. Yet, it should be noted that there may be countries/regions where water availability can pose a major obstruction to the development of green value chains. Here it should be noted that for the steel value chain, Case 1, i.e. the import of H_2, is the only case with implicit transportation of water from the RE-rich to the RE-scarce region. In all other cases, the water could be cycled between the electrolyser and the DR shaft for on-site H_2 production [1]. This could add another reason for why importing DRI or importing semi-finished steel could be cheaper compared to importing H_2, but this constitutes only a minor point for most RE-rich exporters and we therefore neglect it in our estimations.

We assume the operational capacity factor (OCF) to be 95 % 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.

Transport costs. Depending on the considered import case, transport costs are added for the respective traded goods, representing international trade based on shipping (and pipelines for Case 1A). Specifically, Case 1 adds transport costs for H_2, Case 2 for intermediates (DRI, NH_3, MeOH), and Case 3 for (semi-)finished products (HRC, urea, ethylene). We assume that CO_2 is not traded but produced from DAC at the point where it is needed. Moreover, we add transport costs for iron ore in the Base Case and Case 1, as we assume the exporting country of DRI to be a producer of iron ore. This assumption is justified since the largest three iron-ore exporting countries (Australia, Brazil, and South Africa) all have ample RE potentials.

Specific (i.e. per mass) transport costs are researched and reported in Tab. S8. In principle, specific transport costs are dependent on distance, yet in practice we can assume generic values independent of distance and specific cases. This is particularly the case for shipping (as confirmed by UNCTADstat data), where harbour dues, terminal costs, and liquefaction (esp. H_2) make up a large share of the total transport cost.

For shipping-based H_2 transport, specific costs are in the range of 2.0–2.6 $\mathrm{USD/kg_{H_2}}$ in 2030, depending on distance and transport medium used (LH_2, LOHC, ammonia) [66]. 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 $\mathrm{USD/kg_{H_2}}$ of transport cost, depending mainly on whether new pipelines are built or old ones are repurposed [66]. This corresponds to 14–28 EUR/MWh, hence we choose 15 EUR/MWh.

Commodities other than H_2 are established in international trade and country-specific bilateral transport costs in 2016 are reported by [67], which we analyse in the Supplementary Information and report in Tab. S8. While transport costs for iron ore were at only 2.5 EUR/t in 2016, these drastically increased in recent years, are in the range of 5–40 EUR/t now, and are predicted to peak soon [68, 69]. [70] derive transport costs of 35 EUR/t for NH_3 and MeOH for today based on literature review. We conclude with the values reported in Tab. S8, which are supposed to capture relative trends from the 2016 UNCTADstat data and also account for absolute trends in recent markets.

Retrofitting and repurposing of grey production capacity. When determining the required investment in our estimations, another question arises on whether new green production plants will need to be newly built in both RE-scarce importing and RE-rich exporting regions or if the former can repurpose/retrofit existing capacities. Clearly, new electrolysis, DAC, DR, EAF, casting, MeOH synth., and MtO plant capacity would need to be built to meet future demands of the respective green products. On the contrary, hot-rolling plants, HB plants, and Urea synth. plants could, in principle, be repurposed/retrofitted. In the case of Haber-Bosch, this will likely require retrofitting the heat supply, which in today's grey HB plants is satisfied through integrated SMR and which would need to be replaced with electrified heating. Urea synthesis capacity can likely be reused without the need for large investment. Regarding the production of green ethylene, it should be noted that a competing route would be via the cracking of green naphtha, which would repurpose existing steam-cracker capacity and hence make better use of fossil infrastructure yet at the expense of likely lower energy efficiency and whose study is beyond the scope of this work. More generally beyond technology-specific considerations, integration into existing infrastructure, the lack of free space for construction, and the requirement of continued operation of other plants in an existing industrial park create obstacles for brown-field investments that are not existent for green-field investments, potentially resulting in significantly higher cost. In summary, investment into new capacity is the same across both regions, whereas the option of repurposing hot-rolling, Haber-Bosch, and urea plants is studied in the sensitivity analysis (Fig. 1).

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 annuity factor used in the calculation of the $LCOP$ below. 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 Fig. 1. For simplicity and to demonstrate the minor effect of capital and financing cost, we assume a low value of 18 years for the book lifetime of new green facilities independent of the technical lifetime of plants. Notably, while financing costs can also increase the cost of wind and solar capacities and hence electricity prices, our analysis treats as electricity prices as an exogenous parameter independent of financing costs.

Calculating the levelised cost of production. Based on these assumptions and the curated techno-economic data (see below), we can calculate the levelised cost of production, $LCOP$, as follows:

$$LCOP = \frac{ANF \times CAPEX + FOPEX}{OCF} + VOPEX + \sum_k d_k \times p_k + \sum_g d_g \times tc_g, \tag{1}$$

ANF is the annuity factor 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 total capital expenditure in units of annual production capacity, $FOPEX$ is the annual fixed operational expenditures per annual production capacity, $OCF \in [0,1]$ operational capacity factor, $VOPEX$ is the variable operational expenditure per output quantity (non-energy, non-feedstock), d_k is the specific demand for feedstock or energy carrier k, p_k is the associated price, d_g is the specific demand of transported intermediate feedstock or energy carrier g, and tc_g is the associated specific transport cost.

Other assumptions. 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 negligible and roughly the same, such that no competitive advantage emerges from cleaner production in one or the other region (e.g. carbon costs due to carbon pricing).

When estimating the potential green-relocation protection in Germany, we take the 2040 projections for steel demand from a study of long-term scenarios on German industry decarbonisation [21] and for ammonia and ethylene demand from a study of the green transformation of the German chemical industry [22].

Potential exporting countries in the German case-study

The conceptual framework and quantitative estimations presented in this work are kept generic and do not assume specific exporting countries. Yet, in our case study of German imports and potential green-relocation protection, we try to illustrate future export corridors and hence list potential exporting countries. To identify such candidates, we analyse countries with high RE potentials according to the following aspects: 1) whether a country produces and exports the respective commodity based on fossils today, 2) whether substantial green projects have been announced, and, in the case of steel, 3) the availability of iron ore. This procedure results in a non-exhaustive list of potential candidates presented in Tab. S9.

Data availability

A copy of input data and results is published on Zenodo [71]. This includes (i) an Excel spreadsheet file reporting techno-economic assumptions obtained from POSTED, (ii) several plain-text files containing other assumptions and data needed to reproduce all results, (iii) the results reported in Figs. 4, 5, and 6, and (iv) a Jupyter notebook showcasing how to results can be obtained with basic Python code.

Moreover, results of our study can be reproduced with adjusted assumptions via an interactive webapp [72], which also allows viewing individual cost components for every process in each value chain shown in Fig. 5.

Code availability

A permanent copy of the software code needed to reproduce all figures and run the interactive webapp is publicly available on Zenodo, which may also be viewed via GitHub [73]. The software uses data and analysis tools from POSTED (the Potsdam open-source techno-economic database) v0.2.3 [33] and builds on the PIW (Potsdam Interactive Webapp) framework library v0.8.2 [74].

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Acknowledgments

We thank Gunnar Luderer, Tom Brown, Johannes Hampp, Matthias Schimmel, Thobias Sach, Diego Bietenholz, Sascha Samadi, Clemens Schneider, Krystin Unverzagt, and Jarusch Müßel for their valuable discussions and comments while preparing and revising the manuscript, and Clara Bachorz and Paul Effing for their help with curating techno-economic data and writing software code for POSTED.

P.C.V. and F.U. disclose support for the research for this work by the Kopernikus-Ariadne project by the German Federal Ministry of Education and Research [grant numbers 03SFK5A, 03SFK5A0-2], the INTEGRATE project by the German Federal Ministry for Economic Affairs and Climate Action [grant number 01LP1928C], and the HyValue project [grant number 333151]. F.U. and L.G. disclose support for the research for this work by the CCfD project by the German Federal Ministry for Economic Affairs and Climate Action [grant number DE64B88F-54CC-4CFB-B802-7CEC1AA2E542].

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.

Additional information

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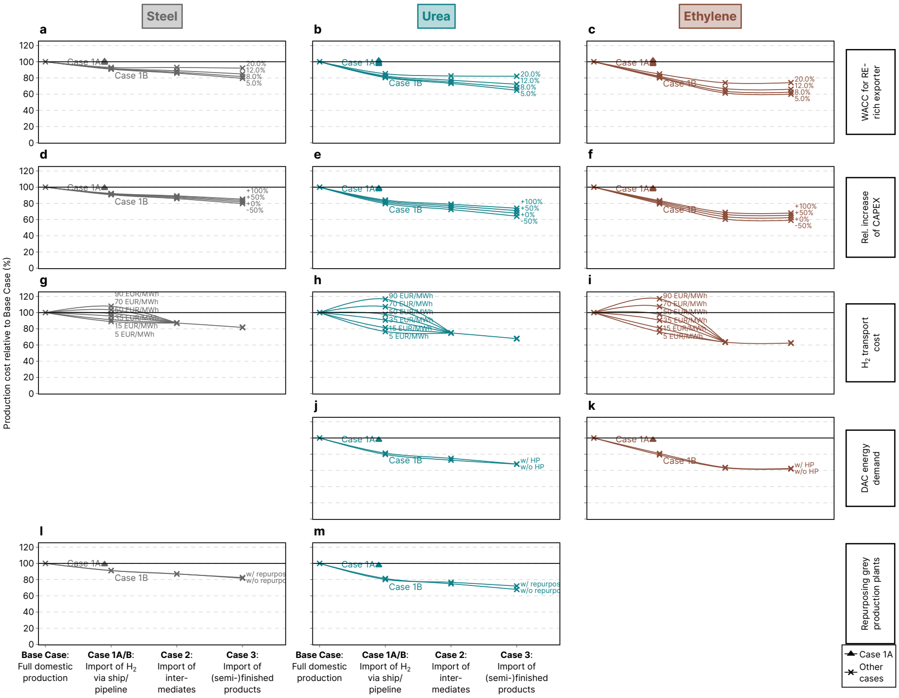
Extended data figures



Extended Data Fig. 1 Sensitivity analysis. Shown are the main results from Fig. 4 with electricity-price difference of 40 EUR/MWh, while varying the WACC on the RE-rich exporter between 5 % and 20 % (a–c), rel. changes in CAPEX between −50 % and +100 % (d–f), transport cost for H_2 between 5 EUR/MWh and 90 EUR/MWh (g–i), whether the heat for DAC is provided by a heatpump or not (j–k), and whether existing grey plants (hot rolling in steel, Haber-Bosch, urea synth.) can be repurposed (l–m).

Supplementary information

Extended list of private and societal factors influencing green relocation

Table S1 Extended list of factors that can influence investment decisions of the private sector. Those marked with an asterisk (*) are accounted for in the quantitative estimations presented in this article.

Incentivising factors	Inhibiting factors
Renewables pull*, i.e. energy-cost savings due to lower electricity prices in the RE-rich compared to the RE-scarce region.	**Transport penalty***, i.e. additional transport cost associated with the trade of intermediate goods. The magnitude of this cost penalty is particularly relevant for trading H_2. While this penalty generally inhibits imports, it may also incentivise deeper relocation (e.g. from imports of H_2 to imports of intermediates).
Lower wages, i.e. a decrease in labour cost and hence operational 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 only 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.	**Financing penalty***, 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.
Availability of space for construction, which is often ample in RE-rich regions.	**Lost proximity to other producers**, i.e. clustering synergies and economies of scope. This includes lost opportunities of co-production, heat recovery, and waste recovery (esp. chemicals).
Complexity of plant integration, which can be challenging in complex arrangements of existing industrial sites.	**Lost proximity to customers**, 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.
Gained proximity to non-energy resources, resulting in cost reductions and efficiency gains (esp. iron ore in steel).	**Infrastructure penalty**, including more general infrastructure not considered as clustering synergies, such as access to road, rail, or marine transport, as well as to fresh water, electricity, and other basic services. This may pose a particular challenge in developing countries.
	Availability of skilled labour, which is typically lower in less developed countries.
	Certification of production, 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.
Market structure and prices, which ultimately determine private revenues. The higher the market price (compared to production cost) and hence the higher the added value of a commodity, the higher (lower) the impact on relocation for upstream (downstream) products. E.g. the price of H_2 may be a lot higher than its production cost, which could amplify the renewables pull, whereas high market prices of industrial commodities (NH_3, MeOH, steel, fertiliser, etc.) will dampen the impacts of the renewables pull.	
Complexity of planning and approval procedures, which can vary greatly on both sides.	

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

Category	**Risks**	**Opportunities**
Overall cost	Overestimation of the real total cost benefit resulting from green relocation	Reduction of total transformation cost as a result of green relocation
Energy prices	Higher energy prices in RE-rich region due to opportunity cost arising from exports	Cheaper energy prices in RE-scarce region
Product prices (steel, fertiliser, other basic materials, etc)	–	Lower product prices in RE-scarce region
Energy transition & climate mitigation	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
Development in RE-rich region (economic, infrastructure, desalinated water)	Introducing neocolonial structures	Accelerated through foreign investments
Jobs & value creation (also needs to be assessed on a local level, accounting for structural differences within countries)	Jobs and value creation lost in RE-scarce region; key technologies (e.g. electrolysers, direct reduction) built up elsewhere	Jobs and value creation added in RE-rich region; key technologies (e.g. electrolysers, direct-reduction shafts) can still be supplied by RE-scarce regions
Geopolitical	Concerns over geopolitical interdependencies	Strengthening of international relations/cooperation
Investments	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
Policy	Need to deal with other downsides of green relocation	No need to create a green-relocation protection mechanism
Supply chain	Remote production jeopardises supply chain reliability	With some products (iron ore for steel) there already is a dependency, so relocation of production may have little effect

Future cross-regional electricity price differences

Future regional electricity-price differences are uncertain, complex, and inherently dependent on regional circumstances. While the simplest regional comparison can be based on LCOE of renewable electricity generation, we introduce five layers of additional complexity and associated uncertainties that can increase price differentials far beyond pure LCOE comparisons. Note that these layers interact and thus the individual effects do not add up linearly. The layers can be understood as increasingly accounting for energy system effects. Therefore, it would be ideal if future work estimated price differences and production costs with a full energy system and scenario perspective based on dedicated modelling that includes the energy part of green value chains.

Based on these thoughts and associated literature estimates, we then define three cases to represent broad plausible ranges of future price differentials: low, medium, and high. These cases correspond to the three cases for the renewables pull in the main paper: weak, medium, and strong. Note that the discussions here focus on electricity price differences. Other cost components such as transport, labour, or financing costs are analysed separately. Throughout the paper, we do not account for additional country-specific regulatory context such as taxes, levies, or subsidies.

Six layers of complexity

1) Renewable electricity LCOE. The first and simplest level of cross-regional comparisons can be based on regional LCOE of renewable electricity generation. For 2021, IRENA reports [75] most of utility-scale solar PV projects to be in the range of 20–170 USD/MWh in 2021 with an average of ∼50 USD/MWh, and most of wind onshore projects to be in the range of 10–100 USD/MWh in 2021 with an average of ∼35 USD/MWh. Comparing solar PV LCOE of selected resource-constrained countries such as Germany (∼60 USD/MWh) and or Japan (∼90 USD/MWh) with solar-rich countries such as Australia (40 USD/MWh) and India (30 USD/MWh) gives cost differences of 20–60 USD/MWh. Comparing wind onshore LCOE of selected resource-constrained countries such as Germany (∼50 USD/MWh) and or Japan (∼140 USD/MWh) with windy countries such as Australia (40 USD/MWh) and India (30 USD/MWh) gives cost differences of 10–120 USD/MWh.

With further decreasing renewable capacity costs, absolute cross-regional LCOE differences decrease. Based on progressive cost decline projections by [76], solar PV LCOE differences between Germany and Australia decrease to 15–20 USD/MWh in 2030 and 10-15 USD/MWh in 2040. Note that regional differences in financing costs (WACC) can substantially change these differences (for a discussion see the annex in the IRENA report [75]).

2) Marginal costs of renewable supply (supply curves with limited regional renewable potentials). Supply curves typically increase with increasing overall generation (at a given year) due to higher costs at lower

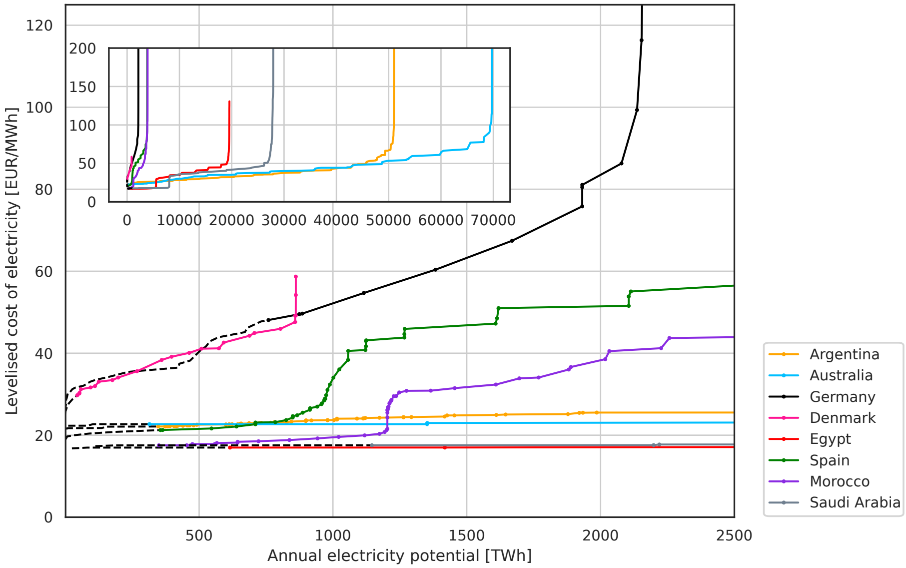


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Fig. S1 Modelled electricity supply curves for 2030 at 10% p.a. WACC. Dashed black parts are reserved for meeting domestic electricity demand and unavailable for export. The inlet contains the same plot on a larger scale. The visible stepwise increases in LCOE for Spain and Morocco is where the cheapest electricity potentials from low cost PV are exhausted and the onshore and offshore wind enter the supply curve.

quality renewable sites. Both average and marginal costs of supply can thus be substantially higher than LCOE calculated for the best sites. [77] derive such renewable electricity supply curves for different regions (Fig. S1). They demonstrate that for renewable-constrained countries (e.g. Germany), marginal costs i) gradually increase due to cross-sectoral domestic electricity demands (dashed part of the lines) and ii) steeply increase once a region-specific generation threshold is crossed, while for RE-rich countries such as Australia, renewable supply curves are basically flat. This increases the resulting electricity cost differences. Based on LCOE modelling for 2030 by [77], the LCOE for Germany is ∼50 EUR/MWh (assuming an annual demand of ∼750 TW h) and for Australia is ∼20 EUR/MWh, resulting in an LCOE difference of ∼30 EUR/MWh.

3) The temporal profile of electricity demand and flexible operation. The basic LCOE metric evaluates each unit of electricity irrespective of the hour in which it is generated, yet energy services typically require a specific temporal profile, for example a continuous baseload profile for many industrial applications. Providing a specific temporal profile is more costly than LCOE estimates imply, especially based on variable renewable electricity sources such as solar PV and wind power [78, 79]. These additional costs are typically lower when projects are integrated in energy systems that provide flexibility through large-scale electricity grids (pooling wind power, solar PV, and dispatchable generation sources), central and large-scale H_2 cavern storage, central electricity storage, as well as demand-side flexibility. For offgrid ("island") projects, providing baseload electricity or H_2 is more challenging. If low-cost H_2 storage (e.g. through salt caverns) is available, H_2 can be supplied at a continuous profile (baseload H_2) without the requirement of baseload electricity generation. Without low-cost H_2 storage, electricity supply and H_2 supply are more closely linked, and supplying baseload H_2 to offgrid industrial processes requires electricity storage, for example by batteries. [76] estimate the costs of both baseload H_2 and baseload electricity supply from wind and solar PV power for offgrid projects across global regions. If the electricity demand can be flexibilised – through H_2 storage or through flexible H_2 demand associated with flexible operation of industrial processes – electricity costs can be reduced. For offgrid systems, electricity costs would then be in the range of LCOE. A grid-connected project can substantially lower its electricity costs compared to the average annual whole-sale price in a system, as the electricity demand can be shifted to zero- and low-price hours (Figure 2).

4) Grid costs. Industrial producers in RE-scarce regions will typically rely on a grid connection to supply their electricity needs, while producing and exporting H_2 or basic materials from RE-rich regions can also be realised through offgrid ("island") projects. While grid-connected projects benefit from flexible and reliable energy supply, we argue that the best offgrid project sites can realise cost advantages due to saving electricity and H_2 grid costs, which typically are a substantial part of industrial electricity and future H_2 prices. This holds true in particular for offgrid projects that do not require a specific temporal electricity or H_2 profile due to low-cost H_2 storage or flexible operation of the H_2-consuming industrial process.

Note that future grid fees are uncertain in at least two respects. First, future overall grid costs and the associated average grid costs per unit of electricity consumed across sectors and end-use applications are uncertain. Both overall grid costs as well as electricity consumption will likely increase. For Germany, annualised electricity transport costs (excluding distribution grids here) increases by a factor of 3–4 in 2045 (climate neutrality target) compared to 2021, while electricity consumption approximately doubles across scenarios[1]. These projections could translate into an approximate doubling of today's grid fees in Germany.

Secondly, there is regulatory uncertainty with respect to how grid fees are allocated and designed. In Germany, new electrolysers that are built until end of 2026 are exempt from grid fees, which can be understood as policy support that will likely phase out once markets and technologies are more mature. In the case of Germany, households' grid fees recently increased to ~90 EUR/MWh in 2023[2], while energy-intensive industries typically pay much lower fees in the range of 20–30 EUR/MWh. However, today's regulation often

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[1] Long-term scenarios for Germany, see slide 20 in https://langfristszenarien.de/enertile-explorer-wAssets/docs/Consentec-TUBER_BMWK_LFS3_Webinar_Netze_T45_final_v2.pdf.

[2] See https://www.verivox.de/strom/themen/netznutzungsentgelt/.

disincentivises flexible operation as grid fees are rather high at lower full-load hours. In 2021, Consentec[3] calculated grid fees for a hypothetical flexible electrolyser in Germany to be in the range of 20–60 EUR/MWh.

5) Barriers to high deployment rates of renewable electricity generation. Countries or supranational unions often have ambitious renewable deployment targets. For example, the EU wants to increase their renewable energy share across end-use sectors from 22 % in 2021 to 42.5 % in 2030. This is in accordance with ambitious GHG emission reduction targets that are enforced through EU policies such as the carbon cap and trade system EU-ETS, where CO_2 emission certificates will be phased out at around 2040. Hence, there are and will be high demands and high willingness to pay for renewable electricity.

At the same time, there are substantial barriers that can limit renewable deployment rates especially in countries that are densely populated and have limited renewable potential. Barriers include a lack of social acceptance, delays in expansion of transmission grids, as well as delays in approval and planning procedures.

If renewable electricity expansion advances too slowly, substantial scarcity will likely translate into scarcity prices that are much higher than the costs of renewable electricity projects. High prices could occur in electricity spot markets as well as in markets for renewable power purchase agreements (PPAs). Such scarcity prices are less likely in RE-rich countries. In particular, offgrid projects with integrated electricity supply do not face electricity price risks.

As a result, cross-regional price differentials increase as producers of H_2 or basic materials in renewable-constrained energy systems would likely have to pay such scarcity prices. While the size of these effects are difficult to predict, there is empirical evidence showing that high demand and scarcity can substantially increase renewable electricity prices. 10-year PPA prices for solar, onshore wind, and offshore wind technology in the EU have doubled during the energy crisis in 2022 to an average of 107.80 EUR/MWh[4], which is roughly twice as high as renewable project costs. While PPA prices during the recent energy crisis represent an extreme situation, European renewable PPA prices in 2023 as well as 2025-future prices remain at a high level above renewable LCOE partially due to supply scarcity[5].

6) Infrastructure availability. An additional requirement is the availability of supply-chain specific export and import infrastructure. Bottlenecks can lead to scarcity prices for associated imports. For example, limited availability of H_2 import pipelines or H_2 and NH_3 terminal infrastructure can increase domestic H_2 or NH_3 prices. Other bottlenecks include qualified workforce or

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[3] See https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_07_IND_FlexNetz/A-EW_224_Netzkostenallokation_WEB.pdf.

[4] See https://www.pv-magazine.com/2022/10/04/european-ppa-prices-rise-to-e0-1078-kwh/.

[5] See https://s3.eu-west-1.amazonaws.com/icis.ada.website.live/wp-content/uploads/2022/10/10183635/Renewable-PPAs-and-a-review-of-the-commodity-price-spike-on-renewable-hydrogen-production-costs.pdf and https://www.power-technology.com/news/european-solar-ppa-price-drop/.

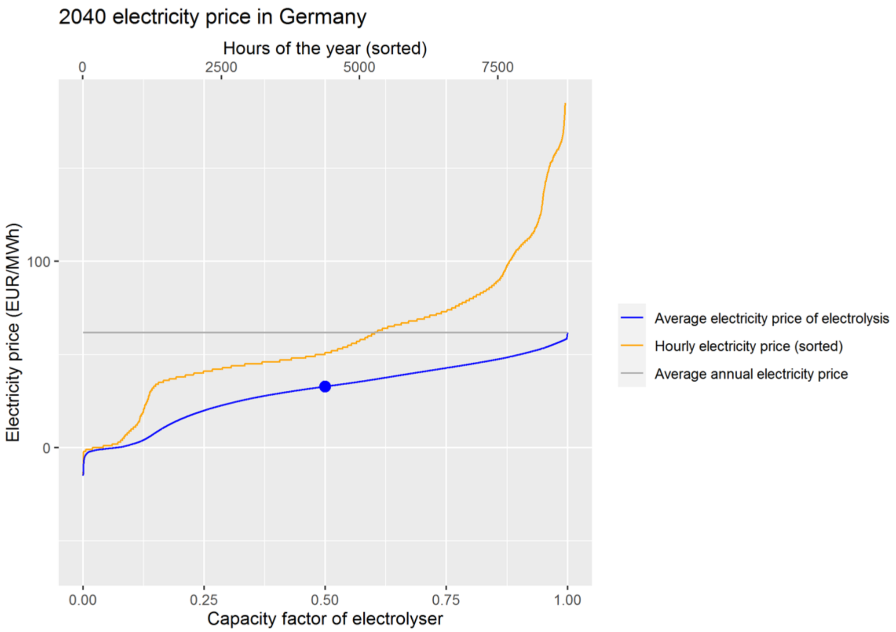

Fig. S2 Price duration curves. Based on modelled hourly electricity prices for Germany in 2040 (sorted, orange line, without grid costs) and the average electricity price of a flexible electrolyser as a function of full-load hours (annual capacity factor). At a capacity factor of 50 %, an electrolyser can substantially reduce its average electricity costs (~30 EUR/MWh) compared to the annual average electricity price (~70 EUR/MWh). Price data is taken from a study on long-term scenarios for Germany using the Enertile model[6].

regulatory and institutional infrastructure. As a consequence, the availability of import routes will broaden in time. We anticipate that for the focus year in this paper (2040), import and export infrastructure bottlenecks will likely be resolved such that most supply chains are available.

Summary. While renewable LCOE differences between RE-scarce and RE-rich countries are in the range of 20–50 EUR/MWh, additional scarcity and system costs in RE-constrained regions can lead to price differences that are much higher than pure LCOE differences would suggest. The core reason is that market-based electricity prices of industrial producers in RE-constrained countries (without regulation and policy intervention) will likely be higher than low renewable LCOE due to potential scarcities and system costs, while producers in offgrid projects in RE-rich countries pay electricity costs that are roughly in the range of low-cost renewable LCOE, particularly at locations that have access to low-cost H_2 storage and for industrial processes that can be operated flexibly.

In addition to those six layers of complexity, there are region-specific regulations and subsidies that impact price differentials in both directions. In our framework, we account for this as "regulatory interventions" (scheme in Fig. 2) and not as part of the renewables pull, which arises from regional price differentials that are only the result of techno-economic aspects (including scarcity prices and system costs).

Renewables-pull cases in the main paper

We differentiate three cases of electricity prices (Tab. S3, compare with Tab. 1), which represent uncertainty and regional heterogeneity. For each case, we further differentiate prices between flexible processes (electrolysis) and baseload processes (all other). Combining wind and solar PV can lead to high electrolyser capacity factors of 50 % [76], whereas we assume 95 % for baseload demand.

Table S3 RE prices for flexible electrolyser and baseload demand across the three price cases. The electricity prices were used in our estimates with results presented in Fig. 4 and Fig. 5.

Price case	**Electricity price** (EUR/MWh)			
	In RE-rich region		In RE-scarce region	
	For a flexible electrolyser (OCF 50 %)	For a baseload process (OCF 95 %)	For a flexible electrolyser (OCF 50 %)	For a baseload process (OCF 95 %)
Weak pull	30	50	50	70
	LCOE of 20 EUR/MWh (flexible) and 40 EUR/MWh (baseload), plus additional storage and transport infrastructure costs of 10 EUR/MWh.		LCOE of 50 EUR/MWh (flexible) and 70 EUR/MWh (baseload), accounting for increasing marginal costs in RE-scarce regions. Optimistically assuming that electrolysis and the new industrial processes overall are exempt from electricity grid fees and that renewable expansion barriers can be overcome such that there are no scarcity prices.	
Medium pull	30	50	70	90
	LCOE of 20 EUR/MWh (flexible) and 40 EUR/MWh (baseload), plus additional storage and transport infrastructure costs of 10 EUR/MWh.		Modelled electricity prices of 30 EUR/MWh (flexible) and 70 EUR/MWh (baseload), also accounting for increasing marginal costs in RE-scarce regions. Electricity-grid fees of 40 EUR/MWh (for electrolysis due to 50 % capacity factor) and 20 EUR/MWh (for baseload electricity). Optimistically assuming that renewable expansion barriers can be overcome such that there are no scarcity prices.	
Strong pull	15	35	85	105
	Best-case LCOE with negligible system and infrastructure costs.		Modelled electricity prices of 30 EUR/MWh (flexible) and 70 EUR/MWh (baseload), also accounting for increasing marginal costs in RE-scarce regions, plus additional grid fees of 40 EUR/MWh and 20 EUR/MWh, plus additional 15 EUR/MWh scarcity price markup due to barriers in rapid renewable expansion.	

1. In the "**weak**" case, we derive regional price differences of only 20 EUR/MWh, leading to a comparably weak renewables pull. For this purpose, we combine rather optimistic assumptions in RE-scarce regions with rather pessimistic assumptions in RE-rich regions, and we only account for layers 1–3 from the previous section.

   - For electrolysis, electricity costs are parameterised by pure LCOEs in 2040, while accounting for the marginal cost increase in RE-scarce regions (layers 1 and 2 above, also compare Fig. S1). This yields 20 EUR/MWh in the RE-rich and 50 EUR/MWh in the RE-scarce region. The latter can be realised for instance through renewable PPAs.
   - For baseload electricity provision, we take assumptions from [76], who estimate the cost of baseload electricity supply from wind and solar PV power across global regions. This yields 40 EUR/MWh in the RE-rich and 70 EUR/MWh in the RE-scarce region.
   - Furthermore, we optimistically assume that grid costs are small (layer 4) and electricity scarcity prices in RE-scarce regions (layer 5) can be avoided by removing barriers to a rapid expansion of RE generation.
   - For the RE-rich region, we add 10 EUR/MWh to account for additional storage and transport infrastructure costs that is required, for example, to meet the temporal demand profile of the industrial processes.

2. In a "**medium**" case, we derive regional price differences of 40 EUR/MWh. While the assumptions on the RE-rich side remain the same as in the weak case, we now parameterise the RE-scarce region based on modelled electricity prices for Germany and grid costs. Thereby, we account for layers 1–4 from the previous section.

   - For the grid-connected project in a RE-scarce region, we assume that hydrogen can be stored at low costs (in geological salt caverns) and that thus electrolysers can flexibly operate and benefit from the 50 % lowest hourly electricity prices in the year 2040 (see price duration curves in Fig. S2). This leads to electricity prices of only 30 EUR/MWh (instead of ~70 EUR/MWh baseload electricity price). Again, we assume that RE scarcities can be avoided.
   - In addition, we add grid costs of 20–40 EUR/MWh. 40 EUR/MWh for a flexible application with low capacity factor such as electrolysers, and 20 EUR/MWh for baseload electricity demands. This reflects current regulations in Germany[3]. These values will heavily rely on future regulatory decisions.

3. In a "**strong**" case, we derive regional price differences of 70 EUR/MWh, leading to a strong renewables pull. For this purpose, we combine pessimistic assumptions for RE-scarce regions with optimistic assumptions in RE-rich regions. Most importantly, we here take layers 1–6 from the previous section into account by adding RE scarcities. These scarcities arise

due to delays in expansions of RE generation and grids along with a sustained high willingness to pay resulting from strong political commitments to emission-reduction targets (e.g. in the EU-ETS).

- On the RE-scarce side, prices are the same as in the medium case, but with an additional cost markup of 15 EUR/MWh.
- On the RE-rich side, we assume that low-cost H_2 storage (e.g. in salt caverns) is available such that electricity costs of an electrolyser are determined by renewable LCOE (15 EUR/MWh) without additional costs for buffering electricity (e.g. battery costs).

Analysis of UNCTADstat transport costs data

[67] present a Global Transport Costs Dataset on International Trade (GTCDIT), which "records bilateral international merchandise trade in value and quantity, broken down by commodity group and mode of transport (air, sea, railway, road, other modes), alongside its associated transport costs, for 2016", is publicly available via the website[7] of UNCTADstat (the statistics department of the United Nations Conference on Trade and Development), and builds up on the UN Comtrade database.

We query GTCDIT for codes (based on the Harmonised System of the World Customs Organisation) corresponding to the respective commodities (see Tab. S4) and present specific (i.e. per mass) transport cost as a function of the annual amount traded (Fig. S3). The observed specific transport costs are typically more noisy for bilateral trade relations with a low annual traded quantity, so plotting the specific transport costs as a function of traded quantity allows to separate out the noise and identify trends in the data. Based on the data presented in Fig. S3, we derive 2016 transport costs of 2.5 EUR/t

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[7] https://unctadstat.unctad.org/

Table S4 Harmonised System codes used for queries of the Global Transport Costs Dataset on International Trade. Codes for semi-finished steel use regular expressions (REGEX).

Commodity	**Harmonised System codes queried**
Iron ore	260111, 260112, 260120
DRI	720310, 720390
Semi-finished steel	720[6-9][0-9][0-9], 72[1-2][0-9][0-9][0-9]
NH_3	281410
Urea	310210
MeOH	290511
Ethylene	290121

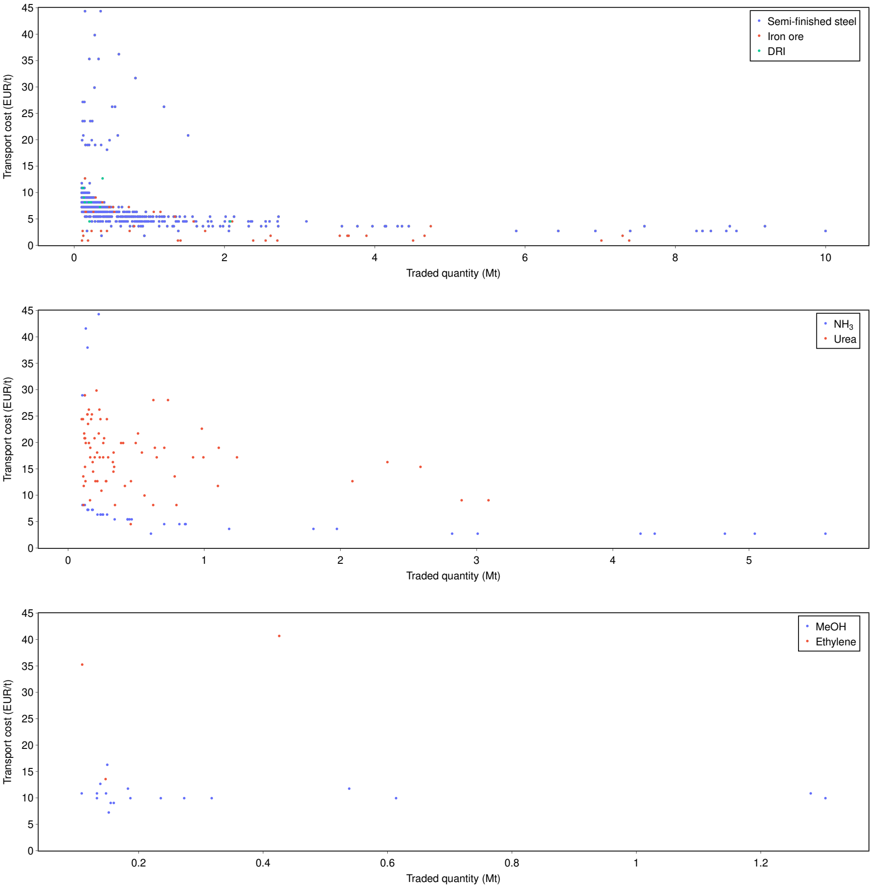

Fig. S3 Transport costs of selected commodities. Data taken from the Global Transport Costs Dataset on International Trade [67] based on Harmonised System codes reported in Tab. 2.

for iron ore and 5.0 EUR/t for semi-finished steel. While DRI (or rather hot-briquetted iron (HBI)) was not traded in as large quantities as iron ore or steel in 2016, the little data available indicates that it is at least not more expensive to transport than semi-finished steel. It is possible that HBI may end up being even as cheap to transport as iron ore, since it is a dry bulk freight that can be filled on ships (like iron ore), and is hence easier to handle and incurs lower harbour costs compared to loading cargo such as steel slabs or rolled coil. While DRI reoxidates when exposed to ambient air during transport, this effect is small after the surfaces has been passivated through briquetting. NH_3, which can be liquefied easily and transported with LPG tankers, incurred specific transport costs of around 5 EUR/t in 2016, whereas urea (a dry chemical) incurs much higher costs of approximately 20 EUR/t. MeOH, which is liquid at ambient temperature and atmospheric pressure and can be transported in tankers, incurs costs of 10 EUR/t. Finally, ethylene is gaseous at ambient temperatures with a boiling point of $-103.7\,^{\circ}\mathrm{C}$ and needs to be liquefied for transport. Based on the little available data (and transport costs for LNG, which also requires liquefaction at very low temperatures), we conclude costs of 30 EUR/t.

The GTCDIT is prone to errors and only accounts for transportation between country borders, while omitting further transportation and distribution costs within countries. Moreover, maritime transport costs have seen drastic increases in recent years. Nonetheless, it is useful for understanding relative cost difference, especially between intermediate and (semi-)finished products.

Flexible operation, circularity, and demand reduction

We discuss three 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, 2) circularity, and 3) demand reduction and material substitution.

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 as well as from the transport and buildings sectors 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 electrolysers. 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_2 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) [30, 31] and assessing the potentials of individual technologies [32, 80] 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_2 and hence electricity demand for steel. Similarly, the use of captured CO_2 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_2 is associated with a number of limitations, some of which might result in high prices for these feedstocks.

Capturing CO_2 from a PS requires investment into appropriate infrastructure that can separate CO_2 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_2 is not for free. Moreover, a carbon price may need to be paid for CO_2 released from a PS, depending on whether the CO_2 is of fossil or atmospheric origin and how soon the CO_2 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_2 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_2 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 [81] and to what extent the quality of secondary steel may come closer to that of primary steel [82].

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 [83]. 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_2 (the focus of our study), demand reduction, and fertiliser substitution [84].

List of announcements from the private sector

To demonstrate the impact of energy prices and the renewables pull on industrial relocation today, we present a non-exhaustive list of announcements from the private sector on fossil and green relocation in Germany based on work by [85] and [5] (Tab. S5). This list includes information on two aspects: 1.) Industrial relocation is already underway due to current high fossil energy prices (due to the Russian invasion of the Ukraine and the resulting European gas crisis), and 2.) green relocation is also already occurring due to the renewables pull.

Table S5 List of announcements from the private sector. This includes both fossil relocation (due to the European gas crisis) and green relocation (due to the renewables pull). Text quoted verbatim from secondary sources is printed in italics.

Announcement	**Date**	**Primary source**	**Secondary source**
Yara reduces ammonia production in Europe by 40 % due to high gas prices and imports ammonia instead, keeping the downstream fertiliser production running as usual.	Sep 2021	[86]	[85]
BASF reduces ammonia production in DE and BE due to high gas prices.	Sep 2021	[87]	[85]
SKW Priesteritz reduces ammonia production in DE by 20 % due to high gas price.	Oct 2021	[88]	[85]
Yara re-increases ammonia production in Europe.	Dec 2021	[89]	[85]
Yara reduces ammonia production in Europe.	Mar 2022	[90]	[85]
BASF cuts 2,600 jobs globally — two thirds of them in Germany — and shuts down one of its two NH_3 plants in Ludwigshafen.	Feb 2023	[91]	–
BASF and Yara are considering to build a new blue NH_3 plant in the USA.	June 2023	[92]	–
Air Products, ACWA Power and NEOM signed an agreement for a large-scale green ammonia production facility for export to global markets. The project partners aim to harness the “unique profile” of Saudi Arabia’s sun and wind resources.	June 2020	[93]	[5]
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 them “superior competitive advantage”.	2020	[94]	[5]
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”.	Aug 2021	[95]	[5]
ArcelorMittal plans to produce HBI for European markets in a DR plant in Texas, USA, where its coast presents “advantageous weather conditions to produce renewable energy powered green hydrogen”.	Apr 2022	[96]	–

Other display items

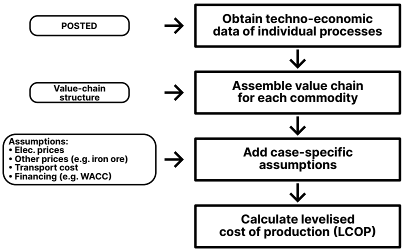

Fig. S4 An overview of processing steps taken to obtain the levelised cost of production, from which we derive our quantitative estimations of the renewables pull. We obtain techno-economic data for individual technologies from POSTED [33], from which we build the full value chain of processes for each commodity. We then add case-specific assumptions (electricity prices, other feedstock prices, transport costs, and financing assumptions), such that we can computed the levelised cost of production (LCOP).

Table S6 Terminology used within this article.

Category	Term	Explanation
Cost changes associated with production relocation from the RE-scarce to the RE-rich region	**Energy-cost savings**	Production-cost savings due to reduced electricity prices leading to lower energy cost.
	Transport penalty	Production-cost surplus due to increased transport cost of traded goods.
	Financing penalty	Production-cost surplus due to increased financing cost (higher WACC). Note that our analysis treats electricity prices as an external parameter that is independent of assumptions on the financing cost of renewables. These two parameters are of course correlated, which has to be accounted for when interpreting our results.
	Relocation savings	The total production-cost savings that result from the above three components.
Effects related to production relocation due to reduced energy cost	**Renewables pull**	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.
	Green relocation (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 in order to enable an open and unbiased debate.
RE availability and its difference between the RE-rich and RE-scarce regions	**Electricity-price difference**	The difference in effective electricity prices between the RE-scarce and the RE-rich region. The electricity-price savings depend linearly on the electricity-price difference.
Regions considered in this work for generic relocation analysis	**RE-scarce region**	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.
	RE-rich region	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.

Table S7 Main technology assumptions derived from literature review based on POSTED [33]. For more details, check the Data Availability statement. The caloric heat content of H_2 assumes the lower heating value (LHV). Annotations: (1)CAPEX given in specific units of output per annual production capacity. (2)Only covering the primary feedstocks of the respective production steps, i.e. HBI, NH_3, and MeOH. (3)For all relocation cases, except for Case 2, where an additional 0.159 MWh/t are needed to reheat the imported HBI. (4)Of which 0.43 MW h are provided as natural gas to provide the carbon content for steel. (5)Mixed output of Ethylene, Propylene, and other by-products.

Process	Electrolysis	DR	EAF	DAC	Heat pump
Ref. unit	MW h	t	t	t	MW h
CAPEX(1) (EUR)	41	321	235	174	67
Elec. demand (MW h)	1.4	0.1	0.57(3)	1.1	0.3
Heat demand (MW h)	–	0.96(4)	0.16	2.3	–
H_2 demand (MW h)	–	1.9	–	–	–
Feedstock(2) **demand** (t)	–	1.4 (ore)	1.0 (DRI)	–	–

Process	Haber-Bosch	Urea synth.	MeOH synth.	MtO
Ref. unit	t	t	t	t(5)
CAPEX(1) (EUR)	446	213	355	395
Elec. demand (MW h)	0.8	0.13	2.1	1.4
Heat demand (MW h)	–	0.91	–	–
H_2 demand (MW h)	5.9	–	6.4	–
Feedstock(2) **demand** (t)	–	0.58 (NH_3), 0.74 (CO_2)	1.4 (CO_2)	2.3 (MeOH)

Table S8 Assumed specific transport costs.

Commodity	**Import subcases**	**GTCDIT values for 2016**	**Assumed values for 2040**
H_2	Case 1A		50 EUR/MWh
H_2	Case 1B		15 EUR/MWh
Iron ore	Base Case, Case 1	2.5 EUR/t	10 EUR/t
DRI	Case 2	5 EUR/t	20 EUR/t
HRC	Case 3	5 EUR/t	20 EUR/t
NH_3	Case 2	5 EUR/t	30 EUR/t
Urea	Case 3	20 EUR/t	50 EUR/t
MeOH	Case 2	10 EUR/t	30 EUR/t
Ethylene	Case 3	30 EUR/t	80 EUR/t

Table S9 Potential exporting countries in the German case-study.

Country	Analysis
Norway	Green and blue H_2 project announcements, with planned pipeline transport to Germany. [97]
Morocco	Green H_2 project announcements, with planned pipeline transport via Spain and France. [98]
Chile	Green NH_3 projects planned, with envisaged exports to Europe. [99]
Australia	First LH_2 exports established to Japan; several green H_2 project announcements; governmental project subsidies of 50 MAUD and 50 MEUR for green H_2 exported as NH_3 and MeOH announced. [100]
Sweden	Existing steel industry; iron-ore availability; first green steel already produced. [101]
Brazil	Second largest exporter of iron ore in the world; several green H_2 projects announced. [102]
Canada	Large urea producer and exporter today; green NH_3 project announcements with German off-takers. [103]
Saudi-Arabia	Third largest NH_3 exporter in the world and large urea producer; green NH_3 project announcements, with plans to import and crack NH_3 in Hamburg. [104]
Iceland	Low-carbon MeOH project announcements; high share of RE today and very low predicted future RE prices. [105]
USA	Large producer and exporter of grey MeOH and Ethylene today; green MeOH project announcements; bio-based green ethylene project announcements [106, 107].