S4 SUPPLEMENTARY MATERIAL

CHAPTER 7

A sub-national perspective: comparing impacts of green hydrogen exports with localizing green steel production for the Brazilian state of Ceará

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Contents

SM4.1. Introduction

The goal of this study is to compare the climate impacts, costs, and local socioeconomic benefits of two possible scenarios: 1) producing green steel in Ceará (Brazil) from green hydrogen produced in Ceará, followed by export to IJmuiden (the Netherlands) and of 2) producing green steel in IJmuiden (the Netherlands) from green hydrogen produced in Ceará. In short, we will call these cases the 'green hydrogen export' case and the 'green steel export' case, respectively (Table S1).

While emissions throughout the process account for climate change impacts, only the socio-economic impacts within the state of Ceará are calculated. Hence, from an environmental life-cycle assessment (LCA) perspective, the system boundaries are cradle-to-gate, covering the climate change impacts of green hydrogen production including for renewable electricity production and battery production, as well as iron ore mining, transport of the iron ore, and green steel production using direct reduction of iron ore (DRI) which uses hydrogen as the reductant, followed by further processing in the electric arc furnace (EAF) to produce steel with specific qualities- including energy and material consumption during these processes. The construction of the electrolyzer and steel production facility is included, as well as transport: either for transporting green steel by ship from Ceará to the Netherlands, or for shipping liquified green hydrogen and iron ore from Brazil to the Netherlands (Table S1). The use phase of the steel is not included in this LCA. The cost for the steel user is based on the levelized cost of steel production (LCOS) and on transport costs (Sections SM4.2.2, SM4.4).

From a socioeconomic perspective, however, only the construction and operational expenditures taking place within Ceará are taken into account. For example, when steel production happens in the Netherlands, the construction and operation of the steel plant are not included in the applied shock, and hence are not directly contributing to economic growth and employment in Ceará (even though there are indirect effects from green hydrogen exports, which are always taken into account).

Table S1- Characteristics of the green hydrogen export case and the green steel export case

1. Green hydrogen export	2. Green steel export
• Green hydrogen is produced in Ceará, liquified, and shipped to IJmuiden. • Iron ore is mined in the Carajás mine in Brazil, transported by rail to the nearest port and shipped to IJmuiden. • Through DRI-EAF and casting, steel is produced in IJmuiden.	• Green hydrogen is produced in Ceará. • Iron ore is mined in the Carajás mine in Brazil and transported by rail to Port of Pecém. • Through DRI-EAF and casting, steel is produced in the Port of Pecém, and shipped to IJmuiden.

In order to capture only the effects on the local economy, the shares of each investment component that is spent in Ceará is calculated via local content scenarios. Assumptions for local content scenarios are based on a literature review, a field visit to the Port of Pecém in May 2022, and expert consultations. A detailed analysis of the qualitative data is available in an earlier publication[1] . Key experts were consulted again in September 2024 to revalidate assumptions and confirm their ongoing relevance. Ceará is home to two wind turbine assembly factories: one from Vestas and one from Aeris. The Brazilian electrolyzer manufacturer Hytron has a memorandum of understanding (MoU) with the government of Ceará to construct an electrolyzer assembly plant in the state. However, no companies currently manufacture solar panels, batteries, steel furnaces, or hydrogen liquefaction equipment, nor have any with plans to do so in the coming years been identified. Hence, it is assumed that only wind turbines and electrolyzers could be supplied by local factories in the high local content scenario. More information about the local content scenarios is available in Section SM4.2.3.

While the two export scenarios reflect the differences in the connection between the green hydrogen production and its use further in the value chain (i.e., forward linkages), these new economic activities could present different levels of connections with local suppliers backwards in the value chain, depending on whether they source their inputs locally or import them (i.e., backward linkages). To capture the difference in indirect effects resulting from these linkages backwards in the value chain, we use two local content scenarios: plant equipment is assumed to be either locally supplied (high local content scenario) or imported (low local content scenario) (Figure S1).

		Backward linkages	
		Low	**High**
Forward linkages	**High**	All equipment imported, Green steel exports	Local equipment where possible, Green steel exports
	Low	All equipment imported, Green hydrogen exports	Local equipment where possible, Green hydrogen exports

Figure S1 - Linkages with the local economy in different import and export scenarios

Section S2 explains the assumptions related to the system configuration and technology costs. Section S3 explains the life-cycle assessment methodology conducted to evaluate the climate change impacts. Section S4 explains the input-output modelling methodology used to estimate impacts on output, value added, employment (disaggregated by gender) and household income from salaries.

SM4.2. Assumptions

This section describes the main assumptions concerning system design, production processes, technologies, and export scenarios that are common to both the life-cycle assessment and the input-output modelling.

Figure S2 summarizes the main assumptions regarding the physical quantities from the production required for the new production plants (electricity, electrolysis, liquefaction, green steel). These are explained in detail in Section S2.1. Assumptions on capital and operational costs of these technologies are described in Section SM4.2.2. Assumptions on local content are described in Section SM4.2.3.

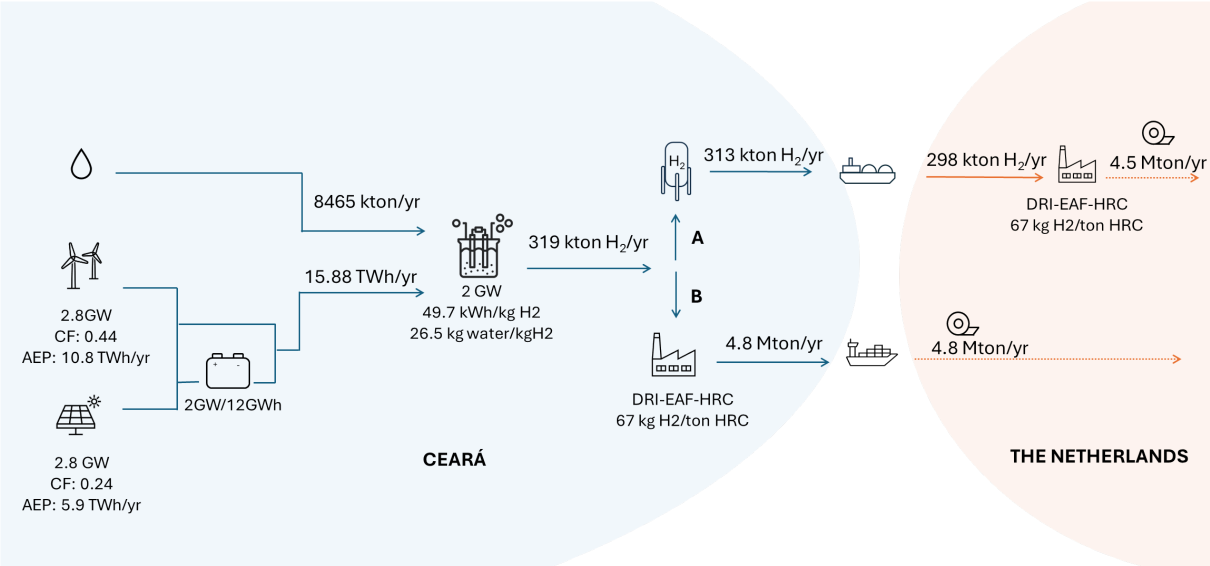

Figure S2 - Overview of the main physical input-output quantities and assumptions linking the different value chain steps

SM4.2.1. Core assumptions on system design and physical input and output quantities

SM4.2.1.1. Green hydrogen production

The study assumes an electrolysis capacity of 2 GW in the Brazilian State of Ceará, in the Port of Pecém. This is based on plans announced in over 20 MoUs signed between investors and the government of Ceará. Individual MoUs announce plans for the short term (i.e., 2025-2030) and for the long term (i.e., 2030 onwards). Announcements for short-term comprise individual plants on the range of 20-500 MW, with a median size of 100 MW. All short-term announcements together add to approximately 2 giga-watts of installed electrolysis capacity. Announcements for the long term (i.e., after 2030) are mostly for plants in the giga-watt scale and add up to over 9GW of planned installed capacity[1]. We do not take long term announcements into account given uncertainties regarding both the technology progress and the structure of the economy by then.

Green hydrogen production is assumed to use alkaline electrolysis cells (AEC), as detailed in Table S2. In the electrolyzer, water is split into hydrogen and oxygen using renewable electricity, with the co-produced oxygen being vented (Figure S3). The water requirement includes both feed water and cooling water, which we assume to be deionized tap water. Additionally, a potassium oxide (KOH) electrolyte is used. The electrolyzer has a lifetime of 20 years[2] We assume two days of maintenance outage and a two percent forced outage rate[3], resulting in a maximum possible operating time of 8538h/year, contingent on the availability of renewable electricity.

Table S2 - Overview of parameters for green hydrogen production using alkaline electrolysis cells

Process	Operating data per kg H_2	References
Electricity input (kWh)	49.7	[4]
Potassium oxide electrolyte (g)	3.7	[5]
Feed water (kg)	8.9	[6]
Cooling water (5 circulation cycles) (kg)	17.6	[6,7]

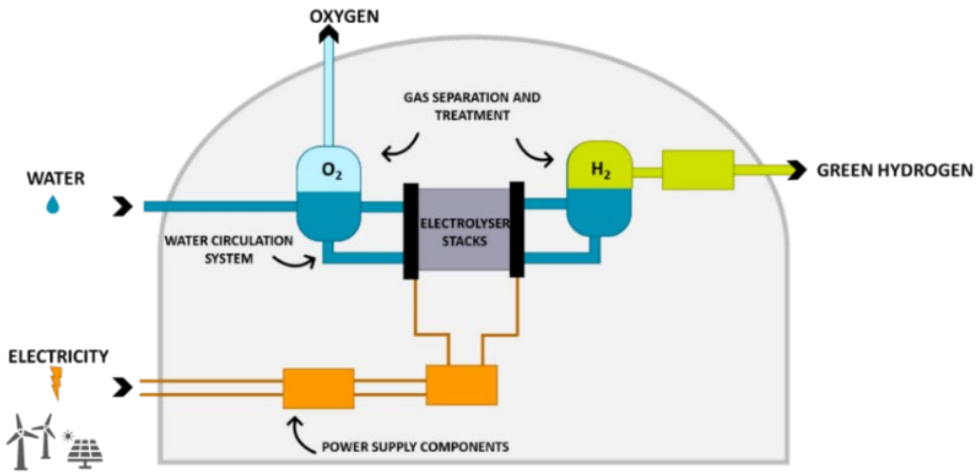

Figure S3 -Representation of an electrolysis plant components. Based on IRENA (2020)

The electrolyzers are assumed to operate independently of the grid, relying exclusively on electricity from solar and wind sources, complemented by a battery system. This is based on the findings from Caiafa et al.[1], which reflect the expectations of stakeholders for the future design of the green hydrogen hub in Ceará. For green hydrogen exports to qualify for green certificates required for imports in the European Union, the renewable electricity generation must be "additional" to what is already connected to the grid[8]. Given the complexities of demonstrating temporal correlation between electrolysis and renewable electricity from the grid, project developers focusing on exports to the EU are opting for isolated systems with dedicated generation from new solar and wind-based power sources[1] These developers prioritize solar and wind systems, complemented by batteries, over other renewable sources such as hydropower. This preference is due to the fact that the North-East of Brazil has a high abundance of solar and wind resources, and, being located on the equator, the relatively limited day-to-day variation in solar irradiance and wind speed, making these two sources largely complementary to each other on a daily basis[1].

The local capacity factor for solar photovoltaics (PV) is 24% ($CFsolar$) and 44% for onshore wind ($CFonshore\ wind$) (Table S3). The capacity factors represent the ratio of the actual energy output to the maximum possible energy output that a wind turbine or solar panel could generate. Wind capacity factors based on Ceará Solar and Wind Atlas[9]. Solar capacity factors are calculated using data from the Danish Energy Agency for technology factors and Ceará's GHI as provided in the Ceará Solar and Wind Atlas[3,9]. Assuming solar and wind are fully complementary and consistent, the maximum combined capacity factor ($CFsolar + CFonshorewind$) would be 68%, or 16.3 hours per day.

To maximize the operational hours of the electrolyzers, the solar and wind electricity facilities can be oversized and complemented with a battery that allows the electrolyzer to operate with a time lag from when the renewable electricity is produced. We assume the use of a mainstream lithium nickel manganese cobalt oxide battery, which stores enough electricity to run the electrolyzer for 6 hours. Beyond this capacity, a battery is no longer a cost-effective storage solution[10]. The resulting nameplate capacity of the battery is 12 GWh given the 2GW of electrolysis capacity. By effectively adding 6 hours of operation per day, the operational capacity factor of the electrolyzer ($CFelectrolyser$) can reach up to 93%, or 22.3 hours per day. Considering 8538 as the maximum yearly operating hours (excluding planned and forced outages for maintenance), this would result in 7940 hours of yearly operating time.

The same assumptions regarding solar and wind capacity factors and battery capacity are applied to all export and local content scenarios.

Table S3 - Renewable energy capacity factors in Ceará.

Renewable Energy Technology	Conditions	TechPotential	Capacity factor
Solar PV	Global horizontal irradiance (GHI) of 2075 kWh/m^2/year	642 GW	24%

Onshore wind	Wind speed >7m/s at 150m height	94 GW	44%

Based on the assumptions detailed above, it is possible to calculate the annual hydrogen production rate (M_{H_2}, in kt H_2/year; Equation 1), and the total hydrogen production over the lifetime of the electrolyzer (Q_{H_2}, in kt H_2; Equation 2).

$$M_{H_2} = \frac{cap_{electrolyser} \cdot CF_{electrolyser} \cdot hours/year}{P_{electrolyser}} \quad \text{Equation 1}$$

For an electrolyzer capacity ($cap_{electrolyser}$) of 2 GW, an operational capacity factor of the electrolyzer ($CFelectrolyser$) of 93%, 7940 hours of yearly operating time, and an electrolyzer electricity requirement ($P_{electrolyser}$) of 49.7 kWh per kg H_2, M_{H_2} is calculated to be 319 kt H_2/year.

$$Q_{H_2} = M_{H_2} \cdot lifetime_{electrolyser} \quad \text{Equation 2}$$

Based on a lifetime of the electrolyzer ($lifetime_{electrolyser}$) of 20 years [2], Q_{H_2} is calculated to be 6391 kton H_2.

SM4.2.1.2. Electricity production

The required installed capacity of the renewable energy technology ($cap_{facility,ren}$ in GW), where ren is solar PV and onshore wind, is determined by Equation 3, accounting for electricity losses from using a battery.

$$cap_{facility,ren} = cap_{electrolyser} \cdot \frac{CF_{onshore\,wind} + CF_{solar} + f_{battery}}{CF_{onshore\,wind} + CF_{solar}} \cdot (1 + f_{battery} \cdot (\frac{1}{e_{battery}} - 1)) \quad \text{Equation 3}$$

Where $cap_{electrolyser}$ is the electrolyzer capacity (GW), $CFsolar$ and $CFonshore\,wind$ the capacity factors of solar and wind solar power, $e_{battery}$ the roundtrip efficiency of the battery, and $f_{battery}$ the share of electricity passing through the battery before being used in the electrolyzer. We use a roundtrip efficiency of 90% for a lithium nickel manganese cobalt oxide battery[5,11] and assume that up to 25% of electricity passes through the battery, consistent with a battery capacity of 6 hours.

Based on Equation 3, we find that to generate enough electricity to power the battery and compensate for battery losses, the renewable energy capacity needs to be increased by 41% compared to the electrolyzer capacity. Therefore, for an electrolyzer capacity of 2 GW, a solar PV facility of 2.8 GW and an onshore wind facility of 2.8 GW are required.

SM4.2.1.3. Hydrogen liquefaction and shipping

In the green hydrogen export case, hydrogen is transported in its liquified form, requiring cooling to -253 °C. The life-cycle inventory for hydrogen liquefaction and shipping is based on our previous study on green hydrogen production and transport[12]. Since a continuous source of electricity is needed for hydrogen liquefaction, grid electricity is used for this.

For shipping, a 160,000 m^3 liquid hydrogen tanker is assumed[13]. With a volumetric density of liquid hydrogen of 71.1 kg per m^3, each tanker can carry 11.376 kton of hydrogen, equivalent to approximately 13 days of production. The distance between the Port of Pecém and IJmuiden is 7500 km, and at a shipping speed of 16 knots[14], the journey would take 10.5 days.

Storing a liquid energy carrier under cryogenic conditions results in boil-off gas, which can be recirculated and reliquefied during storage on land but leads to mass loss during shipping and loading/unloading. The mass loss of 0.3% per day from boil-off gas during shipping[15] is assumed to contribute to global warming, based on a 100-year global warming potential of 11.6 kgCO_2-eq/kg H_2[16].

The tanker is expected to be fueled by heavy fuel oil in the near future (2025), pending technological developments that would allow boil-off gas to be used as shipping fuel[14]. Electricity for liquefaction, re-liquefaction of hydrogen during land storage, and loading liquid hydrogen into the tanker is assumed to be supplied by the North-East Brazilian grid mix. Electricity use for unloading liquid hydrogen is assumed to be supplied by the Dutch grid mix.

SM4.2.1.4. Iron ore mining and transport

We assume iron ore is mined in the Carajás mine, the largest iron ore mine in the world, located in northern Brazil. This assumption applies to both the green hydrogen export case and green steel export case, given the high quality of the iron ore and the fact that the Netherlands already imports iron ore from Brazil[17].

The location of iron ore pelletizing depends on both the export scenario and the local content scenario. In the green hydrogen export scenario, all iron ore pelletizing is assumed to occur near the Carajás mine, with the pellets transported to IJmuiden by rail and ship, regardless of the local content configuration. In the green steel export scenario, iron ore is either fully processed near the Carajás mine and transported by rail to Pecém (low local content) or approximately half of the iron ore is transported to be processed locally in Ceará, with the remaining pellets sourced from Carajás (high local content).

In both scenarios, transport within Brazil is done by rail, using a conventional diesel train[18]. For the green hydrogen export case, the transport distance by rail is approximately 1000 km to the port of Ponta de Madeira[18], from where it is shipped to IJmuiden by a dry bulk carrier, covering an additional distance of 7600 km. In the green steel export case, steel production takes place in the Port of Pecém, to which transport is fully undertaken by rail, covering a distance of approximately 2000 km.

In the sensitivity analysis we evaluate a scenario where instead of a diesel train, an electric train powered by the North-East Brazil grid mix is used.

SM4.2.1.5. Steel production and transport

Direct reduction of iron ore (DRI) is carried out using hydrogen as the reductant. In the DRI shaft furnace, sponge iron is produced and subsequently processed in the electric arc furnace (EAF) to achieve specific steel qualities[19] (Figure S4). In the base case, hydrogen is used for iron ore reduction in the shaft furnace, while natural gas is used for hydrogen pre-heating, EAF heating and ladle heating (H_2-NG-DRI;Table S4). In the sensitivity analysis, we evaluate a scenario where hydrogen is used for both iron ore reduction and heating, replacing natural gas from the initial configuration (H_2-DRI; Table S4).

The electricity requirements for the EAF are supplied by the North-East Brazilian grid mix in the green steel export case, and by the Dutch grid mix in the green hydrogen export case.

Assuming all produced hydrogen is used, 4,768,912 t/year of steel can be produced in Ceará, considering a hydrogen requirement of 67kg of hydrogen per ton of Hot Rolled Coil (HRC) and an annual production of 319 kton H_2/year. A smaller amount of steel can be produced for the same annual green hydrogen production when green hydrogen is liquefied and transported by ship (4.5Mt/year, see Figure S4 and Section SM4.3.4) due to conversion and transport losses.

Table S4 - Inventory for the production of 1 ton of steel through DRI-EAF, casting and hot rolling for the configuration using hydrogen only for reduction, and natural gas for heating (H2-NG-DRI), or using hydrogen for reduction and heating (H2-DRI). Based on Rosner et al (2023)

	H_2-NG-DRI	**H_2-DRI**
Process	**Input per ton of steel**	**Input per ton of steel**

Iron ore pellets (ton)	1.63	1.63
Hydrogen (kg)	67	76
Natural gas (GJ)	1.06	0
Electricity (kWh)	550	550
Carbon (kg)	34	34
Lime (kg)	51	51
Raw water withdrawal(ton)	1.2	1.2
Anode (kg)	3.5	3.5
Refractory lining (kg)	15.5	15.5
Process	**Output per ton of steel**	**Output per ton of steel**
Slag (ton)	0.17	0.17
Surface water discharge (ton)	0.44	0.44
Direct CO_2 emissions (ton)	0.16	0.10

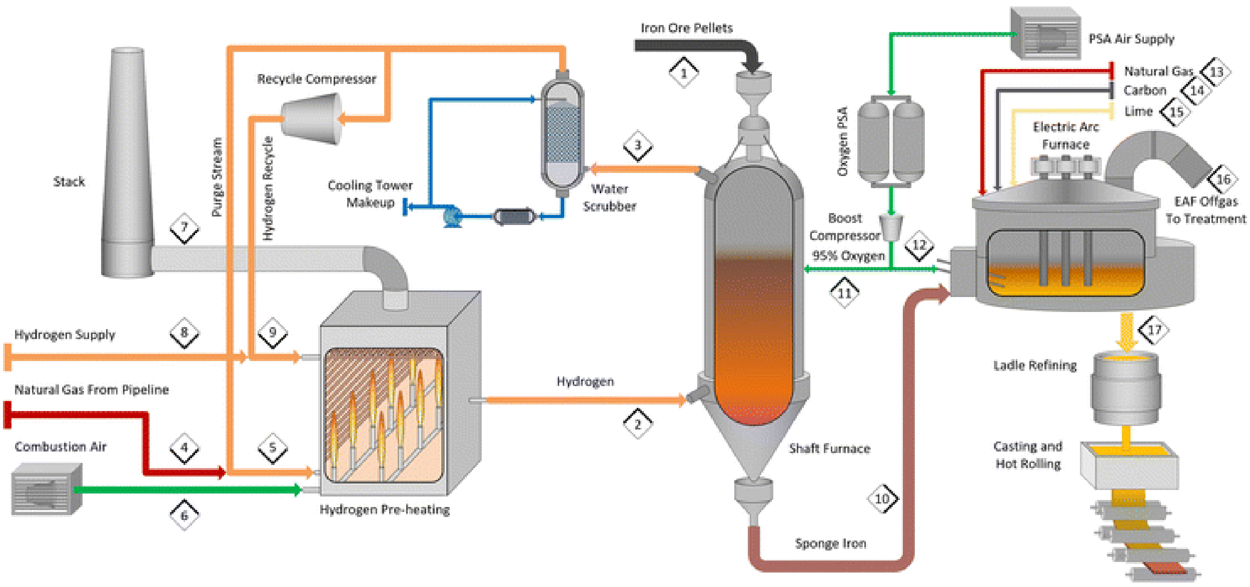

Figure S4 - Flowsheet of the integrated hydrogen-based DRI steel mill, using hydrogen for iron ore reduction in the shaft furnace, and using natural gas for hydrogen pre-heating, EAF heating and ladle heating (H2-NG-DRI) (Rosner et al., 2023a).

In the sensitivity analysis, we assess the scenario in which sponge iron is produced in Ceará and shipped to IJmuiden, for steel production in the EAF. Inputs from the base case (H2-NG-DRI) for DRI-EAF steelmaking are divided between DRI in Ceará and EAF in IJmuiden, based on the flowsheets in Rosner et al[19] (Table S5).

Table S5 - Inventory for the production of 1 ton of steel in the H2-NG-DRI configuration, based on Rosner et al (2023) for the sponge iron export scenario in the sensitivity analysis. The last two columns indicate the share of inputs used in the DRI phase producing sponge iron in Ceará, and in the EAF phase producing steel in IJmuiden.

	H_2-NG-DRI	**DRI in Ceará**	**EAF in IJmuiden**
Process	**Input per ton of steel**	**Input per ton of steel (% of H_2-NG-DRI total)**	**Input per ton of steel (% of H_2-NG-DRI total)**
Iron ore pellets (ton)	1.63	100	0
Hydrogen (kg)	67	100	0
Natural gas (GJ)	1.06	88	12
Electricity (kWh)	550	17	83
Carbon (kg)	34	0	100
Lime (kg)	51	0	100
Raw water withdrawal(ton)	1.2	100	0
Anode (kg)	3.5	0	100
Refractory lining (kg)	15.5	0	100
Process	**Output per ton of steel**	**Output per ton of steel (% of H_2-NG-DRI total)**	**Output per ton of steel (%of H_2-NG-DRI total)**
Slag (ton)	0.17	0	100
Surface water discharge (ton)	0.44	100	0
Direct CO_2 emissions (ton)	0.16	22	78

SM4.2.2. Cost assumptions

Cost assumptions for electricity and green hydrogen in this study are based on the most recent studies found, which usually account for the period 2018-2021. The most recent sub-national supply and use tables (SUTs) available for Ceará were published by the Brazilian Institute of Geography and Statistics (IBGE) in 2022 and refer to the economic year of 2018[20] (see Section S4 for more details about the tables). The table is the first published by the institute for the sub-national level and has a high sectoral aggregation, making any effort to update the table virtually impossible. Since the cost data covers a similar period of the SUTs and this was a period of relatively low inflation, no price correction was carried out to arrive to 2018 prices. The only occasion where cost assumptions were deflated was for steel production costs, since the main reference used is from 2023[19] and the authors report inflating cost assumptions to match 2022 prices due to the high inflation period between 2021-2022.

Costs are not available by origin of equipment. This implies that this study is unable to differentiate between costs in a high and in a low content scenario for equipment sourcing.

SM4.2.2.1. Green hydrogen production

Cost assumptions for hydrogen production are as following. Total installation costs include direct, indirect, and owner costs. Direct costs cover the investment required for purchasing the electrolyzer system and constructing the facility[21,22]. These costs include the electrolyzer stack as well as the balance of plant components such as the drier, cooling system, de-oxygenation unit, water de-ionization equipment, and the power supply[21,23]. Some estimates for direct costs also include installation on-site, interconnecting piping and other materials, and services from contractors and suppliers[22]. Indirect costs involve expenses related to engineering, project management, construction supervision, and commissioning. Owner costs cover project management by the owner, land leases during construction, insurance, grid fees, and electricity consumption. In many studies, contingency costs are added to cover risks due to uncertainties[22,24]. Estimates for costs can be found in the Table S6 below.

Table S6 - Comparison of low and high estimates for electrolysis systems CAPEX costs

Study	Direct costs		Indirect costs		Owner costs	
	Definition	**Value**	**Definition**	**Value**	**Definition**	**Value**
International Renewable Energy (IRENA)[21]	Electrolyzer system	500-1000 USD/kW	n.a	n.a.	n.a.	n.a
United Kingdom BE&IS Department [23]	Electrolyzer system and civil works	720-960 USD/kW	n.a	n.a	n.a	n.a
Danish Energy Agency (DEA)[3]	Electrolyzer system plus 10% installation costs	440-880 USD/kW	n.a	n.a	n.a	n.a
Institute for Sustainable Process Technology (ISPT)[22]	Electrolyzer system plus 3% of civil works	600-1160 USD/kW	Expenses for engineering, project management, construction supervision and management, and commissioning costs (no cost break-down) (90-218 USD/kw) and	90-218 USD/kW	Owner project management, electricity consumption and land lease during construction, as well as insurances and grid fees (no cost break-down)	36-70 USD/kW

			Contingency (184 USD/kw)			
Lazard[25]	Electrolyzer system	310-920 USD/kW	n.a	n.a	n.a	n.a
National Renewable Energy Laboratory (NREL)[24]	Electrolyzer system (460 USD/kW) plus 9.3 USD/kW for construction (site preparation) (2%)	470 USD/kW	Up-front permitting costs (70USD/kW), Engineering and design (46USD/kW) Contingency (70USD/kW)	116-186 USD/kW	5 acres of land for 131MW electrolysis at USD 50,000.00 the acre	1.90 USD/kW

Note: Based on conversion of 1GBP = 1.2 USD and 1EUR = 1.10USD.

In this study, an average value of 736 USD/kW is derived from Table S6, with 714 USD/kW allocated to system costs and 22 USD/kW (or 3% of direct costs) attributed to construction. A value of 168 USD/kW is assumed for indirect and owner costs. While the ISPT[22] study estimates 23% for contingency costs (184 USD/kW), the NREL[24] study presents a lower estimate (70 USD/kW), likely because the NREL model is based on a 131MW plant, whereas the ISPT study looks at a much larger 1GW plant, which involves greater uncertainties due to the absence of operational giga-scale plants. Given that this study considers the first large-scale green hydrogen hub in Brazil, which carries significant first-of-a-kind project risks but focuses on projects in the 100-500MW range, an average contingency cost of 120 USD/kW is used. This leads to a total installation cost of 1023 USD/kW.

Different assumptions for electrolysis plant OPEX were found in the literature (see Table S7). We assume fixed operational expenditures to consist of insurance and direct labor. The NREL (2018) H2A model assumes 2% of initial capital expenditures (CAPEX) to go to taxes and insurances and Lazard[25] assumes 1% of insurance, so our assumption is 1% of initial CAPEX, or 10.24 USD/kW/year. Assumptions for direct labor in the electrolysis plant are based on expert consultations[1]. Experts indicated that a 20-100 MW electrolysis plant in Ceará would employ between 5-10 people working full-time (full-time equivalent (FTE)) in the operation phase. This would lead to an employment factor of 0.25-0.5 FTE/MW for a 20 MW plant and 0.05-0.1 FTE/MW for a 100MW plant. The H2A model from NREL[24] assumes 10 FTE for a 131 MW plant, hence 0.076 FTE/MW. Therefore, we assume a value of 0.07 FTE/MW of electrolysis capacity. The average salary is taken from salary data from the Brazilian Ministry of Employment[26] for workers in the energy sector in Ceará, and is 35,510 USD/year for 1 FTE, leading to direct labor costs of 2.485 USD/kW/year. Annuitized stack replacements are assumed to be 2% of initial CAPEX, that is, 20.48 USD/kW/year.

Table S7 - Operational expenditures for green hydrogen production found in the literature review

Study	OPEX definition
UK BE&IS[23]	Variable OPEX as annuitized stack replacement costs, as well as costs for water and electricity inputs. Fixed OPEX including direct labor, administration/general overheads, insurance/local taxes, but excluding cost of hydrogen compression equipment.
Lazard[25]	OPEX includes water costs, electricity costs, warranty and insurance (1% of initial CAPEX/year) and "other O&M"(1.5% of initial Capex/year).
Gallardo et al[27]	OPEX costs including electricity cost and O&M cost (2% of initial CAPEX/ year)
IRENA[28]	Includes OPEX as 2% of initial CAPEX/year. No definition of OPEX cost items provided.
Eichman et al[29]	Estimates fixed O&M at 42$/kW/yr. In addition, estimates storage costs 623–1000 $/kg of hydrogen. Also add an installation cost multiplier of 1.2.
NREL[24]	NREL hydrogen production model (H2A) for central electrolysis (version 3.2018) provides OPEX costs for a ~110 MW PEM electrolysis plant. They estimate OPEX fixed at 5.5% of initial CAPEX, that can be disaggregated by: 2% for taxes and insurances, 2% for material costs for maintenance and repairs,1.5% for labor cost and General& Administrative (G&A) costs, assuming 10FTE employees with an 50$ hourly wage and a 20% rate for G&A over labor costs. They also recognize

	cost components for which they do not have values, for instance for licensing, permits and fees. In addition to these fixed inputs they include energy and water costs in the OPEX.
DEA[3]	Includes only Fixed O&M costs as 2% of CAPEX.

Variable costs are calculated assuming the yearly production of hydrogen (see Section SM4.2.1). For an annual production of 319.5kton of hydrogen, 8467 kton/year of water would be required. We assume water cost of 0.002 USD/kg of water based on Lazard[25]. This leads to water costs of 8.47 USD/year per kilo-watt of electrolysis capacity. Electricity costs are based on the electricity consumption of 15.88 TWh/year and the levelized cost of electricity according to the electricity production cost assumptions, calculated to be 64.17 USD/MWh, as will be described in Section SM4.2.2.2).

The sales of price of green hydrogen is assumed to be the levelized cost of hydrogen (LCOH), since this is the minimum sales price required for a zero profit condition. In the green hydrogen exports case, the LCOH includes liquefaction and storage costs in Pecém, while in the green steel exports case the LCOH includes the investment and operational costs of the electrolysis plant only. A weighted average cost of capital of 10% is assumed, as in the report from IRENA[30]. The LCOH obtained in this study is 4.17 USD/kgH_2, excluding any liquefaction, storage, or shipping costs. This somewhat higher LCOH when compared to IRENA's estimates can be explained by the need to oversize the renewable energy facilities and to add a battery considering the assumption of dedicated generation (see Section SM4.4.1). When liquefaction, storage, and ship loading costs are included (see Section SM4.2.2.3), the sales price of hydrogen becomes 6.65 USD/kgH_2.

SM4.2.2.2. Electricity production

Total installation costs of 849 USD/kW for solar photovoltaics and 1237 USD/kW for onshore wind are assumed in this study, which can be translated into 1189USD and 1732USD per kW of electrolysis installed capacity(kWH_2), respectively, given a scaling factor of 1.4. IRENA[31] has total installed costs for onshore wind and solar photovoltaics in Brazil for the year of 2021. Both the EIM-ES[32] and NREL JEDI[33] models were also consulted. Given that IRENA[31] offers more recent and country-specific data, this study primarily uses the IRENA figures when available, while incorporating EIM-ES estimates for land and contingency costs, missing in the IRENA[31] data. For onshore wind, only total installation costs are available in the IRENA report[31]. Costs by component are hence calculated by taking the cost disaggregation from previous studies[32–34] and the country-specific total installed costs for Brazil from IRENA[31]. IRENA reports total installed costs for onshore wind in Brazil to be 1150 USD/kW in 2021. To this, we add 49 USD/kW for contingency and 49 USD/kW for transport of the turbines, as reported by Fearnehough & Skribbe[32]. The disaggregation of CAPEX by cost item is available on Table S8.

Regarding the operational expenditures, we assume total operation and maintenance (O&M) costs for onshore wind of 55 USD/kW/year. This includes 18 USD/kW/year for maintenance and 12 USD/kW/year for operation, as well as 2.5 USD/kW/year for land lease, as reported by Fearnehough and Skribbe[32]. Regarding employment factors, the literature has reported values between 0.1-10.7 FTE/MW of installed capacity, with a median of 0.64 FTE/MW and an average of 2.13 FTE/MW[35–39]. We take the median value for this study, which leads to an annual direct labor expenditure of 23 USD/kW/year. These costs are in line with the IRENA[31] study that reports a total O&M cost of 49-53 USD/kW/year for onshore wind in Denmark and Germany and with the work from Vasconcellos & Caiado Couto[34] that assume a total of 45 USD/kW/year for onshore wind in Brazil, but do not include labor costs.

For Solar PV, we assume 60 USD/kW/year for total O&M expenditures. The EIM-ES reports 9.5 USD/kW/year for operation and 11.5 USD/kW/year for maintenance, comprising materials only[32]. IRENA[31] does not provide O&M data for Solar PV. Regarding employment factors, the literature reports values between 0.12-4.8 FTE/MW, with a median of 1.1 FTE/MW and an average of 1.4 FTE/MW[35–38]. Assuming the median value of 1.1 FTE/MW and salaries for the energy sector in Ceará, salary expenditures for solar PV are assumed to be 39 USD/kW/year.

For the battery system, we assume 1410 USD/kW and 35 USD/kW/year for installation and operational costs, respectively, for a 1kW-6kWh battery[40].

Table S8 - Cost assumptions for electricity production

Technology	**CAPEX item**	**USD/kW**	**OPEX item**	**USD/kW/year**
Solar PV	Modules	369	Maintenance	11.5
	Inverters	36	Operation	9.5
	BoS hardware	129	Direct labor	39
	Installation	155		
	Design and engineering	9		
	Other (PR, permitting, customer)	51		
	Contingency and fees	97		
	Land	3		
	Total CAPEX	849	Total OPEX	60
Onshore Wind	Nacelle	444	Maintenance	18
	Blades	180	Operation	12
	Tower	155	Land lease	2.5
	Construction (Civil works + Installation)	189	Direct labor	23
	Electrical balance of plants	133		
	Project planning and management	38		
	Contingency and finance	49		
	Transport	49		
	Total CAPEX	1237	Total OPEX	55
Battery	Battery system (1kW/6kWh)	1410	Maintenance	35
	Total CAPEX	1410	Total OPEX	35

Hence, for an scaling factor of 1.4 and a battery system of 6h storage duration, annual O&M costs for the electricity supply of the electrolysis plant would be 196 USD/kWH$_2$/year: 77.5 USD/kWH$_2$/year coming from the onshore wind farm, 84 USD/kWH$_2$/year from the solar PV plant, and 35 USD/ kWH2 from the battery maintenance. Assuming an real weighted average cost of capital (WACC) of 6%[30], the calculated levelized cost of electricity (LCOE) for the entire system (including energy storage) is 64.17 USD/MWh.

SM4.2.2.3. Hydrogen liquefaction and shipping

Capital costs for liquefaction and storage are assumed to be USD 2000/kWH$_2$ and USD 87/kWH$_2$, respectively, based on a liquefaction unit of 50tH$_2$/day[41] and costs of USD 15/kgH2[41] for a storage capacity greater than 100 000m3. Capital costs for liquefaction plants[41].

Table S9 - Cost assumptions hydrogen liquefaction and storage

CAPEX item	USD/kWH2	OPEX item	USD/kgH2/year
Liquefaction plant	2000	Electricity	0.977
Storage	87	Direct labor	0.028
Total	2087		1.004

Operational costs are assumed to be a total of USD 1.004/year per kilogram of hydrogen (kgH2) produced, the equivalent of USD 160/year per kW of installed capacity of hydrogen (kWH2) given our hydrogen production assumptions. This comprises of USD 156/year of electricity costs and USD 4.43/year for direct labor costs. This reflects an electricity cost of USD 0.977/kgH2, based on the calculated total electricity requirement of 12.5213 kWh/kgH2, including re-liquefaction of BOG during storage, and electricity prices for industrial consumers in Brazil[42] of USD 78/MWh. Regarding direct employment, we assume a total of 30 full-time equivalent direct jobs for a 50t/d liquefaction capacity, based on a recently inaugurated Air Liquide liquefaction plant in Nevada, United States, with 30t/d capacity and 25 FTE expected[43] (i.e. we assume employment factors do not increase linearly with scale, as with most technologies in the green hydrogen value chain[1]). Considering 18 liquefaction units would be required, this leads to a total of 525 FTE directly employed. Assuming the average salary for the industrial gases sector in Ceará (USD 16882/FTE/year[26]), this leads to salary expenditures of USD 0.028 /kgH2/year. The levelized cost of liquefaction and storage (LCOLS) is then calculated assuming a similar WACC as for the green hydrogen electrolysis (i.e., 10%). We find a LCOLS of 2.49 USD, which is in the mid-range of the costs reported by IRENA[41] given the relatively small scale of the plant.

Regarding the loading of the liquid hydrogen into ships, we assume the existing LNG terminal in the Port of Pecém would be repurposed for hydrogen terminalling, since activities around the Ports for the international trade of hydrogen would resemble those of liquified natural gas (LNG)[41]. Hence, we base the cost assumptions for liquid hydrogen on the costs for LNG. Fluxys, the Belgian transmission system operator (TSO) that also operates in Brazil, reports a price of 1.17€/MWh of LNG loaded. If we assume similar prices for green hydrogen, this would lead to a 0.04588 USD/kgH2.

The building of new ships and the sea transport of hydrogen are not taken into account in the economic impact analysis since it is assumed that these activities would be carried out by firms outside of Ceará.

The sales price of exported liquid hydrogen at the Ceará's border (i.e., FOB) is calculated to be USD 6.7/kgH2, and includes liquefaction, storage, and terminalling (ship loading) at the Port of Pecém (Equation 4).

Equation 4

$$H2price_{FOB} = LCOH + LCOLS + H2cost_{terminalling}$$

This refers to USD 4.17/kgH2 from production, 2.49 USD/kgH2 from liquefaction and storage, and USD 0.05/kgH2 from ship loading.

SM4.2.2.4. Iron ore mining and transport

Iron mining is considered to take place outside of Ceará and is an existing sector, so no investment and operational expenditures are exogenously specified in this study for this economic activity. We simply assume that the new steel plant would be purchasing iron ore pellets from existing producers at current market prices and transport margins, as explained below in Section SM4.2.3, which will lead to economic impacts in the sector due to increased demand. The location of iron ore pelletizing depends on both the export scenario and the local content scenario. In the green hydrogen export scenario, all iron ore pelletizing is assumed to occur near the Carajás mine, with the pellets transported to IJmuiden by rail and ship, regardless of the local content configuration. In the green steel export scenario, iron ore is either fully processed near the Carajás mine and transported by rail to Pecém (low local content) or approximately half of the iron ore is transported to be processed locally in Ceará, with the remaining pellets sourced from Carajás (high local content) (Section SM4.2.3).

SM4.2.2.5. Steel production and transport

Capital and operational expenditures are based on the same study used to derive the life-cycle inventory to ensure consistency of the production technology[19], with some adjustments. Capital expenditures are deflated where needed to reflect US dollars in the year of 2018, since the authors report inflating prices to match 2022 US dollars. Prices for raw material inputs are adjusted based on additional sources reporting prices for 2018 as needed[44,45].

In the green steel exports scenario, the steel plant is located in the same industrial complex as the electrolysis plant, avoiding the need for the liquefaction and shipping steps. As they would be located spatially together, transport costs are considered to be minimal and are hence left out of the analysis (since transport within the Port complex in IJmuiden is also not taken into account). It is assumed that the local sales price of hydrogen within the industrial complex at the Port of Pecém would be equal to the levelized cost of hydrogen (LCOH).

Equation 5

$$H2price_{PEC\acute{E}M} = LCOH$$

Moreover, the green steel exports scenario, prices for electricity[42] and natural gas[46] are assumed to be the prices for industrial consumers in Brazil in the year of 2018. Labor costs are calculated taking the Rosner et al study[19] employment factors and adjusting salaries to reflect the average salaries in the Iron and Steel sector in Ceará in 2018, based on data from the Brazilian Ministry of Employment[26].

When steel is produced in Ceará, we consider an additional transport cost of steel of 5 USD/t[47] to bring the steel to the port in IJmuiden.

In the green steel exports scenario, the export price of steel is assumed to be the levelized cost of steel production (LCOS).

In the green hydrogen export scenario, the steel plant in IJmuiden would pay a price for green hydrogen that would be equivalent to the FOB green hydrogen price, plus the transport by ship to IJmuiden and regasification costs at destination. It is assumed that costs associated with the loss of hydrogen due to boil-off gas during transportation are already priced into shipping costs from techno-economic studies. Transport within the Port complex in IJmuiden is also not taken into account. Costs for shipping green hydrogen from Pecém to IJmuiden and for regasification of liquefied hydrogen in IJmuiden are based on the average estimates by IRENA[41], with shipping costs being adjusted to the distance between Pecém and IJmuiden (approximately 7500 km). The green hydrogen price in IJmuiden adds up to 9.18USD/kgH2, consisting of the 6.7 USD/kgH2 FOB price, plus 1.73 USD/kgH2 of shipping and 0.75 USD/kgH2 of regasification.

Additionally, the prices for electricity[48] and natural gas[49] are assumed to be the prices for industrial consumers in the Netherlands in the year of 2018. These prices are taken from EUROSTAT, using average exchange rate of 1 EUR = 1.1810 USD for 2019[50]. Labor costs are also calculated taking the Rosner et al study[19] employment factors and adjusting salaries to reflect the average salaries paid by Tata Steel IJmuiden[45], the single largest steel producer in the Netherlands.

Equation 6

$$H2price_{IJMUIDEN} = H2price_{FOB} + H2cost_{shipping} + H2cost_{regasification}$$

The year of 2018 is chosen to match the input-output tables for Ceará. For the cost analysis, a sensitivity analysis is carried out to also assess the difference in costs after 2022, given the energy crisis in Europe.

The CAPEX and OPEX are summarized in Table S10, and Table S11, respectively.

Finally, we assume the same WACC as liquefaction and storage (i.e., 10%). While Rosner et al.[19] use a much lower rate (5%), their rate is based exclusively on debt, while Damodaran[51] 47and the IEA[52] show capital costs for the steel industry as being much higher, around 6-9%. Additionally, Damodaran[51] estimates for capital costs for the chemical industry (to which hydrogen and liquefaction belong) are around 7.5%, which is relatively similar than the estimates for steel (6.85%). Assuming a 10% WACC for "green steel" allows incorporating a higher risk than for traditional steel given the low maturity of the technology and market while ensuring it has a similar rate as for the other "green" immature industries. A similar rate avoids that results on the share of value added going to operating surplus are different solely due to different WACCs. Given these assumptions, we find a levelized cost of steel

(LCOS) of 652 USD/t when green steel is produced in Ceará (see Section SM4.4.3). Since the levelized cost is higher than the operational expenditures, the difference is allocated to gross operating surplus (see Section SM4.5.2.3). A sensitivity analysis is performed to assess the impact of different assumptions on the cost of capital on the results (see Section SM4.6.2).

Table S10 - Capital expenditures for a H-DRI-EAF steel plant of 4.77Mt production capacity

CAPEX item	USD/t
Shaft furnace	100
Pre-Heater	3
Recycle compressor	6
EAF & Casting	205
Cooling tower	18
Buildings, storage, water service	66
Electrical & instrumentation	32
Other plant equipment	92
Preproduction costs	72
Inventory	38
Other owner costs	93
Total CAPEX	725

*Table S11 - Operational expenditures for a 4.77Mt H-DRI-EAF steel plant in Ceará, Brazil. *Inputs where prices differ between export scenarios*

Export scenario	Input	Input per ton of HRC	Unit price	USD per ton of steel
Green steel exports	Iron ore pellets (ton)	1.6	117.8	192
	Hydrogen (kg)*	67	4.17	279
	Natural gas (GJ)*	1.06	15.2	16
	Electricity (kWh)*	550	0.078	43
	Carbon (kg)	35.8	0.179	6
	Lime (kg)	51	0.100	5
	Raw water withdrawal(ton)	1.20	2.0	2
	Labor (FTE)*	0.0013	12142.4	15
	Steel transport	1	5	5
	Total OPEX/year			565
Green hydrogen exports	Iron ore pellets (ton)	1.6	117.8	192
	Hydrogen (kg)*	67	9.18	615
	Natural gas (GJ)*	1.06	7.43	8
	Electricity (kWh)*	550	0.073	40
	Carbon (kg)	35.8	0.179	6
	Lime (kg)	51	0.100	5
	Raw water withdrawal(ton)	1.20	2.0	2
	Labor (FTE)*	0.0013	94019	120

Total OPEX/year	989

SM4.2.3. Local content assumptions

Table S12 summarizes the assumptions on local content for the main inputs into green hydrogen production, renewable electricity generation, hydrogen liquefaction and storage, and green steel production. Assumptions for local content scenarios are based on a literature review, a field visit to the Port of Pecém in May 2022, and expert consultations. A detailed analysis of the qualitative data is available in an earlier publication[1] . Key experts were consulted again in September 2024 to revalidate assumptions and confirm their ongoing relevance.

Plant equipment is assumed to be either locally supplied whenever local capabilities exist (‘high local content scenario’) or imported (‘low local content scenario’). Ceará is home to two wind turbine assembly factories: one from Vestas and one from Aeris. The Brazilian electrolyzer manufacturer Hytron has a memorandum of understanding (MoU) with the government of Ceará to construct an electrolyzer assembly plant in the state. However, no companies that manufacture solar panels, batteries, steel furnaces, or hydrogen liquefaction equipment, nor have any with plans to do so in the coming years could be identified. Hence, it is assumed that only wind turbines and electrolyzers could be supplied by local factories in the high local content scenario, while other equipment is always imported.

Iron ore is assumed to be mined in the Carajás mine, the largest in the world, located in the Brazilian state of Pará. The location for processing iron ore into iron pellets depends on both exports and local content scenarios. In the green steel exports scenario, it is either assumed that that iron ore is processed into iron ore pellets close to the Carajás mine and then transported to Pecém via rail (LowLC) or that approximately half of the iron ore pellets come from a local pelletizing plant (HighLC), with the remaining iron ore pellets coming from the pelletizing plant close to the Carajás mine. In the green hydrogen exports scenario, iron ore is assumed to be processed into iron ore pellets close to the Carajás mine and then transported to IJmuiden (via rail followed by shipping), independently of local content scenarios. Natural gas and coal are assumed to be always imported, as Ceará does not produce any natural gas[53] or coal[54].

In addition, electricity is always assumed to be sourced locally, be it from the dedicated renewable electricity generation facility (for the case of green hydrogen) or from the electricity grid (for the case of liquefaction and storage and green steel).

Moreover, financial services and project management and engineering services can be local or imported. Labor is always assumed to be sourced locally at the production location. When maintenance services are outsourced, it is assumed that it takes the average import share of the economy. Real state and in-land transport services are assumed to be sourced according to average import shares in the economy.

These assumptions are operationalized as follows. In the LCA, the Ecoinvent datasets used to quantify emissions for manufacturing wind turbines and electrolyzers have a global scope, limiting differentiation between local content scenarios. For modelling wind turbine manufacturing, electricity is assumed to be sourced locally in the high local content scenario (North-East Brazil grid mix), while in the low local content scenario the global grid mix is used. Emissions from electrolyzer manufacturing, primarily from the production of steel and other metals[55], were modelled using the same global market activities in both local content scenarios, with no difference in emissions as a result. For iron ore pelletizing, the Ecoinvent dataset for Quebec was adapted to make it applicable to the North-East of Brazil. Since both the Carajás mine and Ceará fall within this region, it was not possible to distinguish between pelletizing close to the Carajás mine (low local content) or in Ceará (high local content), with no difference in emissions as a result.

In the cost analysis, data on equipment costs is not available according to the origin. Hence, a quantitative analysis of the cost difference between different local content scenarios was not possible. While there is some qualitative evidence indicating that Brazilian equipment could be more expensive[1], this could not be translated into quantitative cost differences. Commodity inputs such as iron pellets and coke are assumed to have a single global price as they are internationally traded. While services are not internationally traded, local price data was not available, so prices from international studies are taken instead. Prices for natural gas, electricity, and labor, are adjusted to reflect prices at the production location (see Sections SM4.2.2 and SM4.4).

In the input-output modelling, this is operationalized by assigning local content shares to the investment shock (construction phase) and to the expenditures of industries (operation phase) (see Section SM4.5).

As explained before, for the LCA and the cost analysis, all steps are modelled up to when the green steel is available to the steel user at the Port of IJmuiden, Netherlands. However, for the IO impact analysis, only the economic activities taking place in Ceará are modelled. Depending on the exports scenario, either the liquefaction and storage or the production of green steel in Ceará is modelled.

Table S12 - Local content assumptions

Production activity	**Production location**	**Export scenarios**	**Input**	**Assumption**	**Operationalization**		
					LCA	Cost analysis	IO
Green hydrogen	Pecém (Ceará)	Both	Equipment (electrolyzers, compressors, etc)	Local or imported from outside Ceará	Based on Krishnan et al.[56], using global Ecoinvent datasets	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share equals either 1 (HighLC) or 0 (LowLC)
			Renewable electricity	Always local (dedicated RE)	See below	Electricity price equals LCOE of dedicated system	Local content share always equals 1 (allocated to new RE sector)
			Water	Sourced from local market	Brazil-specific Ecoinvent dataset adapted for locally sourced electricity (SSP2-RCP2.6 2025 North-East Brazil grid)	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share from Ceará SUT
Renewable electricity	Pecém (Ceará)	Both	Wind turbines	Local or imported from outside Ceará	Global Ecoinvent dataset adapted for locally sourced electricity (HighLC) and global electricity mix (LowLC)	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share equals either 1 (HighLC) or 0 (LowLC)
			Solar panels	Always imported from outside Ceará	Global Ecoinvent dataset adapted to the Brazilian scope	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share always equals 0
			Battery system	Always imported from outside Ceará	Based on Bauer et al.[57], using global Ecoinvent datasets	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share always equals 0
Liquefaction and storage	Pecém (Ceará)	Both	Equipment	Always imported from outside Ceará	Based on Stolzenburg and Mubala[58]	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share always equals 0
			Electricity	Always local (from the grid)	SSP2-RCP2.6 2025 North-East Brazil grid	Grid electricity prices for industrial consumers in Ceará	Local content share equals share from Ceará SUT

Green steel	Pecém (Ceará)	Green steel exports	Equipment	Always imported from outside Ceará	Ecoinvent dataset for 'Rest of the World'	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share always equals 0
			Iron ore pellets	Assumed to be purchased from an external company processing iron ore into iron pellets located near the Carajás mine	Ecoinvent dataset for Quebec adapted to North-East Brazil geography	Global market price	Local content shares always equals 0
			Carbon	Assumed to come from coal (95% carbon content) mined outside of Ceará	Ecoinvent market process for coal in 'Latin America and the Caribbean'	Global market price	Local content shares always equals 0
			Natural gas	Assumed to be purchased in the Brazilian market	Ecoinvent market process for high pressure natural gas in Brazil	Natural gas prices in Brazil	Local content shares always equals 0
			Water	Always sourced from the local market	Ecoinvent dataset for water in North-East Brazil	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Local content share from Ceará SUT when produced in Pecém
			Electricity	Always local (from the grid)	SSP2-RCP2.6 2025 North-East Brazil grid	Grid electricity prices in the Netherlands and in Brazil	Local content share from Ceará SUT when produced in Pecém
	IJmuiden (Netherlands)	Green hydrogen exports	Equipment	Always imported from outside Ceará	Ecoinvent dataset for Europe	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Not modelled when steel is produced in IJmuiden
			Iron ore pellets	Assumed to be purchased from an external company processing iron ore into iron pellets located near the Carajás mine	Ecoinvent dataset for Quebec adapted to North-East Brazil geography	Global market price	Not modelled when steel is produced in IJmuiden
			Carbon	Assumed to come from coal (95% carbon content) mined outside of Ceará	Ecoinvent market process for coal in 'Europe, without Russia and Turkey'	Global market price	Not modelled when steel is produced in IJmuiden Not modelled when steel is produced in IJmuiden

	Natural gas	Assumed to be purchased in the Dutch market	Ecoinvent market process for high pressure natural gas in the Netherlands	Natural gas prices in the Netherlands and in Brazil	Not modelled when steel is produced in IJmuiden Not modelled when steel is produced in IJmuiden
	Water	Always sourced from the local market	Ecoinvent dataset for water in the Netherlands	Techno-economic studies (no data on cost difference for HighLC and LowLC available)	Not modelled when produced in IJmuiden
	Electricity	Always local (from the grid)	SSP2-RCP2.6 2025 grid in the Netherlands	Grid electricity prices in the Netherlands	Not modelled when produced in IJmuiden

SM4.3. Methodology: environmental life-cycle assessment

Environmental life-cycle assessment (LCA) is a methodology used to quantify the environmental impacts associated with a product or process. In this study, we specifically focus on greenhouse gas emissions or climate change impacts. The functional unit, which measures all inputs and outputs to the process, is defined as 1 kg of green steel (hot rolled coil) in IJmuiden.

Life-Cycle Inventory. To construct the life-cycle inventory, we use data previously published studies in combination with the Ecoinvent database v3.10.

Life-Cycle Impact Assessment. We employ the ReCiPe2016 method (H) v1.1 at midpoint level, using the climate change impact indicator to quantify the GHG emissions of the green hydrogen export and green steel export cases, as summarized in Table S1, and for a high local content and low local content scenario for green hydrogen production. This analysis is conducted using SimaPro v9.6 software in combination with R.

Interpretation. The GHG emissions for the green hydrogen export and green steel export cases are quantified for different steps in the supply chain, to identify the processes with the largest contribution to total GHG emissions. In the base case, we assume that the power input required in the DRI-EAF process is supplied by the local grid mix in the Netherlands (hydrogen export case) and in Brazil (steel export case), with the heat requirement met by natural gas (H2-NG-DRI). In the sensitivity analysis, we assess the impact of 1. using projected electricity grid mixes for 2030 and 2050 instead of 2025, 2. using hydrogen instead of natural gas for the heat requirement in steel production (H2-DRI), and 3. using electric freight trains instead of diesel-powered trains for iron ore transport.

SM4.3.1. Green hydrogen production emissions

The total green hydrogen production emissions, $E_{production,H_2}$ (kgCO2-eq/kg H2), are calculated using Equation 7:

$$E_{production,H_2} = E_{electricity,H_2} + E_{water,H_2} + E_{KOH,H_2} + E_{electrolyser,H_2} + E_{battery,H_2} \qquad \textit{Equation 7}$$

Where: $E_{electricity,H_2}$, E_{water,H_2}, E_{KOH,H_2}, $E_{electrolyser,H_2}$, and $E_{battery,H_2}$ are the emissions in kgCO2-eq/kg H2 associated with the manufacturing of the electricity plant, water supply, potassium oxide (KOH) supply, and the manufacturing of the electrolyzer and battery, respectively.

SM4.3.1.1. Modelling GHG emissions of dedicated renewable electricity

The emissions from manufacturing the electricity plant that powers the electrolyzer are determined by the size of the solar PV and wind power plants needed to provide continuous electricity, in combination with the battery. These emissions ($E_{electricity,H_2}$, in kgCO2-eq/kg H2), are calculated by dividing the total emissions from wind turbine and solar panel manufacturing by the total hydrogen production over the electrolyzer' s lifetime (Q_{H_2}, in kt H2), as shown in Equation 8:

$$E_{electricity,H_2} = \frac{\frac{cap_{facility,ren}}{cap_{unit,solar}} \cdot EF_{unit,solar} + \frac{cap_{facility,ren}}{cap_{unit,wind}} \cdot EF_{unit,wind}}{Q_{H_2} \cdot 10^6} \qquad \textit{Equation 8}$$

Where: $cap_{unit,solar}$ and $cap_{unit,wind}$ are the capacities (GW) of a single wind or solar PV unit, respectively, and $EF_{unit,solar}$ (kgCO2-eq) and $EF_{unit,wind}$ (kgCO2-eq) are the manufacturing emissions of these single units, respectively.

SM4.3.1.1.1. Modelling GHG emissions of the solar PV facility

We use Ecoinvent data for a 570 kWp ground-mounted PV plant, which has lower manufacturing emissions than residential solar PV panels. The Ecoinvent process includes the manufacture of inverters, wafers, mounting system, and electrical installation. The electricity source used in manufacturing is assumed to be the global grid mix. The electricity requirements are as follows: 4577.8 kWh per 500 kW inverter manufacture (requiring 3.13 inverters per 570 kWp installation), 4.7 kWh per m^2 wafer (requiring 4401.7 m^2), and 36 kWh for the erection of the installation. For the erection of the installation, the grid mix in North-East Brazil is used. The emissions of the 570 kWp installation are scaled to the required installed capacity, calculated using Equation 3.

SM4.3.1.1.2. Modelling GHG emissions of the onshore wind facility

We model the emissions associated with onshore wind turbines based on the Ecoinvent entry for the construction and connection of a 4.5 MW onshore wind turbine with a lifetime of 20 years. The electricity requirement for the construction of the wind turbine is 445,000 kWh, with the electricity source adjusted based on the local content scenario: in the high local content scenario turbines are manufactured locally and the grid mix of North-East Brazil is used, while in the low local content scenario the turbines are imported from elsewhere, so the global grid mix is used. The emissions of the 4.5 MW installation are scaled to the required installed capacity, calculated using Equation 3.

SM4.3.1.2. Modelling GHG emissions of water use

We assume that water supply is deionized tap water. The emissions associated with water use in green hydrogen production, E_{water,H_2} (kgCO2-eq/kg H2), are calculated using Equation 9:

$$E_{water,H_2} = (N_{water,feed} + N_{water,cooling}) \cdot (E_{tap} + E_{deionisation}) \qquad \textit{Equation 9}$$

Where: $N_{water,feed}$ and $N_{water,cooling}$ are the required feed water and cooling water, respectively (kg H2O/kg H2) (Table S2), E_{tap} the emissions associated with tap water (kgCO2-eq/kg H2O), and $E_{deionisation}$ the emissions associated with deionisation (kgCO2-eq/kg H2O). We use the Brazil-specific process in Ecoinvent for tap water, and adapt the general Ecoinvent process for water deionization by excluding the water input and adjusting the electricity source for the 2.6 · 10-5 kWh/kg H2O electricity requirement to the grid mix of North-East Brazil.

SM4.3.1.3. Modelling GHG emissions of the potassium oxide electrolyte

The emissions associated with the production of the potassium oxide (KOH) electrolyte used in the electrolyzer, E_{KOH,H_2} (kgCO2-eq/kg H2), are calculated using Equation 10:

$$E_{KOH,H_2} = \frac{cap_{electrolyser}}{M_{H_2}} \cdot N_{KOH} \cdot EI_{KOH} \qquad \textit{Equation 10}$$

Where: N_{KOH} is the annual KOH demand per MW of electrolyzer (kg KOH per year per MW) and EI_{KOH} the emissions of KOH production (kgCO2-eq/kg KOH).

SM4.3.1.4. Modelling GHG emissions of electrolyzer manufacturing

We use an average of alkaline electrolyzers based on the manufacture of a baseline (2020) and a more advanced (2030) design(Krishnan et al., 2024). This includes the manufacturing of the electrolyzer stacks, which have a lifetime of 8 years ($lifetime_{stacks}$), and the balance of plant (BOP), which has a lifetime of 20 years ($lifetime_{electrolyser}$). Emissions from electrolyzer manufacturing ($E_{electrolyser,H_2}$in kgCO_2-eq/kg H_2) are calculated by scaling the emissions found by Krishnan et al.[2] based on 4161 operating hours per year to the 7940 hours in our system (Equation 11). This adjustment is necessary because manufacturing emissions are divided over the total hydrogen produced over the electrolyzer' s lifetime, and more hydrogen is produced if operational hours are increased.

$$E_{electrolyser,H_2} = (EF_{BOP} + EF_{stacks}) \cdot \frac{4161}{7940} \qquad \textit{Equation 11}$$

Where: EF_{BOP} are emissions from the 2025 average construction of the BOP based on 4161 operational hours per year (kgCO$_2$-eq/kg H$_2$), and EF_{stacks} are the manufacturing emissions of the stacks in 2025 based on 4161 operational hours per year (kgCO$_2$-eq/kg H$_2$).

Emissions from electrolyzer manufacturing mainly come from producing steel and other metals. Assuming conventional steel from a market mix is used, these emissions remain unchanged across different local content scenarios.

SM4.3.1.5. Modelling GHG emissions of battery manufacturing

The lithium nickel manganese cobalt oxide battery system includes battery pack, battery management system, energy management system, thermal management system, system container, inverter, and transport. The battery's nameplate capacity (MWh) is calculated by multiplying the electrolyzer capacity by the battery's storage duration ($hours_{battery}$ in hours), and is 12 GWh in our analysis (see Section SM4.2.1). To determine the battery manufacturing emissions ($E_{battery,H_2}$ in kgCO$_2$-eq/kg H$_2$), divide the emission per storage capacity ($EF_{battery,MWh}$ in kgCO$_2$-eq/MWh) by the total hydrogen produced over the electrolyzer' s lifetime (Q_{H_2}, in kt H$_2$), adjusted for the relative lifetimes of the battery and electrolyzer.

$$E_{battery,H_2} = \frac{cap_{electrolyser} \cdot hours_{battery}}{Q_{H_2}} \cdot EF_{battery,MWh} \cdot \frac{lifetime_{electrolyser}}{lifetime_{battery}} \qquad \textit{Equation 12}$$

The battery lifetime ($lifetime_{battery}$) is assumed to be 12 years[57]. $EF_{battery,MWh}$ depends on the emissions intensity of electricity used in manufacturing. We use the mean GHG emissions for battery manufacture in 2020 and 2030 (2°C scenario), as quantified by Bauer et al. [57], which is $87.0 \cdot 10^3$ kgCO$_2$-eq/MWh storage capacity.

SM4.3.2. Hydrogen liquefaction and shipping emissions

Hydrogen liquefaction to prepare gaseous hydrogen for shipping in the green hydrogen export case is assumed to take place in liquefaction facilities with a capacity of 50 tH$_2$/day, which include up to 21 days of storage capacity[58]. Based on the average daily production, 18 of these units are needed. Section SM4.2.1.3 detailed the assumptions on liquefaction and shipping, and the life-cycle inventory used to quantify the emissions can be found in Supplementary Table 8 in de Kleijne et al.[12].

The emissions of hydrogen liquefaction (E_{liqf,H_2} in kgCO$_2$-eq/kg H$_2$) are quantified following Equation 13:

$$E_{liqf,H_2} = \frac{1}{1 - L_{liqf}} \cdot \left(P_{liqf} \cdot EI_{grid,BR} + EF_{liqf\ plant} + L_{liqf} \cdot GWP_{H_2}\right) \qquad \textit{Equation 13}$$

Where L_{liqf} is the loss of hydrogen (as a mass fraction) during liquefaction, GWP_{H_2} the global warming potential of hydrogen (Section SM4.3.6), P_{liqf} the liquefaction electricity requirement (in kWh/kg H$_2$), $EI_{grid,BR}$ the emissions intensity of the North-East Brazilian grid mix (in kgCO$_2$-eq/kWh, see Section SM4.3.1.1), and $EF_{liqf\ plant}$ the manufacturing emissions of the liquefaction facility, scaled to emissions per kg of hydrogen liquefied based on its lifespan and total hydrogen liquefied over the lifespan (kgCO$_2$-eq/kg H$_2$).

During liquid hydrogen storage at land until a tanker can be filled (up to 13 days), all boil-off gas that is formed is first compressed (Equation 14) and then (re-)liquefied (Equation 13).

$$E_{comp,H_2} = \frac{1}{1 - L_{comp}} \cdot \left(P_{comp} \cdot EI_{grid,BR} + EF_{comp\ plant} + L_{comp} \cdot GWP_{H_2}\right) \qquad \textit{Equation 14}$$

Where E_{comp,H_2} are the emissions of hydrogen compression (in kgCO$_2$-eq/kg H$_2$), L_{comp} is the loss of hydrogen (as a mass fraction) during compression, P_{comp} the compression electricity requirement (in kWh/kg H$_2$), and $EF_{comp\,plant}$ the manufacturing emissions of the compression facility, scaled to emissions per kg of hydrogen compressed based on its lifespan and total hydrogen compressed over the lifespan (kgCO$_2$-eq/kg H$_2$).

The emissions of hydrogen loading into the tanker (E_{load,H_2} in kgCO$_2$-eq/kg H$_2$) are quantified following Equation 15:

$$E_{load,H_2} = \frac{1}{1-L_{load}} \cdot \left(P_{load} \cdot EI_{grid,BR} + L_{load} \cdot GWP_{H_2}\right) \qquad \textit{Equation 15}$$

Where L_{load} is the loss of hydrogen (as a mass fraction) during loading, and P_{load} the loading electricity requirement (in kWh/kg H$_2$).

The emissions of hydrogen shipping in the tanker (E_{ship,H_2} in kgCO$_2$-eq/kg H$_2$) are quantified following Equation 16:

$$E_{ship,H_2} = \frac{1}{1-L_{BOG,day} \cdot d_{journey,day}} \cdot \left(d_{journey,km} \cdot EI_{ship} + L_{BOG,day} \cdot d_{journey,day} \cdot GWP_{H_2}\right) \qquad \textit{Equation 16}$$

Where $L_{BOG,day}$ is the rate of hydrogen loss through boil-off gas (as a mass fraction per day), $d_{journey,day}$ the length of the journey in days, $d_{journey,km}$the length of the journey in km (one-way), and $EI_{ship}$the emissions intensity of hydrogen shipping per km (voyage and ballast, including fuel and the manufacturing of the tanker).

The emissions of hydrogen unloading from the tanker (E_{unload,H_2} in kgCO$_2$-eq/kg H$_2$) are quantified following Equation 17:

$$E_{unload,H_2} = \frac{1}{1-L_{unload}} \cdot \left(P_{unload} \cdot EI_{grid,NL} + L_{unload} \cdot GWP_{H_2}\right) \qquad \textit{Equation 17}$$

Where L_{unload} is the loss of hydrogen (as a mass fraction) during unloading, and P_{unload} the unloading electricity requirement (in kWh/kg H$_2$).

The emissions of hydrogen regasification and storage ($E_{storage,H_2}$ in kgCO$_2$-eq/kg H$_2$) are quantified following Equation 18:

$$E_{storage,H_2} = \frac{1}{1-L_{comp}} \cdot \left(L_{comp} \cdot GWP_{H_2}\right) + EF_{storage,manufacture} \qquad \textit{Equation 18}$$

Where $EF_{storage,manufacture}$ are the manufacturing emissions of the storage facility on land with a capacity of 3 days, scaled to emissions per kg of hydrogen stored based on the lifespan of the facility and total hydrogen stored over the lifespan (kgCO$_2$-eq/kg H$_2$).

In general, as losses occur in several consecutive steps of hydrogen processing and transport, more than 1 kg of hydrogen needs to be produced, processed and transported to arrive with 1 kg at the destination. In addition to accounting for hydrogen losses to the environment in the relevant steps through its global warming potential, the relative processing requirement (and associated emissions) in each previous step is increased according to Equation 19:

$$E_{i,total} = \frac{1}{1-L_{i+1}} \cdot E_i \qquad \textit{Equation 19}$$

Where E_i are the emissions of step i (e.g., liquefaction, loading, shipping) in kgCO$_2$-eq/kg H$_2$ processed, L_{i+1} are the losses of hydrogen in step $i+1$, as a fraction, and $E_{i,total}$ the total emissions of step i accounting for the increased processing requirement to have 1 kg of hydrogen after step $i+1$.

SM4.3.3. Iron ore mining, pelletizing and transport emissions

Iron ore pellets are used as input for the shaft furnace, where together with hydrogen, sponge iron is produced (Table S4). The process of iron ore pellet production starts with iron ore mining (assumed to take place in the Carajás mine, see Section SM4.2.1.4), followed by iron ore pelletizing, land transport by rail, and possibly shipping, depending on the export scenario. In the green steel export case, steel production takes place in the Port of Pecém, to which the iron ore is transported by rail covering a distance of approximately 2000 km (Table S13). In the green hydrogen export case, iron ore is transported by rail to the nearest port, followed by shipping (Table S13).

The emissions associated with iron ore pellets ($E_{iron\ ore}$ in kgCO$_2$-eq/kg iron ore) are quantified following Equation 20:

$$E_{iron\ ore} = E_{ore,mining} + E_{ore,pelletizing} + E_{rail,ore} \cdot d_{rail,ore,km} + E_{ship,ore} \cdot d_{ship,ore,km} \qquad \text{Equation 20}$$

Where $E_{ore,mining}$ are the emissions for iron ore mining (in kgCO$_2$-eq/kg iron ore), $E_{ore,pelletizing}$ are the emissions for iron ore pellet production (in kgCO$_2$-eq/kg iron ore), $E_{rail,ore}$ the emissions for iron pellet transport by rail including train manufacture and fuel (in kgCO$_2$-eq/kg iron ore/km), $E_{ship,ore}$the emissions of iron pellet transport by ship including ship manufacture and fuel (in kgCO$_2$-eq/kg iron ore/km), $d_{rail,ore,km}$ the distance of iron pellet transport by rail in km, and $d_{ship,ore,km}$ the distance or iron pellet transport by ship in km. Note that $E_{iron\ ore}$ is dependent on the export scenario.

Ecoinvent processes are used to calculate the emissions associated with these processes. The Ecoinvent entry for iron ore pellet production in Quebec is adapted to the North-East Brazilian situation by selecting location-specific input processes, such as electricity from the North-East Brazilian grid mix. In the high local content scenario, pelletizing is assumed to take place close to the Carajás mine, outside of Ceará, while in the low local content scenario, pelletizing is assumed to take place in Ceará. Since both these locations fall within the region of North-East Brazil, this resulted in no difference in the datasets used.

For rail transport and shipping, the Ecoinvent entry for a diesel-powered freight train and 'Transport, freight, sea, bulk carrier for dry goods (global)' are used, respectively. In the sensitivity analysis, an electric freight train is used instead of the diesel-powered freight train, again based on Ecoinvent, powered by grid electricity.

Table S13 - Overview of iron ore mining, pelletizing and transport processes in the green hydrogen export scenario and green steel export scenario

	Green hydrogen export **Input per ton iron ore**	**Green steel export** **Input per ton iron ore**
Iron ore concentrate production (mining)	1 ton	1 ton
Iron ore pelletizing	1 ton	1 ton
Transport by freight train	1000 km	2000 km
Transport by ship	7600 km	-

SM4.3.4. Steel production and transport emissions

To calculate the emissions of steel production, the life-cycle inventory from Rosner et al.[19] is used, specifically, the 'H$_2$-DRI base case: H$_2$ use for shaft furnace. Natural gas (NG) use for H$_2$ pre-heating, EAF heating, ladle heating'. To this, the construction of an electric arc furnace, refractory lining and anode is added, based on the Ecoinvent entry for electric low-alloyed steel production (see Table S4; H_2-NG-DRI case). For the sensitivity analysis, the 'H_2-DRI total case: H_2 use for shaft furnace, H_2 pre-heating, EAF heating, ladle heating' is used as the basis, subject to the same additions based on the Ecoinvent entry for electric low-alloyed steel production (Table S4; H_2-DRI case).

While steel is produced in IJmuiden in the green hydrogen export case, in the green steel export case steel is shipped by a dry bulk carrier from the Port of Pecém to the Port of IJmuiden, covering a distance of approximately 7500 km.

The emissions associated with steelmaking (E_{steel} in kgCO_2-eq/kg steel) are quantified following Equation 21:

$$E_{steel} = N_{H_2} \cdot E_{H_2} + N_{iron\ ore} \cdot E_{iron\ ore} + E_{steel,ex.elec} + P_{EAF} \cdot EI_{grid} + E_{ship,steel} \cdot d_{ship,steel,km} \quad \text{Equation 21}$$

Where: N_{H_2} and $N_{iron\ ore}$ are the hydrogen and iron ore requirements in kg H_2 per kg steel, and kg iron ore per kg steel, respectively; E_{H_2} and $E_{iron\ ore}$ the export-scenario dependent emissions for hydrogen and iron ore inputs, in kgCO_2-eq/kg H_2 and kgCO_2-eq/kg iron ore, respectively; $E_{steel,ex.elec}$ are the location-dependent emissions associated with DRI-EAF steelmaking, excluding electricity (kgCO_2-eq/kg steel), P_{EAF} the electricity requirement of the EAF (kWh/kg steel), EI_{grid} the location-dependent emissions intensity of the grid mix (kgCO_2-eq/kWh, see section SM4.2.1.2), $E_{ship,steel}$ the emissions of steel transport by ship including ship manufacture and fuel (in kgCO_2-eq/kg steel/km), and $d_{ship,steel,km}$ the distance of steel shipping in km (zero in the green hydrogen export case). Note that E_{steel} depends on the export scenario.

In the green hydrogen export case, hydrogen losses from liquification and shipping add up to an approximate loss of 7%. Therefore, effectively more hydrogen production is required per kg of steel produced (or, conversely, less steel can be manufactured per kg of hydrogen produced). This has been accounted for in the analysis by including not only the emissions of hydrogen production (Equation 7), and of hydrogen transport (Equation 13-Equation 18) in the total emissions of hydrogen inputs to the steelmaking process (E_{H_2}, in kgCO_2-eq/kg H_2), but also correcting for losses following Equation 19.

In the sensitivity analysis where we assess sponge iron production in Ceará and shipping to IJmuiden for EAF-steelmaking, the H_2-NG-DRI case is adapted according to Table S5. The relevant local processes are used, such as the North-East Brazilian grid mix for DRI processes requiring electricity, and the Dutch grid mix for EAF processes. Since sponge iron has a mass of 1.16 times that of finished steel[19], shipping emissions are increased by a factor 1.16 compared to shipping steel from Ceará to IJmuiden.

SM4.3.5. Modelling GHG emissions of grid electricity

Except for electrolysis, we assume grid electricity (high voltage) is used for component manufacturing, hydrogen liquefaction, hydrogen compression, and the electric arc furnace, in the respective locations.

The life-cycle GHG emission intensity of grid electricity is projected using the Premise open-source Python package (version 2.0.2) under an SSP2-RCP2.6 (2°C) scenario. The 2025 grid mix is used in the main analysis, and values for 2030 and 2050 in the sensitivity analysis. As the grid mix decarbonizes, the emission intensity is projected to decrease, potentially reaching negative values in 2050 for the Netherlands and the global market mix (-11.9 and -7 gCO_2-eq/kWh, respectively). However, to avoid skewing results by leading to lower emissions with increased electricity use, we assume an emission intensity of 0 for these two cases for 2050 (Table S14).

Table S14 - Emissions intensities used for grid electricity in North-East Brazil, the Netherlands and the global average, projected for 2025, 2030 and 2050 under a 2°C scenario

	2025	2030	2050
North-East Brazil (gCO_2-eq/kWh)	141.5	103.8	7.0
The Netherlands (gCO_2-eq/kWh)	303.2	258.5	0
Global market mix (gCO_2-eq/kWh)	683.1	496.0	0

SM4.3.6. Hydrogen as indirect greenhouse gas

Hydrogen is an indirect greenhouse gas, which means that when it reaches the atmosphere, it interacts with other components in the atmosphere, resulting in a net warming effect. The global warming potential of 1 kg of hydrogen, over a 100 year time horizon, is 11.6 $kgCO_2$-eq/kg H_2[16].

SM4.4. Methodology: Cost analysis

SM4.4.1. Levelized cost of green hydrogen (LCOH)

The sales price of green hydrogen at the electrolysis plant is considered to be the levelized cost of hydrogen production. The LCOH is calculated as in Equation 22.

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_{H2_t} + OM_{H2_t} + LCOE * P_{electrolyser} * M_{H_{2t}}}{(1 + WACC_{H2})^t}}{\sum_{t=1}^{n} \frac{M_{H_{2t}}}{(1 + WACC_{H2})^t}} \quad \text{Equation 22}$$

Where I_{H2_t} is the investment (CAPEX) expenditure for electrolysis in year t, $OM_{H2,t}$ is the operational expenditures for electrolysis excluding electricity inputs in year t, $WACC_{H2}$ is the weighted average cost of capital for electrolysis, $P_{electrolyser}$ is the electricity requirement for electrolysis per kilogram of hydrogen output, $M_{H_{2t}}$ is the hydrogen output of the electrolysis plant at year t, and $LCOE$ is the levelized cost of electricity.

The levelized cost of electricity for electrolysis is calculated based on the system design and the cost assumptions from Section SM4.2 and the following formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_{wind_t} + OM_{wind_t} + I_{solar_t} + OM_{solar_t} + I_{battery_t} + OM_{battery_t}}{(1 + WACC_{RE})^t}}{\sum_{t=1}^{n} \frac{P_{electrolyser} * M_{H_{2t}}}{(1 + WACC_{RE})^t}} \quad \text{Equation 23}$$

Based on the assumptions from Sections SM4.2.1.1, SM4.2.1.2, SM4.2.2.1, and SM4.2.2.2, the LCOH obtained in this study is 4.17 USD/kgH_2, excluding any hydrogen liquefaction, storage, or shipping costs. This somewhat higher LCOH when compared to IRENA's estimates can be explained by the need to oversize the renewable energy facilities and to add a battery considering the assumption of dedicated generation. This is based on the calculated levelized cost of electricity (LCOE) for the entire system (including energy storage) of 0.06417 USD/kWh.

SM4.4.2. Levelized cost of liquefaction and storage (LCOLS)

The levelized cost of liquefaction and storage is calculated as in Equation 24. The quantity of hydrogen yearly sold by the liquefaction and storage step will be equal to the yearly production of the electrolysis plant $M_{H_{2t}}$ minus the total losses in during liquefaction and storage L_{LS}. The total losses amount to

1.89% (see Section SM4.3.2), meaning that of the 319kton/year of green hydrogen produced by electrolysis, only 313kton/year will be available to be loaded into the ship.

$$LCOLS = \frac{\sum_{t=1}^{n} \frac{I_{liquefaction_t} + OM_{liquefaction_t} + I_{storage_t} + OM_{storage_t}}{(1+WACC_{LS})^t}}{\sum_{t=1}^{n} \frac{M_{H_{2t}} * (1 - L_{LS})}{(1+WACC_{LS})^t}}$$

Equation 24

We find a LCOLS of 2.49 USD/kgH2, which is in the mid-range of the costs reported by IRENA[41]. This can be explained by the relatively small scale of the plant.

SM4.4.3. Levelized cost of green steel (LCOS)

The levelized cost of green steel (LCOS) is different in the two export scenarios. The costs for steel production are described in Section SM4.2.2.5. We assume the steel plants in Ceará and in the Netherlands would pay different total prices for green hydrogen, with the difference referring to the additional steps necessary to liquefy, store, ship, and regasify the green hydrogen when transporting the green hydrogen from Pecém to IJmuiden. Additionally, prices for electricity and natural gas are different in the two locations, and so are labor costs. Hence, steel plants at the two locations will have different operation and management costs (OM). Also, they will have different physical output of green steel (GSP) for a given size of the electrolysis plant in Ceará, due to hydrogen losses in transport. Both locations are assumed to have the same investment costs per tonne of steel capacity and weighted average cost of capital.

$$LCOS_{IJmuiden} = \frac{\sum_{t=1}^{n} \frac{I_{GS_t} + OM_{IJmuiden_t}}{(1+WACC_{GS})^t}}{\sum_{t=1}^{n} \frac{GSP_{IJmuiden_t}}{(1+WACC_{GS})^t}}$$

Equation 25

$$LCOS_{Pecém} = \frac{\sum_{t=1}^{n} \frac{I_{GS_t} + OM_{Pecém_t}}{(1+WACC_{GS})^t}}{\sum_{t=1}^{n} \frac{GSP_{Pecém_t}}{(1+WACC_{GS})^t}}$$

Equation 26

SM4.5. Methodology: Input-output modelling

SM4.5.1. Model specification

In a input-output model with *n* industry sectors, z_{ij} is an element of the $n \times n$ inter-industry transactions matrix Z $[z_{ij}]$, representing the value of purchases of industry *i* output by industry *j* [59]. The *n*-element vector of total industry outputs is defined as x = $[x_i]$, where

$$x_i = z_{i1} + \cdots + z_{in} + f_i$$

Equation 27

and f_i is industry *i*'s sales to final demand. The matrix of direct technical coefficients A = $[\alpha_{ij}]$ represents the value of dollars' worth of input from sector *i* per dollars' worth of output of sector *j*, where

$$\alpha_{ij} = z_{ij}/x_j \quad \forall\, i,j = 1,2, \ldots n$$

Equation 28

The total requirements matrix L = $[l_{ij}]$, also known as the Leontief inverse, is defined by, in matrix notation,

$$L = (I - A)^{-1}$$ *Equation 29*

where A is the matrix of direct technical coefficients and I is an identity matrix of $n \; x \; n$ dimension [59]. In matrix notation:

$$A = Z\hat{x}^{-1}$$ *Equation 30*

$$x = Ax + f$$ *Equation 31*

$$x = (I - A)^{-1}f = Lf$$ *Equation 32*

The impact on output from industry sector j (Δx_j) given a change in final demand from sector i (Δf_i) will be given by:

$$\Delta x = L\Delta f$$ *Equation 33*

During the construction phase, the change in the final demand vector regards the additional inputs required for the construction of the plants. In the operation phase, it equals the exports of liquified green hydrogen (green hydrogen exports scenario) or the exports of green steel (green steel exports scenario). In both export cases, since these two products are not consumed by existing industries in Ceará, the total exports equal the total output of the sector (liquefaction of green hydrogen or green steel production).

The following sections summarize the input-output methodology in this study. Starting from the right side of the Equation 33, we first explain the model specification regarding the Leontief inverse (L) and the change in final demand (Δf) in Section SM4.5.2. We then explain how the output, value-added, income and employment effects are determined in Section SM4.5.3.

SM4.5.2. Model inputs

This study utilizes the Supply and Use tables (SUTs) for the state of Ceará from the year 2018 to derive the Leontief inverse for the region[20]. These tables are structured as 12x12 commodity-by-industry matrices (see Table S15). The procedure for converting the SUTs into an industry-by-industry IOT is based on Guilhoto and Sesso Filho [60,61] and Miller and Blair[59]. This is explained in Section SM4.5.2.1.

The green industries had to be introduced into the table. The approach followed was based on Miller and Blair[59]. This is explained in Section SM4.5.2.2 for the construction phase and in Section SM4.5.2.3 for the operation phase.

In order to capture induced effects, households are endogenized, taking salary and employment data from the RAIS database from the Brazilian Ministry of Employment [26]. This is explained in Section SM4.5.2.4.

Table S15 - Sectors in the SUTs

i	Sector
1	S01: Agriculture
2	S02: Extractive Industries
3	S03: Transformation industries
4	S04: Electricity, gas, water and other utilities
5	S05: Construction
6	S06: Commerce
7	S07: Transport, storage and post services
8	S08: Information and communication
9	S09: Financial activities, insurances and related fees
10	S10: Real estate activities
11	S11: Other activities and services
12	S12: Public administration, defence, healthcare, education and social security

SM4.5.2.1. Input output tables for the state of Ceará

The IBGE provides Use Tables in consumer prices and Supply Tables in producers prices. Moreover, in the Use Tables they show the total use of commodities by industries, not differentiating on whether the commodity is supplied domestically or imported. We follow Guilhoto and Sesso Filho [60,61] to obtain tables containing only the domestic (Ceará) supply at basic prices. We first remove the trade margins (MGC), transport margins (MGT) and taxes net of subsidies (IIL) from the Use Tables at consumer prices to obtain the use tables in basic prices.

$$\mathrm{TSBP} = \mathrm{TSCP} - \mathrm{MGC} - \mathrm{MGT} - \mathrm{IIL} \qquad \textit{Equation 34}$$

where:

TSBP = Total Supply at Basic Prices

TSCP = Total Supply at Consumers Prices

MGC = Trade margins

MGT = Transport margins

IIL = Taxes net of subsidies

Secondly, to obtain the domestic supply only, imports from rest of Brazil (IOB) and imports from rest of the world (IOW) are calculated and also removed from the Use table:

$$\mathrm{DSBP} = \mathrm{TSBP} - \mathrm{IOB} - \mathrm{IOW} \qquad \textit{Equation 35}$$

where:

DSBP = Domestic Supply at Basic Prices

TSBP = Total Supply at Basic Prices

IOB = Imports from the rest of Brazil

IOW = Imports from the rest of the World

With the Use Table including only the domestically available supply at basic prices (U), the matrix of containing the use structure of industries (B) can be obtained. As explained by Miller and Blair [59], the vector of total industry output can be calculated by

$$\mathrm{x} = (\mathrm{I} - \mathrm{DB})^{-1}\mathrm{f} \qquad \textit{Equation 36}$$

where:

x is the vector of total industry output;

B is the use structure matrix containing the use coefficients representing the value of inputs of each commodity by dollars' worth of industry j's output, defined by $\mathrm{B} = \mathrm{U}\hat{\mathrm{x}}^{-1}$;

D is the market shares matrix, defined by $\mathrm{D} = \mathrm{S}'\hat{\mathrm{q}}^{-1}$, where q is the total commodity output and S the supply matrix;

I is the identity matrix;

f is the vector of final demand for industries, defined by $\mathrm{f} = \mathrm{De}$, where e is the final demand for commodities and D the market shares matrix.

The total requirements matrix $(I - DB)^{-1}$ becomes hence the equivalent of the Leontief's inverse (L), where DB is the equivalent of the industry-by-industry technical coefficient matrix A[59].

$$\mathrm{A} = \mathrm{DB} \qquad \text{Equation 37}$$

$$\mathrm{L} = (\mathrm{I} - \mathrm{DB})^{-1} \qquad \text{Equation 38}$$

The impact on output can then be calculated using Equation 33.

SM4.5.2.2. Modelling impacts from investments in the construction phase

In the construction phase, the capital expenditures for each of the new plant k (renewable electricity, green hydrogen, liquefaction and storage, and green steel) described in Section SM4.2.2 are allocated to the existing economic sectors in Ceará (see Table S16). For this, total expenditures need to first be disaggregated into imported and domestic expenditures via local content shares.

$$f_{i,n+k}^{C^D} = f_{i,n+k}^{C^T} - f_{i,n+k}^{C^M} \qquad \textit{Equation 39}$$

where

$f_{i,n+k}^{C^T}$ is the total capital expenditure of the new industry k allocated to industry sector i

$f_{i,n+k}^{C^D}$ is the capital expenditure of the new industry k in the domestic industry sector i

$f_{i,n+k}^{C^M}$ is the capital expenditure of the new industry k allocated to industry sector i spent in imports

Local content shares vary according to local content scenarios *s* (high and low), as previously explained.

$$f_{i,n+k}^{C^{D,s}} = f_{i,n+k}^{C^T} * lcs_{i,n+k}^{C^s} \;\; \forall\, i = 1,2, \dots n \qquad \textit{Equation 40}$$

Then, the vector of change in final demand for domestic industries is the vector obtained by summing the capital expenditures for a given sector from all k new industries that will arise under export case t. That is, while the renewable electricity and green hydrogen electrolysis plants will be built in both export cases, a liquefaction and storage plant needs to be built in the case of green hydrogen exports, but not in the case of green steel exports (and vice-versa).

$$f_i^{C^{D,s,t}} = \sum_{k=1}^{n_k} f_{i,n+k}^{C^{D,s,t}} \;\forall\, i = 1,2, .. n \qquad \textit{Equation 41}$$

$$\Delta f_i^{C^{s,t}} = f_i^{C^{D,s,t}} \quad \forall\; i = 1,2, .. n \qquad \textit{Equation 42}$$

Then, the impact on output in the construction phase can be obtained by post-multiplying the equivalent of the Leontief inverse by the change in final demand.

$$\Delta \mathrm{x}^{\mathrm{C}^{\mathrm{s,t}}} = \mathrm{L} \Delta \mathrm{f}^{\mathrm{C}^{\mathrm{s,t}}} \qquad \textit{Equation 43}$$

Table S16 - Sectoral allocation during construction phase

Technology	Cost item	Sector	Value	Unit
Battery	Battery system	S03: Transformation industries	1410.0	USD/kW
Green Steel	Shaft furnace	S03: Transformation industries	99.8	USD/t
Green Steel	Pre-Heater	S03: Transformation industries	3.1	USD/t
Green Steel	Recycle compressor	S03: Transformation industries	6.3	USD/t
Green Steel	EAF & Casting	S03: Transformation industries	204.6	USD/t
Green Steel	Cooling tower	S03: Transformation industries	17.6	USD/t
Green Steel	Buidings, storage, water service	S05: Construction	66.4	USD/t
Green Steel	Electrical & instrumentation	S03: Transformation industries	32.3	USD/t

Green Steel	Other plant equipment	S03: Transformation industries	91.9	USD/t
Green Steel	Preproduction costs	S03: Transformation industries	71.8	USD/t
Green Steel	Inventory	S03: Transformation industries	38.0	USD/t
Green Steel	Other owner costs	S11: Other activities and services	93.2	USD/t
Green Hydrogen	Electrolyzer (Stack)	S03: Transformation industries	321.0	USD/kWH2
Green Hydrogen	Balance of plants (Gas separation, compression and gas treatment)	S03: Transformation industries	110.0	USD/kWH2
Green Hydrogen	Utilities and Process Automation (Water, piping, ICT)	S03: Transformation industries	86.0	USD/kWH2
Green Hydrogen	Power supply and electronics (Electrical installations)	S03: Transformation industries	196.0	USD/kWH2
Green Hydrogen	Civil, Structural & Architectural (Construction)	S05: Construction	22.0	USD/kWH2
Green Hydrogen	Contingency	S09: Financial activities insurances and related fees	120.0	USD/kWH2
Green Hydrogen	Developer cost	S11: Other activities and services	48.0	USD/kWH2
Green Hydrogen	Indirect costs	S11: Other activities and services	120.0	USD/kWH2
Liquefaction and storage	Storage	S03: Transformation industries	87.0	USD/kWH2
Liquefaction and storage	Equipment	S03: Transformation industries	489.4	USD/kWH2
Liquefaction and storage	Bulk materials	S03: Transformation industries	404.3	USD/kWH2
Liquefaction and storage	Construction	S05: Construction	383.0	USD/kWH2
Liquefaction and storage	Transport and freight of equipment	S07: Transport storage and post services	63.8	USD/kWH2
Liquefaction and storage	Contigency	S09: Financial activities insurances and related fees	361.7	USD/kWH2
Liquefaction and storage	Insurances	S09: Financial activities insurances and related fees	42.6	USD/kWH2
Liquefaction and storage	Owner Costs	S11: Other activities and services	191.5	USD/kWH2
Liquefaction and storage	Project management	S11: Other activities and services	63.8	USD/kWH2
Onshore wind	Nacelle	S03: Transformation industries	444.0	USD/kW
Onshore wind	Blades	S03: Transformation industries	180.0	USD/kW
Onshore wind	Tower	S03: Transformation industries	155.0	USD/kW
Onshore wind	Electrical balance of plants	S03: Transformation industries	133.0	USD/kW
Onshore wind	Construction (Civil works + Installation)	S05: Construction	189.0	USD/kW
Onshore wind	Transport	S07: Transport storage and post services	49.0	USD/kW
Onshore wind	Contingency and finance	S09: Financial activities insurances and related fees	49.0	USD/kW
Onshore wind	Project planning and management	S11: Other activities and services	38.0	USD/kW
Solar photovoltaics	Modules	S03: Transformation industries	369.0	USD/kW
Solar photovoltaics	Inverters	S03: Transformation industries	36.0	USD/kW
Solar photovoltaics	BoS hardware	S03: Transformation industries	129.0	USD/kW
Solar photovoltaics	Installation	S05: Construction	155.0	USD/kW
Solar photovoltaics	Contingency and fees	S09: Financial activities insurances and related fees	97.0	USD/kW
Solar photovoltaics	Land	S10: Real estate activities	3.0	USD/kW
Solar photovoltaics	Design and engineering	S11: Other activities and services	9.0	USD/kW

Solar photovoltaics	Other (PR, permitting, customer)	S11: Other activities and services	51.0	USD/kW

SM4.5.2.3. Impacts during the operation phase: introducing new industries

Since green hydrogen production and liquefaction as well as green steel did not yet exist in the Ceará's economy in 2018, these activities had to be inserted into the IOT. This is only needed for the operation phase, since in the construction phase the change in final demand is limited to the existing sectors and the new industries cannot start operation before construction being finalized.

As explained by Miller and Blair [59], this approach consists in introducing a new column and row for the new sector in the technical coefficients matrix A, and hence, in the Leontief inverse L. This is done by estimating the direct input coefficients of the new sector, that is, $\alpha_{i,n+k}$, where *i* = the existing sectors in Ceará's economy and n+k is one of the k new sectors: renewable electricity for electrolysis (RE), hydrogen production via alkaline electrolysis (GH2), hydrogen liquefaction and storage (LS), and green steel production (GS). For instance, for *i=3,* $\alpha_{3,GH2}$ would represent the share of total expenditures from the green hydrogen sector that are directed to sector 3, in this case the transformation industry.

Based on Equation 28, the direct technical coefficients are found by dividing the amount of domestic sector *i* outputs required as inputs for the new sector ($z^D_{i,n+k}$) by the total outlay of the new sector (x_{n+k}). This is done by allocating operational cost items (see Section SM4.2.2) to specific economic sectors (see Table S17). This ensures that the impact assessment is technology-specific.

Since not all inputs will be sourced from the local industry, total expenditures have to first be disaggregated into domestic industry transactions and imports:

$$z^T_{i,n+k} = z^D_{i,n+k} + z^M_{i,n+k} \qquad \textit{Equation 44}$$

where

$z^T_{i,n+k}$ is the total expenditure of the new industry k allocated to industry sector *i*

$z^D_{i,n+k}$ is the expenditure of the new industry k in the domestic industry sector *i*

$z^M_{i,n+k}$ is the expenditure of the new industry k allocated to industry sector *i* spent in imports

The shares of each investment component that is spent in Ceará is estimated via local content scenarios (s). In these scenarios, local content shares (lcs_i) are used to separate total expenditures into domestic expenditures and imports. The allocation of investment to each domestic industry sector *i* can be calculated by

$$z^{D,s}_{i,n+k} = z^T_{i,n+k} * lcs^s_{i,n+k} \qquad \textit{Equation 45}$$

where $lcs^s_{i,n+k}$ refers to the local content share for domestic sector *i,* according local content share scenario *s*. Once $z^{D,s}_{i,n+k}$s determined, $a^s_{i,n+k}$ can be found by dividing $z^{D,s}_{i,n+k}$ for each productive sector *i* by the total expenditure (x_{n+k}):

$$a^s_{i,n+k} = z^{D,s}_{i,n+k} / x_{n+k} \qquad \textit{Equation 46}$$

Then the direct technical coefficients can be added to a new *(n+k)* x *(n+k)* technical coefficients matrix $\bar{A}^s$, which will contain the *n* x *n* A matrix, $\alpha^s_{i,n+k}$ as the *n+k* column, and zeros as the *n+k* row block representing sales the existing industries, since we assume no output of the new industries are used as inputs for the existing domestic industry (i.e. export assumption):

$$\overline{\mathrm{A}}^{\mathrm{s}} = \begin{bmatrix} \alpha_{1,1} & \cdots & \alpha_{1,n} & \alpha^{s}_{1,n+1} & \cdots & \alpha^{s}_{1,n+k} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \alpha_{n,1} & \cdots & \alpha_{n,n} & \alpha^{s}_{n,n+1} & \cdots & \alpha^{s}_{n,n+k} \\ 0 & \dots & 0 & \alpha^{s}_{n+1,n+1} & \cdots & \alpha^{s}_{n+1,n+k} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \alpha^{s}_{n+k,n+1} & \cdots & \alpha^{s}_{n+k,n+k} \end{bmatrix} \qquad \textit{Equation 47}$$

The Leontief inverse for the operation phase for each local content scenario can be obtained through Equation 48.

$$\overline{\mathrm{L}}^{\,s} = (\mathrm{I} - \overline{\mathrm{A}}^{\mathrm{s}})^{-1} \qquad \textit{Equation 48}$$

The total output of the new industries is sized to be the equivalent of their total sales, given the physical input-output quantities required and the calculated levelized cost as the sales price, given assumptions described in Section SM4.2. Expenditures on intermediate inputs are allocated to (existing or new) industries, expenditures on direct labor allocated to the salary income component of value added, and the difference between the total sales and costs on intermediates and labor is allocated to gross operating surplus (i.e., it is assumed to be capital remuneration). Balance for renewable electricity and green hydrogen is ensured by assuming the entirety of the sales going to a single consuming industry: renewable electricity only sells to green hydrogen industry and the green hydrogen industry only sells to either the liquefaction and storage industry (in the green hydrogen exports scenario) or the green steel industry (in the green steel exports scenario). This ensures that the total expenditures of these two industries equal the expenditures necessary to produce the quantities required to ensure balance in the system.

To isolate the impacts of the new industry sector, we let the change in final demand for the existing sectors to be 0. In this case, as demonstrated by Miller & Blair[59], the final demand for the new sectors will be equal to their total exports in each export scenario *t.* The vector of final demand can then be

$$\Delta\overline{\mathrm{f}}^{\mathrm{O,s,t}} = \begin{bmatrix} f_1^t \\ \vdots \\ f_n^t \\ f_{n+1}^t \\ \vdots \\ f_{n+k}^t \end{bmatrix} \qquad \textit{Equation 49}$$

where

$$f_i^{O,s,t} = \begin{cases} 0, & \forall\, i = 1,2, \dots n \\ 0, & \forall\, i = RE, GH2 \\ x_i^{O,t}, & \forall\, i = LS, GS \end{cases} \qquad \textit{Equation 50}$$

The final demand for renewable electricity and green hydrogen will equal zero since their exports are zero in both scenarios: the entirety of production is being used by the new exporting sector (liquefaction and storage or green steel). For the new exporting sectors, the final demand will equal the total exports for the liquefaction and storage and the green steel sectors. Since liquefaction and storage and green steel only sell products for exports, their total exports equals their total output. This will be either zero or the total sales given prices and physical output quantities depending on the export scenario.

Then, the impact on output in the operation phase can be obtained by post-multiplying the augmented Leontief inverse by the change in final demand due to exports.

$$\Delta x^{O,s,t} = \bar{L}^{s}\Delta\bar{f}^{O,s,t}$$ *Equation 51*

Table S17 - Sectoral allocation during operation phase, considering existing sectors only

Technology	Cost item	Sector	Value	Unit
Battery	Maintenance	S03: Transformation industries	35.0	USD/kW
Green Steel	Iron ore pellets (ton)	S03: Transformation industries	192.0	USD/t
Green Steel	Natural gas (GJ)	S02: Extractive Industries	16.1	USD/t
Green Steel	Electricity (kWh)	S04: Electricity gas water and other utilities	42.9	USD/t
Green Steel	Carbon (kg)	S03: Transformation industries	6.1	USD/t
Green Steel	Lime (kg)	S03: Transformation industries	5.1	USD/t
Green Steel	Raw water withdrawal(ton)	S04: Electricity gas water and other utilities	2.4	USD/t
Green Hydrogen	Maintenance	S03: Transformation industries	21.8	USD/kWH2
Green Hydrogen	Water	S04: Electricity gas water and other utilities	3.4	USD/kWH2
Green Hydrogen	Insurance	S09: Financial activities insurances and related fees	10.9	USD/kWH2
Liquefaction and storage	Electricity	S04: Electricity gas water and other utilities	1.0	USD/kgH2
Liquefaction and storage	Gas terminalling	S04: Electricity gas water and other utilities	0.0	USD/kgH2
Onshore wind	Maintenance	S03: Transformation industries	18.0	USD/kW
Onshore wind	Operation	S04: Electricity gas water and other utilities	12.0	USD/kW
Onshore wind	Land lease	S10: Real estate	2.5	USD/kW
Solar photovoltaics	Maintenance	S03: Transformation industries	11.5	USD/kW
Solar photovoltaics	Operation	S04: Electricity gas water and other utilities	9.5	USD/kW

SM4.5.2.4. Endogenizing households

Similarly to the introduction of a new industry, households are endogenized by adding a new row and column to the technical coefficients matrix. By doing so, households become the *n+k+1* sector in the input-output model, that is now formed by *n* existing productive sectors, k new green sectors (*n+k*) and households (*n+k+1*). Following a similar approach as to Vasconcellos and Caiado Couto[34] and Vale and Perobelli[62], coefficients for household salary remunerations (*hr*) and consumption (*hc*) are added as a row and a column in the inter-industry technical coefficients matrix $\bar{A}^{s}$ to obtain a new technical coefficients matrix with households endogenized ($\bar{\bar{A}}^{s}$):

$$\bar{\bar{A}}^{s} = \begin{bmatrix} \bar{A}^{s} & \bar{h}_{c} \\ \bar{h}_{r} & 0 \end{bmatrix}$$ *Equation 52*

where

$\bar{h}_{r}$ is a row vector including household salary remuneration coefficients for the $n+k$ productive sectors

$\bar{h}_{c}$ is a column vector including household consumption coefficients for the $n+k$ productive sectors

These vectors include the household remuneration and consumption of the *n* existing sectors plus the remuneration and consumption coefficients for the new sectors (Equation 53 and Equation 54).

$$\bar{h}'_{r} = [hr_{1} \quad \cdots \quad hr_{n} \quad hr_{n+1} \quad \dots \quad hr_{n+k}]$$ *Equation 53*

$$\bar{h}_{c} = [hc_{1} \quad \cdots \quad hc_{n} \quad hc_{n+1} \quad \dots \quad hc_{n+k}]$$ *Equation 54*

The vectors with the coefficients for household remunerations can be found by dividing the expenditures with salaries by total expenditures (Equation 55). For existing sectors, these are calculated based on total sectoral salary remuneration data from the RAIS database [26]. For the new industries, this is calculated based on employment factors from the literature review (see Section SM4.2.2) and the average salary for the sector (by gender) reported in the RAIS.

$$hr_j = \frac{r_j}{x_j} \quad \forall\, j = 1,2,\dots,n,n+1,\dots,n+k \qquad \text{Equation 55}$$

Similarly, the coefficients for household consumption can be found by dividing household consumption of each industry by total household remuneration (Equation 56).

$$hc_i = \begin{cases} \frac{c_i}{\sum_{j=1}^{n} r_j} & \forall\, i = 1,2,\dots,n \\ 0 & \forall\, i = n+1,\dots,n+k \end{cases} \qquad \text{Equation 56}$$

where $c = [\, c_1 \quad \cdots \quad c_n]$ is the vector of household consumption of domestic sector i taken from the industry-by-industry input output table and $\sum_{j=1}^{n} r_j$ is the total household income (salaries) associated to the *n* productive sectors. The household consumption of the green sectors is considered to be 0, since these are not final products.

The Leontief inverse for the model with households endogenized (the semi-closed model) can then be obtained as in Equation 57.

$$\bar{\bar{\mathrm{L}}}^{s} = (\mathrm{I} - \bar{\bar{A}}^{s})^{-1} \qquad \text{Equation 57}$$

An extra row is added to the vector for the change in final demand to obtain $\bar{\bar{\Delta}}\mathrm{f}^{O,t}$. The value for the household sector is also set to 0, similarly to all other existing sectors.

$$\Delta\bar{\bar{\mathrm{f}}}^{O,s,t} = \begin{bmatrix} \Delta\bar{\mathrm{f}}^{\mathrm{O,s,t}} \\ 0 \end{bmatrix} \qquad \text{Equation 58}$$

SM4.5.3. Model outputs

This section explains how value added, salary income, and employment effects are calculated based on their respective coefficients and output effects.

Output effects are disaggregated into direct, indirect, and induced effects as follows. Total output effects in project phase *p* are obtained by the multiplication of the Leontief inverse and the change in final demand for that phase, as explained above. Direct output effects – or first round effects – are obtained by post-multiplying the identity matrix by the final demand vector. Indirect output effects are obtained by removing the direct effects from the total output obtained from the open model. Induced effects are the difference between the output effects from the semi-closed model (total effects) and the indirect effects[59,62].

$$\Delta \mathrm{x}^{1^{\mathrm{TOTAL,p,s,t}}} = \bar{\bar{\mathrm{L}}}^{\mathrm{p,s}} \Delta\bar{\bar{\mathrm{f}}}^{\mathrm{p,s,t}} \qquad \text{Equation 59}$$

$$\Delta \mathrm{x}^{1^{\mathrm{DIRECT,p,s,t}}} = \mathrm{I}^{\mathrm{p,s}} \Delta \mathrm{f}^{\mathrm{p,s,t}} \qquad \text{Equation 60}$$

$$\Delta \mathrm{x}^{1^{\mathrm{INDIRECT,p,s,t}}} = \bar{\mathrm{L}}^{\mathrm{p,s}} \Delta\bar{\mathrm{f}}^{\mathrm{p,s,t}} - \Delta \mathrm{x}^{1^{\mathrm{DIRECT,p,s,t}}} \qquad \text{Equation 61}$$

$$\Delta \mathrm{x}^{1^{\mathrm{INDUCED,p,s,t}}} = \Delta \mathrm{x}^{1^{\mathrm{TOTAL,p,s,t}}} - \Delta \mathrm{x}^{1^{\mathrm{INDIRECT,p,s,t}}} \qquad \text{Equation 62}$$

SM4.5.3.1. Value-Added

Following Miller and Blair[59], a vector of value added coefficients w'_c can be found by dividing the value added in each sector *j* by the sector *j* gross output:

$$\mathrm{w}_{c\,j} = \frac{w_j}{x_j} \;\forall\, j = 1,2,\dots,n,n+1,\dots,n+k \qquad \text{Equation 63}$$

For the new industries, the industry value added is calculated based on the expenditures on salaries for direct labor and on the expected gross operating surplus assuming the sales price equals the levelized cost of the commodity. That is, the difference between the total revenues (calculated as the physical quantity sold times the levelized cost) and the expenditures on intermediates plus labor is allocated to gross operating surplus.

The vector of change in total value added generated in sector *j* can then be found by multiplying the value added coefficients by the change in sectoral output in sector *j*:

$$\Delta \mathrm{w}^1 = \widehat{\mathrm{w}'}_{\mathrm{c}}\, \Delta \mathrm{x}^1 = \begin{bmatrix} \mathrm{w}_{\mathrm{c}1} \Delta \mathrm{x}_1^1 \\ \vdots \\ \mathrm{w}_{\mathrm{cn}} \Delta \mathrm{x}_{\mathrm{n}}^1 \\ \vdots \\ \mathrm{w}_{\mathrm{cn+k}} \Delta \mathrm{x}_{n+k}^1 \end{bmatrix} \quad \textit{Equation 64}$$

The disaggregation of total value added effects can then be done in similar way was for output effects.

SM4.5.3.2. Employment and income

Impact on employment and income are calculated by pre-multiplying the total requirements matrices by employment and salary income coefficient vectors to obtain the employment-generation (E) and income-generation (R) matrices, respectively. The vector of income coefficients is $\bar{\bar{\mathrm{h}}}'_{\mathrm{r}}$, or the last row of the direct coefficient matrix $\bar{\bar{\mathrm{A}}}^{\mathrm{s}}$, as defined in the previous section. The vector of employment coefficients $\bar{\bar{e}}'_c$ is determined in the same way as $\bar{\bar{\mathrm{h}}}'_{\mathrm{r}}$, but with total employment in number of employees from the RAIS data instead of salaries in dollar-worth values.

$$\bar{\mathrm{E}}^{\mathrm{s}} = \widehat{\bar{e}'}_{\mathrm{c}} \bar{\mathrm{L}}^{s} \quad \textit{Equation 65}$$

$$\bar{\bar{\mathrm{E}}}^{\mathrm{s}} = \widehat{\bar{\bar{e}}'}_{\mathrm{c}}\, \bar{\bar{\mathrm{L}}}^{\mathrm{s}} \quad \textit{Equation 66}$$

$$\bar{\mathrm{R}}^{\mathrm{s}} = \widehat{\bar{h}'}_{r} \bar{\mathrm{L}}^{s} \quad \textit{Equation 67}$$

$$\bar{\bar{\mathrm{R}}}^{\mathrm{s}} = \widehat{\bar{\bar{h}}'}_{r}\, \bar{\bar{\mathrm{L}}}^{\mathrm{s}} \quad \textit{Equation 68}$$

The direct, indirect, and induced effects on employment and income can then be found by using the diagonal of the vector of direct employment and income coefficients instead of A and by replacing L by E and R, respectively.

Finally, the impacts on employment are disaggregated by gender. This is done by taking the share of each gender (male and female) in total occupation and in total remunerations of each sector in the RAIS data and then multiplying the employment and income effects by these shares. Gender shares for the new green industries are assumed to be the same of their closest existing industry (e.g., existing Iron and Steel for green steel, existing energy sector for renewable electricity, etc).

SM4.6. Supplemental results

SM4.6.1. Hydrogen production emissions by production step

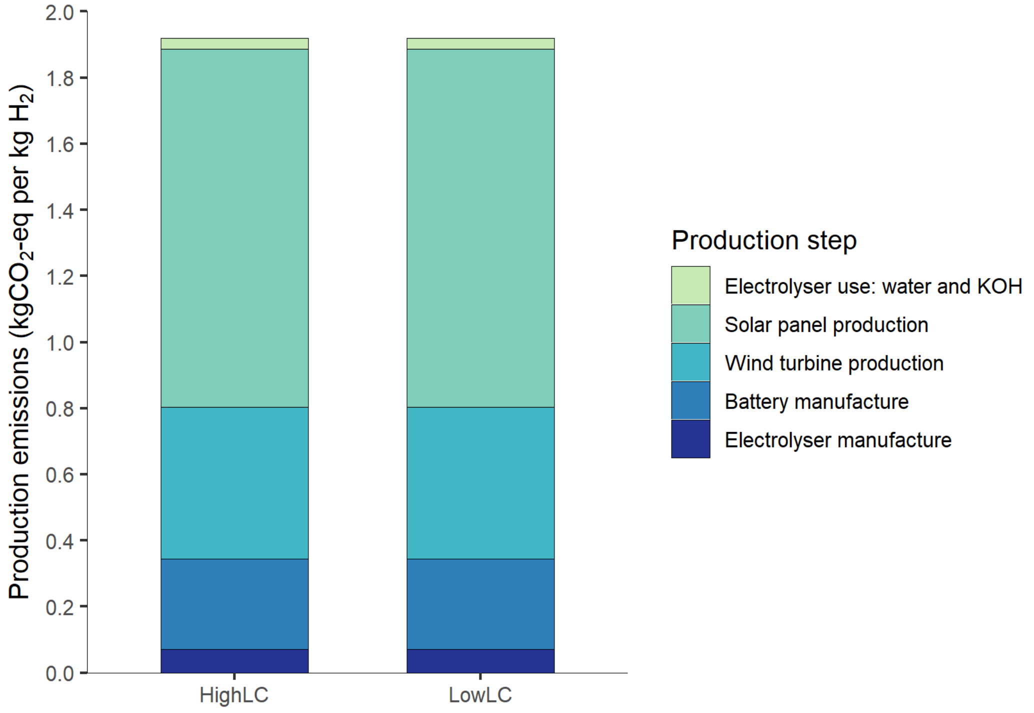

Figure S5 - Greenhouse gas emissions associated with green hydrogen production (in kgCO2-eq per kg H2) in the high local content (HighLC) and the low local content (LowLC) scenario.

SM4.6.2. Results from sensitivity analysis on sponge iron export

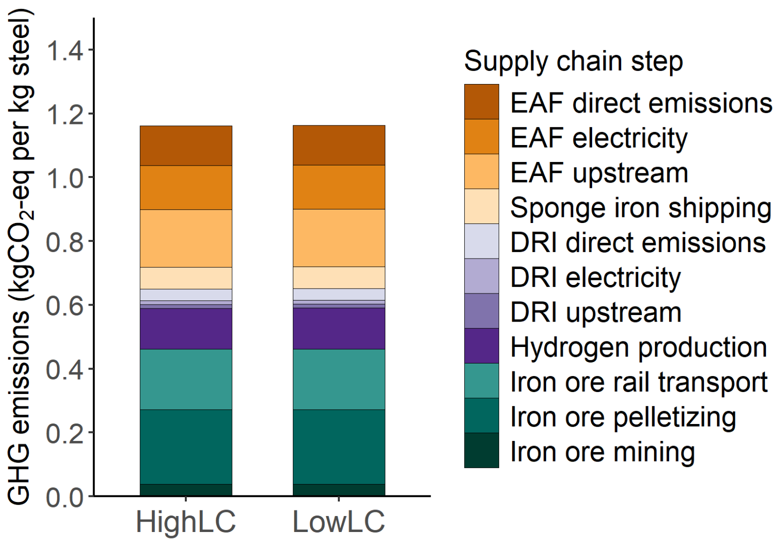

Figure S 6 - Climate impacts of green steel production, disaggregated by supply chain step for the sensitivity analysis scenario of sponge iron export. Climate impacts are shown in kgCO₂eq per kg steel. In the sponge iron export scenario, steps include hydrogen production in Ceará, iron ore mining in the Carajás mine, pelletizing, rail transport to Ceará, hydrogen-based direct reduction of iron ore (DRI) to produce sponge iron in Ceará, shipping of sponge iron followed by electric arc furnace (EAF) steelmaking in Ijmuiden. The high local content (HighLC) scenario, using North-East Brazillian electricity for manufacturing of wind turbines, results in 0.1% lower emissions than the low local content (LowLC) scenario, which uses the global electricity mix.

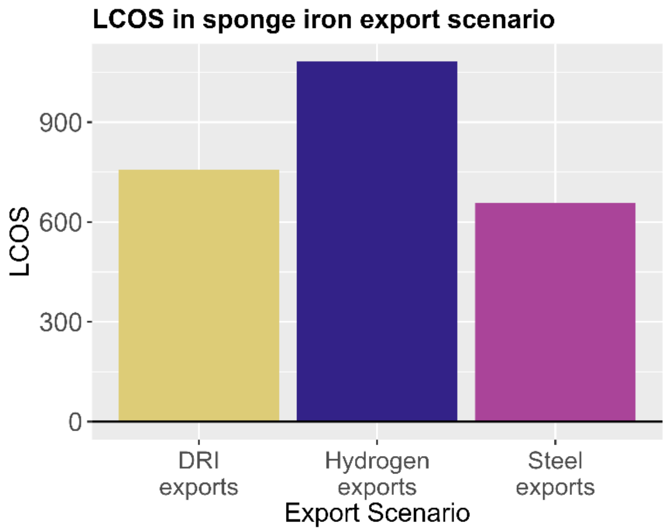

Figure S7 - Cost results for the sensitivity analysis of exporting sponge iron. For employment data, it was assumed that 50% of workers would work at the DRI plant while 50% of workers would work at the EAF plant.

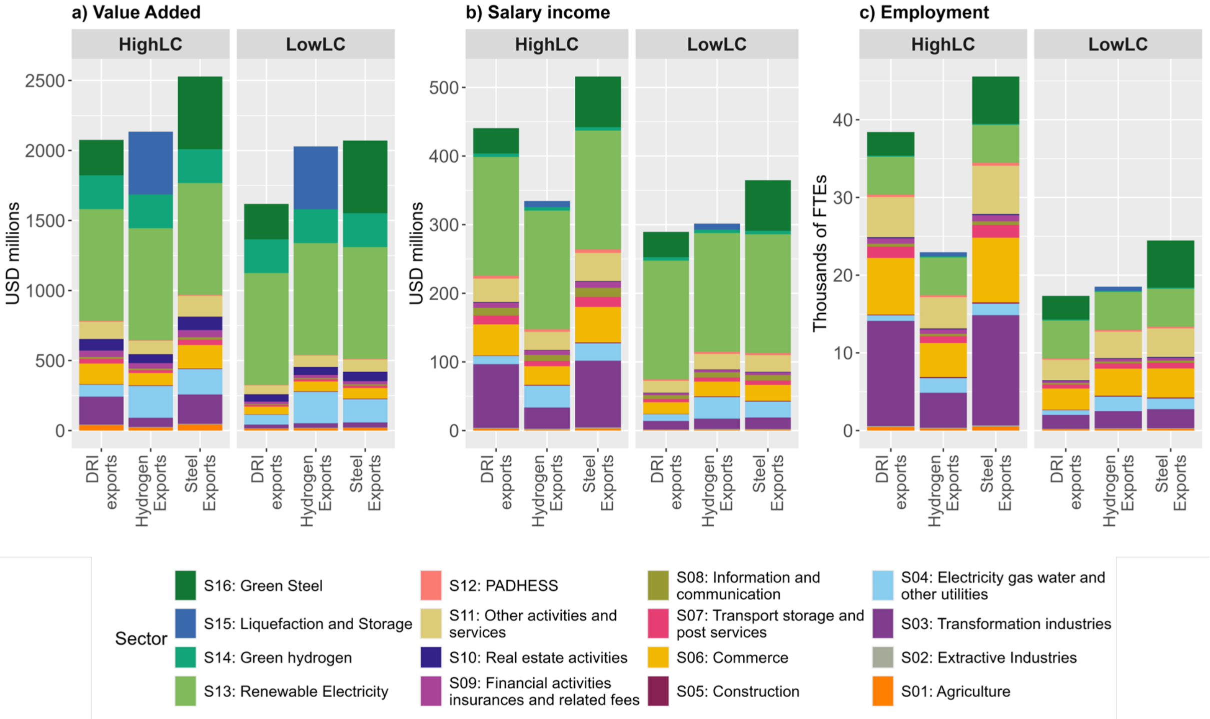

Figure S8 - Socioeconomic impacts of the sponge iron export scenario. For employment data, it was assumed that 50% of workers would work at the DRI plant while 50% of workers would work at the EAF plant.

SM4.6.3. Results from sensitivity analysis on technoeconomic assumptions

Energy prices tend to fluctuate over time. Grid electricity prices in the base year were 78 USD/MWh in Brazil[42] and 73 USD/MWh in the Netherlands[48]. Grid electricity prices in 2023 increased to 103 USD/MWh in Brazil[63] and to 261 USD/MWh in the Netherlands[48]. If these prices are taken into account, then the LCOS in the green steel exports scenario becomes 671 USD/t steel and the LCOS in the green hydrogen exports scenario becomes 1207 USD/t steel. Here, the green steel produced in IJmuiden would hence be 80% more expensive than the green steel produced in Ceará and then transported to IJmuiden (Table S19).

Regarding hydrogen transport costs, the default case assumed the average value from IRENA[41] estimates. The lower and upper bound of IRENA estimates for hydrogen transport costs would lead to a

LCOS in the green hydrogen export scenario of 907 USD/t steel and 1206USD/t steel, respectively. This means costs in the hydrogen export scenario would be 50-83% higher than in the green steel export scenario(Table S19).

The weighted average cost of capital (WACC) impacts the sales price of commodities as it influences the amount of surplus needed to compensate for the initial capital investments, impacting the levelized cost. As such, it impacts industry output, and also total value added via the gross operating surplus component, as expenditures in intermediate inputs and labor remain constant. However, the WACC varies with economic climate and perceived risk.

Therefore, we model a change of the WACC for the levelized cost of green hydrogen (LCOH), liquefaction and storage of green hydrogen (LCOLS), and green steel production (LCOS) from 10% (default assumption) to 6% (low WACC) and 12% (high WACC) (Table S18). We do not model the effect on the levelized cost of energy since renewable electricity is a more mature activity than the others and the renewable electricity price and quantity are the same for all scenarios, not impacting the *difference* between the export scenarios. The results for the LCOS under different WACC assumptions are summarized in Table S19.

Table S18 – LCOH and LCOLS under different WACC assumptions

Levelized cost	Low WACC (6%)	Default (10%)	High WACC (12%)
LCOH	3.96 USD/kgH2	4.17 USD/kgH2	4.28 USD/kgH2
LCOLS	2.06 USD/kgH2	2.49 USD/kgH2	2.72 USD/kgH2

Table S19 - Summary of results for the levelized cost of steel (LCOS) according to different sensitivity analysis cases and production locations

Sensitivity analysis case	Co-locating green steel production in Ceará (Steel exports)	Locating green steel production in the Netherlands (Hydrogen exports or DRI exports)	NL/CE	Co-location savings	Difference to default	
					Steel export	H2 export
Default	658	1082	164%	-39%	100%	100%
H2 replacing natural gas	695	1164	167%	-40%	106%	108%
DRI	658	758	115%	-13%	100%	70%
Energy crisis	671	1207	180%	-44%	102%	112%
TranspHigh	658	1205	183%	-45%	100%	111%
TranspLow	658	987	150%	-33%	100%	91%
RealDevaluation	655	1082	165%	-39%	100%	100%
All WACC 6%	610	661	108%	-8%	93%	61%
All WACC12%	685	1341	196%	-49%	104%	124%
WACC different (CE 10%, NL 6%)	658	688	105%	-4%	100%	64%
WACC different (CE 12%, NL 6%)	685	703	103%	-3%	104%	65%
Energy+Transp	671	1308	195%	-49%	102%	121%
WACC different + TranspLow	685	628	92%	9%	104%	58%
WACC different + DRI	685	743	108%	-8%	104%	69%

Figure S9 shows that whenever both liquefaction and storage and green steel production have the same WACC, the calculated value added from green steel is slightly higher than that of liquefaction and storage. The only two situations where liquefaction and storage would have a higher impact on value added would be 1) when green hydrogen is used to replace natural gas in green steel production, leading to a lower green steel output for a given green hydrogen production and 2) if liquefaction and storage has a higher WACC than green steel, leading to higher value added impacts.

Note, however, that changes in the WACC only affect value added impacts and not employment and salary income as it changes only the gross operating surplus component of the expenditures (Figure S10and Figure S11). Employment and salary income effects are impacted by changes in direct employment expenditures, which can reflect a different employment factor (i.e., number of jobs per unit of output) or a salary that is higher or lower than the default assumption. For employment and salary income, green steel consistently outperforms liquefaction and storage. Even if the employment in liquefaction and storage was +40% higher and employment in green steel was –40% lower than the default assumption, direct employment in green steel would be more than double of that in liquefaction.

Under the default case, approximately half of the iron ore pellets are assumed to be sourced from local firms in the HighLC. If all iron pellets are processed by local firms (PelletDom), employment effects for the green steel exports scenario could increase by up to 50% in the operation phase. If all iron pellets are fully imported in the HighLC (PelletImp), with only wind turbines and electrolyzers still being sourced domestically, employment effects could decrease by 25% in the operation phase in the green steel exports scenario. If iron pellets are fully imported, the difference between HighLC and LowLC also decreases, as only wind turbines and electrolyzers are included in the local content scenarios. The full imports of iron pellets also reduces the difference between the two export scenarios, since iron pellets are only used in the green steel exports scenario. This indicates that localizing iron pellets production could significantly increase the difference between the high and low linkage scenarios.

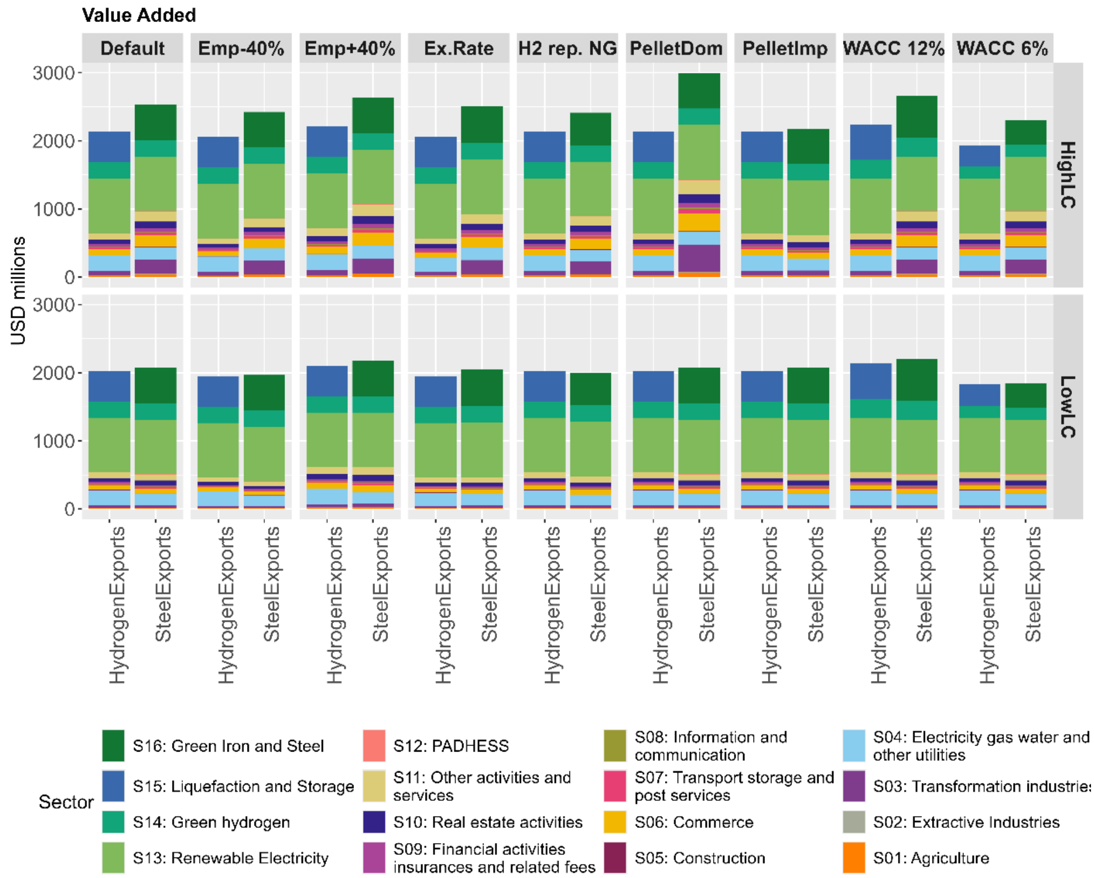

Figure S9 - Sensitivity analysis results for impacts on value added

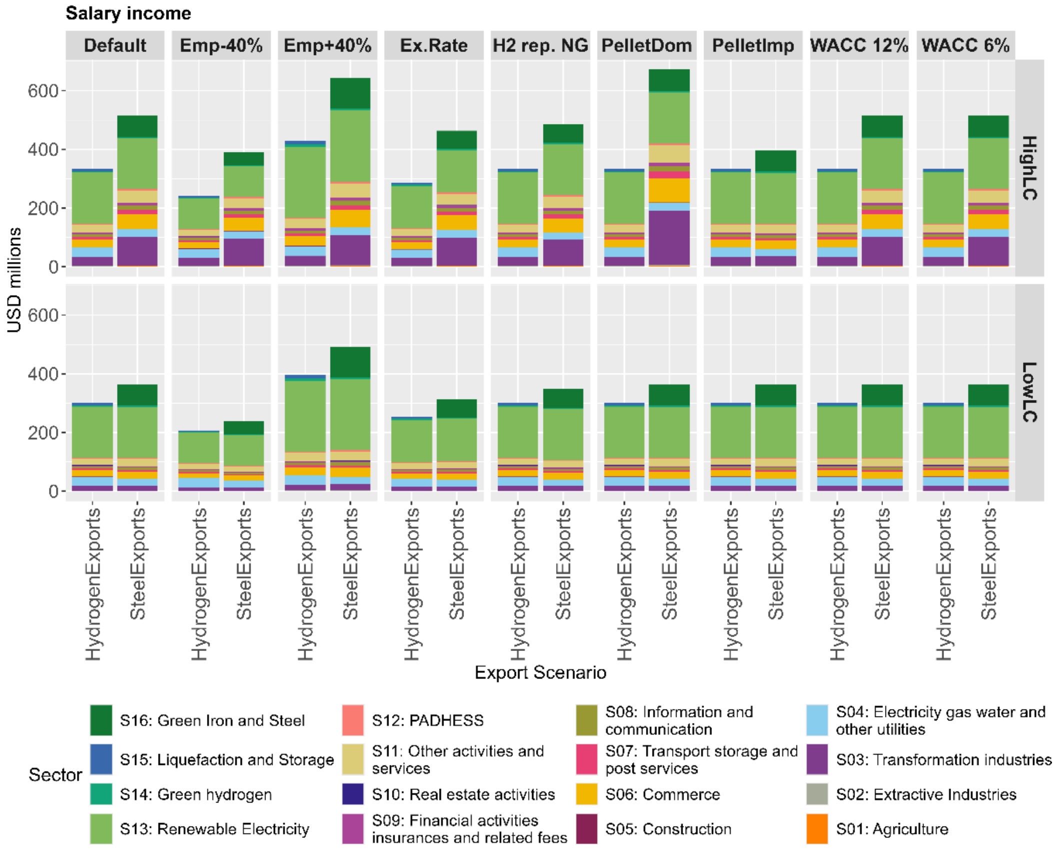

Figure S10- Sensitivity analysis results for impacts on salary income

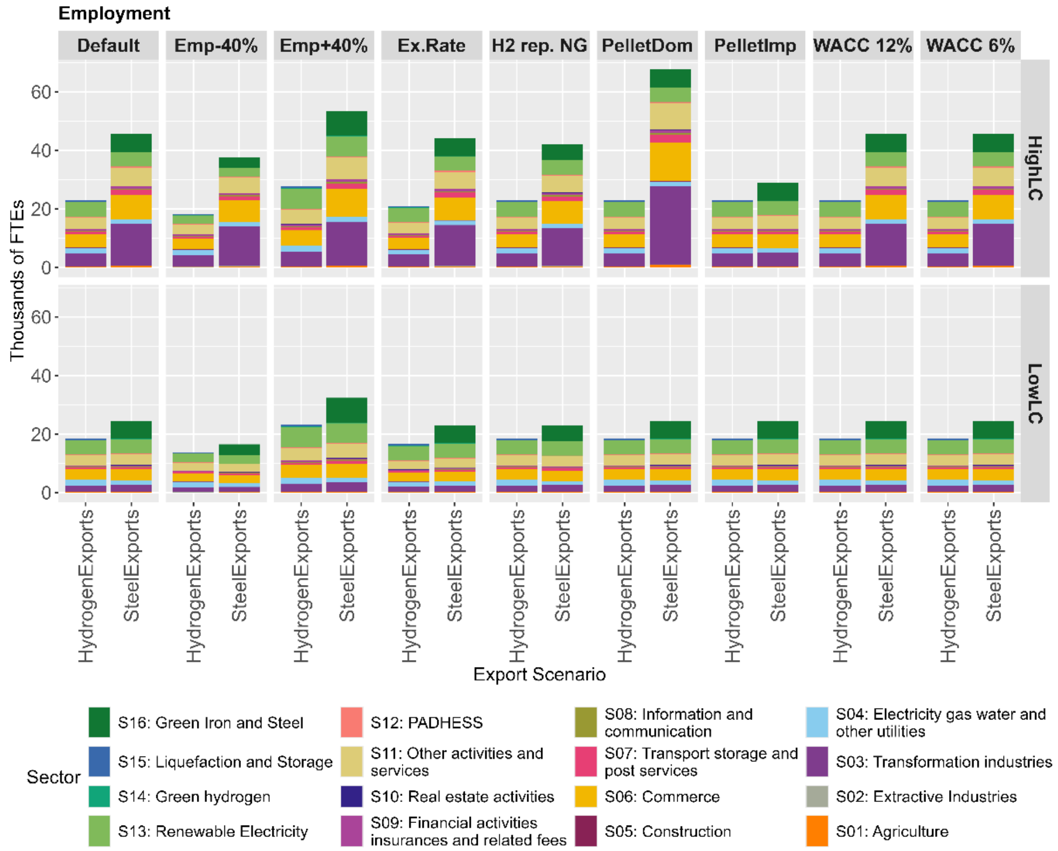

Figure S11 - Sensitivity analysis results for impacts on employment

SM4.7. Supplemental references

1. Caiafa, C., Romijn, H., and de Coninck, H. (2024). Identifying opportunities and risks from green hydrogen: a framework and insights from a developing region in Brazil. Climate Policy, 1–19. https://doi.org/10.1080/14693062.2024.2407848.

2. Krishnan, S., Corona, B., Kramer, G.J., Junginger, M., and Koning, V. (2024). Prospective LCA of alkaline and PEM electrolyser systems. Int J Hydrogen Energy *55*, 26–41. https://doi.org/10.1016/j.ijhydene.2023.10.192.

3. Danish Energy Agency (2022). Technology data. https://ens.dk/en/our-services/projections-and-models/technology-data.

4. Smolinka, T., Wiebe, N., Stechele, P., Palzer, A., Lehner, F., Jansen, M., Kiemel, S., Miehe, R., Wahren, S., and Zimmermann, F. (2018). Studie IndWEDe: Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme (NOW GmbH).

5. Palmer, G., Roberts, A., Hoadley, A., Dargaville, R., and Honnery, D. (2021). Life-cycle greenhouse gas emissions and net energy assessment of large-scale hydrogen production via electrolysis and solar PV. Energy Environ Sci *14*, 5113–5131. https://doi.org/10.1039/d1ee01288f.

6. Gerloff, N. (2021). Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. J Energy Storage *43*, 102759. https://doi.org/10.1016/j.est.2021.102759.

7. Hydrohub (2020). Integration of Hydrohub GigaWatt Electrolysis Facilities in Five Industrial Clusters in The Netherlands.

8. European Commission (2023). Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid a.

9. Government of Ceará (2022). Atlas eólico e solar do estado do Ceará (Ceará's Wind and Solar Atlas).

10. Lazard (2021). Lazard's levelized cost of storage analysis—version 7.0.

11. Terlouw, T., Bauer, C., McKenna, R., and Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy Environ Sci *15*, 3583–3602. https://doi.org/10.1039/d2ee01023b.

12. de Kleijne, K., Huijbregts, M.A.J., Knobloch, F., van Zelm, R., Hilbers, J.P., de Coninck, H., and Hanssen, S. V (2024). Worldwide greenhouse gas emissions of green hydrogen production and transport. Nat Energy. https://doi.org/10.1038/s41560-024-01563-1.

13. Al-Breiki, M., and Bicer, Y. (2020). Investigating the technical feasibility of various energy carriers for alternative and sustainable overseas energy transport scenarios. Energy Convers Manag *209*, 112652. https://doi.org/10.1016/j.enconman.2020.112652.

14. Kolb, S., Müller, J., Luna-Jaspe, N., and Karl, J. (2022). Renewable hydrogen imports for the German energy transition – A comparative life cycle assessment. J Clean Prod *373*. https://doi.org/10.1016/j.jclepro.2022.133289.

15. Wijayanta, A.T., Oda, T., Purnomo, C.W., Kashiwagi, T., and Aziz, M. (2019). Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. Int J Hydrogen Energy *44*, 15026–15044. https://doi.org/10.1016/j.ijhydene.2019.04.112.

16. Sand, M., Skeie, R.B., Sandstad, M., Krishnan, S., Myhre, G., Bryant, H., Derwent, R., Hauglustaine, D., Paulot, F., Prather, M., et al. (2023). A multi-model assessment of the Global Warming Potential of hydrogen. Commun Earth Environ *4*. https://doi.org/10.1038/s43247-023-00857-8.

17. OEC (2024). Iron Ore in Netherlands. https://oec.world/en/profile/bilateral-product/iron-ore/reporter/nld.

18. Fun, M.A., Cepeda, S., Kneipp, R.B., and Caprace, J.-D. (2019). 11th International Seminar on Inland Waterways and Waterborne Transportation: Transportation of Iron Ore-A Case Study of the Northern Brazilian Region https://doi.org/10.17648/sobena-hidroviario-2019-110565.

19. Rosner, F., Papadias, D., Brooks, K., Yoro, K., Ahluwalia, R., Autrey, T., and Breunig, H. (2023). Green steel: design and cost analysis of hydrogen-based direct iron reduction. Energy Environ. Sci. *16*, 4121–4134. https://doi.org/10.1039/D3EE01077E.

20. Instituto Brasileiro de Geografia e Estatística - IBGE (2022). System of Regional Accounts: Ceara. https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9054-contas-regionais-do-brasil.html?edicao=34530.

21. IRENA (2020). Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5oC climate goal.

22. ISPT (2020). Gigawatt green hydrogen plant: state of the art design and total installed capital costs.

23. UK BE&IS (2021). Hydrogen Production Costs (Government of the United Kingdom).

24. NREL (2018). H2A: Hydrogen Analysis Production Models. Current Central Electrolysis version 3.2018. https://www.nrel.gov/hydrogen/h2a-production-models.html.

25. Lazard (2021). Levelized cost of hydrogen analysis (Lazard).

26. Ministry of Employment (2022). RAIS database. http://pdet.mte.gov.br/rais.

27. Gallardo, F.I., Monforti Ferrario, A., Lamagna, M., Bocci, E., Astiaso Garcia, D., and Baeza-Jeria, T.E. (2021). A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. Int J Hydrogen Energy *46*, 13709–13728. https://doi.org/10.1016/j.ijhydene.2020.07.050.

28. IRENA (2018). Hydrogen from renewable power technology outlook for the energy transition (IRENA).

29. Eichman, J., Townsend, A., and Melaina, M. (2016). Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets (National Renewable Energy Laboratory (NREL)).

30. IRENA (2022). Global Hydrogen Trade To Meet The 1.5oC Climate Goal Part III - Green Hydrogen Cost and Potential. 46. https://www.irena.org/Publications/2022/May/Global-hydrogen-trade-Cost.

31. IRENA (2022). Renewable Power Generation Costs.

32. Fearnehough, H., and Skribbe, R. (2022). Economic Impact Model for Electricity Supply Methodology Note February 2. (New Climate Institute).

33. NREL (2022). JEDI Models. https://www.nrel.gov/analysis/jedi/models.html.

34. Vasconcellos, H.A.S., and Caiado Couto, L. (2021). Estimation of socioeconomic impacts of wind power projects in Brazil's Northeast region using Interregional Input-Output Analysis.

Renewable and Sustainable Energy Reviews *149*, 111376. https://doi.org/10.1016/j.rser.2021.111376.

35. Cameron, L., and van der Zwaan, B. (2015). Employment factors for wind and solar energy technologies: A literature review. Renewable and Sustainable Energy Reviews *45*, 160–172. https://doi.org/10.1016/j.rser.2015.01.001.

36. Nasirov, S., Girard, A., Peña, C., Salazar, F., and Simon, F. (2021). Expansion of renewable energy in Chile: Analysis of the effects on employment. Energy *226*, 120410. https://doi.org/10.1016/j.energy.2021.120410.

37. Meyer, I., and Sommer, M.W. (2016). Employment effects of renewable energy deployment - a review. International Journal of Sustainable Development *19*, 217. https://doi.org/10.1504/IJSD.2016.078274.

38. Kattumuri, R., and Kruse, T. (2019). Renewable technologies in Karnataka, India: jobs potential and co-benefits. Clim Dev *11*, 124–137. https://doi.org/10.1080/17565529.2017.1410085.

39. Simas, M., and Pacca, S. (2014). Assessing employment in renewable energy technologies: A case study for wind power in Brazil. Renewable and Sustainable Energy Reviews *31*, 83–90. https://doi.org/10.1016/j.rser.2013.11.046.

40. Cole, W., Frazier, W., and Augustine, C. (2021). Cost Projections for Utility-Scale Battery Storage: 2021 Update (National Renewable Energy Laboratory).

41. IRENA (2022). Global Hydrogen Trade to Meet the 1.5oC Climate Goal Part II - Technology Review of Hydrogen Carriers. 156. https://www.irena.org/Publications/2022/Apr/Global-hydrogen-trade-Part-II.

42. Confederação Nacional da Indústria (2022). Consumidor industrial do Brasil paga a segunda energia mais cara entre principais países exportadores. https://jornalismo.portaldaindustria.com.br/cni/desafio-brasil/07 06 - INFRA Energia.pdf.

43. Air Liquide (2022). Air Liquide inaugurates in the U.S. its largest liquid hydrogen production facility in the world. Press Releases. https://usa.airliquide.com/sites/al_us/files/2022-07/final_nlv_opening_pr_.pdf.

44. Vogl, V., Åhman, M., and Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. J Clean Prod *203*, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279.

45. Tata Steel (2020). Tata Steel IJmuiden BV Report & Accounts 2020.

46. Ministry of Energy and Mines (2018). Boletim mensal de acompanhamento da indústria de gás natural.

47. Verpoort, P.C., Gast, L., Hofmann, A., and Ueckerdt, F. (2024). Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. Nat Energy *9*, 491–503. https://doi.org/10.1038/s41560-024-01492-z.

48. EUROSTAT (2024). Electricity prices for non-household consumers - bi-annual data. Data Browser. https://doi.org/10.2908/nrg_pc_205.

49. EUROSTAT (2024). Gas prices for non-household consumers - bi-annual data. Data Browser. https://doi.org/10.2908/nrg_pc_203 Copy DOI URL.

50. European Central Bank (2025). US dollar (USD). Statistics (Ber). https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

51. Damodaran, A. (2025). Databases: Cost of Capital. Archived data. https://pages.stern.nyu.edu/~adamodar/New_Home_Page/dataarchived.html.

52. IEA (2021). Average weighted average cost of capitals of iron and steel companies by region, 2016-2020.

53. ANP (2025). Boletim da Produção de Petróleo e Gás Natural. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/boletins-anp/boletins/arquivos-bmppgn/2025/fevereiro.pdf.

54. IEA (2025). Coal Supply: Brazil. https://www.iea.org/countries/brazil/coal.

55. Krishnan, S., Corona, B., Kramer, G.J., Junginger, M., and Koning, V. (2024). Prospective LCA of alkaline and PEM electrolyser systems. Int J Hydrogen Energy *55*, 26–41. https://doi.org/10.1016/j.ijhydene.2023.10.192.

56. Schmidt, T.S., Beuse, M., Zhang, X., Steffen, B., Schneider, S.F., Pena-Bello, A., Bauer, C., and Parra, D. (2019). Additional Emissions and Cost from Storing Electricity in Stationary Battery Systems. Environ Sci Technol *53*, 3379–3390. https://doi.org/10.1021/acs.est.8b05313.

57. Bauer, C., Desai, H., Heck, T., Sacchi, R., Schneider, S., Terlouw, T., Treyer, K., and Zhang, X. (2022). Electricity storage and hydrogen – technologies, costs and impacts on climate change (PSI on behalf of the Swiss Federal Office of Energy (SFOE)).

58. Stolzenburg, K., and Mubbala, R. (2013). Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY). Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

59. Miller, R.E., and Blair, P.D. (2021). Input-Output Analysis (Cambridge University Press) https://doi.org/10.1017/9781108676212.

60. Guilhoto, J.J.M., and Sesso Filho, U.A. (2005). Estimação da matriz insumo-produto a partir de dados preliminares das contas nacionais. Economia Aplicada *9*, 1–23.

61. Guilhoto, J.J.M., and Sesso Filho, U.A. (2010). Estimação da matriz insumo-produto utilizando dados preliminares das contas nacionais: aplicação e análise de indicadores econômicos para o Brasil em 2005. Revista Economia & Tecnologia *6*, 1–23. https://doi.org/10.5380/ret.v6i4.26912.

62. Vale, V., and Perobelli, F. (2020). Análise Insumo-Produto: Teoria e Aplicações no R (NEDUR/LATES).

63. EPE (2024). Annual statistical yearbook of electricity 2023. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/anuario-estatistico-de-energia-eletrica.