SUPPLEMENTARY MATERIAL

CHAPTER 6

A global perspective: decarbonizing the Dutch steel industry via green hydrogen imports versus industry relocation

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SM1 Augmenting the MRSUTs

SM1.1 Disaggregating brown steel production from other basic metals

The Dutch Iron and Steel industry is disaggregated from the "C24: Basic Metals" sector, the most disaggregated level available in the FIGARO table for 2019. This disaggregation ensures that the calibration of current steel production technology closely reflects actual physical quantities and prices for that year. The disaggregated use structure of the Dutch iron and steel industry is derived by combining material requirements, commodity price data, and total company revenues for Tata Steel production via BF-BOF in 2019.

The monetary value of the use of a commodity c of an industry j can be obtained by multiplying the physical use of a commodity c ($q^P_{c,j}$) by the price of that commodity (p_c).

$$u_{c,j} = p_c \, q^P_{c,j} \tag{SM3.1}$$

The iron and steel commodity is also disaggregated from other basic metals in both the use and make tables, assuming all iron and steel commodity in the Netherlands is produced by Tata Steel. Trade shares are assumed to be the same as those of the Basic Metals sector for lack of better data. Use coefficients are calculated following Eqs. 6.1 and 6.2 and add up to one since this is simply a disaggregation of an already balanced table. Regarding emissions, we take the tonnes of CO_2 equivalent emissions regulated under the ETS that are reported by Tata Steel relative to the total emissions of the Dutch basic metals. Industry and commodity disaggregation is applied only to the Netherlands, where the existing iron and steel industry is impacted. Thus, the disaggregated iron and steel commodity represents Tata Steel IJmuiden's production, whether produced locally or in Brazil and shipped to current customers.

The Dutch Iron and Steel industry consists of one single large-scale producer, Tata Steel Nederland B.V., which owns one fully integrated plant in IJmuiden (Keys et al., 2019). Tata Steel's plant in IJmuiden has produced around 7Mt/yr of steel in the past decade, about 4% of the production in the European Union, and all via the Blast Furnace-Basic Oxygen Furnace (BF-BOF) technological route (Keys et al., 2019; World Steel Association, 2020).

The most disaggregated level in the FIGARO tables is the industry "C24: Manufacture of Basic Metals", which includes other metal products such as aluminum and copper. Hence, the SUTs had to be disaggregated to differentiate between Tata Steel's production and the rest of the Dutch Basic Metals sector, which is composed mainly of aluminum production (Kortes and van Dril, 2019; Keys et al., 2019).

The use table was disaggregated for both columns and rows to reflect the disaggregation of the Dutch Iron and Steel *industry* from the sector "C24: Manufacture of Basic Metals" and the disaggregation of the Dutch Iron and Steel *commodity* from the "CPA24: Basic Metals" commodity category, respectively. The column disaggregation reflects different production technologies between the two sub-industries whereas the row disaggregation differentiates between the consumption of Dutch steel and consumption of other Dutch basic metal products by all industries and regions.

For the column disaggregation, the production technology for traditional Brown Steel was inferred based on the combination of physical quantities from the material flows from Keys et al. (2019) with data on coal, scrap, and CO2 emission prices from Tata Steel (2020a) and on electricity and natural gas prices for industrial consumers in the Netherlands published by EUROSTAT (EUROSTAT, 2024b,a), as well as supplementary sources such as Vogl et al. (2018) and Rosner et al. (2023) for prices of smaller inputs such as limestone. Table SM3.1 summarizes the physical quantities and prices. As expenditures on these commodities were less than the total expenditures on intermediate inputs reported by Tata Steel

(2020a), the remaining amount of expenditures on intermediate goods was allocated to the commodities for which no data from material flows was available. These commodities were related to services and other consumables (i.e. office materials), so it is logical that they did not appear in the material flows data. The allocation was done assuming a similar expenditure structure among these remaining commodities as the aggregated basic metals industry since no other data was available. This would essentially imply that, in the disaggregated table, Tata Steel has a similar structure of expenditure on individual services and other consumables relative to total expenditures on services and other consumables than other Dutch basic metals industries, but a different expenditure structure for the commodities used in the manufacturing process and also a different share of expenditures going to commodities for manufacturing process versus to other services and consumables. Margins from FIGARO tables were used to adjust from consumer to producer prices. Employment costs are directly available from Tata Steel (2020a), as well as profits, which were allocated to the gross operating surplus. The net taxes on production were split proportionally to the share of the EU Emissions Trading System (ETS) regulated emissions for Tata Steel (Tata Steel, 2020b; Keys et al., 2019; Kortes and van Dril, 2019) relative to the total sector emissions from the FIGARO table. The intermediates plus the value added components added up to the total company revenue reported by Tata Steel (2020a). Trade shares from the aggregated sector were used to assign total commodity use to commodities from different regions. The remaining values for each commodity and value-added component were assigned to the "Other Basic Metals" industry column. The column of use coefficients was constructed by dividing commodity expenditures by total output (see SM3.1.2.1).

Table SM3.1: Summary of physical quantities and prices for the iron and steel production process via the BF-BOF technological route in the IJmuiden plant

Input	Self prod	Input per ts	Unit	Unit cost (EUR)	Source	CPA	€ per ts
Iron fine	No	1.15	t	74	Tata Steel (2020)	B	85.13
Coal	No	0.40	t	163	Tata Steel (2020)	B	65.20
Pulverized Coal	No	0.22	t	70	IEA (2020)	B	15.09
Limestone	No	0.1	kg	0.1	Volgt et al (2018)	B	0.01
Natural gas	No	372.34	kWh	0.022	EUROSTAT (2024)	B	8.30
Lump ore	No	0.04	t	74	Tata Steel (2020)	B	2.94
Burnt lime	No	0.02	t	100	Volgt et al (2018)	B	2.41
Natural gas	No	67.80	kWh	0.022	EUROSTAT (2024)	B	1.51
Dolomite lime	No	0.01	t	100	Volgt et al (2018)	B	0.85
Oil	No	0.01	barrels	57.7	OECD (2024)	C19	0.59
Oxygen	No	0.18	t	55	Volgt et al (2018)	C20	10.00
Coke	Yes	0.28	t	0	Self produced	C19	0.00
Pellets	Yes	0.66	t	0	Self produced	C24	0.00
Sinter	Yes	0.53	t	0	Self produced	C24	0.00
Electricity	No	259.65	kWh	0.068	EUROSTAT (2024)	D	17.70
Electricity	Yes	19.70	kWh	0	Self produced	D	0.00
Scrap steel	No	0.17	t	221	Tata Steel (2020)	E	37.62

The disaggregation of the row was done to ensure that the disaggregated commodity reflected the iron and steel commodity produced by Tata Steel that is consumed by all other industries. The revenues by destination reported by Tata Steel (2020a) were used to allocate the total purchases by all industries in a given world region. Then, this total amount was allocated to individual consumer industries within the same region assuming the same proportion as for the aggregated basic metals sector since no other data was available. The remaining sales of the aggregated basic metals commodity were allocated to the disaggregated "Other basic metals" commodity row.

The total commodity output of the Dutch Iron and Steel commodity in the use table was equal to the total output of Tata Steel since it is assumed that this is a single industry producing a single commodity. Similarly, in the make table, since the disaggregated iron and steel commodity was exclusively produced by Tata Steel, the value equivalent to the industry and commodity output was inserted in the respective cell with zeros for the other cells in the new row and column. The same value was deducted from the old column and row of the aggregated Basic Metals sector. Therefore, both in the use and make tables, the sum of the ”Iron and Steel” and ”Other Basic metals” columns and rows always add up to column and row of the aggregated matrix.

SM1.2 Inserting new industries and commodities

SM3.1.2.1 Green steel production

For the change in steel production technology, it was assumed that only the expenditures on commodities directly used in the manufacturing process would change, but that the expenditures on other services and consumables would remain the same. Hence, the construction of the new industry column in the use tables was done by deducting the values of manufacturing commodities computed based on material flows for the Brown Steel (BF-BOF route) and adding the calculated values for the Green Steel technology, following the Rosner et al. (2023) H-DRI-T case, which offers the highest emission reduction potential. Given that Tata Steel plant in IJmuiden is fully integrated, producing its own coke, pellets, and pig iron (Keys et al., 2019), we assume the Green Steel plant would also be integrated for both industry location cases.

The required quantities of material and labor inputs for this production route are summarized in Table SM3.2. The prices of globally traded commodities were assumed to be the same for both the green hydrogen imports and the relocation scenarios. Unit costs for natural gas, electricity and labor were taken to reflect the prices for industrial consumers in the Netherlands and Brazil, respectively (EUROSTAT, 2024b,a; EPE, 2020). The price of green hydrogen was assumed to be the levelized cost of hydrogen (LCOH) production, as this would be the minimum sales price for a zero profit condition (see SM3.1.2.2). This price is the same in both scenarios, but it is assumed that the scenario of green hydrogen imports would require additional steps of liquefaction, shipping of liquefied hydrogen, and hydrogen regasification, which incurs additional costs. In this scenario, no steel would be transported from Brazil to the Netherlands in this scenario. In the relocation scenario, additional steps for hydrogen transport are not needed, but each tonne of steel has to be transported from Brazil to the Netherlands, so the transport cost of steel is added instead. Labor costs are based on Tata Steel reports for operations in the Netherlands (Tata Steel, 2020a) and on data from the Brazilian Ministry of Employment (Ministry of Employment, 2022) on salaries for the iron and steel sector in the state of Ceará, where the green export hub is located.

Direct emissions for green steel were taken from Rosner et al. (2023). Since the Green Steel plant would integrate pelletizing, coke production, iron reduction, and steelmaking, we take the emissions from these four steps as the direct emissions for green steel production to ensure comparability with brown steel. This leads to an emission factor of 0.366 kgCO2/kgsteel.

Since our analysis used input output data for 2019, all price assumptions are based on data for the year 2019 to ensure values are in real terms. Nevertheless, these prices have presented strong variation in the previous years following, e.g., the energy crisis in Europe, and will change substantially as energy systems decarbonize and new carbon pricing regulations come into force. Therefore, we also conducted a sensitivity analysis for the price increases of green and brown steel compared to the prices of brown steel in 2019 considering different prices for electricity, green hydrogen, natural gas, and carbon (see SM3.2).

Table SM3.2: Summary of physical quantities and prices for the iron and steel production process via the H-DRI technological route in the IJmuiden plant. Physical quantities for material inputs are based on the H-DRI-T steelmaking route from Rosner et al (2023).

Green steel production	Input per ts	Unit	Unit cost (EUR)	Cost source	EUR/ts
Common assumptions					
Carbon	34	kg	0.2	Rosner et al (2023)	5.4
Lime	51	kg	0.1	Vogl et al (2018)	5.1
Coal	0.01	t	163	Tata Steel (2020)	2.1
Iron fine	1.73	t	74	Tata Steel (2020)	128
Raw water withdrawal	1.20	t	2.0	Lazard (2021)	2.4
Green H2 imports scenario					
Natural gas (NL)	203	kWh	0.0223	EUROSTAT (2024)	4.5
Electricity (NL)	585	kWh	0.0682	EUROSTAT (2024)	40
Labour (NL)	0.0013	FTE	79610	Tata Steel (2020)	101
Hydrogen production	76	kg	3.19	Calculated and IRENA (2022)	242
Hydrogen liquefaction	76	kg	2.57	IRENA (2022)	195
Hydrogen regasification	76	kg	0.67	IRENA (2022)	51
Hydrogen transport	76	kg	1.5	IRENA (2022)	117
Steel transport	0	t	5.0	Verpoort et al (2024)	0
Relocation scenario					
Natural gas (BR)	203	kWh	0.0381	ANP (2024)	9.9
Electricity (BR)	585	kWh	0.1086	EPE(2019)	64
Labour (BR)	0.0013	FTE	10807	Ministry of Employment (2024)	14
Hydrogen production	76	kg	3.19	Calculated and IRENA (2022)	242
Hydrogen liquefaction	0	kg	2.57	IRENA (2022)	0
Hydrogen regasification	0	kg	0.67	IRENA (2022)	0
Hydrogen transport	0	kg	1.5	IRENA (2022)	0
Steel transport	1	t	5.0	Verpoort et al (2024)	5

Capital expenditures for the construction of the green steel plant were taken from the same study used to derive the life cycle inventory to ensure consistency in the production technology (Rosner et al., 2023). Since Rosner et al. (2023) inflate prices to the year of 2022, we deflate them back to reflect 2019 prices.

Table SM3.3: Capital expenditures for the construction of the Green Steel plant based on Rosner et al (2023)

Sector	CAPEX item	Rosner et al (2023)	USD 2019/ts	EUR 2019/ts
C26-C33	Shaft furnace	116	100	89
C26-C33	Pre-Heater	4	3	3
C26-C33	Recycle compressor	7	6	6
C26-C33	EAF & Casting	237	205	182
C26-C33	Cooling tower	20	18	16
F	Buidings, storage, water	77	66	59
C26-C33	Electrical & instrumentation	38	32	29
C26-C33	Other plant equipment	107	92	82
C26-C33	Preproduction costs	83	72	64
I-U	Other owner costs	108	93	83
Total		797	687	612

Since the prices and the physical output of steel are kept constant for the model in real terms, the use coefficients are obtained by dividing commodity expenditures by Tata Steel's output of 2019.

The use values for the Green Iron & Steel sector in the Netherlands are based on physical quantities from material flows and the equivalent commodity prices as the Dutch Brown Steel sector since the model is in constant prices. The Green Iron & Steel sector in Brazil has the same physical quantities as green steel in the Netherlands, but prices are adapted to regional prices for inputs that are not easily traded (i.e., electricity, labor) or adapted to reflect difference in transport costs for green hydrogen between scenarios. The use values for the new industries in the augmentation process are in constant prices, so their use values are:

$$u^*_{c,j} = p^0_c \, q^{P^*}_{c,j} \tag{SM3.2}$$

where the values from the baseline matrices are denoted by a 0 superscript, the augmented matrices before balancing are denoted by a * superscript.

Since the green steel industries are new industries producing an existing commodity, the use columns for the Green Iron & Steel industries are calculated to be consistent with the production of the same physical output as the current production of the Dutch Brown Iron & Steel industry. The physical quantity of steel output should remain constant in this case since we are not altering the use structure of other industries or the final demand patterns. Since the model is in constant prices, the total output of the new industry in monetary terms should be equal to that of the industry replaced, as both the physical quantity and the price of steel sold are unchanged. However, since the input structure of the industry is different, the total expenditures of the new industry will not be equal to its total sales (i.e., the system is unbalanced).

To obtain the new use structure for the Green Iron and Steel sector (both in the Netherlands and Brazil) one cannot simply divide the use values by the total expenditures obtained by summing over the new expenditures. At this stage, the total expenditures of the industry will not be equal to the total output, since the new input structure will affect the price of commodities, but here prices are still kept constant.

This means that if the physical quantities produced by the industry do not change, the monetary output should remain equal to the industry being replaced, that is, the Brown Iron and Steel industry in the Netherlands.

Table SM3.4 shows an example of how dividing $u_{i,j}$ by the column sum would introduce a bias on the physical quantities for the new steel technology. Take the use of iron ore, for instance. In this example, the industry would use 1.16 physical units of iron ore (e.g., metric tonnes) to produce one physical unit of its output (e.g., one metric tonne of steel) under the old technology. For given unit prices for iron ore and steel (74 and 600, respectively), the total expenditure on iron ore would represent 14% of the total revenue from selling steel. Here, the total use and total supply are equal since the table is already balanced. With the new technology, only the physical input quantities change and unit prices are kept constant. Let us suppose that, to produce the same 1 metric tonne of steel, a higher iron input is needed under the new technology: 1.73t instead of 1.16t. This represents a 49% increase in the input of iron ore for the same physical quantity of steel output. Given that all unit prices remain constant (e.g., of both inputs and of steel), this should lead to an equivalent increase in the $u^*_{c,j}$ and $b^*_{c,j}$ for green steel compared to brown steel.

Therefore, in real terms, the coefficient denoting the use of commodity c by industry j under the new technology in industry j should increase or decrease proportionally to the ratio between the physical inputs of commodity c required for the production of one unit of physical output from industry j under the new and the old technologies. This can be verified in the example in Table SM3.4. The coefficient for iron ore inputs into steel production is now 0.214, a 49.7% increase from the old technology, consistently with the 49% increase in the physical input. However, if one divides the commodity expenditures by the total expenditures (i.e., the column sum), the obtained coefficient for iron ore is 7% *lower* than in the old technology. Since prices are kept constant, this would imply that the technological change shock being modeled would be that of a *decrease* in the consumption of iron ore per tonne of steel produced and not that of an increase, as initially intended. This bias would affect the output and price indexes of all industries and commodities through the Leontief inverse and through the value added coefficients if the quantities of primary inputs change.

Table SM3.4: Example of change in industry use structure taking into account physical quantities and prices

	Old technology				New technology					
Use										
	$q^{P,use}_{c,j}$	p_c	$u_{c,j}$	$b_{c,j}$	$q^{P,use}_{c,j}$	p_c	$u_{c,j}$	$b_{c,j}$	if colsum	bias in $q^{P,use}_{c,j}$
Iron ore [ton]	1.16	74	85.7	0.143	1.73	74	128.0	0.213	0.133	-39%
Coal [ton]	0.4	163	65.2	0.109	0.034	163	5.43	0.009	0.006	-39%
Electricity [kWh]	261	0.07	17.8	0.030	550	0.07	37	0.062	0.038	-39%
Hydrogen [kg]	0	4.65	0.0	0.000	67	4.65	277	0.461	0.287	-39%
Hydrogen Transport [kg]	0	1.3	0.0	0.000	67	1.30	87			
Other interm			258.2	0.430			258.2	0.430	0.267	-39%
VA			173	0.288			173	0.288	0.179	-39%
Total use			600	1.000			966	1.609	1.000	
Supply										
	$q^{P,sup}_{c,j}$	p_c	$s_{c,j}$		$q^{P,sup}_{c,j}$	p_c	$s_{c,j}$			
Steel [ton]	1	600	600		1	600	600			
Total Supply			600				600			

Note: This is an example based on the material flows, the full material flows are available in the Appendix.

This implies that the use coefficients for the new industry technology (i.e., green steel) may not add up to one in the augmented use table (U^*), but this is necessary to properly reflect the underlying changes in physical quantities. Once prices effects have been calculated, a new table can be obtained (U^1) where the use coefficients will add up to one (see Chapter 5).

The trade structures are assumed to be the same as those of the closest existing industry. That is, both Brown and Green Steel in the Netherlands take the trade shares of Basic Metals in the Netherlands, while Green Steel in Brazil takes the trade shares of Basic Metals in Brazil. Since iron and steel produced in the Netherlands is the only commodity that was disaggregated into Iron and Steel, the trade shares for this commodity equal one for the Netherlands as region of origin and zero for all other regions in the baseline and green hydrogen imports location scenarios. When Dutch iron and steel production moves to Brazil in the relocation scenario, the trade shares become one for Brazil and zero for all other regions of origin. Changing trade shares is what allows modeling the different industry location scenarios.

Regarding the make matrix, Dutch Iron and Steel is always produced by a single industry: either produced entirely by the Dutch Brown Steel industry in the baseline scenario, or by the Dutch Green Steel industry in the green hydrogen imports scenario, or by the Brazilian Green Steel industry in the relocation scenario. The changes in the market shares matrix is what captures the technological change shock.

SM3.1.2.2 Green hydrogen and renewable electricity

Following the Rosner et al. (2023) H-DRI-T case, an input of 76kg of hydrogen would be needed to produce one metric tonne of steel. Assuming an annual production capacity of 172 kilograms of hydrogen per kilo-watt of installed electrolysis capacity (172 kgH2/kWH2) and an hydrogen input of of 76kgH2/ts, we calculate that 0.44kW of electrolysis capacity would be required to meet the demand of an steel plant with production capacity of 1 metric tonne of steel per year (tspy). The sales price of green hydrogen is considered to be the levelized cost of hydrogen (LCOH) produced in Ceará, since this is the minimum sales price for a zero profit condition and the green hydrogen market is expected to be highly competitive (Caiafa et al., 2024). The LCOH was calculated based on the capital and operational expenditures a WACC of 10% was assumed following IRENA (2022c). These were obtained by cost component (IRENA, 2020a; UK BE&IS, 2021; Lazard, 2021; ISPT, 2020; Danish Energy Agency, 2022; Caiafa et al., 2023) and then allocated to economic sectors. Labour costs are estimated by combining the FTE requirements for an electrolysis plant mentioned in Caiafa et al. (2024) with salary data for the state of Ceará (where the hydrogen export hub would be located)(Ministry of Employment, 2022).

One of the main cost drivers of the LCOH is the electricity input (see Table SM3.5). It is assumed that 49.7 kWh are needed to produce one kilogram of hydrogen, following de Kleijne et al. (2024). For hydrogen to be considered green according to European regulations, the electrolysis plant must show that the electricity used comes from an additional renewable energy project (European Commission, 2023). This means that approximately 3800 kilowatt-hour of additional renewable electricity per year (3800 kWh/yr) would be required for the production of 76 kilograms of hydrogen per year (76 kgH2/yr) necessary for the production of 1 metric tonne of steel per year (tspy). Given that European regulations do not yet require an hourly correlation (European Commission, 2023), we assume that an onshore wind farm located in the North-East of Brazil would be able to provide sufficient electricity if properly oversized, since it would likely be able to balance daily and hourly unbalances with the Brazilian electricity grid. The Brazilian grid already has 88% of renewable electricity generation with 63% coming from dispatchable hydropower and relatively low seasonality due to being in the tropics (IRENA, 2022a; Caiafa et al., 2024).

Therefore, we assume the additional electricity would be bought via a power purchase agreement (PPA) with a newly built onshore wind farm. The assumed price for the PPA is 48 EUR/MWh, as IRENA (2017) reported a PPA price for contracts in Brazil of 53.9 USD/MWh in 2017. As electricity prices are the main driver for green hydrogen prices, and there are considerable uncertainties about actual future prices, we also perform a sensitivity analysis on this assumption to see impacts on green hydrogen (and hence green steel) prices (see SM3.2). With this electricity price, the LCOH is 3.19 EUR/kgH2, similar to reported by IRENA (2022c). The costs of hydrogen liquefaction, shipping, and regasification are based on IRENA (2022b).

The capital and operational expenditures for onshore wind used to construct the change in final demand and the use column of the renewable electricity industry were based on onshore wind costs in Brazil (IRENA, 2020b; EPE, 2022) and a capacity factor of 47% in Ceará (Government of Ceará, 2022). These include direct labor costs adjusted for local salaries based on local labour market data (Ministry of Employment, 2022) and employment factors taken from the literature (Cameron and van der Zwaan, 2015; Kattumuri and Kruse, 2019; Nasirov et al., 2021). Based on these costs and assuming a Weighted Average Cost of Capital (WACC) of 6% and a project lifetime of 25 years (IRENA, 2022c), the LCOE of onshore wind is calculated to be 36.93 USD/MWh (32.87 EUR/MWh), similar to IEA (2020). This shows that the PPA prices already include a margin that could help cover grid balancing costs.

Tables SM3.5 and SM3.6 summarize the assumptions for the production technology of green hydrogen and renewable electricity.

Table SM3.5: Expenditures for green hydrogen production. Capital expenditures refer to the one-off investment cost necessary for building the electrolysis plant for green hydrogen production. Assuming an annual production capacity of 172 kilograms of hydrogen per kilo-watt of installed capacity (172 kgH2/kWH2) and an hydrogen input of of 76kgH2/ts, 0.44kW of electrolysis capacity would be required to meet the demand of an steel plant with production capacity of 1 metric tonne of steel per year (tspy). Operational expenditures for green hydrogen production are shown for a kilogram of hydrogen (kgH2) and a metric tonne of steel (ts).

Green hydrogen production					
Capital expenditures	***CPA***	***USD/kWH2***	***EUR/kWH2***	***EUR/tspy***	***%***
Electrolyzer system	CPA_C26TC33	713	635	279	70%
Civil, Structural & Achitectural	CPA_F	22	20	9	2%
Planning, engineering & fees	CPA_IU	288	256	113	28%
Total		1023	910	401	100%
Operational expenditures	***CPA***	***USD/kgH2***	***EUR/kgh2***	***EUR/ts***	***%***
Maintenance (Materials)	CPA_C26TC33	0.127	0.11	8.6	3.54%
Insurance	CPA_IU	0.063	0.06	4.3	1.77%
Electricity	CPA_RE	2.7	2.4	182.3	75.28%
Water	CPA_E	0.0	0.02	1.35	0.56%
Direct labour	D1	0.015	0.01	0.98	0.41%
Gross operating surplus	B2A3G	0.7	0.6	44.3	18.45%
Total		3.58	3.19	242	100%

The liquefaction of hydrogen and the subsequent storage of liquefied hydrogen before ship loading are required in the decarbonization option where hydrogen is imported to the Netherlands. The capital expenses for hydrogen liquefaction and storage are assumed to be USD 2000 and USD 87 per kW of

Table SM3.6: Expenditures for renewable electricity production. Capital expenditures relate to the one-off investment costs for building the renewable electricity plant with the capacity of providing the additional 3800 kilowatt-hour of renewable electricity per year (3800 kWh/yr) required for the production of 76 kilograms of hydrogen per year (76 kgH2/yr) necessary for the production of 1 metric tonne of steel per year (tspy). Considering a capacity factor of 47% for onshore wind in Ceará, approximately 0.92kW of installed onshore wind capacity would be necessary to meet this electricity demand. Operational expenditures are shown for a kilowatt-hour of electricity and a metric tonne of steel (ts), considering an input of 50kWh/kgH2 and 76kgH2/ts. The total operational cost in EUR/kWh equals the levelized cost of electricity (LCOE) with the difference between the LCOE and the operational expenditures being allocated to gross operating surplus. When a higher electricity price is assumed, the adjustment is conducted by allocating the difference to gross operating surplus and adjusting coefficients for consumer industries.

Renewable electricity production						
Capital expenditures	***CPA***	***USD/kW***	***USD/tspy***	***EUR/kW***	***EUR/tspy***	***%***
Nacelle	C26-C33	444	410	395	365	35.9%
Blades	C26-C33	180	166	160	148	14.6%
Tower	C26-C33	155	143	138	127	12.5%
Construction	F	189	174	168	155	15.3%
Electrical balance of plants	C26-C33	133	123	118	109	10.8%
Planning & management	I-U	38	35	34	31	3.1%
Contingency and finance	I-U	49	45	44	40	4.0%
Transport	H	49	45	44	40	4.0%
Total		1237	1142	1101	1016	100.0%
Operational expenditures	***CPA***	***USD/kWh***	***USD/ts***	***EUR/kWh***	***EUR/ts***	***%***
Operation	D	0.003	11	0.0026	9.9	5.4%
Maintenance	C26-C33	0.004	17	0.0039	14.8	8.1%
Land lease	I-U	0.001	2	0.0005	2.1	1.1%
Direct labour	D1	0.006	21	0.0049	18.7	10.3%
Gross operating surplus	B2A3G	0.040	154	0.0360	136.9	75.1%
Total		0.054	205	0.0480	182.3	100.0%

installed hydrogen capacity, consist of equipment (23%), bulk materials (19%), construction (18%), contingency (17%), owner costs (9%), transport and freight of equipment (3%), project management (3%), insurances (2%), and other (6%) (IRENA, 2022b). Considering that 12.5 kWh/kgH2 are needed for liquefaction and storage of hydrogen (de Kleijne et al., 2024), and given prices of 108 EUR/MWh for industrial electricity consumers in Brazil, this leads to an electricity cost of 1.21 EUR/kgH2. Regarding labor, we assume an average of 30 FTE for a capacity of 50 t/d (i.e., 18.25 ktH2/year). This is based on data for a recently inaugurated Air Liquide liquefaction plant in Nevada, United States, which has 30t/d capacity expects and expects 25 FTE (Air Liquide, 2022). Our assumption reflects expected economies of scale in the sector. Considering that 1kW of electrolysis capacity would produce 172 kgH2/year, the employment factor would be 0.00028 FTE/kW of liquefaction capacity. Considering the average yearly salary for the industrial gases sector in Ceará was USD 16882/FTE (Ministry of Employment, 2022), this leads to an expenditure of 4.76 USD/year (4.24 EUR/year) per kW of liquefaction capacity, or an average of 0.028 USD/kgH2 (or 0.025 EUR/kgH2). considering the same WACC as for green hydrogen electrolysis, this leads to a levelized cost of liquefaction and storage (LCOLS) of 2.72 USD/kgH2 (2.42 EUR/kgH2). This is equivalent to the average estimate of IRENA (2022b) for the liquefaction step. Costs are summarized in Table SM3.7. Since electricity costs are significant for liquefaction, a sensitivity analysis is also conducted on this step (see SM3.2).

Table SM3.7: Expenditures for the liquefaction of green hydrogen

Liquefaction and storage of hydrogen						
Capital expenditures	CPA	USD/kWH2	EUR/kWH2	USD/tspy	EUR/tspy	%
Cement	C21-C23	210	187	92	82	10%
Steel, aluminium, copper	C24	210	187	92	82	10%
Equipment	C26-C33	508	452	223	199	24%
Construction	F	360	320	158	141	17%
Transport and freight	H	60	53	26	23	3%
Project management, fin services, other	IU	740	659	326	290	35%
Total		2087	1857	918	817	100%
Operational expenditures	CPA	USD/kgH2	EUR/kgH2	USD/ts	EUR/ts	%
Electricity	D	1.52	1.35	115	103	52.57%
Direct labour	D1	0.028	0.025	2.1	1.9	0.96%
Gross operating surplus	B2A3G	1.34	1.20	102	91	46.47%
Total		2.89	2.57	220	195	100%

For transport, IRENA (2022b) estimates costs are between 1.8-2.8 USD/kgH2 for a transport distance of 10,000km. We take the mid-point of this estimate. Given that there are 7,500km between Pecém and Rotterdam, this leads to a cost of 1.73 USD/kgH2 (1.54 EUR/kgH2). For reconversion in the Netherlands, we take the mid-point estimate from IRENA (2022b), that is, 0.75 USD/kgH2 (0.67 EUR/kgH2). Table SM3.8 compares the estimates from IRENA (2022b) and our assumptions.

The use column of the new industries producing new commodities can be estimated in a similar fashion as in Eq SM3.2. There is, however, a difference in the approach for obtaining use coefficients compared to the previous case where a new industry produced an existing commodity. For these industries, an approach can be followed to ensure total output and total input are equal, so that use structure coefficients add up to one in the augmented table.

For example, the use values of the green hydrogen industry can be calculated on the basis of the physical inputs required for producing the physical output of hydrogen needed for green steel production

Table SM3.8: Comparison between IRENA cost estimates and our assumptions. IRENA costs for transport are based on 10,000 km distance while ours are based on the 7,000 km distance between the ports of Pecém and Rotterdam.

Total costs of liquefied hydrogen	IRENA	2019 EUR	Our assumption	
	USD/kgH2	EUR/kgH2	USD/kgH2	EUR/kgH2
Liquefaction and storage	1.7-3.7	1.51-3.29	2.89	2.57
Shipping	1.8-2.8	1.60-2.49	1.73	1.54
Reconversion	0.5-1	0.45-0.89	0.75	0.67

and the base year input prices. Then, based on these values and an assumed weighted average cost of capital, one can calculate the levelized cost of hydrogen, which can be interpreted as the minimum sales price for a zero-profit condition. By multiplying the physical output of green hydrogen by its levelized cost, one obtains the total sales from the industry. The difference between total sales and estimated costs for intermediates plus labor can be allocated to gross operating surplus. This will ensure that the total column sum will equal the total row sum and use coefficients will add to one. The balancing condition here is that the monetary and physical output of green hydrogen equals the consumption of green hydrogen (GH_2) by the green steel (GS) industry and no other industry consumes the green hydrogen commodity. The same balancing procedure can be applied to renewable electricity.

For the make matrix, all of the new commodities are produced by a single industry at the time. Since each new industry produces a single commodity, the balancing can be done directly by using the real industry and commodity output from the use table. Green hydrogen, and renewable electricity for electrolysis are exclusively produced by their respective new industries in Brazil. For the rows of the use table, it was assumed that none of the existing sectors buy electricity from the additional onshore wind electricity, so sales of renewable electricity were equal to the total purchases from green hydrogen electrolysis. For green hydrogen, it was assumed that all output was sold to the green steel sector in Brazil or in the Netherlands, depending on the industry location scenario.

Hence, to obtain the total output for the green hydrogen and renewable electricity industries (x_{GH_2} and x_{RE}), the total physical quantity required of each input ($q^P_{GH_2}$ and q^P_{RE}) was multiplied by its respective price (i.e., levelized cost), under the assumption that each commodity would be produced by a single sector and that each sector would produce a single commodity so that industry and commodity monetary outputs are equal to the use of that commodity by its consumer industries ($u_{GH_2,GS}$ and u_{RE,GH_2}). The difference between the total sales (obtained by multiplying the levelized cost and quantities demanded) and the total operating costs from intermediate inputs and labor was allocated to gross operating surplus.

The balancing condition here is that the monetary and physical output of green hydrogen equals the consumption of green hydrogen (GH_2) by the green steel (GS) industry and that the output of renewable electricity equals the consumption of renewable electricity commodity (RE) by the green hydrogen sector. This can be verified in Tables SM3.2, SM3.5, SM3.6, and SM3.7. For instance, to produce one tonne of green steel via the H-DRI route (Table SM3.2), 242 EUR worth of green hydrogen is needed as input. If green hydrogen is shipped to the Netherlands, an additional 195 EUR is needed per tonne of steel for liquefaction and storage of hydrogen. These are exactly the total operational expenditures of green hydrogen production (Table SM3.5) and liquefaction and storage (Table SM3.7) when harmonized per tonne of steel.

$$x_{GH2} = q^M_{GH2} = u_{GH_2,GS} = p_{GH_2}\, q^P_{GH_2,GS} \qquad \text{(SM3.3)}$$

$$x_{RE} = q^{M}_{RE} = u_{RE,GH_2} = p_{RE_2}\ q^{P}_{RE,GH_2} \tag{SM3.4}$$

Trade shares from existing Brazilian sectors were used to distribute industry demand for commodities from different regions. For RE, the import shares of Brazilian electricity sector (BR_D) were used, while for green hydrogen, the shares from the Brazilian chemical industry were used (BR_C20), except for renewable electricity and water that were assumed to be sourced in Brazil only.

SM2 Sensitivity analysis

As mentioned above, prices for electricity and carbon substantially influence the prices of green hydrogen and green steel, but are expected to vary. Hence, we conduct a sensitivity analysis looking at a low and a high price option.

As a low price option for grid electricity, we take the levelized cost of energy (LCOE) for onshore wind energy in both countries reported by the IEA (34 USD/MWh for Brazil and 41 USD/MWh for the Netherlands)(IEA, 2020), instead of the prices for industrial consumers. It is considered that the LCOE is the minimum sales price for an energy source, and, onshore wind being a cheap source in both countries, its LCOE could be a good indication of how low prices can get in the long term. As a high price option, we take the electricity prices for industrial consumers following the energy crises in 2023 (221€/MWh for the Netherlands and 113€ MWh for Brazil) (Statistics Netherlands, 2024; EPE, 2024; European Central Bank, 2024).

Grid electricity prices apply only for the electricity used by the green steel and the liquefaction plants. As previously explained, it was already assumed that green hydrogen would use electricity from onshore wind via a PPA. Here, the minimum price assumed is also then the LCOE. However, using grid electricity is not an option for green hydrogen, so the highest price option would be the levelized cost of a dedicated system combining solar photovoltaics, onshore wind, and a battery. This reflects the situation where green hydrogen producers face stricter requirements regarding the use of the grid for balancing and need to obtain a dedicated generation system. Assuming a capacity factor of 47% for onshore wind and 24% for solar photovoltaics (PV) in Ceará (Government of Ceará, 2022) and a good complementary between the two energy sources (Caiafa et al., 2024), the combined capacity factor would be 71% or an average of 17h per day. To maximize the operational hours of the electrolyzers, we consider that the the solar and wind electricity facilities are oversized and complemented with a battery with 6 hour storage capacity. To provide extra electricity for the battery, we assume the solar and wind facilities need to be over-sized by 40% (so 1.4 kW of installed capacity of onshore wind and 1.4 kW of solar photovoltaic for each 1 kW of electrolysis capacity). Total installation costs of 849 USD/kW for solar photovoltaics and 1237 USD/kW for onshore wind are assumed in this study (IRENA, 2022d; Fearnehough and Skribbe, 2022; Vasconcellos and Caiado Couto, 2021). Regarding the operational expenditures, we assume total operation and maintenance (O&M) costs for onshore wind of 55 USD/kW/year and 60 USD/kW/year for solar photovoltaics, both including costs for direct labour (IRENA, 2022d; Fearnehough and Skribbe, 2022; Vasconcellos and Caiado Couto, 2021). Regarding employment factors, the literature has estimated values between 0.1-10.7 FTE/MW of installed capacity for onshore wind, with a median of 0.64 FTE/MW, and 0.12-4.8 FTE/MW, with a median of 1.1 FTE/MW, for solar photovoltaics (Cameron and van der Zwaan, 2015; Kattumuri and Kruse, 2019; Nasirov et al., 2021; Simas and Pacca, 2014). 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(Cole et al., 2021). Assuming an real weighted average cost of capital (WACC) of 6%(IRENA, 2022c), the calculated levelized cost of electricity (LCOE) for the entire system (including energy storage) is 64.17 USD/MWh. This leads to a LCOH of 4.17 USD/kgH2 or 3.71 EUR/kgH2 (see Table SM3.9).

These electricity price assumptions lead to a LCOH of 2.43 and 3.71 EUR/kgH2 and a LCOLS of 1.63 and 2.63 in the low and high price options, respectively. For the carbon price, we take a CO2 price of 25€/t of CO2 as reported by Tata Steel (2020b) as the baseline price, and then simulate CO2 prices of 100€/t and 300€/t. For natural gas prices, we take the prices for 2019 and 2022 for the Netherlands (EUROSTAT, 2024b) and for Brazil (ANP, 2024) (using average exchange rate of 4.4134 for 2019 and 5.4399 for 2022 as according to European Central Bank (2024)).

Electricity price assumption	**Price (EUR/MWh)**	**LCOH (EUR/kgH2)**	**LCOLS (EUR/kgH2**
LCOE onshore wind	32.9	2.43	1.63
LCOE onshore wind+solarPV+battery	57.1	3.71	1.93
Auction onshore wind	41	2.83	1.73
PPA onshore wind	48	3.19	1.82
Industrial consumers 2019	108	6.17	2.57
Industrial consumers 2021	113	6.43	2.63

Table SM3.9: Assumptions for electricity prices and implication for the levelized cost of hydrogen and the levelized cost of storage

Figures SM3.1, SM3.2, and SM3.3 show the results of the sensitivity analysis for impacts on value added. It shows that, even though the changes in the technical coefficients (and hence in the multipliers) do slightly impact the effect, it does not change the main findings from the default results regarding the distribution of value added between regions, sectors, and value added types, and regarding the difference on total global value added between the two scenarios. This implies that, regardless of the price assumptions, the relocation scenario always has a lower total cost but a stronger distributive effect between regions and the highest share of value added coming from renewable electricity and electrolysis is in the form of gross operating surplus.

Figure SM3.4 shows the sensitivity analysis results for the consumer price index in different regions. It can be seen that even the lowest price effect in the green hydrogen imports option is higher than the highest price effect of the relocation option. This shows that the conclusions of the green hydrogen imports option leading to a higher price effect for consumers is robust.

Figures SM3.5, SM3.6, and SM3.7 show the price effects of the two green steel industry location options relative to Dutch brown steel (taking different price assumptions also for brown steel). They show that while low energy and hydrogen prices help to make green steel more competitive with brown steel, price assumptions do not change the conclusions that Dutch green steel is substantially more expensive than Brazilian green steel due to transport and liquefaction of hydrogen and due to labour costs. Moreover, in all green hydrogen price assumptions, Brazilian green steel can become competitive with Dutch brown steel at a carbon price of 300€/tCO2 (and even at 100€/tCO2 in the lower price assumptions), but Dutch green steel prices never get close to Dutch brown steel prices.

Figure SM3.1: Sensitivity analysis results for value added on global level

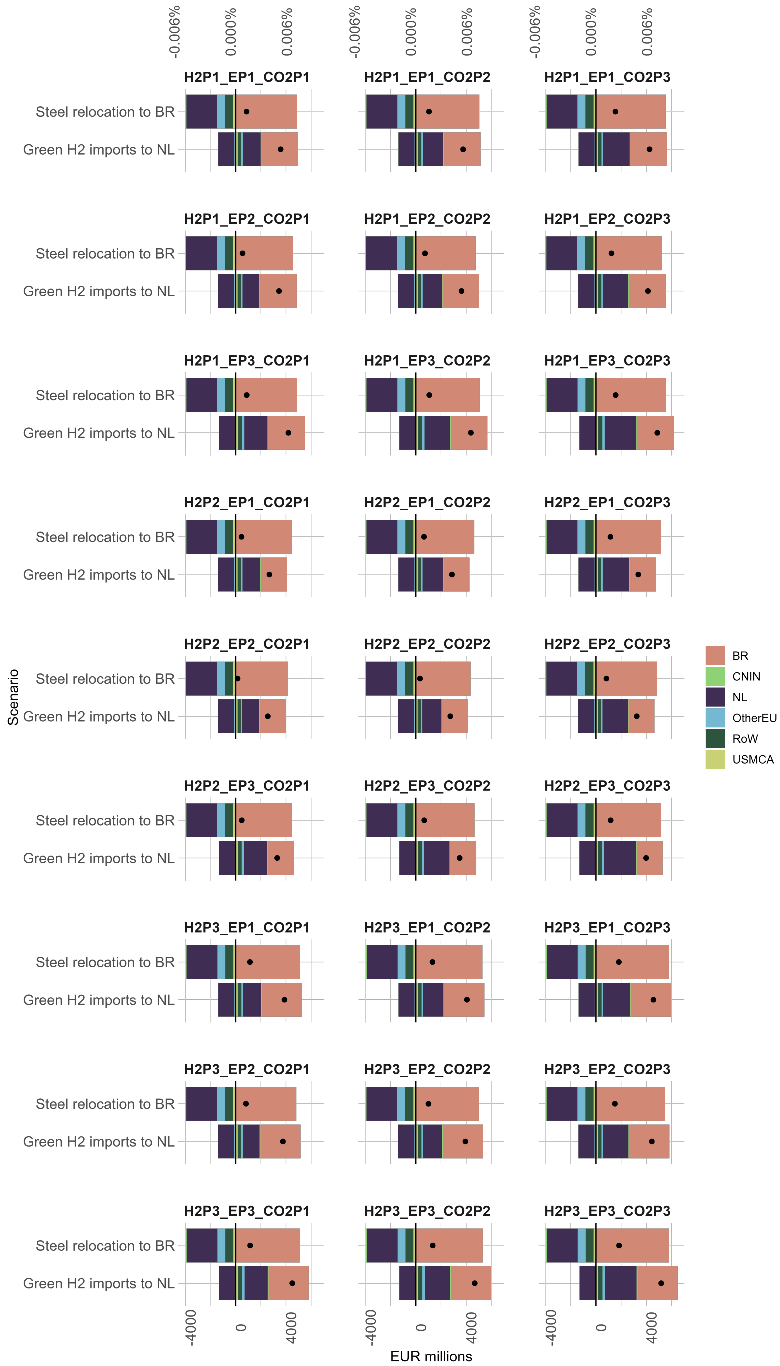


Figure SM3.2: Sensitivity analysis results for regional value added, by value added type

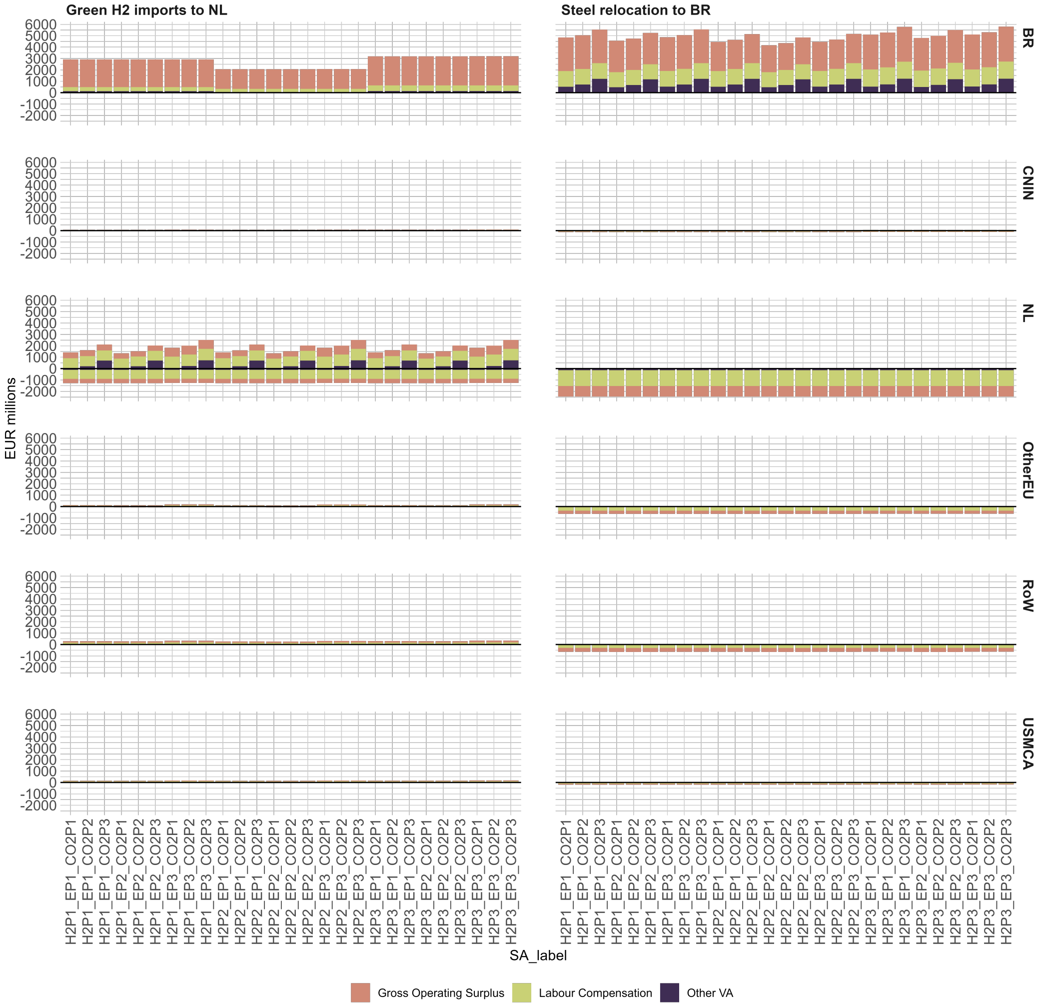


Figure SM3.3: Sensitivity analysis results for regional value added, by sector

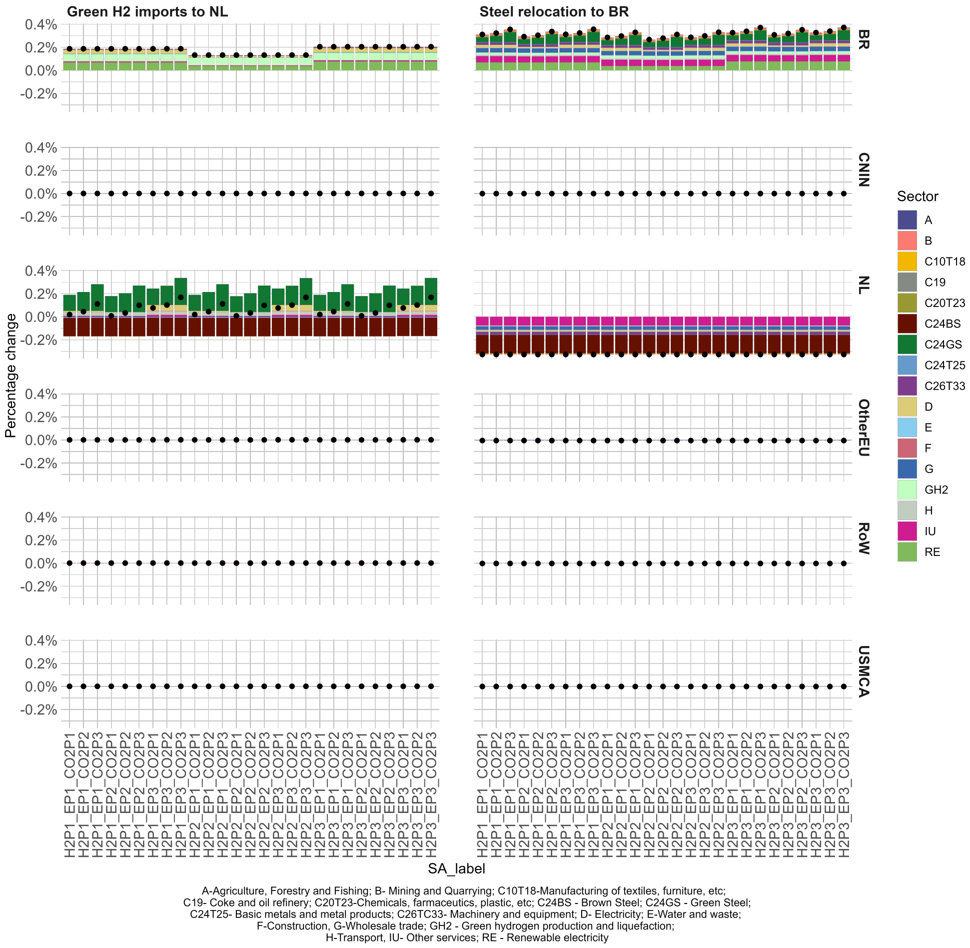


Figure SM3.4: Sensitivity analysis results for the consumer price index

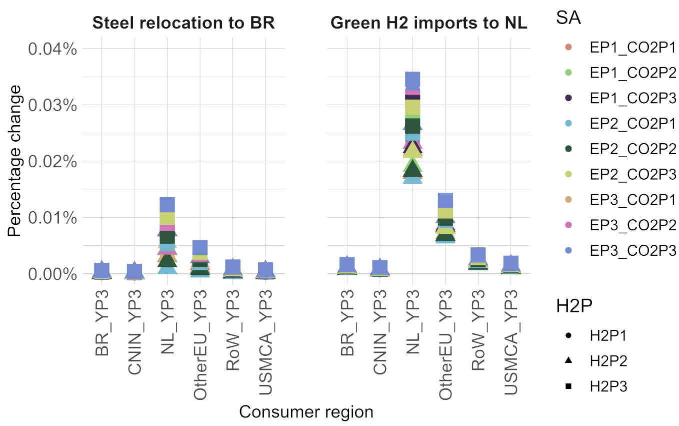


Figure SM3.5: Price effects for Dutch Iron and Steel commodity relative to 2019 Dutch Brown Steel prices, default assumption on green hydrogen prices (H2P1)

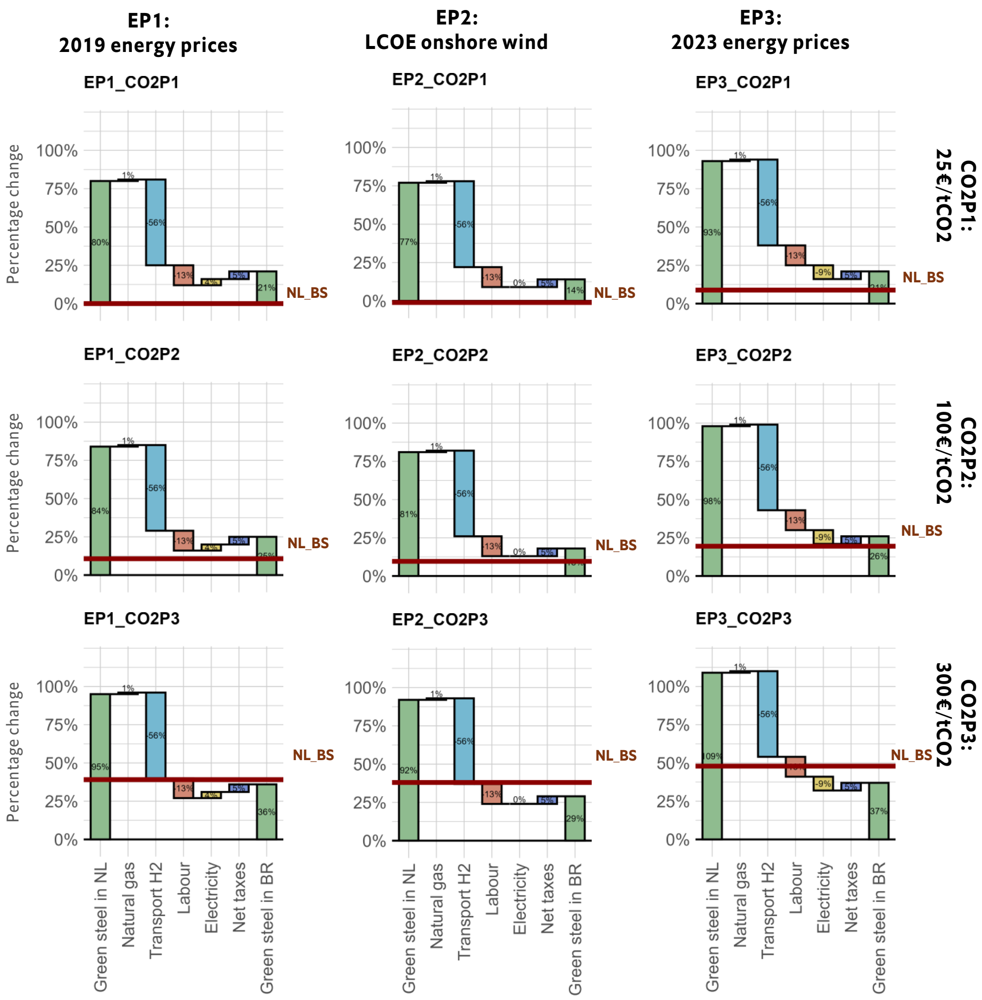


Figure SM3.6: Price effects for Dutch Iron and Steel commodity relative to 2019 Dutch Brown Steel prices, assumption of low green hydrogen prices (H2P2)

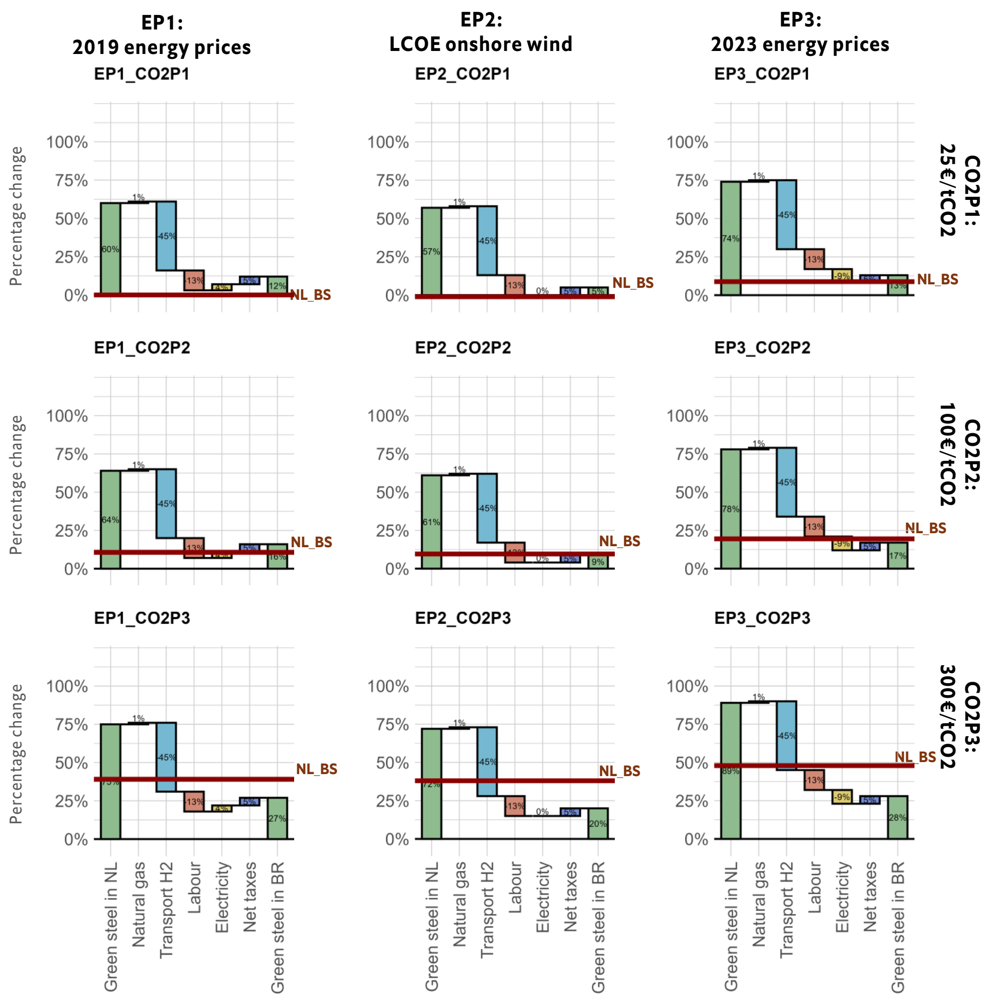
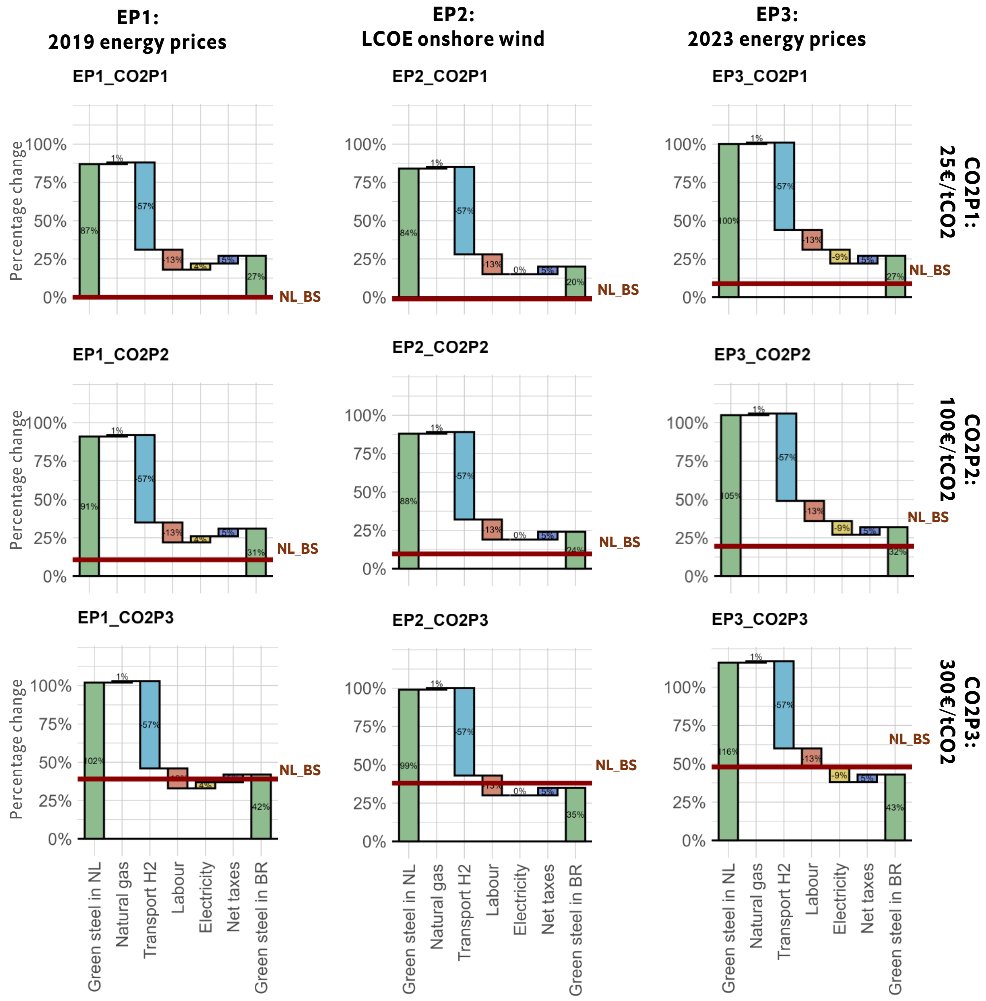


Figure SM3.7: Price effects for Dutch Iron and Steel commodity relative to 2019 Dutch Brown Steel prices, assumption of high green hydrogen prices (H2P3)



SM3 Supplementary results

To check the impact of region-specific emission intensities, we simulate the two location options with the Brazilian industries having the same emission coefficients as the China and India (CNIN) region. Brazil has already approximately 47% of total energy supply coming from renewables, with less than 6% coming from coal-based generation. This led to a relatively low CO_2 intensity: the emission factor for electricity and heat generation in 2022 in Brazil was only 74 tCO_2/GWh, while that of the Netherlands was 293 tCO_2/GWh, and the world average was closer to 500 tCO_2/GWh. Other emerging economies with a higher reliance on fossil fuels had significantly higher emission factors. For instance, China had an emission factor of 569 tCO_2/GWh and India one of 723 tCO_2/GWh.

Results are summarized in Figures SM3.8 and SM3.9.

Shifting from BF-BOF in the Netherlands to H-DRI-EAF under the two location scenarios would lead to an increase, rather than a decrease, in CO_2 emissions globally, if Brazil had the same emission intensity as the CNIN economy. A higher emission intensity increases emissions for the electricity for the green hydrogen liquefaction (green hydrogen imports option) and for the EAF (relocation option). This suggests the need for the emission intensity for these activities to be low for the H-DRI-EAF route to lead to net CO_2 emission reductions. However, the difference between the location options still holds: relocation would lead to lower emissions than green hydrogen imports when both the EAF and the liquefaction step would happen in the same green hydrogen producing country. However, importing green hydrogen from Brazil to the Netherlands would lead to lower emissions than relocating green steel production to a high-emitting region.

Moreover, we also check what the impact of carbon prices would be if emissions from electricity use (Scope 2 emissions) are included in the total carbon cost.

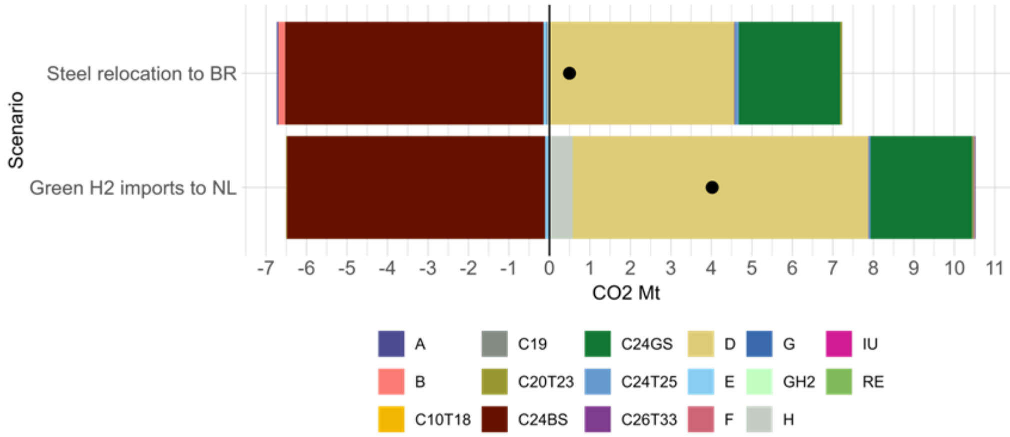
	Emissions			CO_2 costs (P25)			CO_2 costs (P100)			CO_2 costs (P300)		
Industry	Scope 1	Scope 2	Total	Scope 1	Scope 2	Total	Scope 1	Scope 2	Total	Scope 1	Scope 2	Total
BS NL	0.924	0.783	1.71	23	20	43	92	78	171	277	235	512
GS NL	0.363	0.181	0.54	9	5	14	36	18	54	109	54	163
GS BR	0.363	0.041	0.40	9	1	10	36	4	40	109	12	121
GS IN	0.363	0.765	1.13	9	19	28	36	77	113	109	230	338
GS CN	0.363	0.736	1.01	9	18	27	36	74	110	109	221	330

Table SM3.10: Total carbon cost per ton of steel for different production technologies in countries with varying emission intensities.

To check for the possibility of regional hydrogen hubs, we simulate the possibility of having Spain instead of Brazil as the renewable energy rich region. Costs for hydrogen shipping are adjusted for the new distance and the option of transporting hydrogen by repurposed pipelines is added. Hydrogen transport costs decrease from EUR 6.4/kgH_2 in the Brazil case to EUR 3.6/kgH_2 if hydrogen is transported from Spain by ship or to EUR 0.8/kgH_2 if transported via repurposed pipelines. Labor costs are based on ArcelorMittal's steel plant in Sestao ArcelorMittal Spain (2023) and energy prices are taken from EUROSTAT (EUROSTAT, 2024b,a). We assume the green hydrogen produced in Spain would be sold at the same free-on-board (FOB) price as the green hydrogen produced in Brazil.

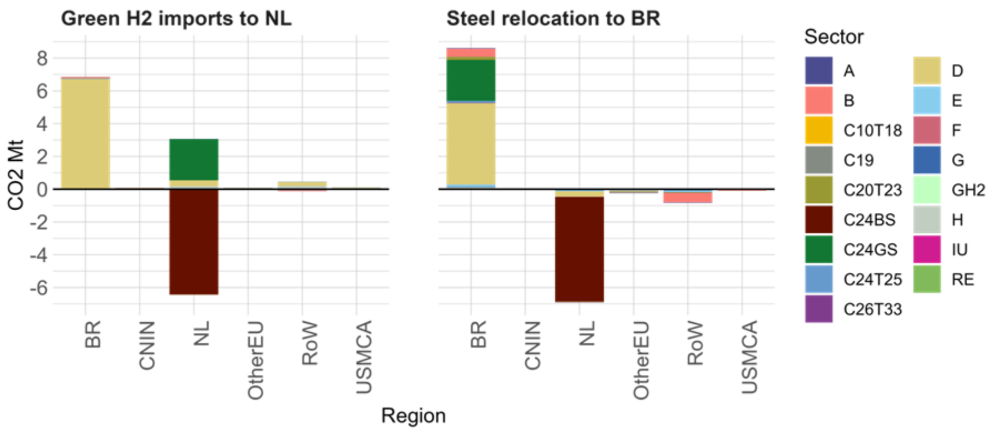
The direct price increase is considered as the difference in the sum of the column of coefficients for the green steel industry in the different locations compared to the brown steel industry in the Netherlands.

Figure SM3.10 shows the results. The option of regional hubs would lead to a net price effect that is in-between the two options analyzed in this study.



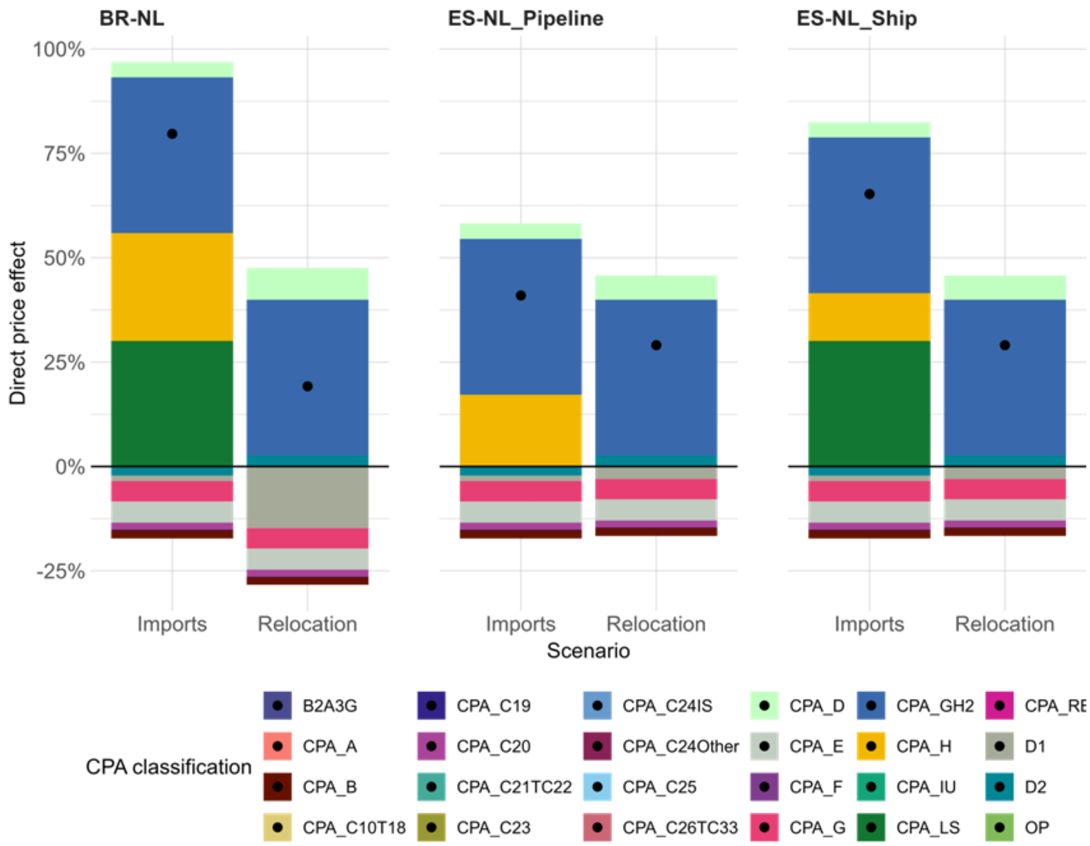
Sector description: A-Agriculture, Forestry and Fishing; B- Mining and Quarrying; C10T18- Manufacturing of textiles, furniture, etc; C19- Coke and oil refinery; C20T23- Chemicals, pharmaceutics, plastic, etc; C24BS – Dutch Brown Steel sector; C24GS – Dutch or Brazilian Green Steel sector C24T25- Basic metals and metal products; C26TC33- Machinery and equipment; D- Electricity, gas, steam and air conditioning supply; E-Water and waste; F-Construction, G-Wholesale trade; GH2 – Brazilian Green Hydrogen Sector; H-Transport, IU-Other services; RE- Renewable electricity for green hydrogen production in Brazil

Figure SM3.8: Global impacts on CO_2 emissions if Brazil had the same emission coefficients as the China-India region



Sector description: A-Agriculture, Forestry and Fishing; B- Mining and Quarrying; C10T18- Manufacturing of textiles, furniture, etc; C19- Coke and oil refinery; C20T23- Chemicals, pharmaceutics, plastic, etc; C24BS – Dutch Brown Steel sector; C24GS – Dutch or Brazilian Green Steel sector C24T25- Basic metals and metal products; C26TC33- Machinery and equipment; D- Electricity, gas, steam and air conditioning supply; E-Water and waste; F-Construction, G-Wholesale trade; GH2 – Brazilian Green Hydrogen Sector; H-Transport, IU- Other services; RE- Renewable electricity for green hydrogen production in Brazil

Figure SM3.9: Regional impacts on CO_2 emissions if Brazil had the same emission coefficients as the China-India region



Product classification: A-Agriculture, Forestry and Fishing; B- Mining and Quarrying; C10T18-Manufacturing of textiles, furniture, etc; C19- Coke and oil refinery; C20- Chemicals; C21TC22-Pharmaceuticals, plastics, rubber; C23–Other non-metallic mineral products; C24IS – Dutch Iron and Steel; C24Other- Other iron and steel products than Dutch Iron and Steel; C25– Fabricated metal products, except machinery and equipment; C26TC33- Electronics, electrical equipment, machinery, vehicles; D- Electricity, gas, steam and air conditioning supply; E-Water and waste; F-Construction, G-Wholesale trade; GH2 – Brazilian Green Hydrogen Sector; H-Transport, IU-Other services; LS- Liquefaction and storage of green hydrogen; RE- Renewable electricity for green hydrogen production in Brazil

Adjustments and Value added components: D1- Compensation of employees; D2 – Net taxes; B2A3G – Gross operating surplus; OP-direct purchases by residents abroad and by non-residents in the domestic territory

Figure SM3.10: Direct price increase in the price of the Dutch iron and steel commodity considering the option of ”regional hubs”

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