Exploration of the effects of (partially) replacing Dutch fertiliser and iron and steel production with imports

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Summary

In this report an exploration is presented on the effects of renewable hydrogen imports on the fertiliser and iron and steel sectors. In the coming decades the Dutch iron and steel and fertiliser industries will need to reduce emissions in order to meet European and national climate targets. For both sectors renewable hydrogen (from electrolysis based on renewable electricity) forms an important part of the long-term decarbonisation strategy. The Netherlands plans to have a significant domestic electrolysis capacity to produce renewable hydrogen. Yet, domestic production could be insufficient to meet the demand for hydrogen requiring the import of renewable hydrogen. It could also prove cheaper to import renewable hydrogen from regions with more geographically favourable conditions.

In particular when it is cheaper to import renewable hydrogen, the question arises whether it is also economically favourable to (partially) relocate the production of fertilisers or iron and steel to the country with low-cost renewable hydrogen production. In such a scenario finished or semi-finished products are imported instead of renewable hydrogen (carriers). A consequence would be the (partial) relocation of industrial supply chains to regions with low-cost renewable hydrogen production. Relocation as referred to in this report does not require the same company to have both production abroad and in the Netherlands. The company in the Netherlands can also outsource production or acquire (semi-)finished products from the international market.

The aim of the study is to explore the effects of certain activities within the fertiliser and steel industries relocating to regions where renewable hydrogen production can be cheaper. The analysis in this report looks into which parts of the supply chain are more or less likely to shut down in the Netherlands in favour of imports of (semi-)finished products and the factors influencing the likelihood of a (partial) shutdown occurring. The assessment is based on a literature review, own analyses and interviews with the three main players in the Dutch iron and steel and fertiliser industries: Tata Steel Netherlands (TSN), Yara Sluiskil and OCI. Future development of renewable hydrogen costs, both in the Netherlands and for import, are highly uncertain. There are also many additional factors at play that can influence decisions to maintain production here or opt for imports, that are not easily quantified. These include, but are not limited to, development of the prices of products, transport infrastructure, investment and policy climates and the value of existing expertise and an educated workforce. It is therefore not possible to quantify the chance of a change in the supply chain occurring. As a result the analysis is mostly focused on the transport cost of renewable hydrogen (carriers) and semi-finished fertiliser and steel products and the effects that these transport costs have on the rest of the production chain in the Netherlands. The primary goal of the assessment is to provide policy makers with insights into the techno-economic factors that may drive decisions to shut down, relocate or outsource production and the effects (partial) shutdowns can have on the industry in the Netherlands.

The analysis compares renewable hydrogen based production in the Netherlands versus renewable hydrogen based production in other countries and the export of (semi-finished) products to the Netherlands. The report timeframe focuses on long-term technological development, meaning that intermediate steps based on natural gas or CCS are not considered. For cost data we assume mature renewable hydrogen production technologies and renewable hydrogen based fertiliser and steel production technologies. The report does not concentrate on the future competitive position of these industries or delve into carbon leakage resulting from varying policy ambitions across different global regions.

This report is part of a larger research project, where an exploration of possible relocation risks has been conducted for heavy industries, also including refineries and the large volume organic chemicals industries. The objective has been to provide support to the Ministry of Climate and Green Growth (previously Ministry of Economic Affairs and Climate Policy) and serve as a starting point for broader discussions on future developments within these sectors.

In the following paragraphs the results for the fertiliser industry and the iron and steel industry are briefly summarised. In the next pages the results are described in a longer summary.

Fertiliser industry

In the case of a shift to a renewable hydrogen based production process, the future fertiliser production chain in the Netherlands is sensitive to the availability of sufficient and cost-efficient renewable hydrogen and ammonia. Although the future development of global renewable hydrogen and ammonia costs remains uncertain, there is a trend in the literature indicating favourable conditions in regions with abundant renewable resources, while conditions in North-Western Europe are less favourable. In any scenario where there is sufficient affordable renewable hydrogen, there is no strong techno-economic justification for relocation of ammonia production or other parts of the fertiliser industry. However, if green hydrogen is imported into the Netherlands, the continuation of domestic ammonia production based on renewable hydrogen becomes less likely. The potential outsourcing of renewable ammonia production does not necessarily lead to the relocation of the rest of the fertiliser production chain, as the cost of transporting ammonia is limited.

Iron and steel

The competitiveness of a Dutch iron and steel industry based on renewable hydrogen depends on the costs of iron ore, hydrogen, electricity and the transport of feedstocks and(semi-finished) products. Our analysis, along with the literature, indicates that there is significant uncertainty about the future costs of many key inputs. If domestic renewable hydrogen production in the Netherlands is insufficient, or if it is cheaper to import renewable hydrogen, there is consensus in the literature that it would also be more cost-effective to import crude steel from the renewable hydrogen producing country. Our analysis aligns with these findings from literature.

Importing hydrogen or Hot Briquetted Iron (HBI) is more costly than importing crude steel. This suggests that if there is a reason to import hydrogen, replacing the entire domestic supply chain with crude steel imports is the most cost-effective option. Yet even if this apears more cost-effective on paper, there must be sufficient availability of feedstocks (iron ore, hydrogen, scrap steel) and products (HBI and crude steel), all of which are currently uncertain. Moreover, it is also uncertain how intangible factors such as existing assets, infrastructure, staff and expertise, might influence the decision to maintain local production or partially switch to an import-based production chain. Replacing part of the domestic production chain with imports will primarily affect TSN’s own operations and the operations of suppliers.

Fertiliser industry

A base case explores a fertiliser industry with domestic fertiliser production based on domestic renewable hydrogen production. To explore the effects on the production of fertilisers and other products in the Netherlands a second scenario assumes that renewable hydrogen or ammonia is imported instead.
The reasons for import could be due to insufficient renewable hydrogen production in the Netherlands or because it is cheaper to import hydrogen (carriers) from other regions. The second case implicitly assumes there is sufficient hydrogen production to cover global demand. These two possibilities are of course interlinked: if it is cheaper to import hydrogen carriers, it is likely that there will be less domestic hydrogen production. On the other hand, large amounts of domestic hydrogen production will have a downward effect on hydrogen prices, positively influencing the position of domestic production compared to imports.

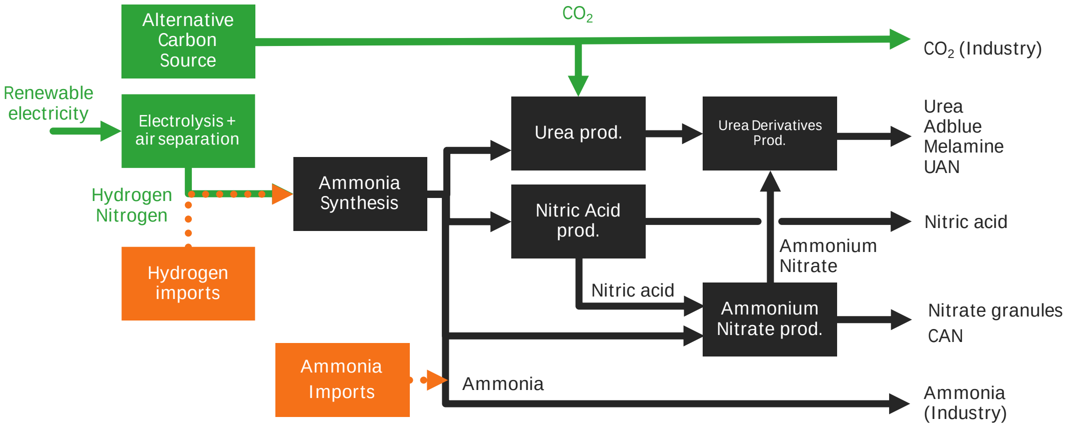

Figure 1.1: Overview of the production chains considered in the assessment. The baseline is a complete production chain in the Netherlands starting with domestic renewable hydrogen production. A second scenario explores the effects that imports of renewable hydrogen or ammonia have on the production of fertilisers and other products in the Netherlands.

The competitiveness of the Dutch fertiliser industry depends on the provision of sufficient amounts of affordable ammonia. Without affordable ammonia the Dutch fertiliser industry will struggle to remain competitive on international markets.
The viability of producers in the fertiliser industry depends on the competitiveness of their products. Fertiliser products are homogeneous and easily transportable commodities. If the price of products is no longer competitive, the chance that production is shut down in favour of imports increases. It also has an effect on the Dutch fertiliser industry's position on the international market. Exports are currently important for the operations of the Dutch fertiliser industry. For all products made in the Dutch fertiliser industry, the supply chain can be traced back to the production of ammonia. As a result, affordable ammonia is key for fertiliser products cost-competitiveness.

The production of sufficient affordable ammonia domestically, requires sufficient and affordable renewable hydrogen available in the Netherlands. The future development of production cost of renewable hydrogen and ammonia are highly uncertain and many scenarios are still possible. While generally literature suggests the geographic variables relevant for production costs do not favour production in North-Western Europe on the international markets, there is no certainty that this means renewable hydrogen will only be imported.

The cost of hydrogen provision can make up more than 75% of the total production costs of ammonia. The cost of renewable hydrogen production, and in turn the cost of renewable ammonia production, is largely dependent on geographical factors including wind speeds, solar irradiance and land-availability. The literature consulted for this study shows a trend, which suggests that these geographical factors do not favour North-Western Europe (including the Netherlands). These outcomes remain highly uncertain and many scenarios are still possible. It is impossible to conclude definitively that it will cost more to produce renewable hydrogen in the Netherlands than to import it. The following analysis is therefore a theoretical one, starting from the assumption that renewable hydrogen is imported.

If the hydrogen produced domestically is either insufficient to meet demand or not cost-competitive with import options, import of hydrogen (carriers) is to be expected. If there is import of hydrogen carriers, the import and direct use of ammonia for fertiliser production arises as a cost-effective option.

Figure 1.2 displays the levelized cost of hydrogen transport for the most prominent hydrogen transport mediums. Except for direct ammonia, all mediums end up delivering hydrogen directly. For these mediums delivering hydrogen directly, the cost optimal transportation medium is dependent on the distance of transport, where multiple methods could end up with similar levelized costs of transport. However, Figure 1.2 also shows that the most cost optimal medium for transporting hydrogen is to transport ammonia which is not cracked back to hydrogen, but rather used to meet existing ammonia demand. Although this method does not directly yield hydrogen, the imported ammonia can displace domestically produced ammonia in regions with existing operational ammonia production capacity. In essence this frees up the hydrogen that would otherwise be used for ammonia production to be utilized elsewhere.

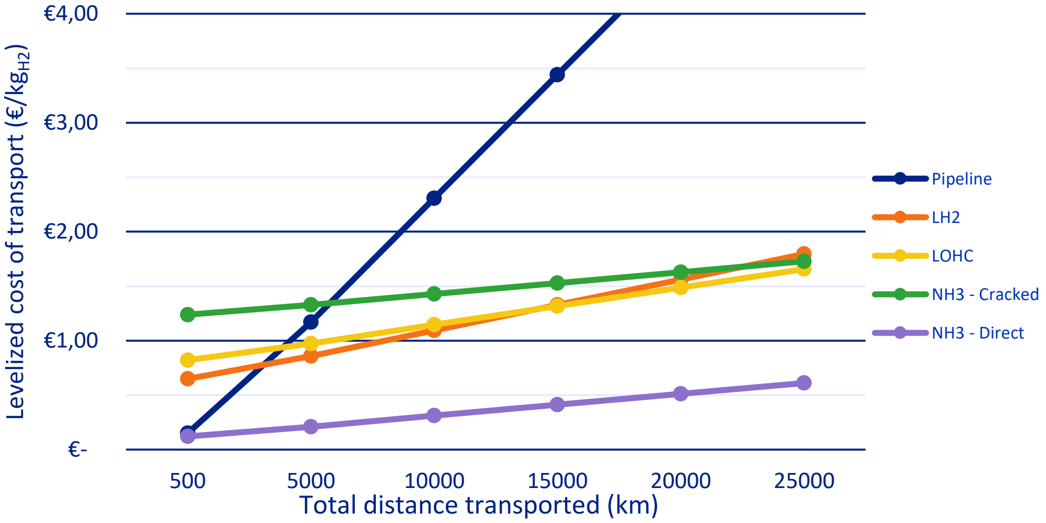

Figure 1.2: Cost comparison of hydrogen transport modes for different mediums[1], adapted from (Ortiz Cebolla, Dolci, & Weidner, 2022). The pipeline transports compressed H_2, the remaining carriers are all transported by maritime shipping. The hydrogen transport costs are levelized based on the hydrogen content for each carrier. For direct ammonia, this means the levelized cost are calculated using the hydrogen content of ammonia.

To illustrate with an example, if an importer pays about €0.60/kg_{H2} for the transport of the imported hydrogen by pipeline transport over roughly 2,500km (from Morocco to the Netherlands) and assuming the cost to produce hydrogen in Morocco is 3 €/kg_{H2}, this means the importer is paying €3.60/kg_{H2} for the hydrogen.

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[1] NH_3 - Cracked represents the transport cost of hydrogen that has been cracked back from ammonia. Whereas NH_3 - Direct represents the transport cost of the hydrogen that is still contained in the form of ammonia.

If this €3.60/kg$_{H2}$ is cheaper than domestic production, an ammonia producer in the Netherlands is paying at least €3.60/kg$_{H2}$ for their hydrogen – €0.60/kg$_{H2}$ more than an ammonia producer in Morocco would pay for hydrogen. This results in €106/t$_{NH3}$ extra to source its hydrogen, which is 17% of the current ammonia price. The total transport costs of ammonia over the same distance is only €28/t$_{NH3}$. If the ammonia producer in the Netherlands would import ammonia, and sell the hydrogen it is currently using for its production for €3.60/kg$_{H2}$ (or the equivalent of €106/t$_{NH3}$), it would save at least €78/t$_{NH3}$ per tonne of ammonia imported.

If the €3.60/kg$_{H2}$ is more expensive than domestic production, the ammonia importer in the Netherlands can sell their hydrogen to the hydrogen importer at €3.60/kg$_{H2}$ (the price that the importer pays anyway for hydrogen from Morocco) and still have a net benefit of €78/t$_{NH3}$.

This effect becomes stronger over longer distances. Considering Chile as the exporting country and importing liquid hydrogen (over 14,500km), would result in a benefit of €160/t$_{NH3}$ for the ammonia producer/importer.

Phasing out domestic ammonia production using domestically produced hydrogen is energetically and economically efficient, if there is any hydrogen import to the Netherlands for domestic consumption.

Importing renewable hydrogen as renewable ammonia, and directly using the imported ammonia for fertiliser production, has the lowest levelized cost of hydrogen transport. In a scenario where the Netherlands is a net-importer of renewable hydrogen, a cost-optimal import strategy would therefore be to phase out ammonia production from locally produced renewable hydrogen. Instead, imported renewable ammonia would meet domestic renewable ammonia demand, freeing up renewable hydrogen for other purposes. It would be energetically and economically inefficient to crack renewable ammonia back to renewable hydrogen, while simultaneously producing renewable ammonia from locally produced renewable hydrogen in the same region. Thus, the continuation of ammonia synthesis in the Netherlands is only efficient in the case there is sufficient and cost-competitive domestically produced renewable hydrogen. Although this conclusion holds for a systems based approach, at the level of individual companies these inefficiencies could still occur because of local transport or storage constraints. A high liquidity hydrogen market with ample transport and storage capacities would limit the likelihood of these inefficiencies occurring.

The cost of transport for the import of ammonia has a limited impact on the cost of fertiliser products. This means that the production of fertiliser products in the Netherlands based on imported ammonia could remain cost-competitive internationally. Therefore, the use of imported ammonia does not directly imply relocation of the downstream supply chain.

The transport cost-premium represents the additional cost for a producer importing a certain product on the total production costs, all else being equal (see text box). Figure 1.3 shows the transport cost-premium for various fertiliser products as a result of three different import methods. Firstly, it is clear that the import of hydrogen for the domestic production of ammonia and downstream fertiliser production has a significant impact on the production costs of fertilisers. Considering the degree to which these products are commodified, these margins would substantially impact the business case of such a producer and thus the remaining supply chain. On the other hand, Figure 1.3 shows that importing ammonia has a substantially lower transport cost-premium. This means that the effects on the production costs of the final fertiliser products is limited. This leads to the conclusion that ammonia imports should not necessitate relocation of the downstream supply chain, because the cost-premium for transporting ammonia that is directly used as a feedstock is low compared to the price of fertiliser products. In fact, the Dutch fertiliser industries stated that the costs of shipping finished products is higher than the cost-premium for ammonia shipping. This motivates maintaining downstream fertiliser production close to the fertiliser demand.

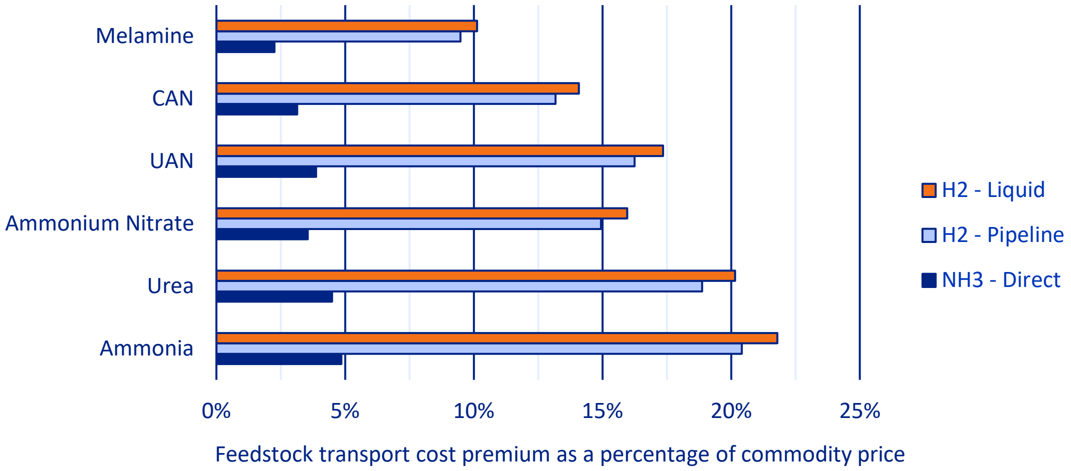

Figure 1.3: Comparison of the cost premium resulting from transportation over 3000 km using various import methods, as a percentage of the current commodity price (Business Analytic, 2024). The cost premium in this case includes only the additional cost of the feedstock (H_2 or NH_3) as a consequence of the transport cost. Downstream complications resulting from decoupling production steps are not considered.

Transport cost-premiums

In order to examine the competitive disadvantage an importer of an (intermediate) product could have as a result of (partial) outsourcing of production, transport cost-premiums are used. The transport cost-premium shows the relative cost increase of the finished product, resulting from the transportation cost of a given (intermediate) product. This can be interpreted as the relative cost difference between an importer and exporter, all else being equal, because the importer has to import a product that cannot be made cost-competitively domestically. This metric is useful because it exhibits the worst case effects on competitiveness for (partial) outsourcing, independent of uncertain geographical cost developments. If the transport cost-premium for an (intermediate) product is low, importing that product is unlikely to affect the competitiveness of the remaining supply chain. If the transport cost-premium for an (intermediate) product is high, importing that product would substantially affect the cost-competitiveness of the downstream supply chain, making imports of more finished products a more attractive option.

The transition to green hydrogen based ammonia production for the fertiliser industry will affect the supply of high purity CO_2 to neighbouring industries and downstream processes. This effect is to be expected both with domestic ammonia production and with ammonia imports.

The main connections to other industries are the export of CO_2 and waste heat to other users (e.g., the food and beverages industry and the greenhouse horticulture) and the sale of some of the intermediate products such as hydrogen and ammonia. Shifting to renewable ammonia will eventually require alternative CO_2 sources for the production of urea, as a consequence of phasing out steam methane reforming (SMR). As urea is mostly used to produce melamine, AdBlue, and for export, it is these activities that will be affected most by the phase-out of the SMR. This study did not focus on this aspect, however, a detailed exploration of the alternatives could provide insights into their feasibility and whether specific actions are required to ensure this transition. Industries that are connected to the fertilisers industry will also be affected most by the phase-out of the SMR capacity.

These connected industries will need to find alternatives regardless of whether the renewable ammonia is domestically produced or imported.

The EU has emphasized the strategic role of the fertiliser industry for long-term autonomy. Its dependence on ammonia means that the ammonia production capacity has strategic value by extension. As a consequence, ensuring security of supply through domestic ammonia production capacities could therefore be considered, even in economically unfavourable conditions.
The EU has noted the importance of ensuring availability, affordability and long-term autonomy of the bloc's fertiliser supply. This indirectly implicates the importance of domestic ammonia production capacity. To ensure these goals are met, policy implementations could trump economically unfavourable conditions, which would lead to domestic production in the EU, even with uncompetitive international production costs. It should be noted that this could favour countries with more abundant renewable energy resources and land availability (including offshore space for offshore wind).

Conclusions

The main findings of this exploration highlight that in the case of a shift to a renewable hydrogen based production process, the future fertiliser production chain in the Netherlands is sensitive to the availability of sufficient and cost-efficient renewable hydrogen and ammonia. Although the future development of global renewable hydrogen and ammonia costs are uncertain, there is a trend in literature indicating favourable conditions in regions with abundant renewable resources, with less favourable conditions in North-Western Europe. If there are green hydrogen imports in the Netherlands, the continuation of domestic ammonia production based on renewable hydrogen becomes less likely. What becomes clear from the transport cost-premium is that the potential outsourcing of renewable ammonia production does not necessarily result in the relocation of the rest of the fertiliser production chain. In any case where there is sufficient affordable renewable hydrogen, there is no techno-economic basis for relocation of ammonia production or other parts of the fertiliser industry.

Policy considerations

The future of the fertiliser production chain in the Netherlands is linked to domestic hydrogen production and import. With sufficient domestic production of affordable green hydrogen, ammonia production in the Netherlands can remain cost-competitive. In the case of hydrogen import, maintaining domestic ammonia production capacity is not economically and energetically efficient.
Political ambitions of the Netherlands in regards to domestic renewable hydrogen production and import strategies will shape the policies affecting them. It is important to realise that these ambitions directly influence the likelihood of the relocation of domestic renewable ammonia production, from a techno-economic perspective. Policies affecting renewable hydrogen imports and domestic renewable ammonia production are strongly connected and policy considerations on these topics therefore need to take this into account.

Explore options for maintaining the downstream fertiliser production in case of a shift to ammonia imports.
The present analysis shows that the fertiliser industry can remain cost-competitive with imported renewable ammonia. This indicates that the downstream fertiliser production can be maintained in the Netherlands, even if there is no ammonia production in the Netherlands. Options for maintaining the fertiliser production chain if there is no domestic ammonia production need to be explored further. These including securing supply of

renewable ammonia at affordable prices with trade agreements and developing ammonia import and storage infrastructure.

Alternative sources of CO_2 are needed for continuing production of certain downstream products and for neighbouring industries.
Phasing out fossil-based hydrogen production for the production of ammonia eliminates an existing source of CO_2 for some of the downstream products (urea, AdBlue and melamine) and surrounding industries (like food and beverages and the greenhouse horticulture). In both a scenario where renewable ammonia is produced in the Netherlands and where the ammonia is imports, alternative sources of CO_2 will be required to continue these operations. Policies accommodating CO_2 supply through national sourcing strategies could minimize the complexity these industries experience when setting up new supply chains.

When considering strategic independence of fertiliser production, multiple factors need to be taken into account.
As discussed, the fertiliser industry is considered strategic by the EU and to ensure security of supply policies can be put in place ensuring domestic production even if the economic conditions are unfavourable. When considering strategic independence, it is important to weigh all relevant factors. This includes the current dependence on natural gas imports for ammonia production. A shift to renewable hydrogen based production can lead to new dependencies. Although the future of global ammonia trade is uncertain, it is expected that there will be a variety of exporting countries. This can reduce the risks associated with an import dependence. Complete independence from imports is possible with domestic renewable hydrogen and ammonia production. There will be a price for this independence, based on the price of domestic hydrogen versus imported ammonia and the required investments for switching the ammonia production capacity from SMR to the synthesis of ammonia based on green hydrogen and nitrogen from air separation.

Iron and steel industry

Production costs of steel depend on existing geographical variables, such as cost of capital, labour costs and the cost of iron ore. These dynamics will be different for a renewable hydrogen-based production process, where electricity and hydrogen costs will significantly impact production costs. For regions importing feedstocks, the transport costs also impact the production costs.

For existing production plants, there are many cost drivers that determine the Levelized Cost of (Crude) Steel (LCOS) production. Most of these cost drivers are geographical to some degree.

These include the cost of coal and natural gas, but also the cost of capital, labour, and iron-ore prices. Phasing out coal and natural gas based methods will introduce additional geographical dependencies: electricity and hydrogen. These commodities are harder to transport than coal and natural gas, which results in an increased transport cost-premium (see text box). This will make the geographical dependency stronger and potentially creates an incentive for relocating production to regions with more favourable geographical conditions for renewable hydrogen production.

The future development of electricity and hydrogen costs are highly uncertain and many scenarios are possible.

As mentioned previously, a higher dependency on electricity and hydrogen for renewable hydrogen-based steelmaking will introduce new complexities and costs for the import of feedstocks. The existing literature suggests that this will worsen the cost-competitiveness in regions with less economically favourable renewable resources. The literature consulted for this study also suggests that North-Western Europe is unlikely to be among the favourable regions. Analysis of hydrogen and electricity cost projections in various studies does show that these projections are highly uncertain. This uncertainty is a result of the unpredictability of the development of electricity and hydrogen production costs over the long-term.

An analysis was performed in order to exhibit the degree to which these geographical factors can affect the total production costs. Figure 1.4 shows the resulting production costs for selected countries. The graph exhibits the cost factors and shows the geographical dependencies of the levelized cost of steel production. It is important to reiterate that these outcomes are dependent on a number of highly uncertain assumptions. The outcomes should be interpreted as one possible scenario and the graph serves to give an example of the resulting geographical cost differences.

Transport cost-premiums

In order to examine the competitive disadvantage an importer of an (intermediate) product could have as a result of (partial) outsourcing of production, transport cost-premiums are used. The transport cost-premium shows the relative cost increase of the finished product, resulting from the transportation cost of a given (intermediate) product. This can be interpreted as the relative cost difference between an importer and exporter, all else being equal, because the importer has to import a product that cannot be made cost-competitively domestically. This metric is useful because it exhibits the worst case effects on competitiveness for (partial) outsourcing, independent of uncertain geographical cost developments. If the transport cost-premium for an (intermediate) product is low, importing that product is unlikely to affect the competitiveness of the remaining supply chain. If the transport cost-premium for an (intermediate) product is high, importing that product would substantially affect the cost-competitiveness of the downstream supply chain, making imports of more finished products a more attractive option.

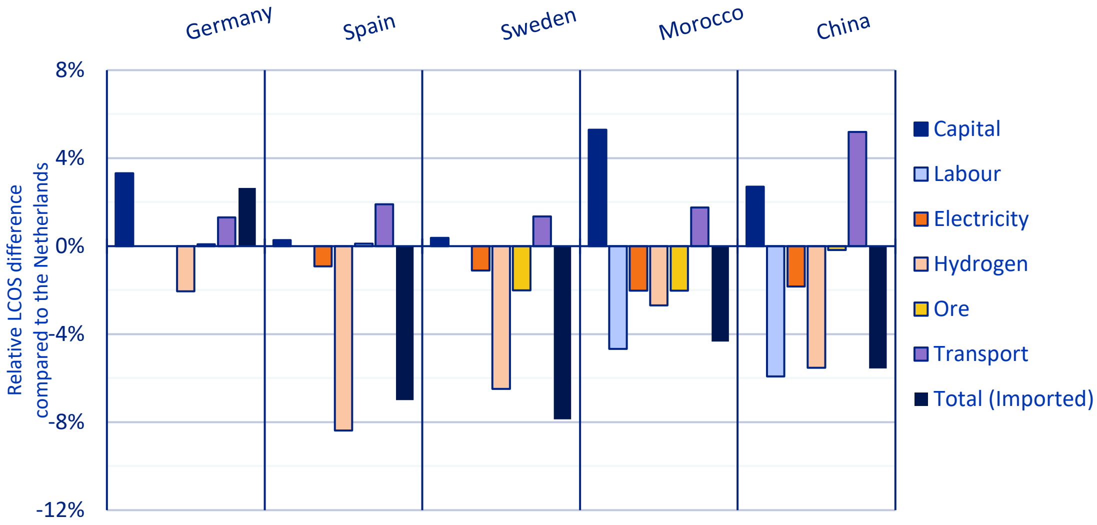

Figure 1.4: Difference in levelized cost of crude steel production in different countries and transport of the crude steel to the Netherlands compared to domestic production in the Netherlands. The totals are the sum of all these differences and display the final cost difference. The assumptions and methodology for the calculations are shown in Appendix b. Results given indicate long-term indications, and remain highly uncertain.

The transport cost-premium (see text box) for hydrogen import in the case of steel is significant. This means that insufficient cost-competitive hydrogen availability would make other modes of import economically favourable. This entails the import of Hot Briquetted Iron (HBI) or even crude or finished steel, with the latter having the lowest transport cost-premium.

In Figure 1.5, the transport cost-premiums for the import of certain products is given for key (intermediate) products in the supply chain. Firstly, it becomes clear that the transport of hydrogen at longer distances would contribute substantially to the total steel production cost. This suggests that relying on the import of hydrogen, would pose difficulties for the cost-competitiveness of downstream steel products. This increases the likelihood of further relocation of downstream production steps. For the import of hydrogen, iron-ore still has to be imported as well. Although this is also the case for the existing process, the import of HBI or steel does not require import of iron-ore. The transport cost-premium resulting from HBI-import has significantly smaller impact on production costs, especially at longer distances. Nonetheless, the import of crude or finished steel has the lowest transport costs. This avoids the costs of briquetting the HBI for transport and preheating for smelting. The difference in the transport cost-premium between HBI and crude or finished steel imports does appear to be relatively small.

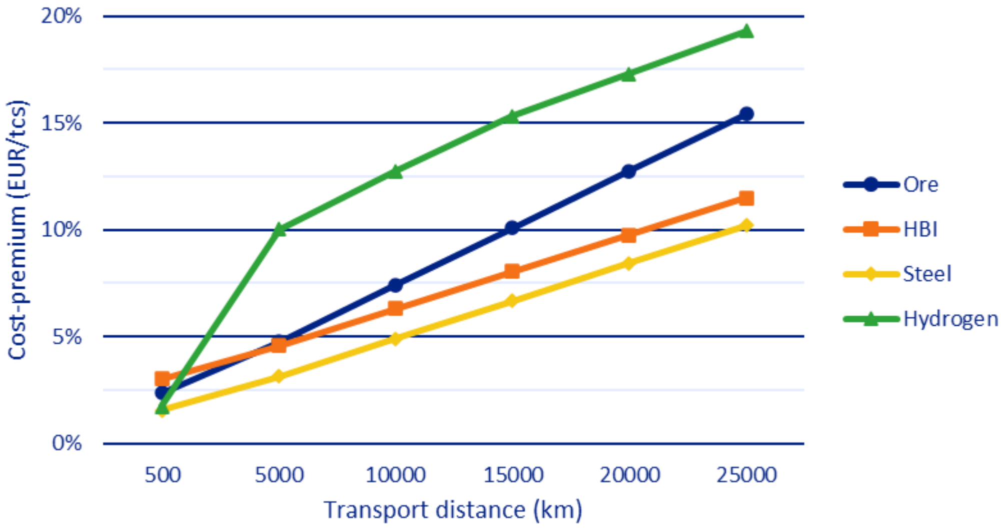

Figure 1.5: Transport cost-premiums resulting from transport costs at different stages of the supply chain for various distances, for a crude-steel price of €500/t_{CS}. See the text box for guidance on interpreting the transport cost-premium. The hydrogen transport costs represent the option with the lowest levelized cost of hydrogen transport at each distance for all options shown in Figure 1.2, in order to minimize the transport cost-premium. The transport medium for hydrogen therefore varies for different distances.

The advantage of integrated production could be an incentive for greenfield Direct Reduced Iron (DRI) facilities to integrate steel production on-site. This could hinder the development of an HBI market. Overall, the emergence of a high liquidity HBI-market appears unlikely in the short-term and uncertain in the long-term.

As shown previously, the integration of the full production process is energetically and economically the most efficient. This could be an incentive for greenfield DRI facilities, which have to choose between producing and exporting HBI or integrating steelmaking, to choose the latter option. This could hinder the development of an HBI market. Overall, the consulted literature is sceptical about the emergence of a high liquidity HBI market on the short-term. A lack of liquidity would likely result in high costs and dependency on a limited number of suppliers, which hurts the business case for steelmakers using imported HBI.

The previously mentioned drawbacks for both hydrogen and HBI imports suggest a significant impact on the cost-competitiveness of renewable hydrogen-based steel production in the Netherlands, in the case of insufficient cost-competitive renewable electricity and hydrogen availability. Sufficient cost-competitive renewable electricity and hydrogen supply in the Netherlands are therefore important for the cost-competitiveness of renewable hydrogen-based steelmaking in the Netherlands.

Importing intermediate products for the domestic production of steel could significantly change the existing business case. The effect on cost-competitiveness is most prominent in the case of hydrogen imports, but uncertainties surrounding the availability of HBI also adds substantial complexity. That means that the business case of renewable hydrogen-based steel production in the Netherlands (compared to renewable hydrogen-based steelmaking elsewhere) is dependent on the availability of sufficient affordable renewable electricity and hydrogen.

Production costs only tell part of the story. Steel quality, customers' willingness to pay, **and relative effects of higher steel costs in final products also influence competitiveness. Other factors also influence the decision for a production location.**

Finished steel is not a homogeneous commodity, and the quality of steel could significantly affect the willingness to pay by customers. Higher production costs for higher quality steel are therefore not necessarily a threat to competitiveness. Furthermore, increased steel costs have limited effects on the production costs of steel-based products. For example, a 20% increase in steel costs results in an approximate 1% uptick in the overall cost of a car. This could mean that even if significant cost differences manifest, high-quality steel could remain preferential, with increased costs being passed down to the customer for the end-product.

Next to the cost factors, there are many contributors that are harder to quantify, which also influence the decision for a production location. These include the value of existing assets, infrastructure, staff and expertise.

The EU has declared steel a strategic commodity and has stated it will make efforts to safeguard the bloc's production capacity. The same strategic concerns can affect the **decision-making** process for member states' domestic production capacities, **outweighing concerns over cost-competitiveness.**

The fundamental importance of steel to modern society is ubiquitous. The EU has stated openly that it plans on maintaining steelmaking capacity for strategic purposes. This means that any techno-economic disadvantages the EU as a bloc might have, could be compensated through policy measures. It is not yet clear what such a policy framework would be, and as such it is unclear whether the steel production in the Netherlands can count on EU support. Nonetheless, although the support for steel production capacity within the EU has been openly declared, individual member states might also consider steel of strategic importance to their individual sovereignty. The Dutch government could decide to compensate the techno-economic disadvantages through policy measures domestically as well.

A shutdown of Dutch steel production capacity would affect existing customers, who will have to find new suppliers. As a result, the steel consumers could face increased costs, in particular offtakers for specialty steel.

The effect relocation of steel production would have on Tata Steel Netherlands (TSN) clients such as the automotive and packaging sectors is not clear. If TSN is unable to compete with other steel suppliers, this implies that the customers need to have access to alternative, cheaper steel sources. Yet the customers could still see an increase in steel costs due to transport costs. The effect of higher steel prices can also be limited for some specialised higher-value products like cars. It has not been possible to establish whether specialty steel consumers will face significant challenges in acquiring steel in case of relocation. TSN also expects a (partial) shutdown of production in the Netherlands to impact R&D activities at universities and that contractors and suppliers will be impacted by reduced activity from a large customer.

Conclusions

The competitiveness of a Dutch iron and steel industry producing steel based on renewable hydrogen depends on the costs of iron ore, hydrogen, electricity and transport of feedstocks and(semi-finished) products. Our analysis and literature indicate that there is significant uncertainty about the development of costs of many of the key inputs. Most pronounced are the geographical differences in renewable electricity and hydrogen costs. This includes the development of renewable electricity costs in the Netherlands and the cost of hydrogen produced from this electricity. If there is insufficient domestic renewable hydrogen production in the Netherlands, or it is cheaper to import renewable hydrogen, there is a consensus in literature that it should also be more cost-effective to import crude steel produced in the renewable hydrogen producing country. Our analysis aligns with these findings from literature.

Importing HBI is more costly than importing crude steel as 1.2 tonnes of HBI are required per tonne of crude steel. However, the cost difference between crude steel imports and HBI imports generally does not exceed 10%. Hydrogen is most difficult and costly to transport, making domestic steel production based on imported hydrogen the least cost-efficient option of the import scenarios. These results suggest that if there is a reason to import hydrogen, replacing the entire domestic supply chain with crude steel imports is the most cost-effective option. The results also indicate that if an investor is setting up a supply chain for the production of steel using hydrogen, there is a cost-optimizing incentive to integrate the whole production chain up to crude steel in a region where cheap renewable hydrogen is available.

Yet even if an option is more cost-optimal on paper, there needs to be sufficient availability of feedstocks (iron ore, hydrogen, scrap steel) and products (HBI and crude steel), all of which is currently uncertain. It is also uncertain how intangible factors such as existing assets, infrastructure, staff and expertise influence the decision to maintain local production or partially switch to an import-based production chain.

(Partially) replacing the domestic production chain with imports will primarily affect TSN's own operations and the operations of suppliers. Due to uncertainties about product specificity and uncertainty with regard to potential supply chain replacements, it is impossible to conclude which of TSN's customers will be significantly affected by a change in the domestic production approach.

Policy Considerations

The costs to produce and transport hydrogen are important factors influencing the position of green steelmaking in the Netherlands versus other locations. Renewable hydrogen-based steelmaking in the Netherlands is therefore strongly linked to the position of the Netherlands as a producer and importer of hydrogen.

Due to the significant transport premium for hydrogen, the analysis shows that if there is a reliance on imported renewable hydrogen, it is likely more cost-effective to import HBI, crude steel or steel products. The position of renewable hydrogen-based steelmaking in the Netherlands is therefore dependent on sufficient and affordable renewable hydrogen availability in the Netherlands. This links the position of renewable hydrogen-based steelmaking to the position of the Netherlands as a producer and importer of hydrogen.

The capacity of TSN and their clients to absorb higher costs is an important determinant for whether green steelmaking in the Netherlands will be viable compared to the import of (semi-finished) products.

The analysis shows that the transport cost-premiums for importing HBI or crude steel are below 5% at a distance of 5000 km. At the same distance the transport premium for hydrogen is around 10%. What the analysis does not show is what the transport premiums mean for TSN or their clients. Whether the transport premiums can be absorbed and/or passed on to clients is therefore an important factor influencing potential relocation or outsourcing decisions.

Decisions to shift from production in the Netherlands to imports also depends on the timely availability of alternative options, like green HBI or crude steel. If such alternatives are not timely available it may support a decision to continue production here. It is important to follow international developments.

Currently there are limited plans globally for producing green steel and there is no existing HBI trade. The potential shift to imports of HBI or crude steel therefore depend on investments in new, clean steelmaking facilities in other countries. These are large capital-intensive plants and are therefore uncertain. Coupled with long investment lead times, maintaining a good overview of the international development of new, renewable hydrogen-based steelmaking plants is vital to making a good assessment of the chance of partial shutdowns, shifts to imports and the effects of such a change in the production chain.

It is relevant to reiterate that in this study we do not consider carbon leakage, which would imply domestic steelmaking being replaced by fossil-based steelmaking elsewhere. The risks and consequences of carbon leakage are not necessarily the same as (partially) switching production to a supply chain relying on imports of green hydrogen, green HBI or green crude steel.

Contents

Appendices

1 Introduction

1.1 Motivation

The Netherlands has an extensive highly competitive heavy industry sector, with a handful of large refineries, several large chemical industry clusters, and a number of large base metal companies, including iron and steel. This situation has emerged as a result of a combination of factors, including:

- the abundant availability of natural gas in the Dutch subsurface,
- the location by the sea, central to the large North-West European market, with large seaports that allow large-scale imports of fossil fuels and raw materials, and
- the availability of highly skilled people and a well-developed infrastructure with excellent connections to the hinterland for the transit of raw materials, semi-finished products and products.

However, with the disappearance of relatively cheap domestic natural gas and the need to eventually reduce industry emissions to net zero, a new situation is now beginning to emerge. On the other hand, offshore wind energy resources in the Netherlands are large and can be used to produce renewable hydrogen. Adapting to changing conditions will require fundamental changes in industrial processes, significantly reducing the use of fossil fuels for both energy and raw material purposes and replacing them with renewable and circular resources. These fundamental changes can profoundly alter the landscape of industrial activities. Major investments are required for the adjustments. The question is to what extent these investments in adapting industry will take place in the Netherlands or whether investments will take place elsewhere, resulting in the relocation of industrial activities.

In principle, the Dutch government would prefer that companies adapt here rather than move industrial activities elsewhere. The Dutch government is therefore willing to support the industry in achieving their sustainability goals and collaborates with the largest industrial emitters to implement sustainable technologies that will lead to substantial reduction of fossil fuel use and CO_2 emissions. The so called “customized agreements (maatwerkafspraken)” cover, among other industries, the iron and steel and the fertiliser industry in the Netherlands.

The iron and steel sector in the Netherlands plans to shift to a hydrogen-based steelmaking process. For the fertilisers industry, the use of electrolysis-based hydrogen is also an important part of the decarbonisation strategy. However, both industries operate in a competitive global market. The transition to renewable hydrogen may pose economic challenges, potentially leading to increased costs and the risk of displacing existing processes. Industries located in regions with economically less favourable conditions for electrolysis-based hydrogen production with renewable electricity may find it advantageous to import semi-finished products from more favourable locations. Examples are the import of renewable ammonia for the production of fertilisers and other products instead of producing ammonia in the Netherlands, and the import of reduced iron ore in the form of hot briquetted iron (HBI) which can be used to produce steel instead of importing virgin iron ore. But ultimately it may of course also be more attractive, from an economic point of view at least, not to import ammonia and reduced iron ore, but fertiliser and crude steel.

In this context, there is a need for an exploration of the effects that switching to renewable hydrogen imports can have on the Dutch iron and steel and the fertilisers industries. Such critical information will empower policymakers in making industrial transformation strategies and formulate responsive policies as needed, aligning with national interests and strategic objectives.

1.2 Objectives

The ministry of Economic Affairs and Climate Policy (EZK) has requested TNO to explore the effects of certain activities within the heavy industry relocating to regions where the renewable (hydrogen) energy carriers can be cheaper. This report focuses on two industry clusters, iron and steel, and the fertilisers industries in the Netherlands. This report, thus, is part of a large assignment, where an exploration of possible relocation risks has been conducted for heavy industries, also including refineries and the large volume organic chemicals industries.

The main research question addressed is:
Which specific processes within the iron and steel and fertiliser value chains are most vulnerable to shut down coupled to the import of renewable hydrogen carriers or semi-finished products?

In addition, the following two follow-up questions are briefly addressed:

- How can partial shut-down of production capacity in the Netherlands disturb the operations of and synergies with other industry in the Netherlands that are interlinked with the iron and steel or fertiliser industry?
- What are the key factors, next to costs, for companies to decide on down-scaling of their domestic operations and relocating some of them?

It is essential to clarify that this study does not concentrate on the competitive position of these industries or delve into carbon leakage resulting from varying policy ambitions across different global regions. Instead, the study examines the cost-supply dynamics of renewable hydrogen energy carriers and potential intermediates, exploring what potential effects are of imports on specific parts of the processes. As the report focuses on renewable hydrogen (see definition below), blue hydrogen from natural gas with CCS is not considered within the scope of the study.

1.3 Definitions and methodology

In this report we frequently refer to renewable hydrogen and to relocation of industrial processes. The definitions of the terms as used in this report are given below.

By **renewable hydrogen** we refer to hydrogen produced through electrolysis using renewable electricity from, for example, solar PV or wind energy. Sometimes only hydrogen is used in the text. This also refers to renewable hydrogen.

Renewable hydrogen carriers refer to chemicals that are used to transport renewable hydrogen, such as ammonia, liquid organic hydrogen carriers (LOHC) or methanol. The hydrogen does not always have to be recovered from the hydrogen carriers. Ammonia and methanol, for example, can also directly be used as feedstocks or for energy purposes in industry or the transport sector.

By **relocation** we refer to the partial or complete replacement of the production chain in the Netherlands by imported feedstocks, semi-finished products or finished products. The production abroad and export to the Netherlands does not necessarily have to be done by the same company as the one in the Netherlands. The hydrogen or (semi-)finished products can also be bought from another producer or from an international market. Imports are always considered to also be renewable hydrogen-based production. We do not consider the replacement of production in the Netherlands with fossil-based production elsewhere (i.e., carbon leakage). As we only consider renewable hydrogen (carriers), the European Carbon Border Adjustment Mechanism (C-BAM) is not expected to have any significant effect.

The assessment is based on a literature review, own analyses and interviews with the three main players in the Dutch iron and steel and fertiliser industries: Tata Steel Netherlands (TSN), Yara Sluiskil and OCI. The data used for the own analyses can be found in the Annex. For cost data we consider long-term costs, when the renewable hydrogen production technologies and renewable hydrogen-based steel and fertilisers production technologies are near the end of the learning curve. As it is uncertain if these technologies will reach this status in 2035, 2040, 2050 or beyond we refrain from referring to specific years in this report.

1.4 Report structure

The following chapters dive deeper into each industry and provides a brief overview of these industries, their decarbonization plans, connections with the surrounding industries and an exploration of the effects of switching to imports on the rest of the supply chain. The qualitative assessments are complemented with interviews to large players in each of the industries to better understand the challenges associated to the energy transition and the industrial decarbonization, their intended response to these transitions, and to evaluate whether these transitions pose a risk of industrial relocation along the value chain of each of these industries. More specifically:

- chapter 2 provides the assessments related to the fertiliser sector,
- chapter 3 provides the assessments related to the iron and steel sector.

2 Fertiliser industry

2.1 Fertiliser industry in the Netherlands

2.1.1 Current Status

The fertiliser industry in the Netherlands comprises of 65 companies (CBS, 2024),. The main four companies are Yara Sluiskil B.V., OCI Nitrogen B.V., ICL fertilisers and Rosier Nederland (Batool & Wetzels, 2019). Of these, Yara Sluiskil B.V. and OCI Nitrogen B.V. are significantly larger than the other companies. Both produce nitrogen based fertilisers based on natural gas reforming. Ammonia is produced from natural gas and air as a first step, after which a variety of products are produced including urea, nitric acid, ammonium nitrate, calcium ammonium nitrate and urea ammonium nitrate. OCI Nitrogen B.V. is also the largest producer of melamine in the world (Batool & Wetzels, 2019). Significant amounts of product are exported both within the EU and to outside the EU (Batool & Wetzels, 2019) (strategy&, 2023). Important trade partners are Belgium, Germany, France and South America (Vergeer, Bachaus, de Bruyn, Chris Jongsma, & Chewpreecha, 2021).

The production location in Sluiskil is the largest fertiliser production facility in Northwest Europe (strategy&, 2023). The facility produces around 23% of the total production of Yara worldwide (strategy&, 2023). Yara Sluiskil B.V. has three ammonia plants[2] with a cumulative production capacity of approximately 1.8 Mt ammonia per year (Batool & Wetzels, 2019). Ammonia is both sold directly to customers and used on-site to produce different types of fertiliser. Yara Sluiskil B.V. has ammonia storage tanks and can import and export ammonia to balance production at the Sluiskil plant and other locations, for example during maintenance and during the surge in natural gas prices in 2022 (Yara Sluiskil, 2023). The size of the import/export capacity is not publicly known.

OCI Nitrogen B.V. has two ammonia plants[3], with a production capacity of almost 1.2 Mt ammonia per year. In addition, OCI has an import terminal in Rotterdam with a capacity that is being expanded from 400 kt to 1.2 Mt ammonia per year (OCI Global, 2022). Also, here some of the ammonia is directly sold to customers and the rest is used to produce a range of fertiliser and other derived products such as melamine. The production capacity of the ammonium nitrate plant is not publicly known which means not all the flows can be mapped for OCI Nitrogen.

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[2] Ammonia plant C production capacity 449 kt/a, ammonia D 639 kt/a, and ammonia E 731 kt/a (MIDDEN, 2019 Lako, 2009)

[3] each plant produces 50% of the ammonia

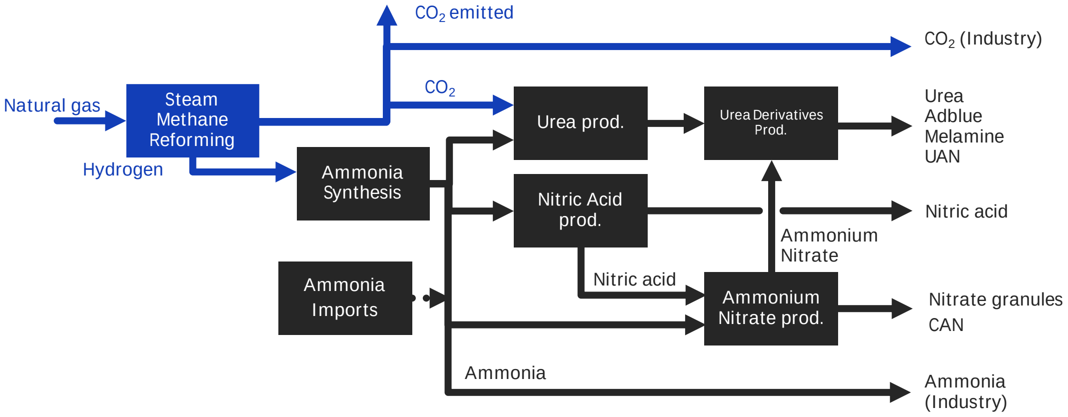

Figure 2.1: Generalised flowchart for both Yara and OCI. When industry is specified, this refers to products being delivered to other industries as a feedstock.

Yara Sluiskil B.V. uses approximately 56 PJ of natural gas annually and OCI Nitrogen B.V. 38 PJ natural gas when producing at maximum capacity for 8000 hours per year (Batool & Wetzels, 2019). A large part of the natural gas is used for non-energetic purposes and gets transformed into products. The total amount of hydrogen needed for ammonia is approximately 296 kt for Yara and 192 kt for OCI, with the current ammonia production capacities (Batool & Wetzels, 2019).

Due to the increased natural gas prices Yara Sluiskil reduced production in 2022. At one point only one of the three ammonia plants was operational.[4] OCI Nitrogen also reduced the production of ammonia from natural gas in 2022 and increased the import of ammonia through its terminal in Rotterdam (OCI Global, 2022).

The main nitrogen fertiliser used in the Netherlands is calcium ammonium nitrate (Table 2.1). We understand from the industry that the urea products produced in the Netherlands are mostly used for the production of melamine, AdBlue and for export.

Table 2.1: Consumption of nitrogen fertiliser products in the Netherlands in 2021

Product	Consumption (kt)
Ammonium nitrate	0.0
Ammonium phosphate	0.5
Ammonium sulfate	20.6
Calcium ammonium nitrate	113.2
Urea	4.3
Urea ammonium nitrate	20.4
Compound nitrogen fertilisers	26.4
Total nitrogen fertilisers	185.5

Source: (International Fertiliser Association, 2024).

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[4] https://energeia.nl/energeia-artikel/40103327/yara-sluiskil-gaat-vanaf-2025-co-opslaan-in-noorwegen

2.1.2 Industry decarbonisation plans

In recent years, the fertiliser industry has been responsible for approximately 28% of the GHG emissions from the chemical industry in the Netherlands (CBS. 2022). Table 2.2 shows the direct emissions of Yara Sluiskil and OCI Nitrogen based on the production process. In line with the reporting for the emission trading scheme (ETS), direct emissions also include CO_2 that is captured in urea or that is sold for other purposes, highlighted as utilisation of high purity CO_2 in the table.

Table 2.2: Estimated CO_2 emissions at Yara Sluiskil in 2021

[Mt CO_{2eq}]	Yara Sluiskil	OCI Nitrogen
CO_2 emission (total)	3.2	2.2
• Of which CO_2 from combustion	0.8	0.7
• Of which high purity CO_2	2.2	1.4
• Of which N_2O emissions	0.2	0.1
Utilisation of high purity CO_2	1.4	1.0

Source: (NEa, 2023), (Lamboo, 2023) and OCI Nitrogen in 2017 (Batool & Wetzels, 2019).

In the short term, Yara Sluiskil B.V. aims to reduce emissions by 1.5 Mt CO_2eq by 2030 (Yara Sluiskil B.V., 2022) (Minister of Economic Affairs and Climate Policy; State Secretary of Infrastructure and Water Management; Provincial Executive of the Province of Zeeland; Yara Sluiskil B.V., 2023), which corresponds to more than 45% of the company total emissions in 2021. A reduction of 0.8 Mt is planned through carbon capture and storage (CCS) and 0.7 Mt through various measures including energy efficiency, reduction of nitrous oxide (laughing gas) emissions, and the use of renewable hydrogen. A binding commercial agreement has been signed with Northern Lights to transport CO_2 released during the production of ammonia in liquid form by ship to Norway for permanent storage under the Norwegian seabed[5]. Yara Sluiskil B.V. intends to achieve CO_2 neutrality by 2050 and indicates that the import of renewable hydrogen is part of the aspirations to achieve climate neutrality (Minister of Economic Affairs and Climate Policy; State Secretary of Infrastructure and Water Management; Provincial Executive of the Province of Zeeland; Yara Sluiskil B.V., 2023).

OCI N.V. aims to reduce CO_2 emissions by 0.8-1.7 Mt by 2030 by producing ammonia from low carbon, circular or renewable hydrogen (Minister of Economic Affairs and Climate Policy; State Secretary of Infrastructure and Water Management; OCI N.V., 2023). This corresponds to 35-77% GHG emissions reduction, compared to emissions in 2020. The actual reduction will depend on the choices made between different pathways. Options being explored include the use of low-carbon hydrogen produced through the gasification of municipal waste[6], purchasing renewable hydrogen delivered by a connection with the national hydrogen network (hynetwork, 2024), or importing ammonia through their terminal in the Port of Rotterdam with delivery by inland ship or a pipeline in the Delta Rhine Corridor (Delta Rhine Corridor, 2024). CCS[7] is mentioned as a possible transition technology. OCI N.V. also

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[5] Yara invests in CCS in Sluiskil and signs binding CO2 transport and storage agreement with Northern Lights – the world's first cross-border CCS-agreement in operation | Yara International

[6] Referring to the FUREC project: https://benelux.rwe.com/locaties-en-projecten/furec/

[7] Where a significant portion of its ammonia plants' CO2 emissions would be liquified and transported to the Port of Rotterdam's CO2 Transfer Hub and Offshore Storage, which would receive and store CO2 in the empty gas fields under the North Sea.

aims to achieve climate neutrality before 2050 (Minister of Economic Affairs and Climate Policy; State Secretary of Infrastructure and Water Management; OCI N.V., 2023).

2.2 Exploration of the effects of imports on the domestic value chain

In this section we explore the potential effects of (partially) shutting down the local production of fertilisers in favour of imports. The analysis focuses on a renewable hydrogen based supply chain. Two scenarios are compared:

1. Production of fertilisers based on domestically produced renewable hydrogen
2. Fertilisers production based on imports of part of the supply chain (hydrogen or ammonia)

Figure 2.2 illustrates the two different paths. The starting point for the second scenario is the assumption that at least renewable hydrogen is imported. The reason for this can be that there is either insufficient renewable hydrogen produced in the Netherlands or that it is cheaper to import the renewable hydrogen. The analysis explores, in case renewable hydrogen is imported, whether it is efficient or economically attractive to import ammonia instead. Furthermore, the analysis explores the effects of hydrogen and ammonia import costs on the production costs of the various end products (i.e. fertilisers, melamine and AdBlue).

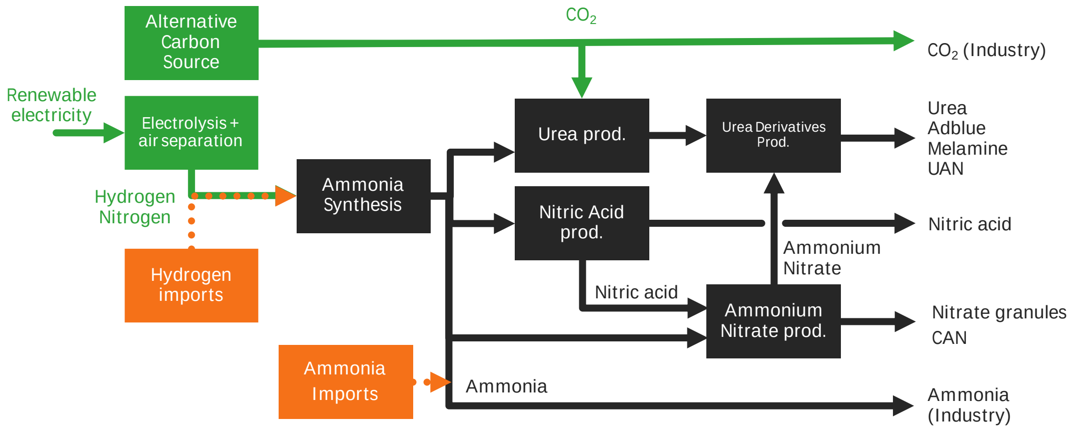

Figure 2.2: Overview of the production chains considered in the assessment. The baseline is a complete production chain in the Netherlands starting with domestic renewable hydrogen production. A comparison is made to explore the effects that imports of renewable hydrogen or ammonia have on the production of fertilisers and other products in the Netherlands.

An overview of data used for calculations in this section can be found in Appendix a.

The section does not explore other reasons for relocation such as large investments and high costs associated with necessary adjustments of existing production processes, more favourable policy in other countries or imports of fossil-based hydrogen, ammonia or fertilisers (i.e. carbon leakage).

The next section (2.3) explores interconnections with other industries and explores the effects that partial shutdown of domestic production in favour of imports can have on these industries.

2.2.1 Renewable ammonia production costs

Geographical comparisons of ammonia production costs are sparse in the literature. Three studies, including the TNO estimates, are exhibited in Table 2.3, which differ significantly on the final production costs.

The first study exhibited is the Fraunhofer study (Hank, et al., 2023). In this study, selected locations are examined for the possibility of export to Germany. The production facility and supply chain is optimized to minimize production costs for each location based on solar and wind patterns. The results discussed in this report concern the local production costs, whereas the original publication also calculates the imported costs to Germany. The second study by Fasihi et al. also uses geographical data to estimate the electricity costs based on solar and wind profiles (Fasihi, Weiss, Savolainen, & Breyer, 2021). However, the Fasihi et al. study does not take into account the geographical feasibility of locations, ignoring limiting factors like densely populated areas and rough terrain. Lastly, the outcomes from the TNO supply chain model are shown. These costs are based rather on known data from each region found in the literature, without specific generalised optimization per location.

All studies demonstrate significant cost variations across different locations. The studies are consistent in which geographies will have lower production costs, with European locations at a disadvantage to more favourable locations in Morocco and Brazil. According to Fasihi et al., the cost difference between domestic production and production in these regions can be around 20%. Although the Fraunhofer study (Hank, et al., 2023) only considers production costs for 2030, the Fasihi et al. (2021) study suggests that the expected cost declines of technologies will further exacerbate these differences.

Table 2.3: Comparison of ammonia production cost estimates,

Country	Fraunhofer (€/t_{NH3}) (2030)	Fasihi et al. (€/t_{NH3}) (2030 | 2050)	TNO (€/t_{NH3}) (2030 | 2040)
Netherlands	-[8]	540 | 440	824 | 654
Spain	1010	470 | 330	-
Ukraine	1050	580 | 410	-
Morocco	1070	445 | 300	587 | 437
Brazil	865	425 | 285	540 | 507

Source: (Hank, et al., 2023), (Fasihi, Weiss, Savolainen, & Breyer, 2021), and internal TNO data[9].

Although the outcomes from the existing literature are uncertain, the common pattern does indicate that renewable ammonia produced domestically in the Netherlands is not expected to be cost-competitive with renewable ammonia production in more cost-optimal regions. The transport costs then dictate to what degree this would affect the cost-competitiveness for domestic and neighbouring export markets for ammonia and downstream fertiliser products.

2.2.2 Renewable hydrogen and ammonia transport costs

Exact transport costs of hydrogen energy carriers are still subject to uncertainty. However, gaseous hydrogen pipeline transport and maritime ammonia transport are relatively mature

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[8] The Fraunhofer study does not include domestic production cost estimates as a reference.

[9] From the supply chain model originating from the HyDelta project (more info here).

technologies and have a much smaller error-margin. Figure 2.3 shows a comparison of various modes of hydrogen transportation, presenting their levelized cost of transport, expressed in €/kg_{H2}. These values exclude the production costs of the hydrogen carriers, hence, they should not be confused with the levelized cost of supplying hydrogen energy carriers. The methods and data used is based on (Ortiz Cebolla, Dolci, & Weidner, 2022).

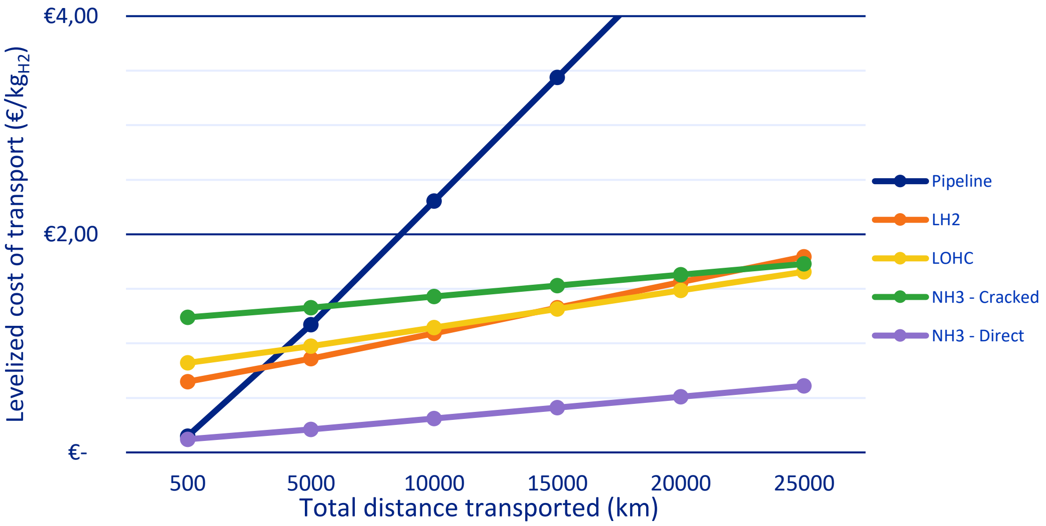

Figure 2.3: Cost comparison of hydrogen transport modes for different mediums[10], adapted from (Ortiz Cebolla, Dolci, & Weidner, 2022). The pipeline transports compressed H_2, the remaining carriers are all transported by maritime shipping. The hydrogen transport costs are levelized based on the hydrogen content for each carrier. For direct ammonia, this means the levelized cost are calculated using the hydrogen content of ammonia. The timeline for these costs are the years 2030-2035, the assumptions are given in Appendix A.

Figure 2.3 shows that, for distances exceeding 500 km, the way to transport hydrogen at the lowest cost is in the form of ammonia, provided that the hydrogen is not recovered from the ammonia, but the ammonia is directly used. If the Netherlands is importing renewable hydrogen for any application, either due to lower import costs or insufficient local production capacity, phasing out of ammonia production from locally produced renewable hydrogen appears as a cost-optimal import strategy. With such a strategy imported renewable ammonia can replace local renewable ammonia production, thereby, freeing up renewable hydrogen for alternative purposes. If all local ammonia consumption is imported and there is a remaining demand for hydrogen imports, other import modes (e.g. pipeline or LOHC) can become the cost-optimal option because of the additional costs associated with the recovery of hydrogen from imported ammonia. E.g. in Figure 2.3, up to around 5000 km compressed hydrogen by pipeline, liquid hydrogen (LH_2) or LOHC are all cheaper options than cracked ammonia. LH_2 and LOHC remain cheaper than cracked ammonia up to around 20,000 km.

To make this argument concrete, an example is presented. The example is that of hydrogen import from Morocco to the Netherlands. In this example there is a hydrogen importer and an ammonia producer. The ammonia producer can also import ammonia instead.

In this example, the importer pays about €0.60/kg_{H2} for the transport of the imported hydrogen by pipeline transport over roughly 2,500km. In this example, this is the cheapest

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[10] NH_3 - Cracked represents the transport cost of hydrogen that has been cracked back from ammonia. Whereas NH_3 - Direct represents the transport cost of the hydrogen that is still contained in the form of ammonia.

transport option according to Figure 2.3. Assuming the cost to produce hydrogen in Morocco is €3/kg$_{H2}$, this means the importer is now paying €3.60/kg$_{H2}$ for the hydrogen. This could be cheaper or more expensive than the existing domestic hydrogen supply. The assumption is made ammonia can also be produced in Morocco using hydrogen of €3/kg$_{H2}$, with minimal influences on price from other cost factors compared to the Netherlands. This is justified considering hydrogen costs are expected to make up more than 85% of ammonia production costs (Hank, et al., 2023).

If this €3.60/kg$_{H2}$ is cheaper than domestic production, the ammonia producer in the Netherlands is paying at least €3.60/kg$_{H2}$ for their hydrogen – €0.60/kg$_{H2}$ more than an ammonia producer in Morocco would pay for hydrogen. This results in €106/t$_{NH3}$ extra to source its hydrogen, which is 17% of the current ammonia price. The total transport costs of ammonia over the same distance is only €28/t$_{NH3}$. If the ammonia producer in the Netherlands would import ammonia from Morocco instead, which was produced with hydrogen at €3/kg$_{H2}$ and similar remaining production costs, it could sell the hydrogen it is currently using for its production for (at least) €3.60/kg$_{H2}$. This means that the hydrogen sourced for the ammonia production now costs €556/t$_{NH3}$[11], rather than €634/t$_{NH3}$, saving at least €78/t$_{NH3}$ per tonne of ammonia imported.

If the €3.60/kg$_{H2}$ is more expensive than domestic production, then there is relatively no disadvantage to an ammonia producer in Morocco. However, an ammonia producer in the Netherlands can sell the hydrogen currently used for ammonia production to the hydrogen importer at €3.60/kg$_{H2}$ (the price that the importer pays anyway for hydrogen from Morocco). Again, the ammonia producer imports ammonia for €28/t$_{NH3}$, displacing 176 kg (€634 worth) of hydrogen per tonne ammonia imported. The hydrogen for the ammonia that is imported instead costs €556/t$_{NH3}$, which results in a net benefit of €78/t$_{NH3}$.

Note that this effect becomes stronger over longer distances, considering the fact that ammonia transport has the lowest marginal cost of all hydrogen transport modes. Considering Chile as the exporting country and importing liquid hydrogen (over 14,500km), would result in a benefit of €160/t$_{NH3}$ for the ammonia producer/importer.

Next we assess the effects of replacing local ammonia production with ammonia imports on the rest of the supply chain for the fertiliser industry. We do this using transport cost-premiums (see box), because of the uncertainty in the long-term development of hydrogen and ammonia production costs. The reason for replacing local production with ammonia imports can be either that there is insufficient local renewable hydrogen production available, or imports being cheaper.

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[11] €3/kg$_{H2}$ times 176kg$_{H2}$/t$_{NH3}$ plus €28/t$_{NH3}$.

Transport cost-premiums

In order to examine the competitive disadvantage an importer of an (intermediate) product could have as a result of (partial) outsourcing of production, transport cost-premiums are used. The transport cost-premium shows the relative cost increase of the finished product, resulting from the transportation cost of a given (intermediate) product. This can be interpreted as the relative cost difference between an importer and exporter, all else being equal, because the importer has to import a product that cannot be made cost-competitively domestically. This metric is useful because it exhibits the worst case effects on competitiveness for (partial) outsourcing, independent of uncertain geographical cost developments. If the transport cost-premium for an (intermediate) product is low, importing that product is unlikely to affect the competitiveness of the remaining supply chain. If the transport cost-premium for an (intermediate) product is high, importing that product would substantially affect the cost-competitiveness of the downstream supply chain, making imports of more finished products a more attractive option.

Figure 2.4 compares the transport cost-premiums for different transportation methods. For imported hydrogen, this represents the added cost to the product from feeding imported hydrogen into the ammonia synthesis loop (the Haber-Bosch process). In the case of ammonia, this corresponds to using imported ammonia as a feedstock in the various downstream processes. In all cases a 3000 km transportation distance is assumed. The data in Figure 2.4 can be interpreted as the price difference between producing various fertilisers in the Netherlands, using imported hydrogen carriers, and production of the same products in the region where the hydrogen carriers are imported from. The figure aligns with the earlier conclusion that the direct use of ammonia is cheaper than the use of imported hydrogen. More specifically, it shows that the transport cost premium is less than 5% of the end product price for all commodities, when directly feeding imported ammonia. For hydrogen imports this premium lies between 8% (Melamine) and 28% (Ammonia).

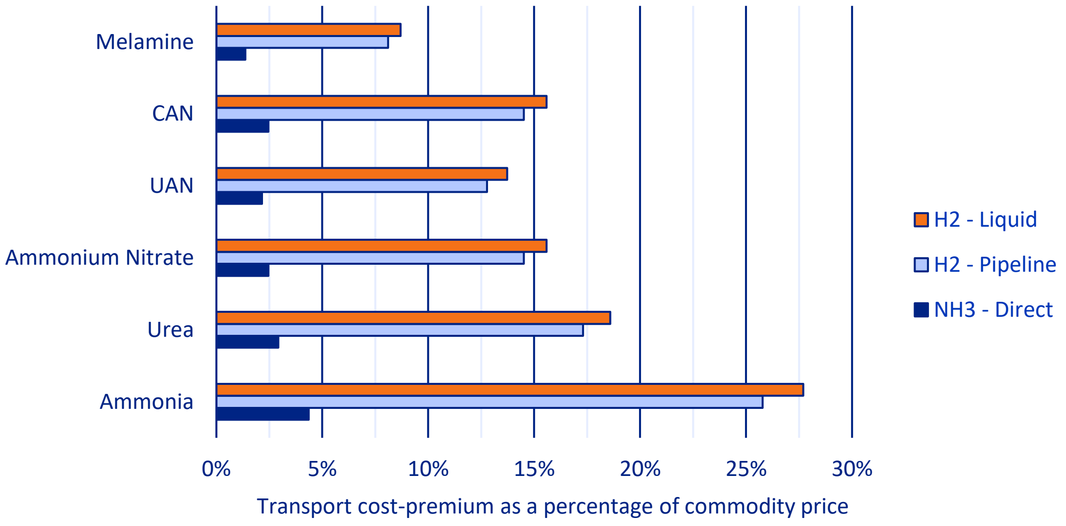

Figure 2.4: Comparison of the cost premium resulting from transportation over 3000km using various import methods, as a percentage of the commodity price (Business Analytic, 2024). The cost premium in this case includes only the additional cost of the feedstock (H_2 or NH_3) as a consequence of the transport cost. Downstream complications resulting from decoupling production steps are not considered.

These costs represent the current cost of fertiliser products. The “green-premium” will likely make the renewable counterparts of these products more expensive, while the transport costs remain the same. This would make the transport cost-premium relatively even less significant.

Thus, renewable ammonia production in the Netherlands depends on the availability of sufficient and cost-competitive domestically produced renewable hydrogen. The cost-premium for transporting ammonia that is directly used as a feedstock is relatively low compared to the price of fertiliser products. This could entail that the benefits of the intangibles (existing infrastructure, expertise, assets) could outweigh the marginal increase in feedstock costs. This suggests that, even in the case of the supply chain shifting to the import of ammonia, this does not necessarily result in the relocation of the downstream supply chain. Both Yara and OCI have indicated that the costs of shipping finished products is higher than the cost-premium for ammonia shipping (interviews Yara and OCI). This motivates maintaining downstream fertiliser production in North-Western Europe, close to the fertiliser demand.

2.3 Interdependencies with other industries

The fertiliser industry provides both energy, in the forms of waste heat, and feedstocks, in the form of hydrogen, ammonia and CO_2, to nearby industries. This section shortly elaborates on these dependencies, as well as the knock-on effects of potential replacements.

Current fertiliser production based on the Steam Methane Reforming (SMR) process produces excess heat. In the case of Yara, part of the excess heat is delivered to greenhouses for horticulture. In case of (partial) relocation, this heat will have to be sourced elsewhere. In the case of local hydrogen production, this heat could be sourced from the waste heat from electrolysis if the electrolysers are located at the fertiliser plant location, as the temperature is generally compatible with horticulture (Royal HaskoningDHV, 2022).

The CO_2 is released as a by-product of hydrogen production through steam methane reforming. Although some of this CO_2 is provided to external industries, most of it is consumed downstream for the production of urea and its derivatives. Phasing out the SMR for fertiliser production will necessitate finding alternative sources of CO_2, both if the SMR is replaced by domestic renewable ammonia production or by ammonia imports.

Yara delivers both residual heat (1.3 PJ per year) and CO_2[12] (50 kt per year) to nearby horticulture (Yara Sluiskil B.V., 2022). There is also 420 kt liquid CO_2 capacity owned and operated by Nippon Gases that is used to deliver CO_2 to nearby horticulture and other industries (Yara Sluiskil B.V., 2022).

Hydrogen is delivered or sometimes exchanged with other industrial plants in the vicinity. These plants are mostly active in the chemical industry. As an example, Yara receives hydrogen from DOW through a retrofitted natural gas pipeline (Yara Sluiskil B.V., 2022). The hydrogen backbone is a likely alternative option for sourcing renewable hydrogen on the long term.

Part of the ammonia produced by the fertilisers industries is exported to other neighbouring industrial plants, predominantly in the chemical sector. The OCI production facilities are highly integrated in the Chemelot site. Ammonia is sold to Fibrant for caprolactam and ammonium sulphate production. Further, ammonia is sold to AnQore for acrylonitrile and

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[12] Yara has four CO_2 liquefaction plants

ammonium sulphate production. There are also interactions with the Utility Support Group (USG) produces and distributes electricity, steam, water, nitrogen and other gases at the Chemelot cluster. CO_2 from the ammonia production process is captured, purified, liquified and shipped to various parties through a cooperation with Carbolim (a joint venture between Air Liquide and Air Products Belgium).

In conclusion, a switch to renewable hydrogen based fertiliser production will influence neighbouring industries, both if the renewable hydrogen and ammonia are produced domestically or if renewable ammonia is imported. The order of the effect depends on the availability of alternatives, including the import of hydrogen from the hydrogen network. Although alternatives for the waste heat and CO_2 supply chain are required, these are not directly coupled to replacing domestic production with imports. Replacement of steam methane reforming for a process based completely on renewable hydrogen will warrant these adaptations regardless. Nonetheless, in the short-term, disruptions of these supply chains are not trivial and require adaptations in the supply chains of all dependant parties.

2.4 Discussion

The results previously shown have been abstracted in order to minimize the sensitivity to parameter assumptions. Nonetheless, there are still sensitivities to be discussed. Most importantly, the costs of transport for each mode of transportation could develop differently than expected. Safety concerns regarding long-distance ammonia transport at scale could hinder the adaptation of ammonia as a transport medium. Furthermore, unexpected technological developments for the transport of hydrogen could change the landscape currently shown in Figure 3.5 and result in one of the transport options becoming significantly cheaper or more expensive. Figure 2.3 does show the fundamental advantage that ammonia has as a transport medium. Advances in ammonia cracking could reduce the relative premium of cracked ammonia, but this will always remain energetically and economically inefficient compared to the direct use of ammonia.

There are certain limitations to the research. The study does not answer the question on how competitive fertiliser production in the Netherlands will be in the long term. While patterns from literature have been assessed, the future development of production costs of electrolytic hydrogen are deemed too uncertain for such an analysis. The resulting analysis is a what-if analysis with a starting point assuming that hydrogen or ammonia are imported and explores the effects of import on the fertiliser supply chain in the Netherlands. The limited use of quantified cost estimates for domestic renewable hydrogen and ammonia production and for imports, results in a more abstract analysis. As a result the analysis is less suited to provide insights on the likelihood of certain scenario's occurring.

In addition, concerns surrounding the strategic importance of ammonia could outweigh any techno-economic disadvantages. The EU has noted the importance of ensuring availability, affordability and long-term autonomy of the bloc's fertiliser supply (European Comission, 2023). This indirectly implicates the importance of domestic ammonia production capacity. To ensure these goals are met, policy implementations could trump economically unfavourable conditions, which would lead to domestic production in the EU, even with uncompetitive international production costs. It should be noted that this could favour countries with more abundant renewable energy resources and land availability (including space at sea for offshore wind). Any member states could make the same decisions based on similar considerations, including the Netherlands.

Further research could provide answers to some remaining questions. For example, a more in depth look at the feasibility and cost of alternative CO_2 sourcing will identify whether companies will require support in this transition. Furthermore, a broad overview of the potential exporting countries and the desirability of strategic dependence on these countries is recommended. Such research could provide the context required to validate the strictly quantitative outcomes generally found in the literature.

2.5 Conclusion

The main findings of this chapter highlight that in the case of a shift to a renewable hydrogen based production process, the future fertiliser production chain in the Netherlands is sensitive to the availability of sufficient and cost-efficient renewable hydrogen and ammonia. Although the developments of renewable hydrogen and ammonia production are uncertain, there is a consensus in the literature reviewed for this study that there will be regional differences in its production cost, with certain regions producing renewable ammonia at lower costs due to better renewable resources. Furthermore, the consulted literature suggests that this advantage will not favour the cost-competitiveness of Northern-European ammonia production. The degree to which this discrepancy could develop is unclear. Even in the case that local renewable hydrogen production is cost-competitive, imports might still be needed if there is a lack of production capacity. Whether renewable ammonia production takes place in the Netherlands therefore depends on the availability of sufficient and cost-competitive renewable hydrogen.

The transportation costs of hydrogen are significant. As a consequence, using imported hydrogen for the synthesis of ammonia significantly impacts the cost competitiveness of fertiliser end-products. At current prices and considering a transportation distance of 3000 km the cost premium ranges from 8% for melamine up to 28% for renewable ammonia. However, when renewable ammonia import is considered, instead of hydrogen, and directly used for the fertilisers production, this option appears as the cheapest option. The cost-premium resulting from the import of ammonia are estimated to range from only 1% for melamine up to 4% for ammonia for a distance of 3000km.

The relative advantage of transporting renewable ammonia for direct use has a consequence for any import and export dynamics, regardless of the production price difference of ammonia. If there are green ammonia imports in the Netherlands, either as a consequence of insufficient local production capacity or imports being cheaper, domestic renewable ammonia production becomes less likely. Imported renewable ammonia would replace local renewable ammonia production, freeing up renewable hydrogen for other uses. At the national level it would not be logical to crack renewable ammonia back to renewable hydrogen, while simultaneously producing renewable ammonia from locally produced renewable hydrogen in the same region.

The limited effect of the cost-premium for importing ammonia on upstream fertiliser products implies that if renewable ammonia is imported, it does not necessarily mean a complete shift to fertiliser imports is also likely. The findings align with Yara and OCI saying that shipping fertiliser products are relatively more expensive than shipping ammonia, implying that there is an incentive to maintain fertiliser production in Europe even if the ammonia production is outsourced.

Shifting to renewable ammonia and as a consequence phasing out the steam methane reformer (SMR) will eventually require alternative CO_2 sources for the production of urea. As urea is mostly used to produce melamine, AdBlue, and for export, it is these activities that will mostly be affected by the phase-out of the SMR. In addition alternative sources of heat and CO_2 need to be found for industries that currently receive that from the fertiliser industry. A detailed exploration of the alternatives could provide insights into their feasibility and whether specific actions are required to ensure this transition.

2.6 Key policy considerations

Based on the conclusions we have formulated a number of policy considerations about green hydrogen based fertiliser production in the Netherlands.

The future of the fertilisers production chain in the Netherlands is linked to domestic hydrogen production and import.

With sufficient domestic production of affordable green hydrogen, ammonia production in the Netherlands can remain cost-competitive. If there are large quantities of renewable ammonia entering the Netherlands for the sake of hydrogen import, the analysis shows that it is economically favourable to use the ammonia directly. As a consequence the ammonia production in the Netherlands will come under pressure. Political ambitions of the Netherlands in regards to domestic renewable hydrogen production and import strategies will shape the policies affecting them. It is important to realise that these ambitions directly influence the likelihood of the viability of domestic renewable ammonia production in the Netherlands, from a techno-economic perspective. Policies affecting renewable hydrogen imports and domestic renewable ammonia production are strongly connected and policy considerations on these topics therefore need to take this into account.

Explore options for maintaining the downstream fertiliser production in case of relocation of the ammonia production.

The present analysis shows that the fertiliser industry can remain cost-competitive with imported renewable ammonia. This indicates that the downstream fertiliser production can be maintained in the Netherlands, even if there is no ammonia production in the Netherlands. Options for maintaining the fertiliser production chain if there is no domestic ammonia production need to be explored further. These including securing supply of renewable ammonia at affordable prices with trade agreements and developing ammonia import and storage infrastructure.

The transition to green hydrogen based ammonia production for the fertiliser industry will require changes in the production chain that are not directly linked to the sourcing strategy of ammonia. Effects on neighbouring industries will therefore happen regardless of a possible shift from domestic ammonia production to ammonia imports.

Phasing out fossil-based hydrogen production for the production of ammonia eliminates an existing source of CO_2 for some of the downstream products (urea, AdBlue and melamine) and surrounding industries (like food and beverages and the greenhouse horticulture). In both a scenario where renewable ammonia is produced in the Netherlands and where the ammonia is imports, alternative sources of CO_2 will be required to continue these operations. While urea is currently mostly produced for export and AdBlue is used for diesel vehicles and therefore demand might decrease eventually, unavailability of CO_2 can influence operations on the short to medium term. Policies accommodating CO_2 supply through national sourcing strategies could minimize the complexity these industries experience when setting up new supply chains.

When considering strategic independence of fertiliser production, multiple factors need to be taken into account.

Firstly, there is the dependence on natural gas imports for current production. Secondly, although the future of global ammonia trade is uncertain, it is expected that there will be a variety of exporting countries. This can reduce the risks associated with an import dependence. Finally, complete independence is possible with domestic renewable hydrogen and ammonia production. There will be a price for this independence, based on the price of domestic hydrogen versus imported hydrogen and the required investments (over €1 billion) for switching the ammonia production capacity from SMR to the synthesis of ammonia based on green hydrogen and nitrogen from air separation.

3 Iron and steel

3.1 Steel in the Netherlands

3.1.1 Current status

Tata Steel Netherlands (TSN) stands as the sole major steel producer in the Netherlands[13]. Currently TSN operates with two blast furnaces in IJmuiden, converting iron ore into graded steel (Keys et al., 2019). Annual production is 6-7 million tonnes of crude steel (Tata Steel, 2022)(Keys et al., 2019). The steel that emerges from the facility is of high quality and is used for the automotive industry, for construction and for packaging. Approximately, one-third (33%) of the produced steel is sold to the automotive industry, another third is sold to construction and around 16% is used in the packaging industry (Guidehouse, 2023). Furthermore, a substantial portion of TSN's output, approximately 80% stays in the EU27, with major destinations being Germany, Belgium and France (CE Delft, 2018). Roughly 20% of their production is directed towards international markets outside the EU.

Figure 3.1 illustrates the flow diagram of Tata steel production process. TSN produces steel via the blast furnace (BF) process. Iron ore is processed into sinter and pellets (iron ore) before entering the BF. In parallel, coal is converted into coke in coke ovens and used in the blast furnaces. Iron is reduced (oxygen removed) in the BF and a hot liquid pig iron is produced. This pig iron is transported to the basic oxygen furnace (BOF) process in which the carbon content is lowered by oxygen blowing. Scrap steel is also commonly added alongside pig iron in the BOF with the purpose of temperature control and to reduce the amount of pig iron required to produce crude steel. Overall, the basic oxygen furnace process allows for efficient and rapid refining of pig iron into high-quality steel.

Approximately 8.13 Mt iron ore is needed to produce roughly 7 Mt crude steel (Keys, van Hout, & Daniëls, 2019). To meet this demand iron ore is imported from various locations to the Netherlands. According to World Steel (2022) the Netherlands imported 24.4 million tonnes of iron ore in 2020 and exported 16.9 million tonnes, giving an apparent consumption of 7.5 million tonnes. According to Tata Steel IJmuiden, ore is mainly imported from Sweden, Canada and Norway (TSN, 2023).

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[13] There are plans for an EAF in the Eemshavenbased on scrap input and with a proposed size of 1 Mt steel production capacity per year. The steel produced will be used to make metal wire. Plans got postponed multiple times due to nitrogen crisis in the Netherlands. Now the plan is to be operational in 2025.
https://www.rtvnoord.nl/nieuws/993156/staalfabriek-van-merksteijn-moet-in-2025-in-de-eemshaven-staan
https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2021.pdf

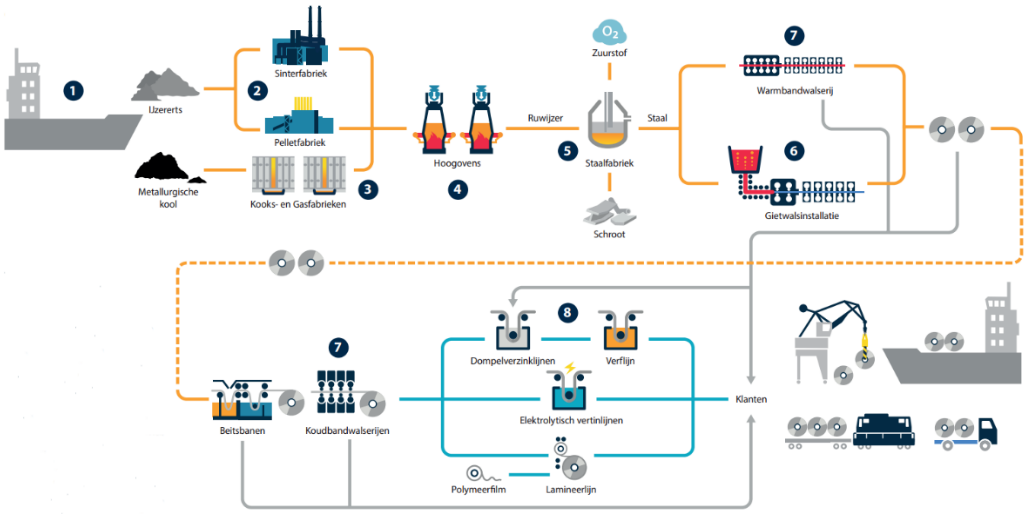

Figure 3.1: Flow diagram of Tate steel production process (Tata Steel Netherlands, 2022). 1: Coal and iron ore are brought in through the seaport. 2: Sinter and pellet plants: Iron ore is processed into sinter and pellets. 3: Coking and Gas Plants: Coal is processed into coke. 4: Blast furnaces: The sinter and pellets are heated and converted into liquid hot metal with the carbon from the coke. 5: Steelworks: Blowing oxygen through the hot metal creates steel. 6: Casting plants: Liquid steel is poured into a mold. After solidification, thick slabs of steel are formed. 7: Hot strip and cold strip rolling mills: The steel slabs are rolled out into a coil. 8: Further processing into coated steel

TSN delivers a variety of steel products, including custom materials, to customers across the world. By revenue, TSN accrues roughly 19% of its steelmaking revenues in the Netherlands (Figure 3.2). By volume roughly 18% of the steel produced in the Netherlands stays in the Netherlands (TSN, 2023). Most of the revenue stems from other European countries, with Germany being the largest importer of TSN products (TSN, 2023).

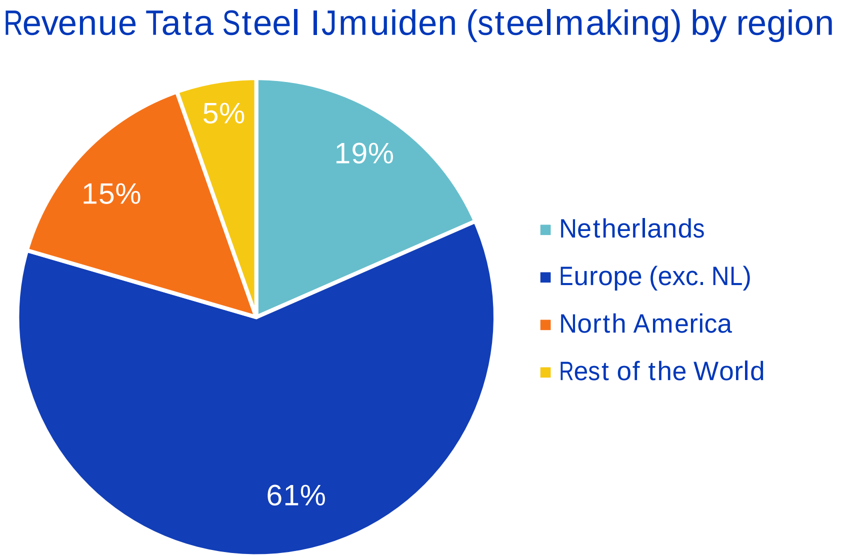

Figure 3.2: The revenue by region over 2023 for Tata steel IJmuiden, which represents all the crude steel making capacity of TSN (Tata Steel Netherlands B.V., 2023).

3.1.2 Decarbonisation plans

In order to decarbonise and reduce the environmental and health impact on the direct environment, Tata Steel Netherlands has announced its intention to switch from the current blast furnace steelmaking process to a Direct Reduced Iron (DRI) production process (Roland Berger, 2021; Ministry of Economic Affairs and Climate Policy, 2022). The switch to DRI is expected to take place in two steps, replacing one of the blast furnaces and a coke plants with a direct reduction plant (DRP) and electric arc furnace (EAF) before 2030 and replacing the other blast furnace and coke plant after 2030. Both natural gas and hydrogen are considered as a reducing agent in the DRI process. Initially, TSN expects to use natural gas as a reduction agent, increasing the share of hydrogen as it becomes available. In the context of the “Tailor-made agreements” between the Dutch government and large emitters, the intention was declared to maximise the use of renewable hydrogen “as soon as possible, subject to affordability and availability considerations” (Ministry of Economic Affairs and Climate Policy, 2022). The end goal is to produce steel using mostly renewable hydrogen and renewable electricity. TSN is exploring multiple options for sourcing renewable hydrogen: own production, import from the Dutch hydrogen network or importing from abroad. Figure 3.3 illustrates the potential hydrogen based steel production in IJmuiden.

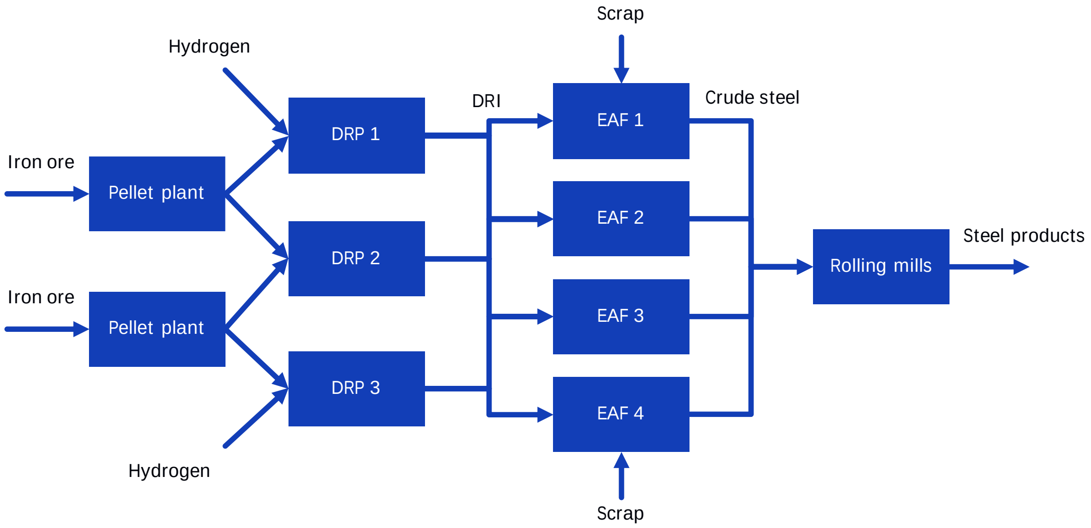

Figure 3.3: Illustration of the potential final hydrogen-based steel production plant in IJmuiden. The amount of direct reduction plants (DRP) and electric arc furnaces (EAF) can still vary and the type of arc furnace is also still being investigated by TSN.

Table 3.2 shows the main material and energy inputs for steelmaking in the Netherlands. In addition, this table introduces the material and energy inputs when it is shifted to hydrogen-based DRI (H-DRI), according to Roland Berger study (2021).

Table 3.2: Materials and energy input to produce 7.05 Mt crude steel and downstream steelmaking processes (Keys et al., 2019; Roland Berger, 2021)

Material	Current (Keys et al.)	H-DRI (Roland Berger)
Iron ore[14]	8.39 Mt	9.6 Mt
Coal[15]	4.34 Mt (125.78 PJ)	0.2 Mt
Natural gas[16]	13.23 PJ	0 PJ
Electricity	-2.62 PJ (net export)	>20.16 PJ
Hydrogen	-	>45.6 PJ

Shifting entirely to H-DRI, while maintaining its current status quo–roughly 7 Mt per year (Keys, van Hout, & Daniëls, 2019) – would require approximately 400 kt of hydrogen per year for TSN. If this hydrogen were to be locally produced using offshore wind, this would require approximately 22 TWh of electricity annually, based on an assumed electrolyser electricity input of 56 kWh/kg hydrogen. This demand equates to roughly 29% of the expected 15.8 GW offshore wind capacity by 2030 (PBL, TNO, CBS & RIVM, 2023) and an estimated 7% of the 70 GW by 2050 (Ministry of Economic Affairs and Climate Policy, 2022), considering 4800 full load hours.

In this future value chain, hydrogen costs will comprise a significant part of steel production costs. If there is insufficient hydrogen available in the Netherlands or it is cheaper to import hydrogen, the import of (semi-)finished products that are more convenient to ship, can become economically favourable (Devlin & Yang, 2022). Hence, locating the iron making process in regions with low costs of hydrogen production may become a promising option for achieving lower cost low-carbon steel production. One possible configuration is the import of hot-briquetted iron (HBI) (Durinck, Gurlit, Müller, & van Albada, 2022). HBI is compacted DRI that is less prone to oxidation, making it preferred for shipping over untreated DRI. Figure 3.4 shows such a supply chain and illustrates that a significant part of the steel supply chain would not be located in the Netherlands in such a scenario.

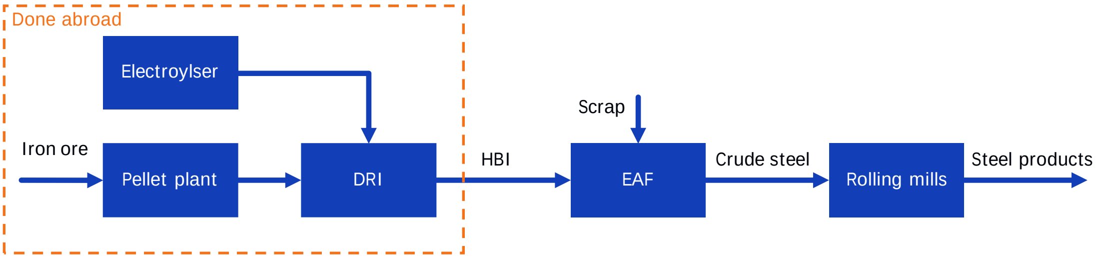

Figure 3.4: Visual representation of the supply chain based on HBI imports.

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[14] The amount of iron ore depends on the type of ore, ore quality, water content, and other factors. The amount therefore varies from study to study. The Roland Berger numbers are considered most accurate for Tata Steel Netherlands IJmuiden (TSN, 2023).

[15] The amount of coal used will drop significantly when switching to hydrogen based DRI. Some coal is still needed to introduce carbon into the steel end products. This coal can also be substituted by biochar.

[16] Here it is assumed that no natural gas will be used anymore when completely switching to hydrogen based DRI, including for downstream processes. Natural gas currently used for downstream steelmaking processes is replaced by electric heating, hydrogen, or other sources for CO_2-free steel production.

3.2 Exploration of the effects of imports on the domestic value chain

In order to assess the factors influencing the iron and steel value chain in the Netherlands in case of imports, the following section analyses the techno-economic drivers of the steelmaking business case. Most prominently the business case for the Netherlands is compared to the business case of potential competitors with better access to renewable energy sources. Initially, the results from the existing literature are exhibited and the patterns that can be deducted are discussed. Subsequently, a number of calculations are shown to illustrate key principles and conditions for competitiveness. Lastly, the findings are discussed and important conditions are reiterated.

3.2.1 Literature review

Several studies have been conducted to calculate the Levelized Cost of (crude) Steel (LCOS) for individual scenarios. These studies vary significantly in their resulting LCOS figures, due to their sensitivity to parameter values. The cost of electricity, for instance, is influenced by numerous factors, including geographical and temporal variations. For temporal resolutions some studies optimize the system to account for fluctuations in supply and demand (Devlin & Yang, Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation, 2022), while others assume a fixed price and continuous process (Vogl, Ahman, & Nilsson, 2018; Wood, Dundas, & Ha, 2020). Furthermore, the scope of the research can have impacts on the final outcome as well. Cost contributors like scrap rates, labour, and material efficiency, as well as revenues from the sale of oxygen, for example, can influence the final LCOS.

A limited number of studies compare various supply chain options, comparing imports at different steps. Their findings are summarised in Table 3.3.

Table 3.3: Overview of existing literature on long-term (2050+) supply chain comparisons for steel. All costs correspond to the LCOS in the importing country expressed in Euro per tonne crude steel (CS). Sources: (Wood, Dundas, & Ha, 2020; Devlin & Yang, 2022; Lopez, Galimova, Fasihi, Bogdanov, & Breyer, 2023)

Author	Exporter | Importer	Hydrogen-import	HBI-import	Steel-import
Wood et al., 2020	Australia | Japan	€660/t_{cs}	€580/t_{cs}	€560/t_{cs}
Devlyn & Yang, 2022	Australia | Japan	€555/t_{cs}	€475/t_{cs}	€430/t_{cs}
Lopez et al., 2023	Morocco | Germany	€430/t_{cs}	€380/t_{cs}	€350/t_{cs}

The absolute supply costs, whether it is renewable hydrogen, HBI, or steel vary significantly, even when the same export and import regions are considered. The LCOS differences relate to implementation of different methodologies and assumptions. Nonetheless, these sources suggest that importing crude steel should be more cost-efficient than importing hydrogen or HBI. The complexity and high cost of hydrogen transport makes it unfavourable compared to transport of the other products. In the case of HBI, the necessity of using more than one tonne of HBI to produce one tonne of crude steel leads to an increased number of shipments per tonne of crude steel. Additionally, imported HBI necessitates preheating, resulting in additional costs. Crude steel stands out as the most easily transportable commodity within the supply chain.

Although steel import appears as the most cost-efficient option, the difference between importing HBI and importing steel consistently remains under 10%. While the cost benefit of steel import is apparent, the difference between HBI import and steel import is less pronounced compared to the contrast with hydrogen import.

3.2.2 The influence of transport costs

Estimating the absolute costs is challenging due to uncertainties in economic and technological developments. While the literature does suggest a trend, it is not conclusive. To provide deeper insight into the underlying principles behind these cost differences, rather than focusing absolute costs, Figure 3.5 shows the cost premiums resulting from imports for various distances. The transportation of iron ore is also included, which was not considered in the existing literature. For an explanation of the transport cost-premium and its interpretation, see the text box below.

Transport cost-premiums

In order to examine the competitive disadvantage an importer of an (intermediate) product could have as a result of (partial) relocation, transport cost-premiums are used. The transport cost-premium shows the relative cost increase of the finished product, resulting from the transportation cost of a given (intermediate) product. This can be interpreted as the relative cost difference between an importer and exporter, all else being equal, because the importer has to import a product that cannot be made cost-competitive domestically. This metric is useful because it exhibits the worst case effects on competitiveness for (partial) relocation, independent of uncertain geographical cost developments. If the transport cost-premium for an (intermediate) product is low, relocation up until that point is unlikely to affect the competitiveness of the remaining supply chain. If the transport cost-premium for an (intermediate) product is high, relocation up until that point could threaten the downstream parts of the supply chain.

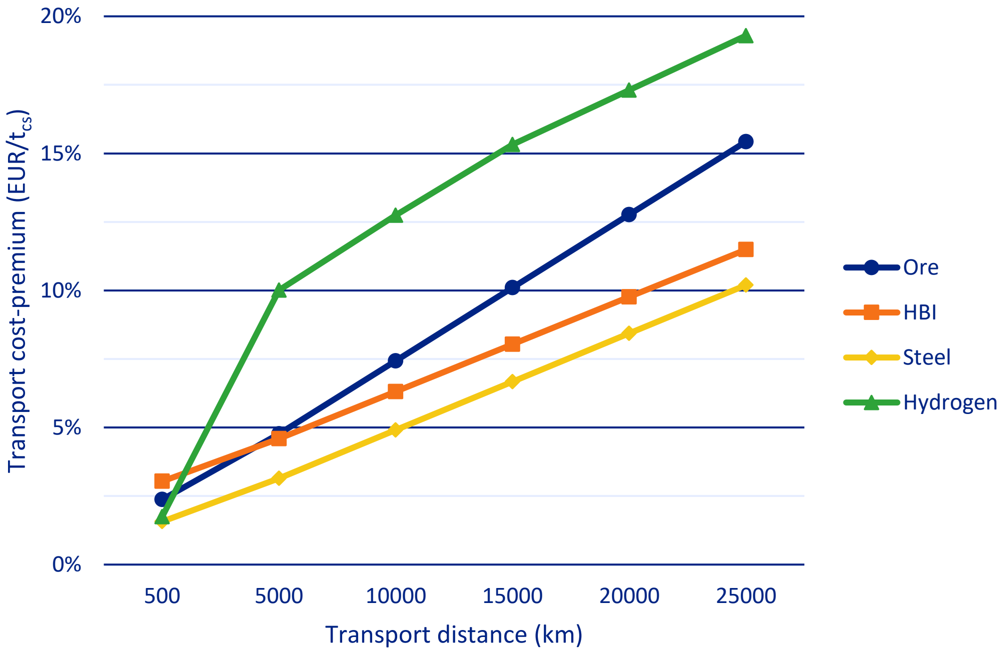

Figure 3.5: Transport cost-premiums resulting from transport costs at different stages of the supply chain for various distances, for a crude-steel price of €500/t$_{CS}$. See the text box for guidance on interpreting the transport cost-premium. The hydrogen transport costs represent the option with the lowest levelized cost of

hydrogen transport at each distance for all options shown in Figure 1.2, in order to minimize the transport cost-premium. The transport medium for hydrogen therefore varies for different distances.

Steel imports emerge as the most cost-effective transportation choice irrespective of the distance travelled. The expenses associated with importing hydrogen and ore are notably higher. Considering that 1.66 tonnes of iron ore are needed to produce 1 tonne of crude steel, alongside the costlier transportation of hydrogen compared to dry-bulk, steel import stands out as the favourable choice. This situation may encourage new investors to integrate the entire supply chain up to crude steel production.

Even so, HBI import does not appear significantly more expensive than steel import concerning the final commodity price. Despite requiring additional pre-heating, the overall costs remain a relatively minor component of total steel production costs. The potential benefit of HBI import may outweigh the disadvantage of the cost premium. However, the uncertainty surrounding its availability presents a challenge.

Producing steel with imported hydrogen incurs the largest cost premium. Importantly, in the case of hydrogen import, ore still needs to be imported for non-ore-producing countries, whereas with HBI, this step is integrated. A marginal pricing assumption implies that any region importing hydrogen would experience this premium compared to the exporting country.

3.2.3 Other cost factors and sensitivity

Aside from the cost premium linked to transport, there are additional costs due to different expenses across different locations. Some of the key factors include electricity prices, hydrogen costs, labour expenses, ore prices and capital investments. While it is feasible to estimate the cost premiums arising from known geographical variations with reasonable accuracy, the challenge lies in the uncertainty surrounding the underlying factors. In other words, it is possible to estimate the cost premium for steel production resulting from a €1/kg_{H2} difference in hydrogen costs. However, it is impossible to determine the true cost difference of hydrogen between two countries in the long-term.

In order to display the uncertainty of these underlying assumptions, Figure 3.6 compares the forecasted long-term costs of electricity and hydrogen production from various studies. The studies have been selected because they include cost projections for both the Netherlands and several other countries. Other studies that do not include cost projections for the Netherlands or include fewer other countries, do showcase similar spreads in cost projections, highlighting the uncertainty in future electricity and hydrogen costs.

From Figure 3.6, it becomes clear that there are starkly different outcomes resulting from different studies. The TNO supply chain model suggests that there are a number of countries that have significantly cheaper electricity and hydrogen. Canada’s hydrogen costs are higher due to the current methodology employed in the supply chain model, where countries where hydropower plays a large role in the electricity generation portfolio are penalised.

In the HyChain model (Kerkhoven & Terwel, 2019), all countries that were selected as comparisons show a competitive cost advantage over the Netherlands, resulting from lower electricity and hydrogen costs. For the Fasihi et al. studies (2021), the cost advantages are more subtle and the Netherlands is no longer at a disadvantage to Germany and Sweden. The main difference between these two studies is the fact that the Fasihi et al. study uses GIS data to estimate the electricity costs based on solar and wind profiles, while the HyChain model uses a dataset composed by the NREL. While the profile approach used by Fasihi et al. allows for more geographical detail, displaying differences for different regions inside larger countries, it does not account for land availability and it excludes offshore wind as well. Although the Fasihi et al. methodology is more likely to be accurate for landlocked countries with abundant available land area, this does not accurately translate to the Netherlands, where there is limited solar availability.

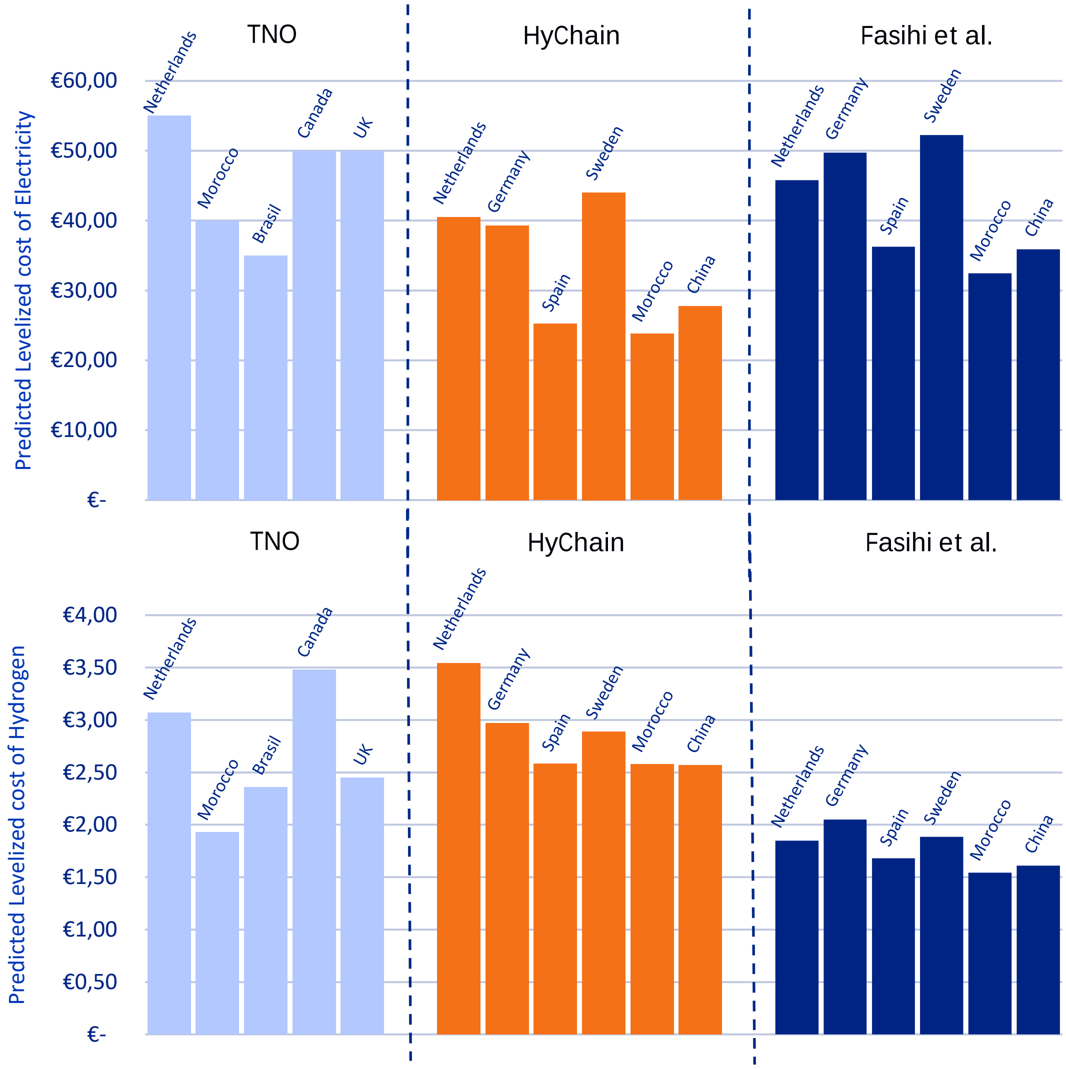

Figure 3.6: Comparison of the LCOE/H forecasts for several sources. Sources were selected based on the criteria of containing both LCOE and LCOH estimates for the Netherlands and several other countries. Due to selective geographical scopes of the TNO. study, the regions shown were adjusted. Sources: TNO analysis, (Kerkhoven & Terwel, 2019), (Fasihi, Weiss, Savolainen, & Breyer, 2021).

Based on these sources, the forecasted costs of electricity and hydrogen in other countries falls within a range of -40% to +15%, when compared to the forecasted costs for the Netherlands. To demonstrate how steel production costs are effected by these factors, Figure 3.7 illustrates the cost differences as a result of changes in these factors. Although the EAF requires a lot of electricity, the overall cost doesn’t change much, at 40% lower electricity costs (30 €/MWh) the effect on the LCOS is -4% and at 15% higher electricity costs (57.5 €/MWh) the effect on LCOS is +1.5%. However, hydrogen costs can have a bigger impact, with 40% lower costs (€1.80/kg_{H2}) the final commodity cost decreases by 10%. Increasing the hydrogen cost by 15% (3.5 €/kg_{H2}) results in 4% higher crude steel costs.

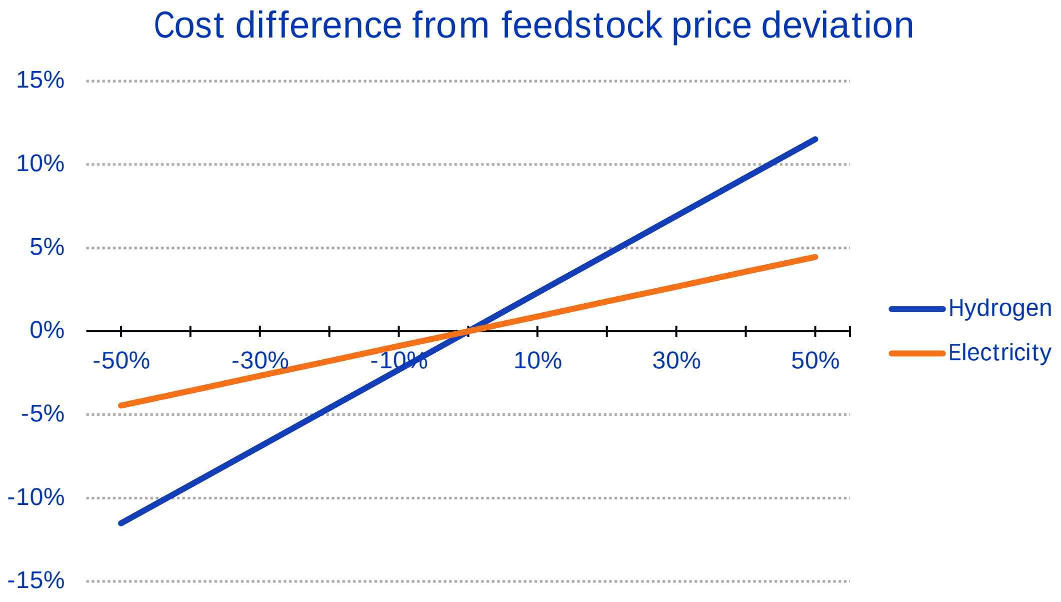

Figure 3.7: The change in production costs of crude steel based on changes in the feedstock costs for a reference case. The reference case assumes €3/kg_{H2}; an electricity cost of €50/MWh; a 7% WACC; labour cost of €56/h; and an iron ore cost of €127/t_{Ore}.

Besides the effects of geographical differences in electricity and hydrogen costs, there are obviously also other factors that vary by country. Figure 3.8 shows the production cost difference of crude steel in different countries compared to production in the Netherlands. Figure 3.8 shows that a large number of geographical cost differences make up the total cost difference. For instance, the cost of capital has a significant impact on total costs due to the capital intensity of steelmaking. In fact the cost of capital is one of the dominant cost drivers in the cost of electricity and hydrogen production as well. Labour costs can have a large impact on total cost differences, especially when comparing more advanced to developing economies. Lastly, although ore is a significant component in the total cost, it is less pronounced in the geographical cost differences, due to its relative ease of transport (compared to electricity and hydrogen).

Figure 3.8 further details the relative comparison broken down to key cost components. These cost factors are uncertain in nature, particularly when it comes to future projections. The figure is meant solely for the purpose of exhibiting some of the key factors, rather than presenting likely outcomes.

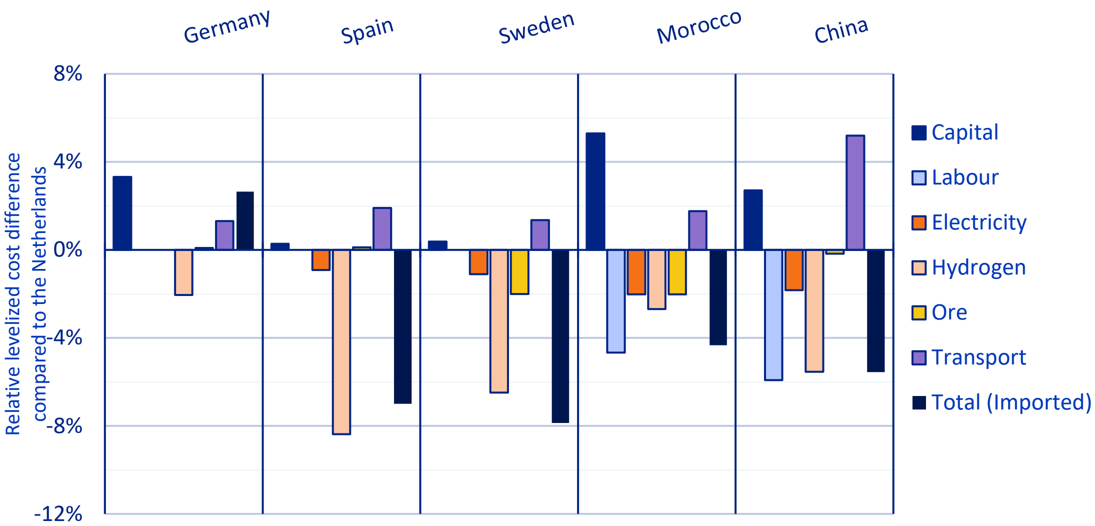

Figure 3.8: Difference in levelized cost of crude steel production in different countries and transport of the crude steel to the Netherlands compared to domestic production in the Netherlands. The totals are the sum of all these differences and display the final cost difference. The assumptions and methodology for the calculations are shown in Appendix b.

3.3 Interdependencies with other industries

TSN IJmuiden supplies steel to its own service centres and facilities in the Netherlands. This includes facilities for producing tubes (Zwijndrecht, Oosterhout, Maastricht) and construction materials (IJsselstein and Geldermalsen). There are two service centres in Maastricht that prepare parts of coils for customers. Unfortunately, no data exist on the customer base for these service centres. An estimated 70%-90% of the steel used at these facilities is from TSN IJmuiden (TSN, 2023). The Tata Steel service centres also distribute to a variety of clients, both in the Netherlands and in neighbouring countries.

In addition to supplying their own facilities, TSN also sells steel to diverse range of clients within the Netherlands, such as VDL, Nedcar and DAF (all automotive), Friesland Campina and Trivium (packaging), customers for construction (like SAB profil) and tubes (TSN, 2023). The apparent steel consumption in the Netherlands was 4.6 Mt in 2021 (WorldSteel), thus TSN's supply of 1.3 Mt to the Netherlands makes up roughly 28% of total steel consumption in the Netherlands (TSN, 2023) (Keys, van Hout, & Daniëls, 2019). This implies that there are supply chains for steel import in place for the remaining 72% of steel consumption in the Netherlands. Product specificity of the steel supplied by TSN in the Netherlands is unclear, so the feasibility of these customers adapting to other steel suppliers (maybe using existing import supply chains) is hard to estimate. Therefore the effect of a partial or complete shutdown of TSN's operations in the Netherlands on its customers is also difficult to estimate. If TSN can no longer compete with other steel producers, it is to be expected that there are alternatives available for these customers. These customers could then accrue a cost premium as a consequence of increased transport costs (TSN, 2023), but the higher costs would then apparently still be acceptable compared to higher cost steel from TSN. Otherwise TSN would still be able to deliver steel to these customers at acceptable costs. Additionally, costumers that use specialty products might not be able to get similar products at the competitor. Setting up alternative supply chains could be more challenging for these specialty steel consumers.

TSN indicates that in case of a shutdown of the steelmaking facilities, the processing facilities will likely be sold to other steel producers. In this case, the primary challenge will be the increased transport cost. Other than that no issues were directly mentioned by TSN. The indirect effects are more clearcut. The effects that relocation could have on R&D is significant given TSN's affiliation to various academic institutions and its own academy. Contractors and suppliers would also lose out on a significant customer, according to TSN.

TSN utilizes its off-gases to meet its own electricity and heat demand. TSN also provides some of the excess off gases to external consumers, the three power plants at IJmuiden. These power plants supply electricity to the whole site and the electricity grid. The amount of excess gas that is sent for power production was quite significant (Keys, van Hout, & Daniëls, 2019). It should be noted that these plants will no longer be in service if TSN switches to a renewable hydrogen based DRI production chain, and therefore this dependency is not considered relevant for the scope of this study.

3.4 Discussion

The uncertainty of many of the main cost parameters has been highlighted in the analysis, but we would like to stress this point once more. The exploration presented here is aimed at providing insights into main cost drivers and the effects of variations in these costs. The underlying uncertainty in the cost projections of key parameters such as electricity and hydrogen costs make it impossible to draw hard conclusions on the future competitiveness of renewable hydrogen based steelmaking in the Netherlands and whether the production will remain or be partially shut down in favour of imports.

Furthermore, as mentioned earlier in the report, the availability of certain feedstocks and products is highly uncertain. Most notably scrap and HBI sourcing could pose a significant challenge. For scrap, sourcing domestically and enabling its international trade is paramount to securing supply (IRENA, 2023). Additionally, numerous European competitors already have scrap supply chains and EAF capacities, which TSN has yet to establish (EUROFER, 2023). For HBI the market is currently non-existent and the question continues to be whether ore-producers will elect to produce HBI or export products further down the supply chain. Especially considering the cost-savings that can be realised by avoiding the reheating of cold HBI when integrating the entire supply chain up to crude steel.

As for the implications of cost differences there are a number of intangible factors that can outweigh tangible discrepancies. Firstly, it is important to acknowledge that even a considerable cost disparity in crude steel can have relatively minimal influence on certain higher-value end products. For example, a 20% increase in steel costs results in an approximate 1% uptick in the overall cost of a car (Cordonnier & Deger, 2022; Vogl, Ahman, & Nilsson, 2018). This could mean that even if significant cost differences manifest, high-quality steel could remain preferential, with increased costs being passed down to the costumer for the end-product.

In addition to costs, there are other factors that could affect the viability of steel production in certain locations. The EAF, for instance, has long been used in the secondary steelmaking route to produce steel from scrap. The integration of scrap supply in the H-DRI-EAF production process could significantly reduce the dependency of steel production costs on hydrogen and iron ore prices. However, this would entail the downscaling of local iron production (Vogl, Ahman, & Nilsson, 2018). Since it is expected that scrap consumption will be limited by availability and quality (Durinck, Gurlit, Müller, & van Albada, 2022), ensuring an adequate supply of high-quality scrap could become a critical factor for the retention of local supply chains. Moreover, steel production requires a complex infrastructure to accommodate supply chains, which is capital intensive (Guevara Opinska, Mahmoud, Bene, & Rademaekers, 2021). Consequently, existing infrastructure provides brownfield plants with a competitive advantage over greenfield counterparts.

In addition to physical assets, TSN also has advantages from intangible assets in its current location. The staff, expertise, and integration with both the labour market and academic world that is present at the current facilities has been built up over the course of decades and will be difficult to replace on the short term for a new greenfield location.

Lastly it is important to emphasize the strategic role of steel production. Steel is an essential commodity in today's economy and will continue to be in the future. This means that regions and governmental bodies can elect to intervene in situations where market dynamics might otherwise cause relocation. The EU is likely to safeguard its steel supply by ensuring sufficient production capacity within its borders, focusing on a resilient single market (Guevara Opinska, Mahmoud, Bene, & Rademaekers, 2021). Member states can elect to maintain steel production capacity in a similar manner.

3.5 Conclusion

In a scenario where Dutch iron and steel industry produces steel based on renewable hydrogen, the competitiveness on the international steel markets is dependent on a number of uncertain factors. These include the costs of iron-ore, electricity, hydrogen and the transport costs of feedstocks or (semi-finished) products such as HBI. Our analysis and literature indicate that there is significant uncertainty about the development of costs of many of the key inputs. Most pronounced are the geographical differences in electricity and hydrogen costs. This includes the development of electricity costs in the Netherlands and the cost of hydrogen produced from this electricity.

Our analysis of transport options showed that crude steel transport emerges as the most cost-efficient method. Hydrogen is more difficult and costly to transport, making domestic steel production based on imported hydrogen the least cost-efficient option of the import scenarios. This simple economic analysis implies that if Dutch steelmaking depends on hydrogen imports, it is more cost-efficient to import crude steel instead. The transport of HBI is also a bit more expensive than transporting steel as more tonnes of HBI are required per tonne of finished product. The additional requirement for pre-heating HBI adds more costs to this route. The cost difference between crude steel imports and HBI imports generally does not exceed 10%. But the analysis shows that if an investor is setting up a supply chain for the production of steel using hydrogen, there is a cost-optimizing incentive to integrate the whole production chain up to crude steel in a region where cheap renewable hydrogen is available. As a consequence this creates uncertainty whether a HBI market will develop in the future. It is therefore not clear whether sufficient HBI will be available for this route to even be a realistic option.

The discussion highlights several caveats regarding the analysis results, emphasizing the practical complications that may diverge from theoretical cost differences. The uncertainty in the availability of feedstocks like scrap and HBI poses challenges, with domestic sourcing and international trade crucial for supply security. TSN faces competition with established European competitors in scrap supply chains and EAF capacities. The intangible factors, including the minimal impact of crude steel cost disparities on higher-value end products, suggest that high-quality steel preferences may persist even with cost differences. TSN's existing advantages in staff expertise, infrastructure, and governmental considerations for strategic steel production underscore the complexities involved in potential relocation decisions.

TSN supplies a diverse range of steel products globally, with most revenues stemming from other European countries, primarily Germany. The company not only serves its own facilities in the Netherlands but also provides steel to various Dutch industries, notably the automotive and packaging sectors. (Partially) replacing the domestic production chain with imports will primarily affect TSN's own operations and the operations of TSN's suppliers. Due to uncertainties about product specificity and uncertainty with regard to potential supply chain replacements, it is impossible to conclude which of TSN's customers will be significantly affected by a change in the domestic production approach.

3.6 Key policy considerations

Based on the conclusions we have formulated a number of policy considerations about green steel production in the Netherlands.

The costs to produce and transport hydrogen are important factors influencing the position of green steelmaking in the Netherlands versus other locations. Renewable hydrogen based steelmaking in the Netherlands is therefore strongly linked to the position of the Netherlands as a producer and importer of hydrogen.
The analysis in this chapter shows that hydrogen costs are an important factor determining the cost of producing crude steel. Cost-competitive emission-free steelmaking in the Netherlands depends on the availability of cost-effective renewable hydrogen. The future costs of hydrogen are uncertain, both for domestically produced hydrogen or imported hydrogen. Yet the analysis shows that the transport premium for hydrogen is significant. If there is a reliance on imported renewable hydrogen, the transport costs imply it is likely more cost-effective to import HBI, crude steel or steel products instead. The position of hydrogen-based steelmaking in the Netherlands is therefore linked to the position of the Netherlands as a producer and importer of hydrogen.

The capacity of TSN and their clients to absorb higher costs is an important determinant for whether green steelmaking in the Netherlands compared to the import of semi-finished products.
The analysis also shows is that the transport cost-premiums for importing HBI or crude steel are below 5% at a distance of 5000 km. At the same distance the transport premium for hydrogen is around 10%. What the analysis does not show is what these premiums would mean for TSN or their clients. There are many intangibles that have not been accounted for. The capacity of TSN and their clients to absorb cost-premiums is an important factor influencing potential relocation or outsourcing decisions.

Decisions to shift from production in the Netherlands to imports also depends on the timely availability of alternative options, like green HBI or crude steel. If such alternatives are not available, it may support a decision to continue production here. It is important to follow international developments.
Currently there are limited plans globally for producing green steel and there is no existing HBI trade. The potential relocation of steelmaking based on renewable hydrogen therefore depends on investments in new, clean steelmaking facilities in other countries. These are large capital-intensive plants and are therefore uncertain. Coupled with long investment lead times, maintaining a good overview of the international development of new, low-carbon steelmaking plants is vital to making a good assessment of the chance of partial

shutdowns, shifts to imports, the effects on the production chain and being able to timely intervene if deemed necessary.

It is relevant to reiterate that in this study we do not consider carbon leakage, which would imply domestic steelmaking being replaced by fossil-based steelmaking elsewhere. The risks of carbon leakage are not necessarily the same as the risks of relocation due to decarbonization.

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Appendix A

Fertiliser Annex

Table A.1: Comparison of transportation methods, adapted from (Ortiz Cebolla, Dolci, & Weidner, 2022). The only adaptation made is the addition of the NH_3 transport without cracking. In this case the packing and unpacking costs are simply deducted from the fixed cost

Transport cost	Marginal (/1000km)	Fixed Cost
Pipeline	€0,23	€0,04
LH_2	€0,05	€0,63
LOHC	€0,03	€0,80
NH_3	€0,02	€1,23
NH_3 (No cracking)	€0,02	€0,11

Table A.2: Costs of commodities produced by the fertiliser industry. Also contains the transport cost-premium (TCP) calculation, using the hydrogen content, resulting from a price increase of the hydrogen used as a feedstock. Prices are taken from (Business Analytic, 2024). The costs are given as the absolute transport cost-premium, as well as the percentage of the commodity price of the transport cost-premium, to display the relevance to competitiveness

Commodity	Prices	H_2-Content	TCP NH_3-Direct	TCP Pipeline	TCP LH_2
Ammonia	€620,-/t	18%	€30,12 | 5%	€126,54 | 20%	€135,17 | 4%
Urea	€380,-/t	10%	€17,07 | 4%	€71,71 | 19%	€76,59 | 4%
A.-Nitrate	€360,-/t	8%	€12,80 | 4%	€53,78 | 15%	€57,45 | 4%
UAN	€300,-/t	7%	€11,61 | 4%	€48,76 | 16%	€52,08 | 4%
CAN	€240,-/t	4%	€7,53 | 3%	€31,64 | 13%	€33,79 | 4%
Melamine	€1.080,-/t	14%	€24,39 | 2%	€102,44 | 9%	€109,42 | 4%

Appendix B
Iron and steel Annex

Methodology: levelized cost of crude steel production calculation

The calculation for the levelized includes the following steps:

- Pelletization
- H-DRI
- EAF
- (Transport).

For each of these steps the following components were included:

- Capital expenditure of assets (Keys, van Hout, & Daniëls, 2019; Vogl, Ahman, & Nilsson, 2018)
- Operation and maintenance of assets (Keys, van Hout, & Daniëls, 2019) Electricity and/or hydrogen consumption (Keys, van Hout, & Daniëls, 2019)
- Labour (Devlin, Kossen, Goldie-Jones, & Yang, 2023)
- Iron ore (Own calculation based on (Devlin, Kossen, Goldie-Jones, & Yang, 2023))
- Miscellaneous feedstocks (alloys, biochar, calcium carbonate, etc.) (Keys, van Hout, & Daniëls, 2019).

Transport cost calculation includes the following cost components:

- Capital (Devlin & Yang, 2022)
- Fuel costs (using the levelized cost of hydrogen of exporter and importer for the trip there and back, respectively) (Devlin & Yang, 2022)
- Port handling costs (Devlin & Yang, 2022).

These costs were all transformed into a levelized cost per tonne of crude steel, where any capital investments were turned into yearly expenditures using a capital recovery factor. The assumptions for each of the parameters are given below.

Table B.1: Cost of seaborn dry-bulk transport, based on (Devlin & Yang, 2022)

Country	Distance	Hours at sea	Days/trip	Transported/year	Cost/t dry bulk
Germany	305 km	21,94	2,91	7.175.083,35	€ 7,31
Spain	3.237 km	232,90	11,70	1.786.559,91	€ 10,63
Sweden	501 km	36,04	3,50	5.971.251,53	€ 7,53
Morocco	2.566 km	184,67	9,69	2.156.914,27	€ 9,87
China	19.492 km	1402,32	60,43	346.021,28	€ 29,03

Table B.2: Calculation of the iron ore cost, based on the same transport methods from Table b.1 and ore costs from the supplementary data from (Devlin, Kossen, Goldie-Jones, & Yang, 2023).

Country	Import	Ore base	Distance	Days/trip	Volume/yr	Transport	Ore cost
Netherlands	Sweden	€ 108,52	501 km	2,75	7.601.194	€ 7,25	€ 115,77
Germany	Sweden	€ 108,52	603 km	2,90	7.198.214	€ 7,55	€ 116,06
Spain	Sweden	€ 108,52	1.200 km	3,80	5.504.748	€ 7,67	€ 116,19
Sweden	-	€ 108,52				€ -	€ 108,52
Morocco	Guinea	€ 99,02	2.855 km	6,28	3.329.503	€ 9,41	€ 108,44
China	-	€ 115,14				€ -	€ 115,14

Table B.3: Variable consumption (Keys, van Hout, & Daniëls, 2019) and cost assumptions (Vogl, Ahman, & Nilsson, 2018; Lopez, Galimova, Fasihi, Bogdanov, & Breyer, 2023)

Cost/Unit	Unit	Ref	Pelletization	DRP (Unit/tCS)	EAF (Unit/tCS)	Finishing (Unit/tCS)	Total
Electricity	MWh	Keys et al.	0.22		0.79	-	1.01
Iron ore	t	Keys et al.	1.51	-	-	-	1.51
Labour	h	Devlin & Yang	-	0.22	0.49	-	0.71
Hydrogen (Feedstock)	kg	Keys et al.	-	43.32	-	-	43.32
Alloys	t	Vogl et al.	-	-	0.01	-	0.01
Biochar	MWh	Lopez et al.	-	-	0.28	-	0.28
Calcium Carb.	t	Keys et al.	-	-	0.07	-	-
Preheating	MWh	Lopez et al.	-	-	0.15	-	0.15

Table B.4: Capital investment assumptions based on (Vogl, Ahman, & Nilsson, 2018)

Plant	Value	Unit	Ref
Pelletizing	€120,00	\$/tIOP/yr	Vogl
H-DRP	€310,00	\$/tDRI/yr	Vogl
EAF	€283,00	\$/tCS/yr	Vogl

Table B.5: List of final assumptions for the calculation of the levelized cost of steel. Ore prices based on data above. LCOE and LCOH based on (Kerkhoven & Terwel, 2019). WACC based on (Ondraczek, Komendantova, & Patt, 2015). Labour prices based on (Devlin, Kossen, Goldie-Jones, & Yang, 2023)

Country	Iron Ore (/t)	LCOE (/MWh)	LCOH (/kg)	WACC	CRF	Labour
Netherlands	€ 115,77	€ 52,00	€ 3,02	7%	9%	€ 56,00
Germany	€ 116,06	€ 50,00	€ 2,74	11%	12%	€ 56,00
Spain	€ 116,19	€ 45,00	€ 1,94	8%	9%	€ 56,00
Sweden	€ 108,52	€ 44,00	€ 2,18	8%	9%	€ 56,00
Morocco	€ 108,44	€ 39,00	€ 2,66	13%	13%	€ 20,00
China	€ 115,14	€ 40,00	€ 2,30	10%	11%	€ 10,33

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