



Advanced Carbon Capture for steel industries integrated in CCUS Clusters

Innovation Action

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D4.12 Life cycle assessment and method to assess North Sea port cluster

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1. Version log

Version	Date	Released by	Nature of Change
0.1	19/03/24	A. B. Ottenbros (SKU)	First draft
0.2	29/03/24	A. B. Ottenbros (SKU)	Incorporating feedback from contributors
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0.4	01/05/24	A. B. Ottenbros (SKU)	Final version to reviewer
1.0	23/07/24	A. B. Ottenbros (SKU)	Final version incorporating feedback from reviewer

2. Definition and acronyms

Acronyms	Definitions
BECCS	Bioenergy with Carbon Capture and Storage
BFG	Blast Furnace Gas
CAPEX	Capital Expenditures
CASOH	Calcium Assisted Steel-mill Off-gas Hydrogen
CCA	Cost of CO ₂ avoided
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
DAC	Direct Air Capture
DISPLACE	High temperature sorption-DISPLACEMENT process using hydrotalcites for CO ₂ sorption and recovery of steam
H&S	Hub and Spoke
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
MINLP	Mixed Integer Non-Linear Programming
MR	Milk Round
NSP	North Sea Port
OPEX	Operating Expenditures
pLCA	Prospective Life Cycle Assessment
RCP	Representative Concentration Pathways
SSP	Shared Socioeconomic Pathway
TEA	Techno-economic Assessment
TMOO	Tiered Multi-Objective Optimization
TRL	Technology Readiness Level

3. Executive summary

To meet the climate goals set in the Paris Agreement, fast decarbonisation in all sectors is needed. Specifically, for the steel industry and other industrial clusters, decarbonisation can be achieved by integrating carbon capture and storage. In the C⁴U project, the implementation of two carbon capture technologies in the steel industry is assessed. This deliverable first dives into the environmental impact of industrial scale CASOH and DISPLACE deployment. The environmental impacts of CASOH and DISPLACE are assessed by a prospective life cycle assessment, using a prospective database that considers, amongst others, the change in the energy supply from 2030 to 2055. This is followed by implementing the life cycle assessment (LCA) method in the optimization of CO₂ transport (pipeline versus barge transport) within the North Sea Port cluster. By combining the economic costs and environmental impacts of different transportation options in a tiered multi-objective optimization, optimal strategies for transport within the North Sea Port are identified.

The results of LCA on industrial scale CASOH and DISPLACE deployment show the environmental benefits these technologies can bring. The produced output hydrogen-nitrogen stream by CASOH can be used to satisfy the internal heat and electricity demand to run the CASOH technology and it was found to be the most environmentally beneficial option. By doing so, natural gas-based heat and grid electricity production are not needed and thus the environmental footprint is lowered. For DISPLACE, similar decarbonisation potentials are obtained for decarbonising flue gas from reheating oven, flue gas from hot stoves and flue gas from a sinter plant. Towards 2055, electricity will be supplied by more renewables, increasing the decarbonisation potential of both technologies. On the other hand, by using the hydrogen-nitrogen stream, the use of grid electricity is avoided and hence the credits become smaller towards 2055. In the future, electricity from the grid becomes more environmentally favourable option for CASOH. It is assumed that in the future heat is always replaced or supplied by natural gas-based heat. The environmental hotspots have been identified. For CASOH these include (a) the replacement of BFG by natural gas-based heat, and (b) the emissions related to the combustion of the hydrogen stream. For DISPLACE the environmental hotspots are the electricity and heat use.

The tiered multi-objective optimization (TMOO) of intra-cluster CO₂ transport in the North Sea Port showed that pipeline operating at 35 bar is the most optimal strategy for CO₂ transport. The power consumed in CO₂ conditioning was found to be the largest contributor to the costs and carbon footprint. Delaying pipeline deployment by longer than two years can result in a shift in the merit order of optimal strategies and barge transport is the preferred option until pipeline deployment is available.

4. Introduction

Iron and steel are indispensable in modern society, yet their production accounts for 15% of the industrial CO₂ emissions¹. On average, the production of one ton of steel corresponds to the emission of 1.85 tons of CO₂². A potential solution to lower CO₂ emissions in the steelmaking industry is to integrate carbon capture utilization and storage (CCUS) technologies. In this way, CO₂ is separated from steel gas and can be used in other processes and/or products or is sequestered in, for example, a geological formation. CCUS technologies can decarbonise steelmaking in one plant, but also have the potential to decarbonise multiple stakeholders within an industrial cluster. For example, by combining CO₂ transportation infrastructure (e.g., pipelines or barges) for sequestration or utilisation of waste streams as a resource for others within the cluster. In the C⁴U project, the integration of two emerging solid based CO₂ capture technologies, DISPLACE and CASOH, in the iron and steel industry is investigated. These two technologies have a combined potential to eliminate up to 90% of the CO₂ emissions in a steel plant³.

Within the interdisciplinary C⁴U project, all major elements needed for successful integration of CO₂ capture technologies are addressed and the capture potential of these technologies on technology readiness level (TRL) 7 is demonstrated³. To assess whether integrating DISPLACE and CASOH in a steel plant is environmentally beneficial and decarbonisation is achieved, a Life Cycle Assessment (LCA) can be performed. LCA is a holistic way to determine and evaluate the environmental impacts of technologies over their entire life cycle and subsequently inform decision-makers. It is a well-established and widely used method and standardized through ISO14040 and 14044^{4,5}. Performing an LCA consists of four iterative main steps: 1) the goal and scope, which sets the aim and boundaries of the study, 2) the Life Cycle Inventory (LCI) where all unit flows and processes needed throughout the system's life cycle are listed and quantified, 3) the life cycle impact assessment (LCIA) where the LCI is converted into impacts in different environmental categories, and 4) interpretation of the results, including analysis on uncertain parameters.

Identification of the major contributors to the environmental impact at an early stage of technology development can help in the further design of the technology on larger scale and hence reduce the total environmental impact. The existing LCA method assesses products which have been in commercial use or technologies at industrial scale⁶. For a fair comparison between the emerging technology and conventional systems, similar TRLs need to be compared. To achieve this, a so called prospective LCA (pLCA) can be performed on emerging technologies which considers upscaling effects to industrial scale (TRL 9) and fore- and background changes over time⁷.

In deliverable 4.11 “Method to address technology scaling”⁸, a framework on how to perform a prospective LCA is drafted based on the framework developed by van der Hulst et al.⁷. With this framework the environmental impact of high TRL DISPLACE and CASOH technologies can be investigated, based on data available from the pilot scale and expert judgement. In brief, three steps are required: 1) definition of the current and future TRL, 2) process scaling where process changes, size scaling and process synergies are identified and modelled and 3) external developments where the impact of future deployment and specifically future electricity mixes are explored.

This report constitutes deliverable 4.12 “Life cycle assessment (LCA) and method to assess the North Sea port cluster”, where the goal is to develop a new LCA approach and apply it to quantify the main environmental impacts of the North Sea Port (NSP) cluster for different industrial scenarios concerning the industrial implementation of DISPLACE and CASOH. For this purpose, the report first determines the prospective life cycle impacts of DISPLACE and CASOH integrated in a steel plant on industrial scale, considering specifically future changes in the grid electricity sources. Followed by an assessment on the economic and environmental benefits of shared CO₂ transportation infrastructure within the NSP cluster composed of a number of large CO₂ emitters. This is performed to determine the optimal CO₂ transportation infrastructure solutions (e.g., pipelines or barges) for the cluster.

This deliverable builds on previous results of the C⁴U project to quantify the environmental impacts of the CO₂ capture and transport technologies in the North Sea Port Cluster. In particular, in deliverable D4.10⁹, an LCA was used to assess the impact of pilot implementations of the DISPLACE and CASOH C⁴U technologies at Technology Readiness Level (TRL) 7. A framework to address technology scaling, specifically for the C⁴U technologies was described in D4.11⁸. In D3.4¹⁰, a techno-economic assessment (TEA) was performed for the C⁴U technologies at industrial scale.

This report first briefly describes the DISPLACE and CASOH technologies. This is followed by a description of the data gathering in the LCI for both technologies and explanation of the integration of these technologies within the North Sea Port cluster via a shared CO₂ transport infrastructure. Lastly, the results of both assessments are described which show the decarbonisation potential of CASOH and DISPLACE.

5. Process descriptions

CASOH and DISPLACE are emerging carbon capture technologies that involve high-temperature gas-solid separation processes and use steel mill off-gasses as input.

5.1. CASOH

CASOH, standing for Calcium Assisted Steel mill Off-gas Hydrogen production, decarbonizes blast furnace gas (BFG) by capturing CO₂ and produces a hydrogen nitrogen fuel stream with increased lower heating value (LHV). Additionally, high-temperature heat is produced, which is re-used within the process to meet part of the heat demand. BFG is produced during steel making in the blast furnace and consist of 23 mol% CO, 21 mol% CO₂, 2 mol% H₂ and 54 mol% N₂.

The working mechanism of CASOH consist of three steps: (1) the water-gas shift reaction enhanced by carbonisation of CaO and catalysed by Cu-based particles, (2) the oxidation of Cu-based catalyst, and (3) the calcination reaction of CaCO₃ to regenerate the sorbent (CaO) (Figure 1). In the first step, CO is, together with steam, converted to CO₂, which in turn binds to CaO to create CaCO₃. Calcium looping can be used as post-combustion CO₂ capture within gas streams. However, regeneration of CaCO₃ is energy demanding and hence calcium-copper looping is incorporated. By converting CuO back to Cu, energy is creating which satisfies the energy demand of the calcination process.

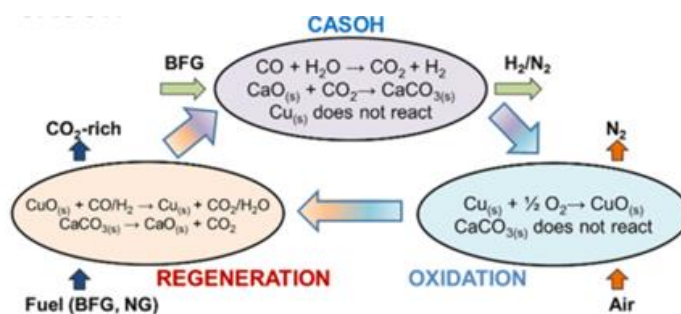


Figure 1: Schematic representation of the CASOH process.

As described in deliverable D3.4¹⁰, the basic design of CASOH faced some limitations: only a third of the BFG is used in the first step for hydrogen production and due to the high nitrogen content in the BFG a CO₂ purification step is additionally needed before the CO₂ stream is fit for

storage. Hence, the CASOH-enhanced case was developed, where an additional fourth step is added to incorporate calcination. As a result, a part of the hydrogen-enriched syngas is redirected to the reduction stage. The extra calcination step serves to reduce the energy demand associated with the reduction process and results in a CO₂ stream with a purity of 99.8%, i.e. above the desired level of purity for storage. A scenario analysis in D3.4¹⁰ showed the lowest energy demand for operating conditions of 0.5 bar and is hence used as basis in this work.

5.2. DISPLACE

DISPLACE, standing for High temperature sorption-DISPLACEMENT process, uses hydrotalcites to recover CO₂ from flue gasses of a steel mill's oxy-fuel burner (Figure 2). In an oxy-fuel burner, BFG is oxidized by combusted in the presence of oxygen. The resulting flue gas is cooled down and compressed and sent through six reactor columns. In the adsorption phase, CO₂ adsorbs on the mixed base-metal oxide adsorbent derived from hydrotalcites, creating a nitrogen rich stream. In the next phase, steam is used to desorb the CO₂ by lowering the partial pressure and competing for the adsorption sites. In this way, a CO₂ rich-stream is generated fit for storage with a purity of 95%. The process is cyclic and works at constant pressure. Heat is recovered in this system; heat from the flue gas, N₂ rich gas and CO₂ rich gas is used to heat water to create steam. A natural gas burner is added to provide additional heat for heating the flue gas at the outlet of the compressor and super-heat steam needed in the reactors.



Figure 2: Schematic representation of the DISPLACE process.

6. Methods

6.1. pLCA of CASOH and DISPLACE on industrial scale

In this section, each of the four steps of the LCA and how the pLCA was performed is described.

Goal and Scope

The goal of the life cycle assessment within this deliverable was to assess the environmental impacts of the CASOH and DISPLACE technologies on full-scale, by using the prospective methodology developed in D4.11. For this, the functional unit is defined as ‘the capture and geological storage of 1 ton of CO₂ in the North Sea’, which is used to express all inputs, outputs, and results. This functional unit was chosen so that the CASOH and DISPLACE technology could be easily compared, considering their different input gasses and output streams. Even though storage is not part of the capture technologies, it is included in the functional unit, to cover the full life cycle of the CO₂ stream and account for the benefits of storage. Additionally, a second functional unit of ‘the production of 1 ton steel’ is used to compare with other conventional carbon capture techniques in the steel industry.

The simplified system boundaries for each application are shown in Figure 3. The impacts related to the construction, operation, and dismantling of the steel mill that lead to the BFG by-product are not modelled. We assumed that the operating conditions of the steel mill are not affected by the uses of the BFG considered here.

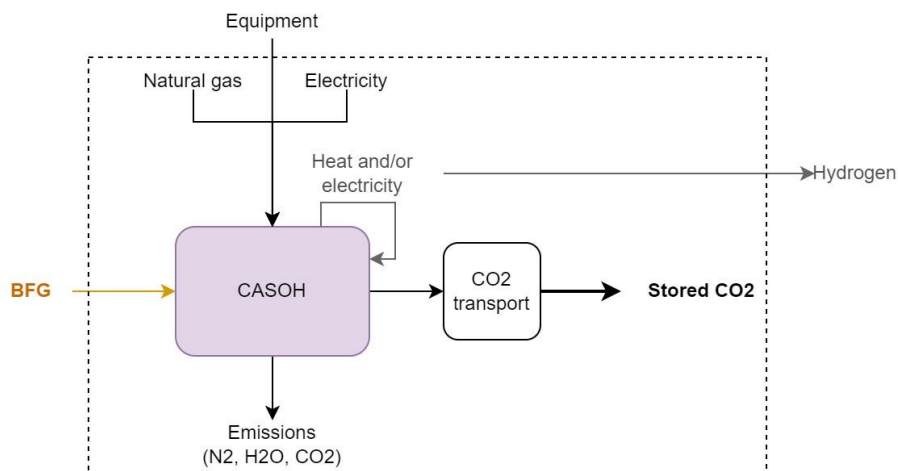
For CASOH three scenarios are investigated considering the use of the hydrogen outlet stream:

1. *Scenario 1:* Hydrogen produced by the process is used to satisfy the heat and electricity requirement of CASOH. It is assumed that the remaining hydrogen replaces conventional heat production from natural gas.
2. *Scenario 2:* Hydrogen produced by the process is used to satisfy the heat requirement of CASOH and electricity is supplied by grid electricity. It is assumed that the remaining hydrogen replaces conventional heat production from natural gas.
3. *Scenario 3:* The heat required by CASOH is provided by natural gas and electricity by grid electricity. All the hydrogen produced in the process is assumed to replace conventional heat production from natural gas.

For DISPLACE three scenarios are investigated, based on different three input flue gasses from the steel mill:

1. *Scenario 1:* flue gas from the reheat oven is used as input.
2. *Scenario 2:* flue gas from the hot stoves is used as input.
3. *Scenario 3:* flue gas from the sinter plant is used as input.

A)



B)

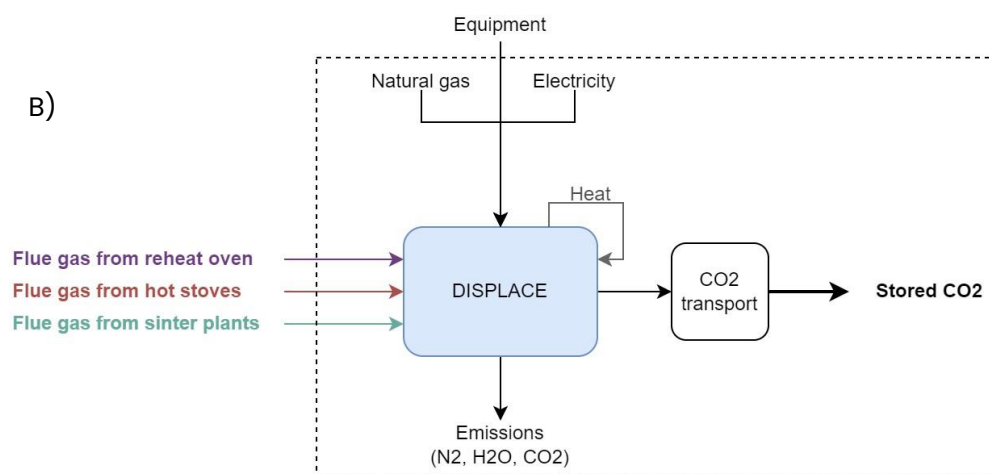


Figure 3: System boundaries for A) CASOH and B) DISPLACE CO₂ capture technologies. All processes within the system boundaries (shown by a dotted line) are included in the LCA model.

Life cycle inventory (LCI)

LCI data was collected in collaboration with work package 3 and deliverable D2.1–D2.2^{11,12} & D3.2–D3.4^{10,13,14}. These deliverables describe the in- and outputs of the techno-economic assessment (TEA) for CASOH and DISPLACE on TRL 7 and on TRL 9. The estimations of electricity, heat and material flows from these deliverables are used as input for the LCI. In collaboration with work package 3, the most up-to-date model output was gathered. As these sources could not provide a full inventory, data from literature was used whenever possible, and assumptions and simplification had to be made otherwise. Data from the deliverables is confidential and hence a confidential appendix to this report is included with all data gathered for the inventory.

Both CASOH and DISPLACE technologies require electricity as an input. The assessment focused on the integration of these technologies within the North Sea Port cluster in the Netherlands. Hence, we modeled the electricity supply composition based on this geographical scope. The components used by CASOH and DISPLACE are mostly made from steel and sorbent material. As shown in D4.10⁹, the equipment has a very low contribution to the total impact and was hence not included in this study (Figure 3). Specifically, it was calculated that per lifetime, 5.5 ton sorbent material is needed, meaning that for each ton of steel produced 7E-5 kg solid sorbents are needed. This was assumed to have a low contribution to the total results. Non-conventional operations, such as start-up or shutdown stages, were not modelled. The captured CO₂ by DISPLACE and CASOH in the North Sea Port is stored in a geological formation in the North Sea. To model the CO₂ transport, the inventory data described by Koornneef et al.¹⁵ in appendix D, E, and F was used (table 1, 2 and 3).

Table 1: Specifications of the inventory of the compression facility expressed per ton CO₂, based on Koornneef et al.¹⁵.

		Amount	Unit
Output to the technosphere: product			
	Compression facility	1.00	p/ton CO ₂
Input from technosphere: materials/fuels			
	Concrete	1.05E-06	m ³ /ton CO ₂
	High alloyed steel	5.24E-05	kg/ton CO ₂
	Copper	1.13E-04	kg/ton CO ₂
	Polyethylene	3.23E-04	kg/ton CO ₂

	Low alloyed steel	9.96E-05	kg/ton CO ₂
	Diesel and heavy fuel oil	3.19E-02	MJ/ton CO ₂
	Electricity (UCPTE)	9.84E-04	kWh/ton CO ₂
Output waste and emissions to treatment			
	Steel recycling	-1.52E-04	kg/ton CO ₂
	Waste concrete	-1.05E-06	m ³ /ton CO ₂
	Plastic waste	-3.23E-04	kg/ton CO ₂

Table 2: Specifications of the inventory of the pipeline infrastructure expressed per ton CO₂, based on Koornneef et al.¹⁵.

		Amount	Unit
Output to the technosphere: product			
	Pipeline infrastructure	1.00	p/ton CO ₂
Input from technosphere: materials/fuels			
	Sand	1.04E+00	kg/ton CO ₂
	Reinforcing steel	1.28E-01	kg/ton CO ₂
	Drawing of steel pipes	1.28E-01	kg/ton CO ₂
	Bitumen	1.23E-03	kg/ton CO ₂
	Polyethylene	2.47E-03	kg/ton CO ₂
	Diesel and heavy fuel oil	1.76E+00	MJ/ton CO ₂
	Transport	1.21E-01	tkm/ton CO ₂
Output waste and emissions to treatment			
	Steel recycling	-1.28E-01	kg/ton CO ₂
	Plastic waste	-1.23E-03	kg/ton CO ₂

Table 3: Specifications of the inventory of the geological storage expressed per ton CO₂, based on Koornneef et al.¹⁵.

		Amount	Unit
Output to the technosphere: product			
	Geological storage	1.00	p/ton CO ₂
Input from technosphere: materials/fuels			
	Sand	3.25E+00	kg/ton CO ₂
	Un-alloyed steel	1.74E-02	kg/ton CO ₂
	High alloyed steel	3.70E-02	kg/ton CO ₂
	Concrete	4.78E-05	m ³ /ton CO ₂
	Copper	1.94E-03	kg/ton CO ₂
	Transport	3.42E-01	tkm/ton CO ₂
Output waste and emissions to treatment			
	Steel recycling	-5.43E-02	kg/ton CO ₂
	Waste concrete	-4.78E-05	m ³ /ton CO ₂

LCI CASOH

The counterfactual approach is adopted to include the avoided production of heat from hydrogen in case of CASOH. A counterfactual is the activity in the “conventional” economy that is being replaced for a given product; in this case the use of heat¹⁶. The extra heat required to replace the current use of BFG as heat in the steel mill for CASOH is also included. In the future, heat pumps could supply heat without the current need for natural gas. However, in this study it is assumed that heat is still supplied by natural gas in the future. The extra heat demand was calculated based on a BFG Lower Heating Value (LHV) of 3.5 MJ/m³¹⁷, a BFG density of 1.25 kg/m³¹⁸, and efficiency of 94%. This leads to 3.7 GJ of heat per functional unit (ton CO₂ captured and stored). BFG is regarded as a waste stream and hence no environmental impacts are modelled for the production of this stream.

The CASOH technology requires water, nitrogen (for heat transfer), natural gas for heat, grid electricity and emits emissions like N₂, NO_x, CO₂ and H₂O. The hydrogen stream produced by

CASOH is combusted to produce heat. The emissions related to the combustion are calculated by assuming full oxidation of the components. Following the counterfactual approach, if hydrogen-based heat is used within CASOH, the production of natural gas-based heat is avoided. Similarly, if hydrogen-based electricity is used within CASOH, production of grid electricity is avoided. The efficiency for heat production from hydrogen was assumed to be 94% and 90% for co-generation (i.e., electricity and heat production)^{19,20}.

LCI DISPLACE

BFG is still used for heat production if DISPLACE is integrated in the steel mill. The resulting flue gasses from oxy-combustion at the reheat oven and hot stoves are decarbonised with DISPLACE. As these flue gasses are normally vented,¹⁹ no counterfactual is assumed. Flue gasses are regarded as waste streams and hence no environmental impacts are modelled for the production of these streams.

The DISPLACE technology requires water, natural gas-based heat, grid electricity and emits compounds like N₂, CO₂ and H₂O. Based on the TEA outcomes, the choice was made to focus on the optimal settings of pressure and temperature for the inlet stream found in D3.4¹⁰, i.e., the cases with the lowest costs of CO₂ avoided (CCA). For flue gas from the reheat oven this was 6 °C at 400 bar, for flue gas from heat stoves 7 °C at 400 bar and for flue gas from the sinter plant this was 5 °C at 400 bar.

LCI conventional carbon capture options

The effectiveness of CASOH and DISPLACE is compared to conventional carbon capture options: monoethanolamine (MEA) and methyldiethanolamine (MDEA). LCI data on mass flows and electricity usage was gathered from deliverable D3.4. Additionally, to include the amount of sorbent (MEA or MDEA) that needs to be replaced due to thermal degradation per functional unit, data from van der Giesen et al.²¹ was used. Specifically, we used 1.5 kg MEA per ton CO₂ captured and stored. Due to the degradation, ammonia forms and is emitted to the air. We used 0.035 kg NH₃ per ton CO₂.²¹ In addition, MEA itself is emitted to the atmosphere for which we assumed 0.0385 kg MEA per ton CO₂ was emitted.²¹ As no degradation potential of MDEA was found, similar values were assumed for MDEA.

Prospective LCA

The prospective LCA was carried out based on the framework described in D4.11⁸ as shown in Figure 4. From TRL 7 to TRL 9 the capture technologies will undergo size scaling, process changes (i.e., efficiency increase in electricity use) and synergies (i.e., heat recovery). Data on these changes for the upscaled CASOH and DISPLACE technologies were gathered from the outcomes of the TEA models developed in work package 3.

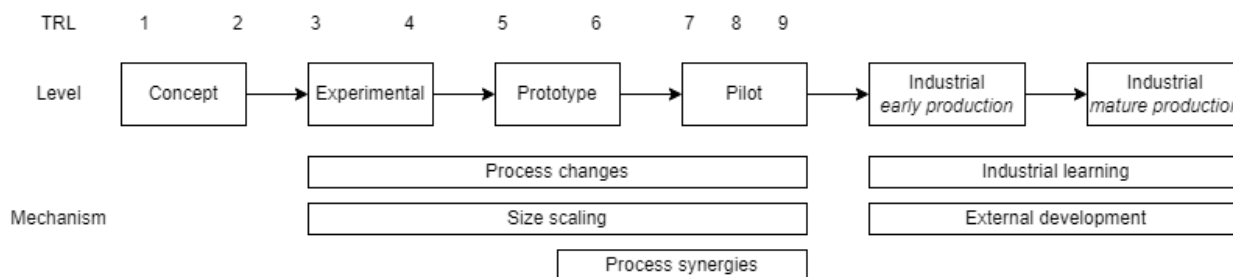


Figure 4: Prospective life cycle assessment framework used in this study, developed by van der Hulst et al. (2020). Industrial learning was not modeled in this study.

External developments are included in prospective LCA. For example, by the time of deployment of CASOH and DISPLACE at TRL9, the electricity grid mix will be different and will most likely include more renewables. A new prospective database was created, to implement changes in the energy, transport and fuel sectors from 2030 to 2055. Other potential future external developments, like efficiency improvement in steel production, are not included.

The prospective database is built by combining the LCA ecoinvent database v3.9.1²² with developments described in IPCC's shared socioeconomic pathway "middle of the road scenario" (SSP2), using premise v1.5.1.²³ SSPs are narratives used to derive a set of future parameters (e.g., population, urbanization) that describe global socioeconomic changes until 2100²⁴. RCPs are narratives for how atmospheric greenhouse gas concentrations might develop.^{25,26} Specifically, in this report three SSP2 representative concentration pathways (RCP) are looked at: 1) RCP base where a global increase in temperature of 3–4 °C is reached by 2100, 2) RCP 2.6 where an increase of 2 °C is reached by 2100, and 3) RCP 1.9 where the Paris agreement is met and the increase in global temperature is 1.5 °C by 2100.

Predicting the environmental impact of large-scale deployment of emerging technologies, inherently includes uncertainty in the upscaling. This holds for both the LCI and the forecasting (i.e., prospective background database). To understand the effect of this forecasting uncertainty, these three future RCP scenarios are investigated.

Impact assessment and interpretation

The environmental impacts were calculated using the ReCiPe 2016 (Hierarchist) life cycle impact assessment method^{27,28}. This method calculates environmental impacts in term of 18 midpoint categories and three areas of protection (endpoint categories). By assessing all 3 endpoint categories, potential burden shifts between different impact categories can be identified, which is crucial for full-scale deployment of CCUS technologies. The first endpoint "damage to human health" assesses the effect of sources on human health. The common unit

is DALY (disability adjusted life years) and accounts for the years that are lost or that a person is disabled due to disease or accident²⁸. The second endpoint is “damage to ecosystems” and represents the impacts on the natural environment²⁸. The unit is PDF*year (potentially disappeared fraction of species in time). The last endpoint is damage to resource availability expressed in USD2013 (U.S. Dollar of 2013) and represents the extra costs to extract minerals and fossil resources in the future²⁸.

First, this report shows the environmental impacts in terms of endpoints first, for the year 2030 when large-scale deployment would be possible. Secondly, a more detailed assessment of the impact on the most important midpoint impact categories (climate change and fine particulate matter formation) is shown. The importance of the midpoint categories is determined by a midpoint to endpoint contribution analysis, where it is investigated which midpoint contribute most to the endpoint levels. Climate change, expressed in kg CO₂-eq, represents the effect of greenhouse gas emissions on the increase in infra-red radiative forcing and global temperature. Fine particulate matter formation, expressed in kg PM_{2.5}-eq, represents the effect of small particulates.²⁸ Next to the scenarios described in the “goal and scope” section, a contribution analysis was performed on both endpoint and midpoint to identify the processes that contribute most to the environmental impact.

In the premise-generated prospective scenarios, hydrogen-based supply chains can become quite significant. Hence, the characterization factor for hydrogen is specifically added to the ReCiPe impact assessment method, according to the ‘premise_gwp’ package.²⁹ Additionally, some scenarios rely on bioenergy with carbon capture and storage (BECCS), direct air capture (DAC) and other types of storing or using atmospheric CO₂.²⁹ To make sure that the negative emissions are considered, negative biogenic CO₂ uptake and positive release flows are characterized.²⁹

6.2. Cluster integration in North Sea Port

The second part of this work focusses on the integration of capture technologies within an industrial cluster: the North Sea Port. Within this cluster, the transportation infrastructure for captured CO₂ can be shared. For this, pipelines and barges are considered as the most suitable modes of transport within the NSP cluster. The goal of this assessment was to identify the best transportation mode, based on both economic and environmental indicators. A multi-objective decision analysis can be used to balance and evaluate between monetary and environmental objectives.³⁰ The outcome of this analysis is the optimal design of multi-modal CO₂ transport that minimizes the increase in total costs and the environmental impact.

TEA and LCA are used to assess the monetary and environmental objectives (e.g., carbon footprint) of the two transport modes and combined in a Tiered Multi-Objective Optimization (TMOO) to find an optimal range of solutions. A functional unit of “conditioning, storing and transport of 1 ton of CO₂ within the NSP from capture to an offtake point for onward shipping” was chosen. Within the NSP, five major industrial CO₂ emitters were identified and their projected CO₂ emissions for 2030 formed the basis amount which needs to be transported. The captured CO₂, from for example CASOH and DISPLACE, was assumed to have high purity and to be liquefied after intra-cluster transportation. The capture, terminal storage and onward transportation outside the NSP were outside the scope of this integration study.

Ten possible cases were developed for the optimization (Table 2) involving four strategies of CO₂ transport (Figure 5), which included low- and high-pressure pipeline transport and two strategies for barge transport ‘Hub and Spoke’ (H&S) and ‘Milk Round’ (MR). In the H&S scenario, each emitter has their own barge transporting CO₂ to an offtake point, while in the MR scenario one single barge collects CO₂ from each emitter sequentially. Yara and AMG are considered as potential off-take points.

Table 2: Specifications for each CO₂ transport case.

Case number	Mode of CO ₂ transport	Transport strategy	Offtake point	Direction of flow	Temperature (°C)	Pressure (bar)	Nodal storage
1	Pipeline	Low pressure	Yara	-	30	35	No
2	Pipeline	High pressure	Yara	-	30	110	No
3	Pipeline	Low pressure	AMG	-	30	35	No
4	Pipeline	High pressure	AMG	-	30	110	No

5	Ship	H&S	Yara	-	-30	20	Yes
6	Ship	H&S	AMG	-	-30	20	Yes
7	Ship	MR	Yara	North	-30	20	Yes
8	Ship	MR	Yara	South	-30	20	Yes
9	Ship	MR	AMG	North	-30	20	Yes
10	Ship	MR	AMG	South	-30	20	Yes

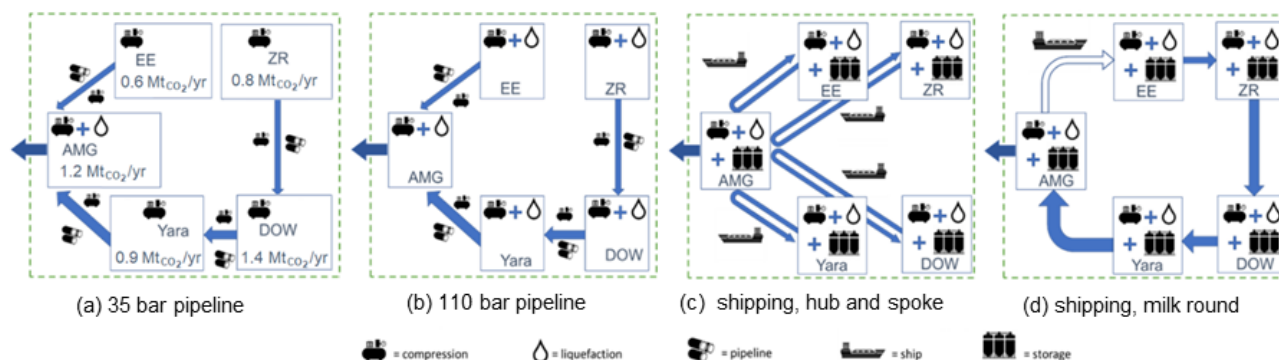


Figure 5: Strategies of CO₂ transport in the NSP cluster.

Techno-economic assessment (TEA)

The operation network costs for pipeline and barge transport were determined with a techno-economic assessment. For the pipeline infrastructure specifically, the pipeline sizes were optimized for minimal costs, i.e., the sum of CAPEX and OPEX, by using Mixed Integer Non-Linear Programming (MINLP) model to determine the optimal internal and external diameters at a set pressure drop. For barge infrastructure, the costs were minimized by minimizing the combination of tonnage and per kilometer shipping costs and interim storage costs. The operational costs for pipeline transport were calculated by the combined costs of compression, liquefaction, initial pipeline investments and re-compression over the annual throughput.³¹ The initial pipeline investments were annualized with a discount rate of 8%. It was assumed that the lifetime of the pipeline was 25 years. The operational costs for barge transport were calculated by the combined costs of compression, initial pipeline investments

and storage over annual throughput plus the tonnage and mileage costs for shipping.³² The lifetime was assumed to be 20 years with a discount rate of 8%.

Life Cycle Assessment (LCA)

LCI data on CO₂ conditioning, shipping, pipeline transport and storage, was collected from the model developed for the TEA. Background processes were taken from Ecoinvent v3.8.³³ For pipeline specifically, a European electricity grid mix, chromium steel and processing steel sheets to pipes were included. For barge transport, two classes of tanker barges were investigated: low capacity for the hub and spoke and high capacity for the milk and round shipping strategy. For each class, data on size and fuel consumption is taken from Friedrich and Bickel (2001).³⁴ Similarly to the life cycle assessment of the CASOH and DISPLACE technologies, the ReCiPe 2016²⁷ impact assessment method was used to convert the LCI to environmental impacts. The assessment focused on human health damage, ecosystem damage and global warming, as they reflect the “triple planetary crisis”.

Tiered multi-objective optimization

The tiered multi-objective optimization (TMOO) model was used to determine the optimal strategy for intra-cluster CO₂ transportation. Based on the constructed Pareto front, the optimal point which minimizes costs and environmental impact per strategy is found by using the weighted sum method. Initially, all possible transport options were included as Pareto optimal solutions and the optimal strategy is defined as ‘tier 1’. By repeating the multi-objective optimization for the strategies excluding the tier 1 solutions was run to determine the next set of optimal solutions, defined as ‘tier 2’. Similarly, by excluding the ‘tier 2’ solutions, the ‘tier 3’ optimal strategies can be identified.

7. Results and Discussion

7.1. Industrial impacts of CASOH and DISPLACE

Endpoint analysis

Figures 6 and 7 show the endpoint analysis for CASOH and DISPLACE respectively, for the year 2030 and per ton of steel produced. The results for climate change are shown in Appendix A. For CASOH, environmental benefits are obtained for damage to ecosystems and damage to human health, due to the large savings of storing CO₂ in a geological formation. In other words, the savings from decarbonising BFG and storing the captured CO₂ outweighs the environmental burdens of operating the CASOH technology. It should be noted that negative values don't indicate negative emissions, as no atmospheric CO₂ is captured. Negative values are obtained as an effect of the choice in system boundaries where the production of the gas (BFG, BOFG and flue gasses) within the steel mill are excluded. For damage to resource availability, no environmental benefits (i.e. negative values) are obtained, as capturing and storing CO₂ does not affect this endpoint category. Scenario 1 (hydrogen is used for heat and electricity) results in the largest environmental benefits and lowest environmental impact, due to the avoidance of natural gas and grid electricity to meet the energy demands. Scenario 3 (natural gas-based heat and grid electricity for heat and electricity) performs the least favourable. The benefit of replacing conventional heat by heat from the hydrogen stream is smaller than the use of grid electricity in scenarios 2 and 3. The replacement of BFG by natural gas-based heat and the emissions related to the combustion of the hydrogen stream are the biggest environmental burdens. The electricity consumption is mainly needed for CO₂ compression. CASOH performs better compared to MEA carbon capture. For MEA carbon capture, the main environmental impact is caused by the emissions of ammonia to the air due to the thermal degradation of MEA²¹.

Net environmental benefits for DISPLACE are observed for damage to human health and ecosystem quality. Similar to CASOH, no environmental savings are obtained in damage to resource availability, as no credits are included in this category for storing CO₂. DISPLACE doesn't produce a stream that can be combusted to avoid conventional heat production, and hence, the environmental savings are smaller compared to the savings of CASOH. Due to the larger heat requirement, decarbonising flue gas from the sinter plant performs worst. Similarly to CASOH, DISPLACE performs better compared to MDEA carbon capture. This is due to the emissions of ammonia to the air.

The environmental impacts of steel production in 2030 are 0.015 DALY per ton steel, 8.2E-6 PDF*yr per ton steel and 220.3 USD₂₀₁₃ per ton steel. The decarbonation potentials seem small compared to the total impact of steel production, but this study, considers the decarbonisation of BFG and flue gasses from the rehear oven, hot stoves and sinter plant. Not all

decarbonisation options are explored. Nevertheless, both CASOH and DISPLACE show net environmental savings, indicating they could be used as part of the decarbonisation of the steel industry.

To understand which midpoints contribute most to these endpoints, a midpoint to endpoint contribution analysis was performed. The results of this analysis are presented in Appendix B showing that the midpoints climate change and fine particulate matter formation were the biggest contributors to the endpoints damage to human health and ecosystem damage. The next section focuses on a detailed assessment of these midpoint categories.

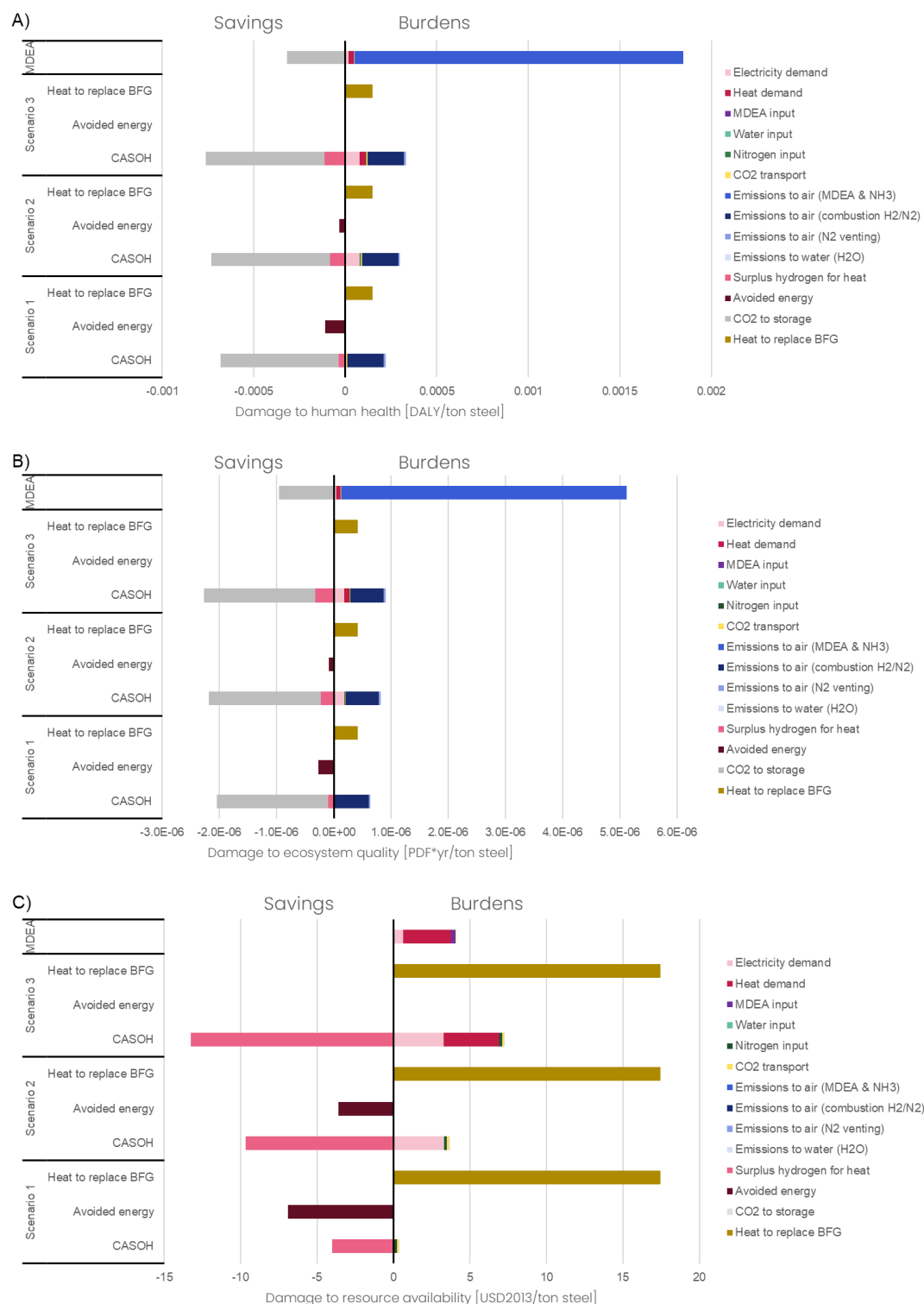


Figure 6: Prospective life cycle assessment results for CASOH for three scenarios and a global temperature increase of 2 °C by 2100. These results are shown for year 2030.

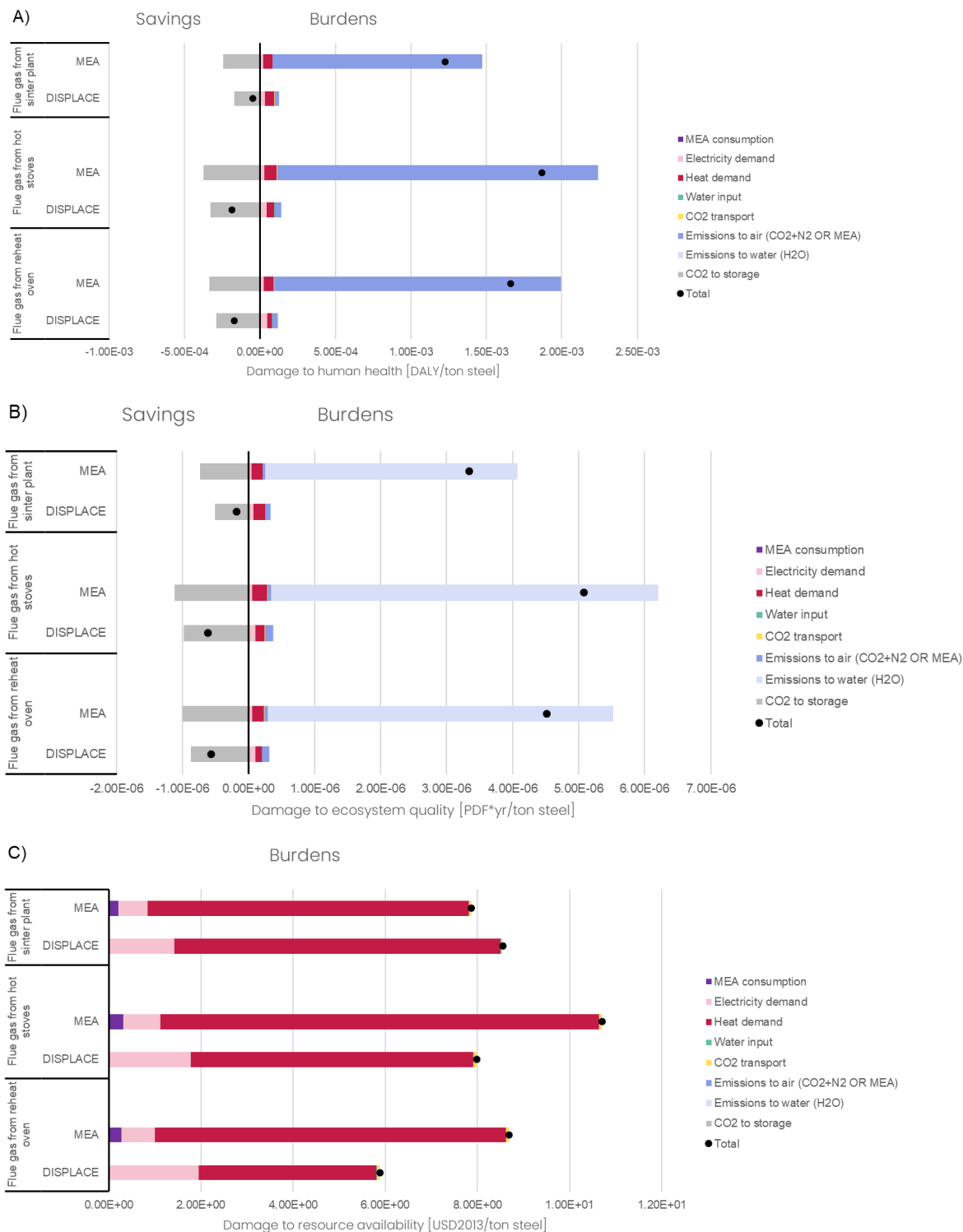


Figure 7: Prospective life cycle assessment results for DISPLACE for three scenarios and a global temperature increase of 2 °C by 2100. These results are shown for year 2030

Midpoint analysis

Figures 8 and 9 show the environmental impact per ton CO₂ captured and stored on midpoint level of industrial scale operation of CASOH for three scenarios from 2020 to 2055 and a global increase in temperature of 2 °C by 2100. Results for the other two prospective scenarios (reaching 3–4 °C and reaching 1.5 °C) are shown in Appendix C. These results show that climate benefits are obtained for almost all scenarios for both CASOH and DISPLACE and in time the climate benefits increase. Similar to the endpoint analysis, scenarios 1 and 2 for CASOH and flue gas from the reheating oven and hot stoves for DISPLACE show higher decarbonisation potentials.

The scenario which reaches 2 °C global warming by 2100 considers the implementation of more renewables towards 2055. Especially for climate change, it can be seen that the carbon footprint of grid electricity decreases. However, this means that the avoided production is less and less favourable towards 2055 for CASOH. Hence, scenario 1 increases in climate change impacts towards 2055, whereas the other two scenarios decrease in impact. DISPLACE also shows an increase in environmental benefits towards 2055.

In the other prospective scenarios, different rates of decarbonisation of the grid electricity are seen (see Appendix C). If 3–4 °C global warming by 2100 is reached, the need for electricity increases faster than the implementation of renewables and hence electricity needs to be supplied by fossil resources from 2040 onwards. This can be seen in the increase in climate impacts of both CASOH and DISPLACE (Appendix C, Figure C1 and C3). In the scenario reaching 1.5 °C global warming by 2100, the implementation of renewables in the electricity grid mix is the fastest and the largest decrease in climate impact can be seen (Appendix C, Figures C2 and C4).

The benefits of storing CO₂ has no effect on fine particulate matter formation and hence less savings are seen. After 2040, electricity is generated partly by biomass combustion combined with CCS and oil and gas combustion combined with CCS. These generation methods result in a lower carbon footprint. However, combusting biomass, oil and gas results in fine particulate matter emissions. Hence, the impact of fine particulate matter emissions by electricity increases after 2040.

Large reductions (~85%) in comparison to the outcomes of TRL 7 (D4.10⁹) are obtained, which is mainly due to optimized energy recovery on larger scale. Additionally, the CO₂ is captured and stored, instead of being vented to the atmosphere.

For DISPLACE the impacts for steel needed in the infrastructure were added and comprised of 0.06%. The low contribution of infrastructure justifies the assumption to leave out the equipment costs.

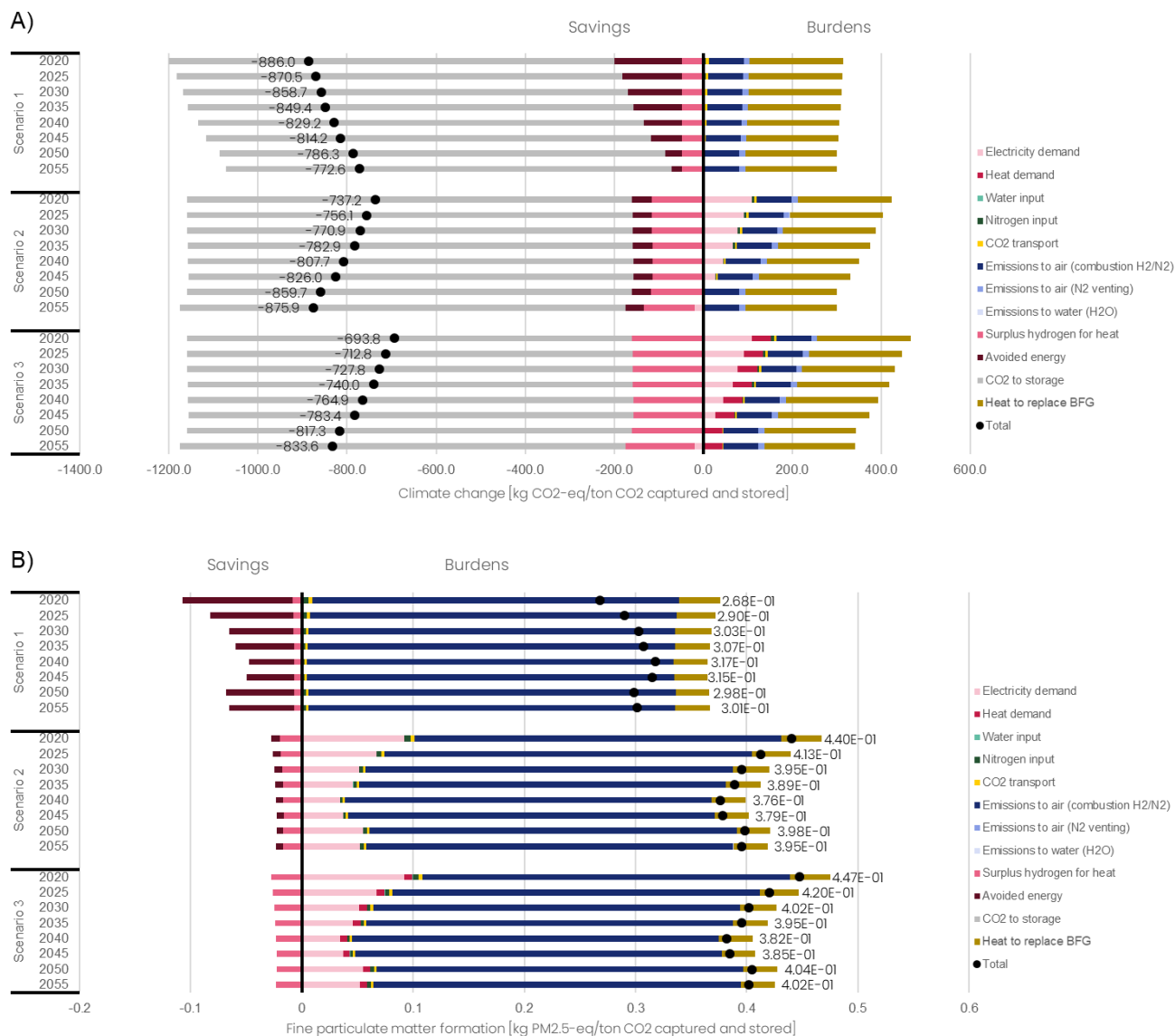


Figure 8: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for CASOH for three scenarios and a global temperature increase of 2 °C by 2100.

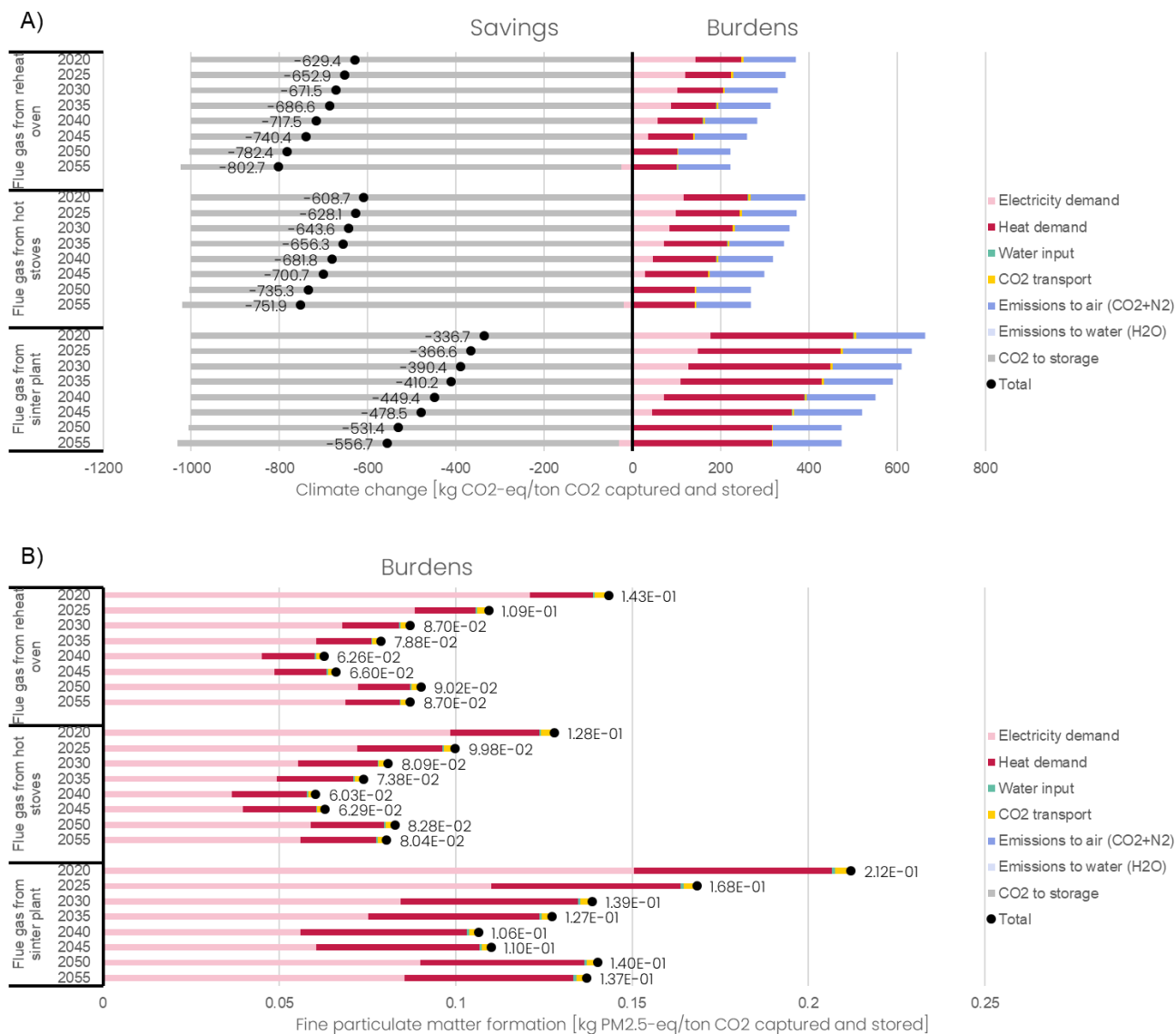


Figure 9: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for DISPLACE for three scenarios and a global temperature increase of 2 °C by 2100.

7.2. Integrated CO₂ transport

Figure 10 shows the network costs for barges and pipeline transport per ton of CO₂ transported in the NSP cluster. CO₂ transportation with pipeline at 35 bar results in the lowest costs. Even though transportation at 35 bar has higher investments in pipelines than 110 bar, the savings in conditioning costs result in lower total costs. For barges, the milk round shipping strategy results in the lowest costs. Servicing the entire network using a single ship benefits from economy of scale, even though the average mileage that a ton of CO₂ covers is greater in this strategy. The main contributor for both pipeline and barges is the energy consumption in compression and liquefaction.

Figure 11 shows the environmental impacts on global warming, human health damage and ecosystem damage per transport option. This shows less variability between the different transport options. Similar to the TEA results, the major contributor is the energy consumption in compression and liquefaction.

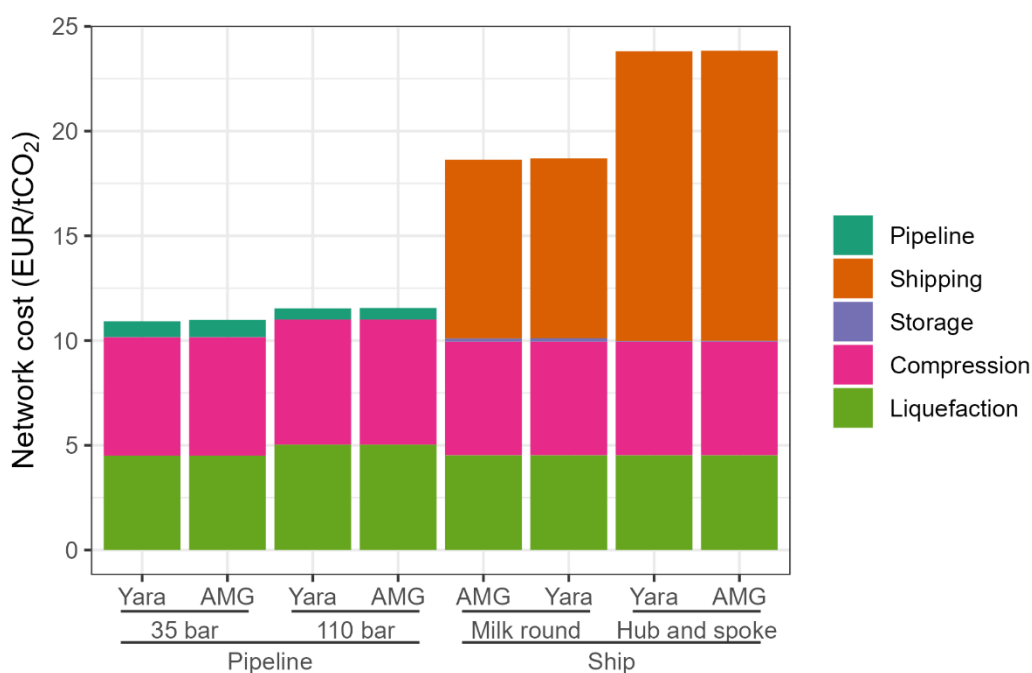


Figure 10: Network costs for eight transport options within the North Sea Port cluster per ton of CO₂ transported.

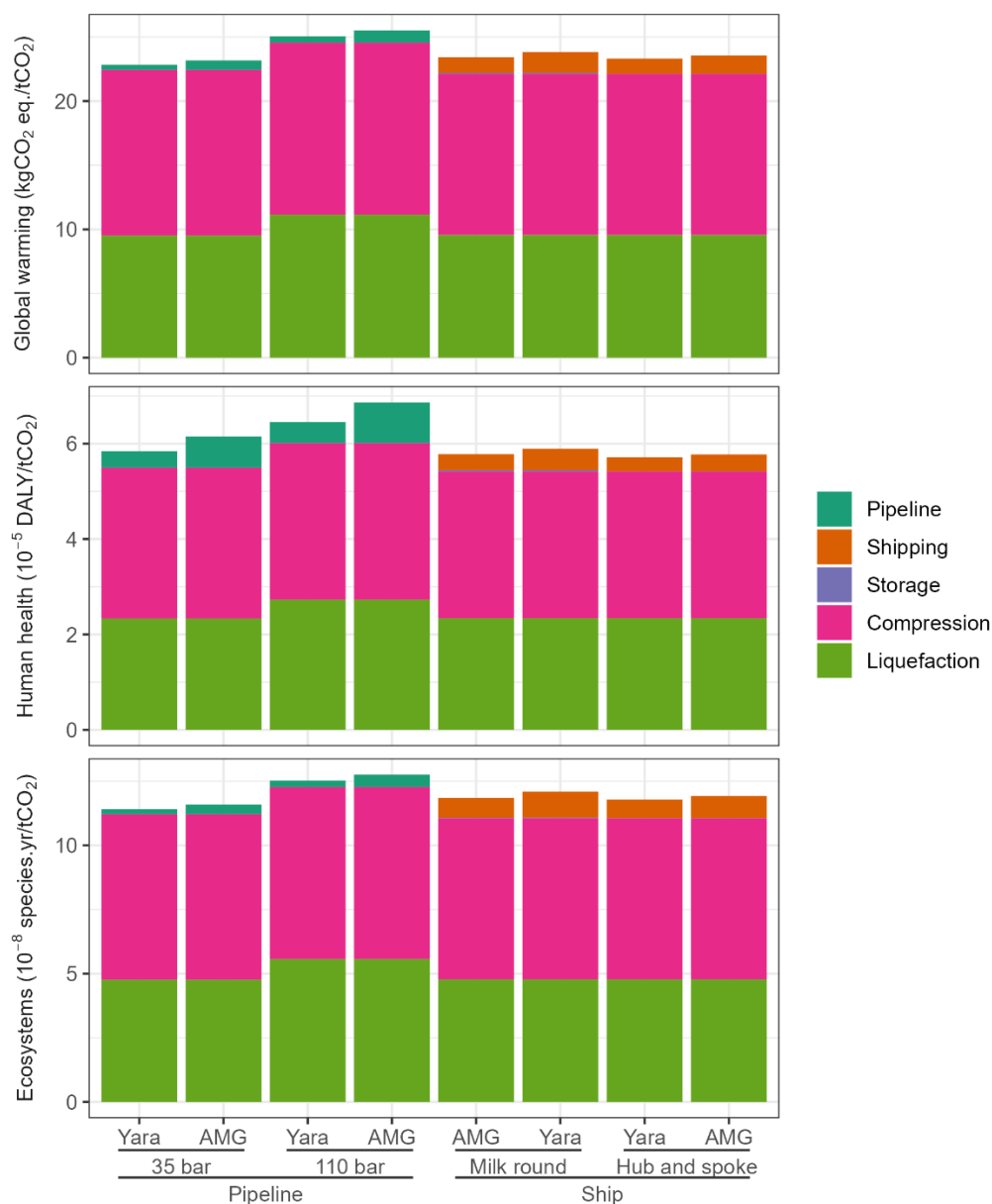


Figure 11: Network environmental impacts for eight transport options within the North Sea Port cluster per ton of CO₂ transported.

In figure 12, the Pareto fronts with the transport cases are displayed and can be seen that the most optimal solutions are the low-pressure pipeline with Yara as offtake point (case 1) and the shipping hub and spoke case with offtake from Yara (case 5). Case 1 results in increase impacts of 2% for human health damage compared to case 5. However, case 5 results in higher

network costs and hence, case 1 is favored. In reality, practical issues, like additional criteria or constraints of the infrastructure system, could arise when employing this optimal transportation modes and hence considering a range of optimal and sub-optimal solutions can aid to secure application of the transport infrastructure (tier 2 to 3).

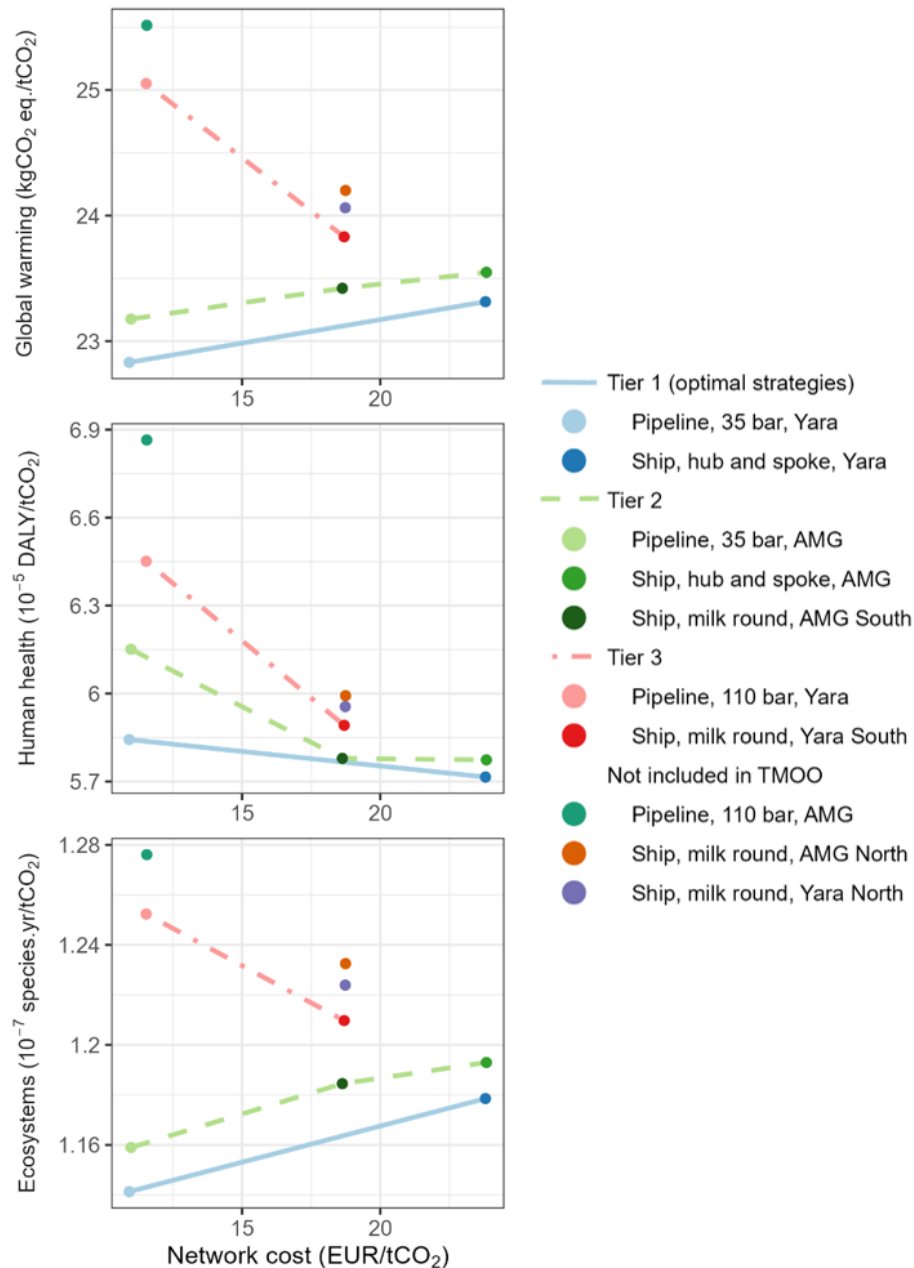


Figure 12: Tiered Pareto fronts as a result of the multi-objective optimization between environmental impacts and network costs.

Barge transportation has the benefit of more rapid implementation compared to pipeline transport. A scenario was investigated where the pipeline construction is delayed and hence CO₂ in the North Sea Port cluster is still being emitted. This delay results in increased CAPEX costs, considering the ETS price that must be paid by the cluster, and increased direct emissions of CO₂ in the environmental impacts (Figure 13). In this scenario where pipeline construction keeps being delayed, the tipping point for financial costs where shipping becomes less costly than pipeline transport was found to be between 1.5 and 2 years of delay. This indicates that shipping is the preferred option till the pipeline infrastructure is available.

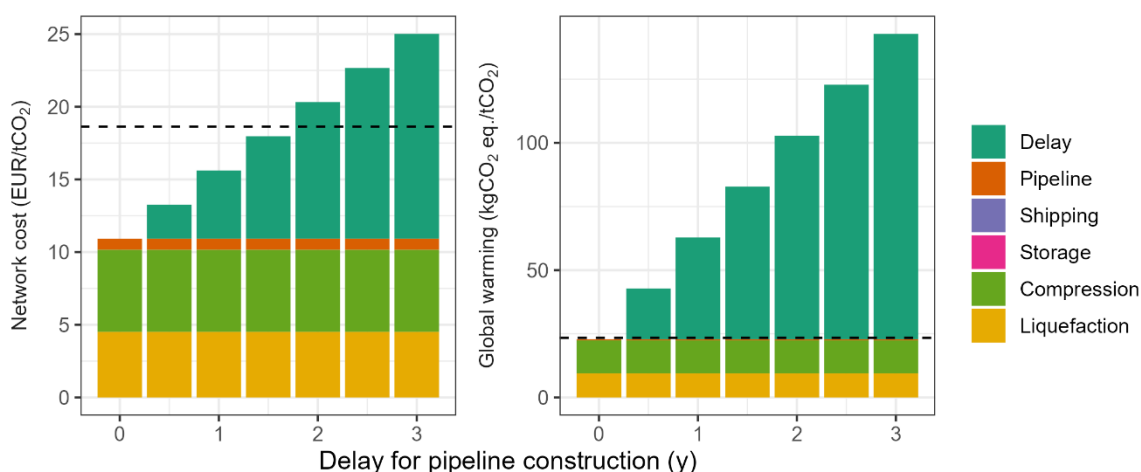


Figure 13: Network costs and global warming impact per ton of CO₂ transported (functional unit) as a function of delay in time for case 1. The dashed line shows the results for case 10 (milk round shipping with offtake at AMG).

As electricity consumption is the biggest contributor to the environmental impact, a scenario was developed considering a greener future electricity mix for 2030. This results in an average decrease of 80% for global warming, 69% for human health damage and 70% for ecosystem damage for all cases. The outcome of the total optimization is not affected, as the cases showed similar energy consumptions.

8. Conclusions

This report summarises the results of environmental impact assessment of the deployment of CCS solutions including CASOH and DISPLACE CO₂ capture technologies and CO₂ transport solutions at industrial scale and in industrial clusters.

The prospective environmental impacts of CASOH and DISPLACE were evaluated on industrial scale. The endpoint analysis showed environmental benefits for all investigated scenarios for CASOH and DISPLACE on damage to human health and ecosystems. The analysis showed that the optimal environmental performance for CASOH was to combust the produced hydrogen nitrogen stream for internal use for heat and electricity. By doing so, natural gas-based heat and grid electricity production is avoided. For the avoided heat and heat needed to replace BFG usage, natural gas-based heat is assumed. Towards 2055, this might also change to heat pumps, resulting in lower (avoided) impacts of these processes. Towards 2055, the grid mix constitutes of more renewables, lowering its carbon footprint. The benefit of avoided usage of grid electricity in this scenario decreases and hence by 2055 using hydrogen and nitrogen stream for solely heat and getting electricity from the grid is the best environmental scenario. DISPLACE also showed climate benefits and showed the largest decarbonisation potential for flue gas from reheat oven and flue gas from hot stoves. The environmental hotspots for CASOH include (a) the replacement of BFG by natural gas-based heat and (b) the emissions related to the combustion of the hydrogen stream. For DISPLACE the environmental hotspots are the electricity and heat use.

The TMOO was developed to evaluate a hierarchy of transportation options within the NSP and showed that pipeline transport at 35 bar results in the most optimal strategy with the lowest costs and carbon footprint. A scenario analysis with a low-carbon electricity mix showed a decrease in carbon footprint of 80% on average between the different strategies. Lastly, it was found that in case of a delay in pipeline construction, barge deployment is favoured if the delay is longer than two years. This holds till pipeline infrastructure is available and thus highlights the urgency for the quick implementation and integration of transportation infrastructures.

Integrating the North Sea Port cluster with CASOH and DISPLACE as carbon capture technologies and integrating CO₂ transport with pipelines is found to be environmentally beneficial.

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Appendix A

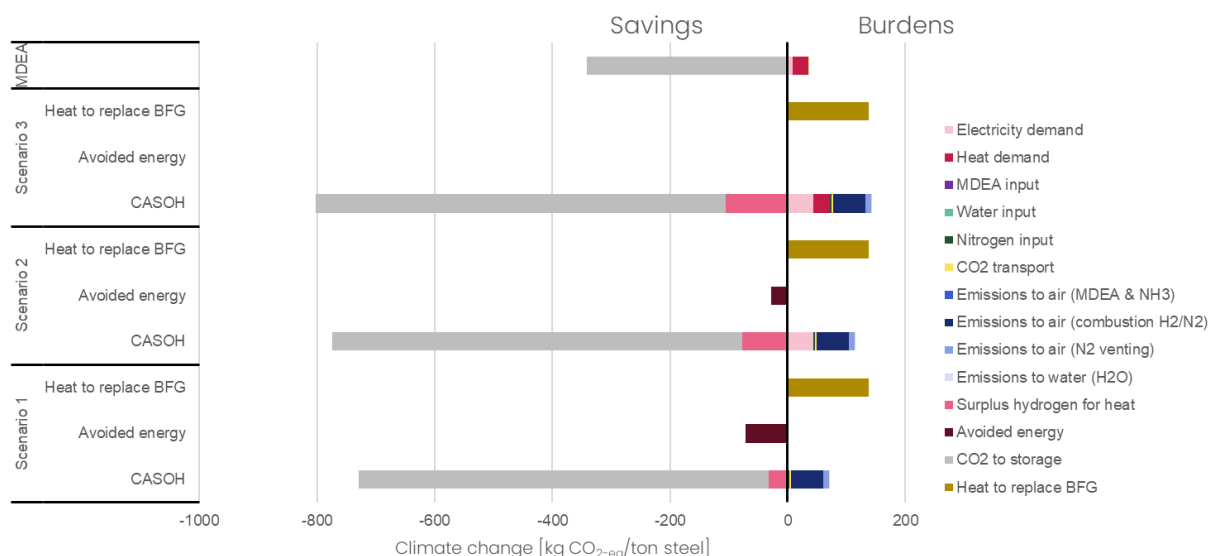


Figure A1: Prospective life cycle assessment results for climate change for CASOH for three scenarios and a global temperature increase of 2 °C by 2100. These results are shown for year 2030.

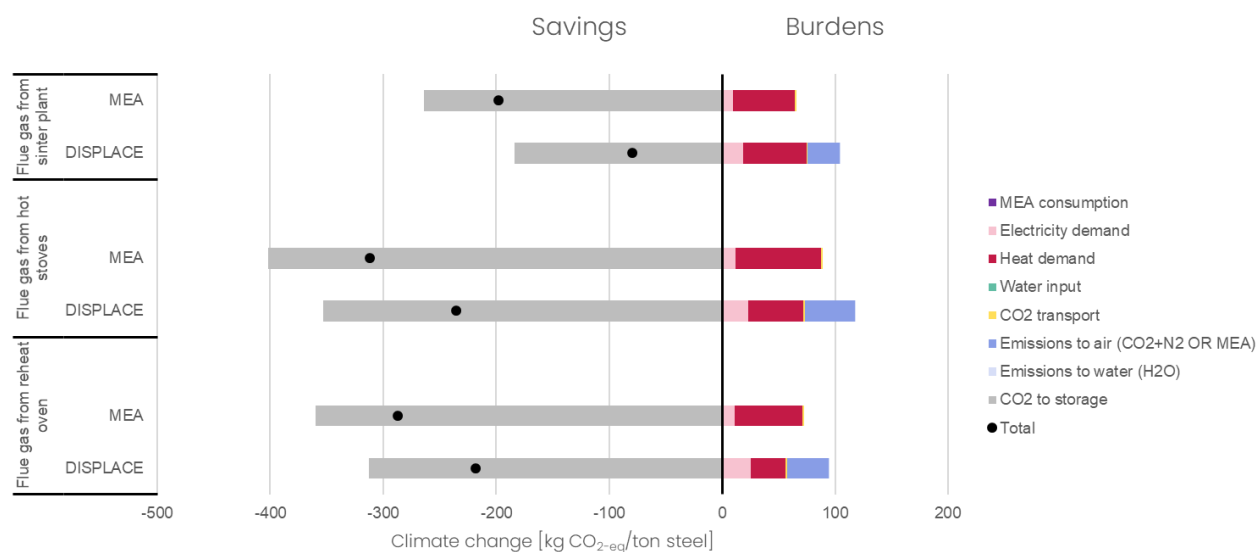


Figure A2: Prospective life cycle assessment results for climate change for DISPLACE for three scenarios and a global temperature increase of 2 °C by 2100. These results are shown for year 2030.

Appendix B



Figure B1: Contribution analysis of midpoints to endpoints for CASOH under three scenarios (see 6.1.2).

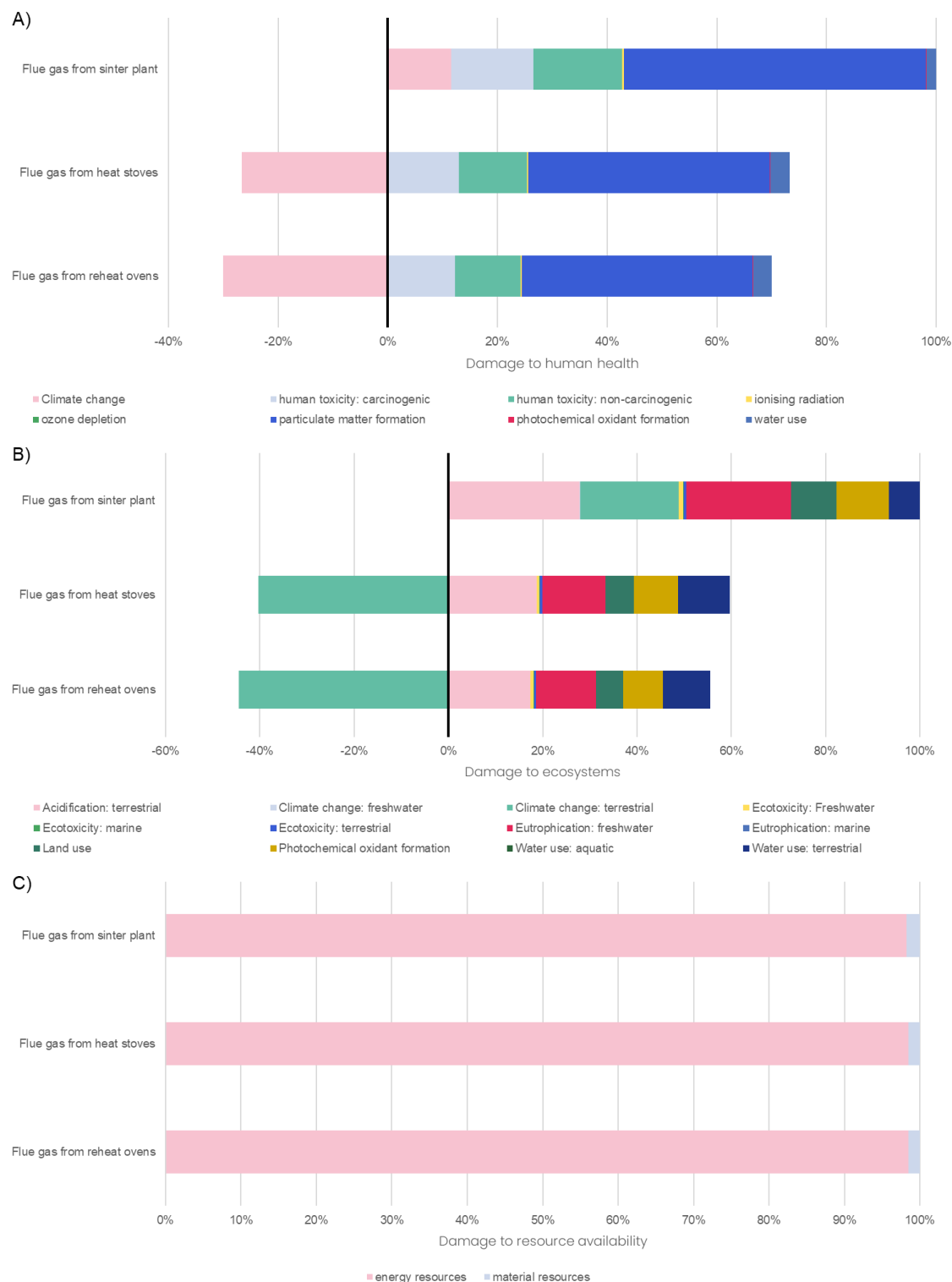


Figure B2: Contribution analysis of midpoints to endpoints for DISPLACE under three scenarios (see 6.1.2).

Appendix C

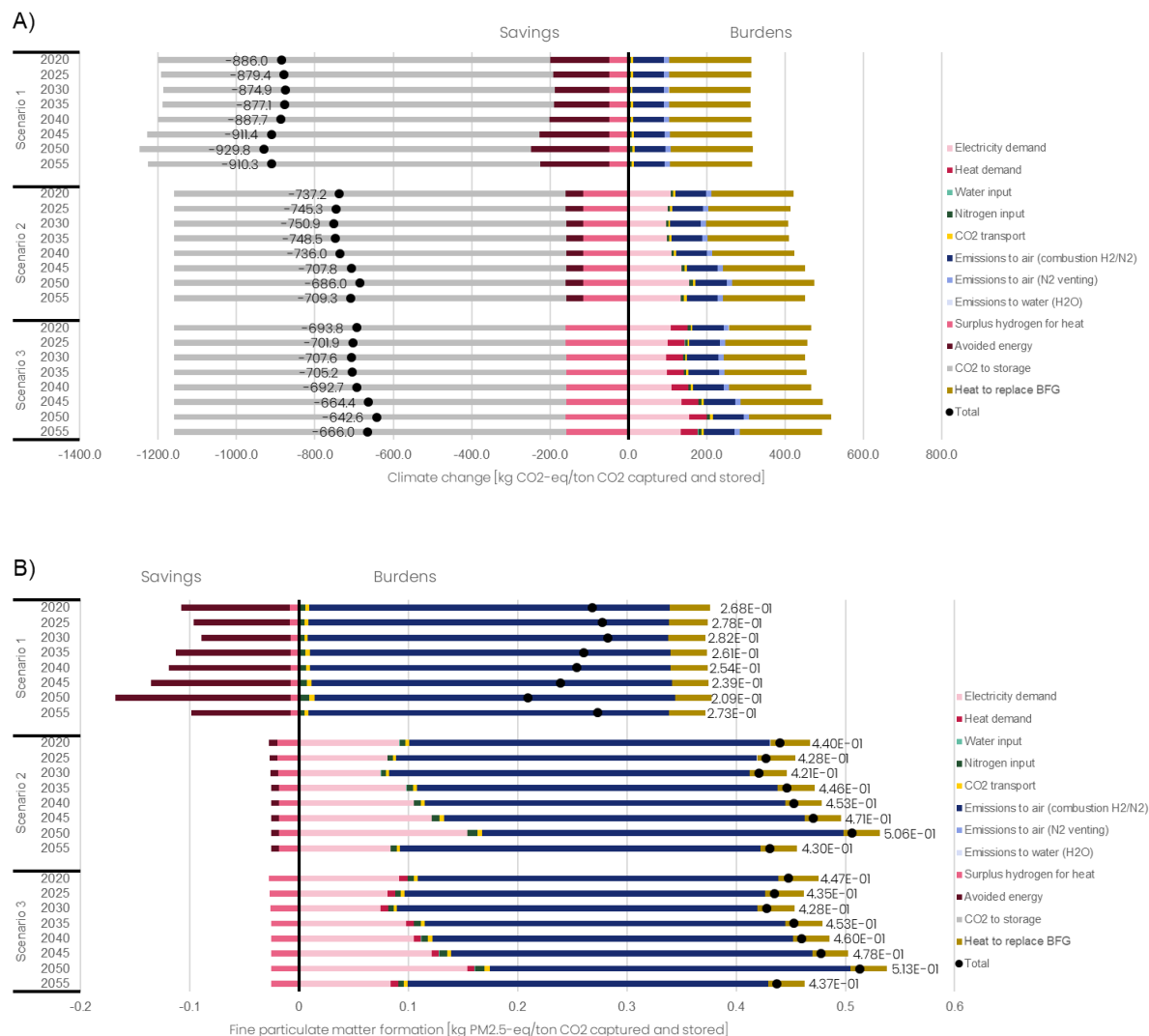
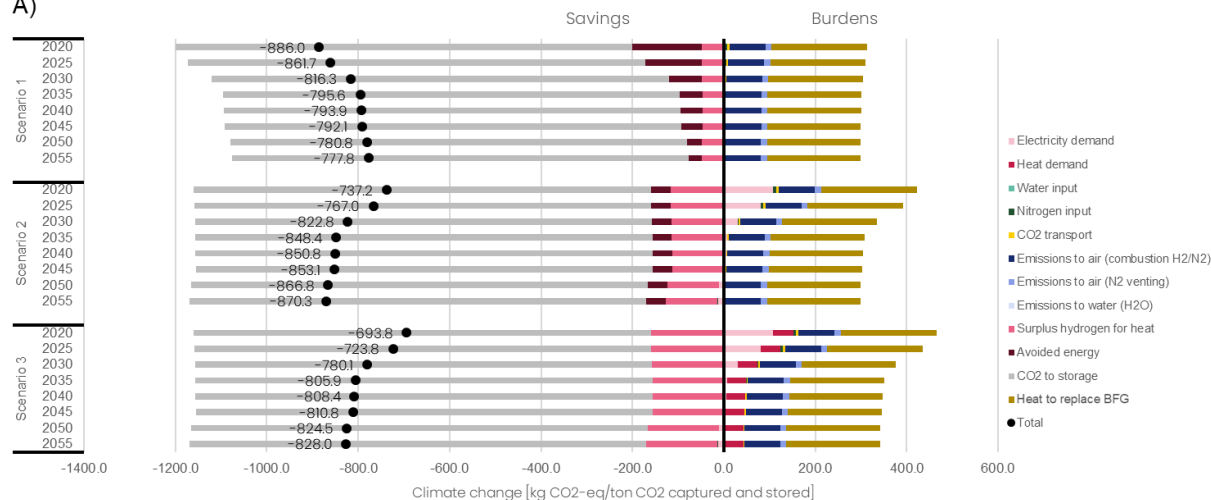


Figure C1: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for CASOH for three scenarios and a global temperature increase of 3–4 °C by 2100.

A)



B)

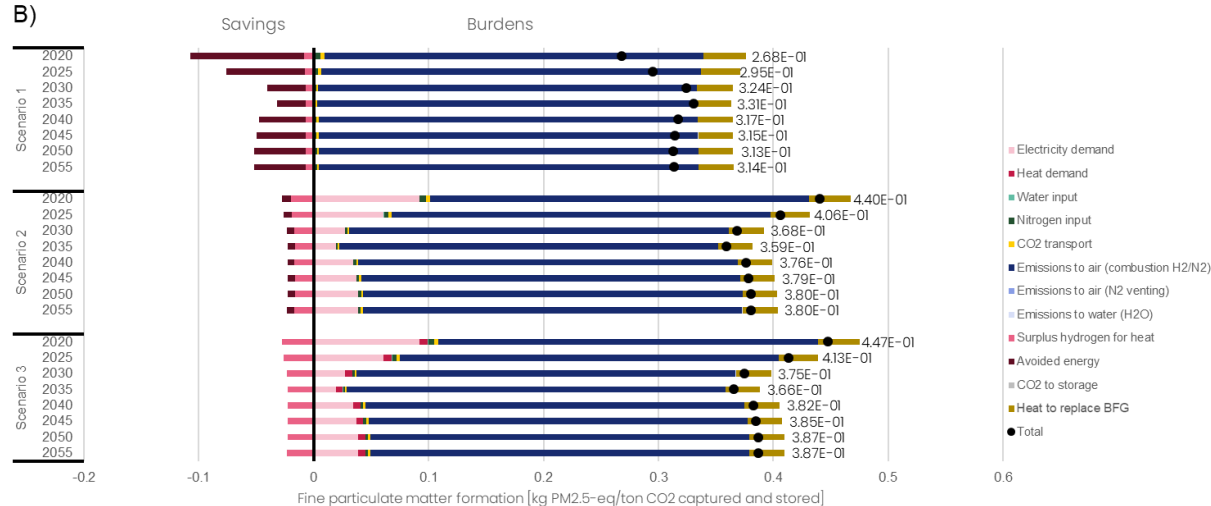


Figure C2: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for CASOH for three scenarios and a global temperature increase of 1.5 °C by 2100.

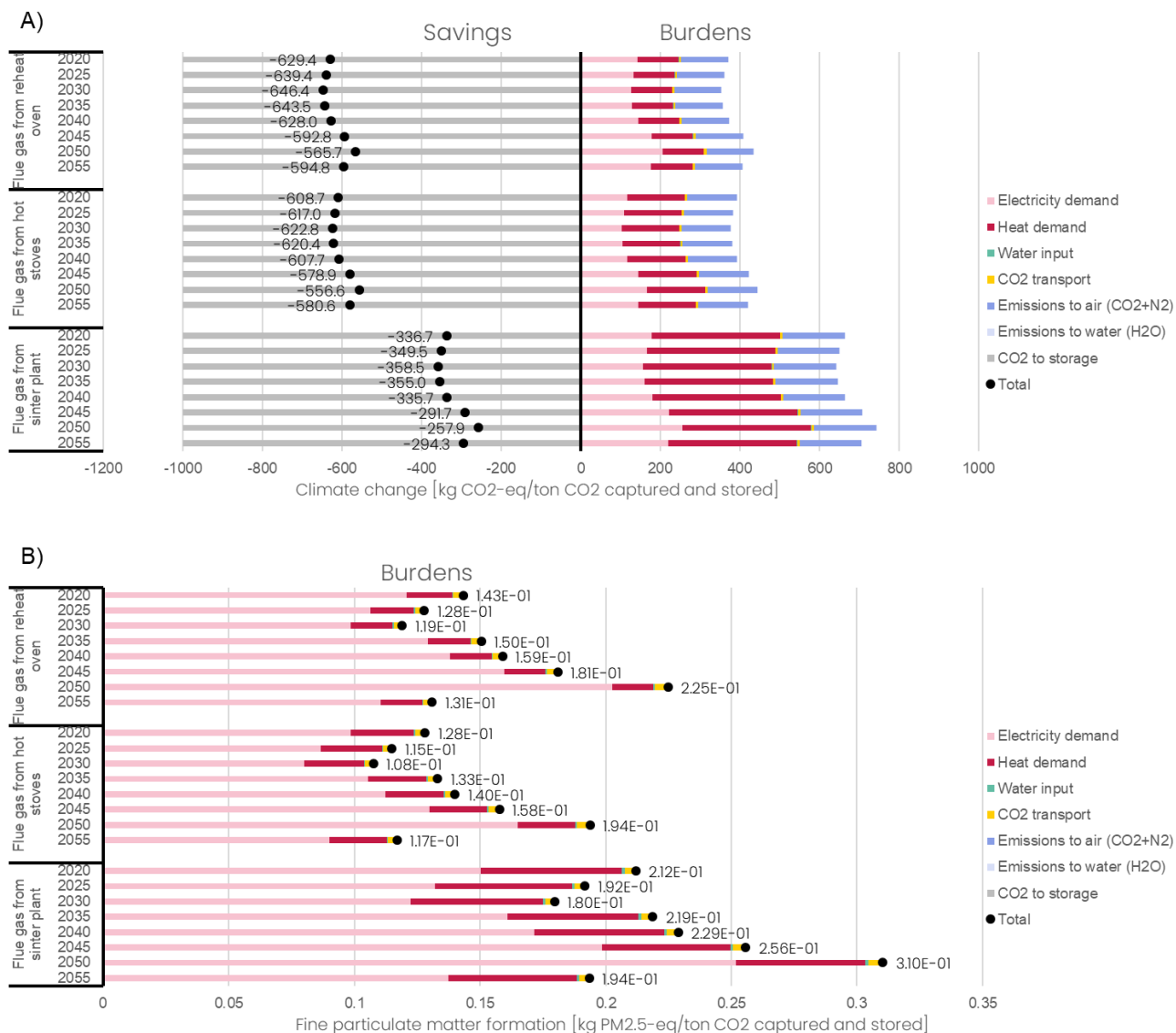


Figure C3: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for DISPLACE for three scenarios and a global temperature increase of 3–4 °C by 2100.

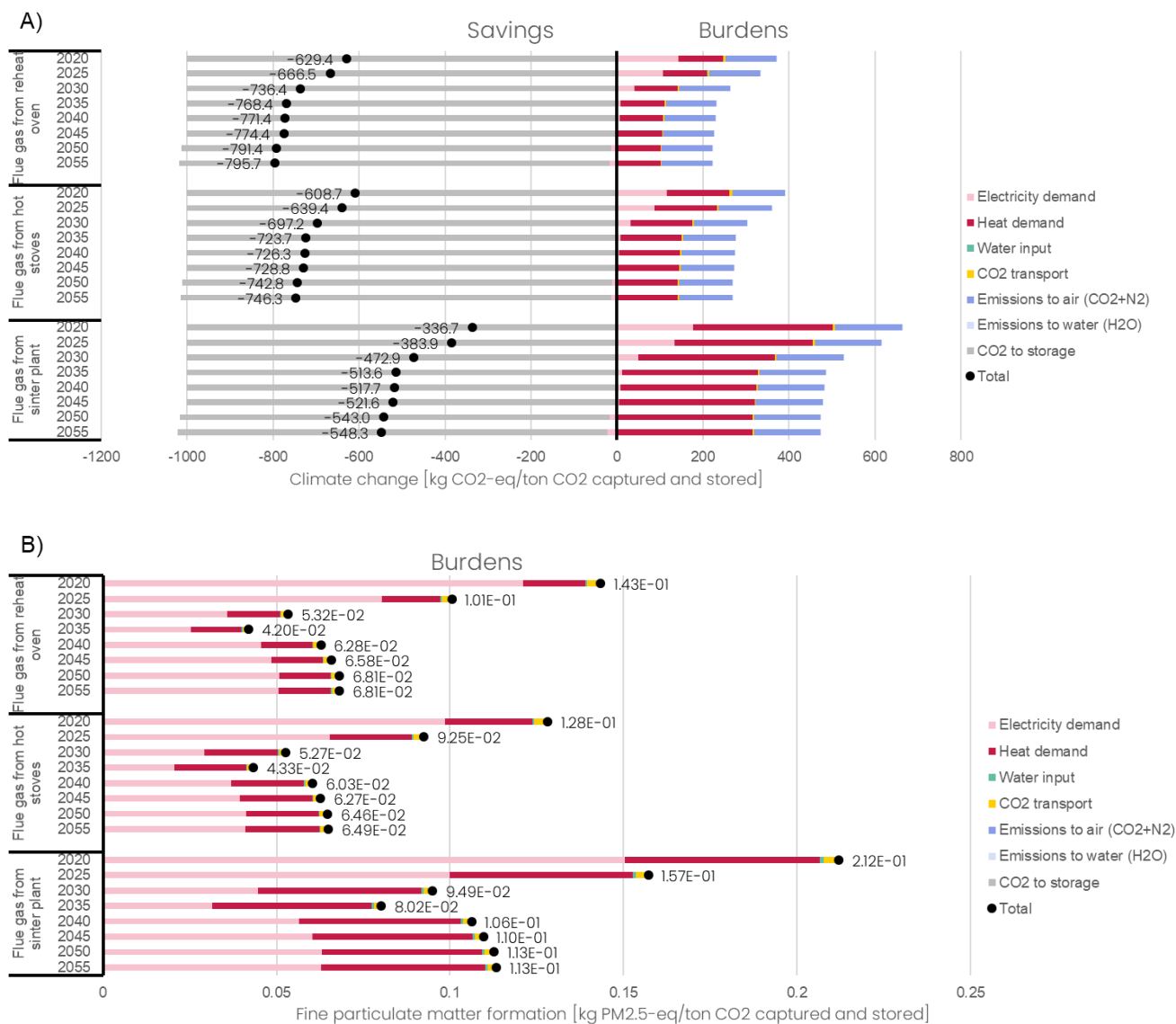


Figure C4: Prospective life cycle assessment results on climate change (A) and fine particulate matter formation (B) for DISPLACE for three scenarios and a global temperature increase of 1.5 °C by 2100.