European
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AIDRES project

"Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes"

Final Report (D3.1-A)

Assessment and geo-mapping of renewable energy demand for technological paths towards carbon neutrality of EU energy-intensive industries

Methodology and results in support to the EU industrial plants database

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September 2023

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Prepared for the European Commission, DG ENER, funded by the European Parliament
under service contract N° ENER/2020/OP/0011/C2/SER/2019-569/SI2.840687

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate B — Just transition, consumers, energy efficiency & innovation
Unit B.5 — Innovation, research, digitalisation, competitiveness

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First edition: September 2023

LEGAL NOTICE

PDF ISBN 978-92-68-07186-1 doi:10.2833/696697 MJ-04-23-816-EN-N

Luxembourg: Publications Office of the European Union, 2023

AIDRES

“Advancing industrial decarbonization by assessing the future use of renewable energies in industrial processes”

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Contents

Table of Abbreviations

AEL	Hydrogen from alkaline electrolyser
AFM	Alternative fuel mixture
AIDRES	Advancing Industrial Decarbonization by assessing the future use of Renewable EnergieS in industrial processes
BF	Blast furnace
BM	Biomass
(BM)MeOH	Methanol synthesis - biomass gasification
(BM+H2)	Hydrogen injection instead of water gas shift (WGS) reaction for biomass gasification
BMC	Bare module Cost Factor
BMW	Biomass Waste
BOF	Basic oxygen furnace
CaL	Calcium looping carbon capture
CAPEX	Capital cost
CC	Carbon capture (Mono-ethanolamine)
CCS	Carbon Capture, (Transport) and Storage
CEM1	Portland cement I - clinker-to-cement ratio of 95%
CEM2	Portland cement II - clinker-to-cement ratio of 70%
CEPCI	Chemical Engineering Plant Cost Index
Coal	Coal
COEL	Co-electrolysis process for syngas production
(COEL)MeOH	Methanol synthesis using co-electrolysis
DEA	Diethanolamine carbon capture (ammonia production process)
DME	Dimethyl ether production
DRI	Direct Reduced Iron electric arc furnace
EAF	Electric Arc Furnace
EL	Electrical furnace
EU-mix	AIDRES mix of production routes
FF55	Fit for 55
FT	Fischer-Tropsch process
H2	Hydrogen production
HNO3	Nitric acid production
LC3	Limestone Calcined Clay product - clinker-to-cement ratio of 50%

LN	Naphtha cracking
(LN+EL)	Naphtha electrical cracking
MEA	Mono-ethanolamine carbon capture
MEOH	Methanol production
MOE	Molten oxide electrolyser
MVR	Mechanical vapor recompression
NG	Natural gas
NG+H2	Natural gas and hydrogen
NH3	Ammonia production
O	Olefins production
OPEX	Operation cost
Oxy	Oxy-combustion
PE	Polyethylene production
PEA	Poly-ethyl-acetate production
REF	Conventional crude oil refining
Scraps EAF	EAF Scraps handling (recycling/secondary route)
TGRBF	Top gas recycling blast furnace
TOTEX	Total cost
TRL	Technology readiness level
Urea	Urea production
WBM	Waste biomass
WPI	Waste Plastic Injection (WPI) Blast Furnace

ABSTRACT

The objective of the AIDRES database is to support the EU-27's long-term goal of achieving a fully integrated industrial strategy. It serves as a valuable resource for the European Commission and industries, offering insights into the effectiveness, efficiency, and cost of potential innovation pathways to achieve carbon neutrality in key sectors such as steel, chemical, cement, glass, fertiliser, and refinery by 2050. The database considers the geographical distribution of annual production for these sectors at the EU-NUTS3 regional level.

To assess and evaluate production routes, the database utilises process integration techniques to generate reference and future optimal production pathways. This approach provides a quantitative, technical, and multi-criteria estimation of energy demand in Europe's major industrial sectors. The focus of decarbonization efforts includes the substitution of less energy-intensive products, electrification of production processes, adoption of oxy-combustion, carbon capture and storage, utilisation of alternative fuels, and biomass.

The database compiles a comprehensive set of information on a per-ton-of-product basis, including energy demand, direct emissions, captured CO_2 quantities, and associated investment and operational costs. Scenarios for reference year 2018 and projections for 2030 and 2050, encompassing energy prices, indirect upstream emissions, CO_2 allowances, and production shifts, are considered to anticipate operational expenditures and total emissions.

Furthermore, the per-ton database is scaled up NUTS3 level based on regional production capacities. This scaling enables the application of the database at EU level for analysing the current state and future evolution of selected heavy industrial sectors. An analysis, based on a specific AIDRES EU mix route use case, indicates a substantial reduction in direct CO_2 emissions by 2050, ranging from 85-96% compared to the average emissions from 2015-2019, meeting the EU Fit for 55 MIX scenario CO_2 emission reduction targets

The AIDRES database and visualisation is supported by the Energy and Industry Geography Lab (EIGL) of the Joint Research Centre (JRC) of the European Commission:
Visualisation: https://energy-industry-geolab.jrc.ec.europa.eu/
Database: https://data.jrc.ec.europa.eu/dataset/14914982-70a9-4d1d-a2fc-cdee4a1d833d

A simplified version of the database in EXCEL format can be found here:
The database “Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes” (AIDRES) (europa.eu)

EXECUTIVE SUMMARY

The IPCC Special Report on 1.5℃ presents compelling evidence in support of the goal to limit global warming to below 2℃, with efforts to achieve a limit of 1.5℃ as outlined in the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC). The report **emphasises the critical importance of attaining global CO_2 emissions neutrality by 2050**, which is a key objective of the Paris Agreement. This objective forms the core of the European Union's (EU) long-term strategy for climate neutrality, which proposes various pathways to facilitate the necessary economic and societal transformations for achieving carbon neutrality within the EU by 2050. The strategy places particular emphasis on the transition to a resource-efficient and circular economy as a prerequisite for achieving this goal. Consequently, the European Green Deal aims to transform the EU into a modern, resource-efficient, and competitive economy, decoupling economic growth from resource consumption and ultimately achieving net-zero emissions of greenhouse gases (GHG) by 2050. To this end, the European Commission has introduced the 'Fit-for-55' package, comprising a series of directives and measures aimed at achieving at least a 55% reduction in GHG emissions compared to 1990 levels. Thus, setting the continent on a trajectory towards reaching the net-zero 2050 objective. Furthermore, the ongoing war in Ukraine has heightened the determination of the European Commission to expedite the phase-out of and reduce dependency on Russian fossil fuels, particularly oil and gas.

In tackling this challenge and seizing the opportunity it presents, the industry has a pivotal role to play. All sectors within industrial value chains, including energy-intensive industries, must actively reduce their carbon footprints and accelerate the transition by offering affordable, clean technological solutions and developing new business models. EU scenarios indicate that energy efficiency measures, as well as direct and indirect electrification, facilitated by the production of zero-carbon energy carriers and production feedstock (such as renewable hydrogen, synthetic fuels, and biomass), alongside carbon capture and use/storage in energy-intensive industries and other sectors, will be vital in achieving carbon neutrality. By implementing energy-saving measures, emissions reductions of 90-95% by 2050 can be achieved. In this way fostering a resource-efficient circular economy, including industrial symbiosis potentials.

The primary objectives of the AIDRES project revolve around analysing and understanding the effectiveness, efficiency, and cost of various innovative pathways towards achieving carbon neutrality in the *steel, chemical, cement, glass, fertiliser, and refinery* sectors across the EU 27 by 2030 and 2050. This comprehensive analysis encompasses the energy requirements of these industrial sectors, their CO_2 emissions, expenses, geographical distribution, and potential synergies with other sectors. **The outcomes of this study are collected in a geographical database. The AIDRES database serves as input for data visualisation by the Energy and Industry Geography Lab (EIGL) of the Joint Research Centre (JRC) and is made available for download and use by the general public, at this link:**
Database: https://data.jrc.ec.europa.eu/dataset/14914982-70a9-4d1d-a2fc-cdee4a1d833d.
Visualisation: https://energy-industry-geolab.jrc.ec.europa.eu/
A simplified version of the database in EXCEL format can be found here:
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This study aims to provide fundamental data to develop a clearer understanding of potential decarbonisation pathways for industries within their respective sites or industrial clusters in the European Union. It primarily focuses on analysing decarbonisation options such as process integration, heat electrification, process electrification, hydrogen production and utilisation, carbon capture and utilisation (CCU), biomass utilisation, carbon capture and storage (CCS), among others. These options are categorised and modelled with OSMOSE[1], using the latest technical and economic parameters specific to each sector and location, forming the foundation of the AIDRES database.

In industrial decarbonisation studies, data collection poses a challenge, especially as energy-related data often involve commercially sensitive information. To address this**, the AIDRES project has collaborated with private industries and sector federations,** using various approaches to extract the required level of detail while ensuring compliance with confidentiality requirements. **The strategy of representing the six industries has been based on the EU Horizon 2020 EPOS project[2], known as "blueprinting", to construct industrially representative process models for their main product outputs, called current and future production routes.** These industrial blueprints facilitate information sharing and communication between different parties, enabling the dissemination of data and knowledge without compromising sensitive information. The blueprints contain detailed information on heat, material, and electricity flows necessary for process operation, tailored to the specific needs of the project. The resulting energy and feedstock consumption, capital cost, fixed operational costs and direct CO_2 emissions at the plant are expressed per ton of product.

In addition, eight scenarios have been added post-hoc to the database for each production route. These scenarios include different values for operational costs of electricity, hydrogen, natural gas, and CO_2 emissions (ETS). Moreover, different levels of electricity and hydrogen CO_2 emission intensities for 2030 and 2050 are explored. These variable parameters can be altered by an end-user without compromising the integrity of the model results.

Furthermore, the study examines and analyses the correlation between additional demand in these industrial sectors and future renewable energy locations within the EU. This mapping is based on geographical information systems (GIS) and relies on the current industrial sites of the respective sectors across the EU. Production information per industrial site is derived from public sources. The mapping is carried out at the plant level and then upscaled to NUTS3 granularity. Consequently, a comprehensive mapping of all relevant industrial plants within the six considered industrial sectors has been conducted.

Finally, the current and future individual production routes obtained from the industrial blueprinting activities are applied to the NUTS3 aggregated production, based on the collected supporting parameters. The results are made available in a technology-rich, spatially explicit database, as well as in various reports and spreadsheets.

In addition to the single production routes, the database also contains a specific use case. To demonstrate a potential low CO_2 emission approach for the six industries and products across the EU, **two synthetic production routes have been devised: AIDRES EU mixes**

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[1] OSMOSE is a tool for the design and analysis of integrated energy systems developed by IPESE/EPFL.

[2] EPOS project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 679386.

2030 and 2050. These routes encompass a combination of individual production routes and are designed for comparison and comprehension on an EU scale. The concept of these AIDRES EU mix routes is introduced to address the uncertainty surrounding which production route will be adopted in the future for each industrial site on NUTS3. **The selection of production routes for 2030 and 2050 takes into consideration the EU Fit-for-55 MIX reference scenario and roadmaps provided by industrial sector associations**, if available, or those proposed by the AIDRES team, which are then reviewed and approved by the sector associations. It should be noted that the AIDRES EU mix route does not aim to predict the future of each production site, as it is unlikely that multiple future low-carbon production technologies would be installed at the same site. **End-users of the AIDRES database have the freedom to construct their specific scenarios at NUTS2 or NUTS3, country, or EU level by selecting individual production routes for each product and sector or by developing a custom mix production route**.

The exercise reveals the significant changes that the six industries must undergo in terms of energy and feedstock demand to achieve the CO_2 emission reduction targets by 2030 and 2050. The AIDRES EU Mix use case demonstrates a reduction in energy and feedstock input across various sectors, particularly in the refinery sector, which experiences a notable decrease in production output by 2050, primarily due to the electrification of transportation. The steel sector also witnesses a decrease in energy and feedstock demand. In some other sectors, there may be a slight increase or no change. However, the most interesting aspect is the transition from fossil-based energy sources to low-carbon alternatives. Electricity demand sees a significant rise across all six industries by 2050. Biomass and green hydrogen can effectively replace a substantial portion of the feedstock currently used in the refinery and chemical industries. Green hydrogen also plays a vital role in decarbonising the steel and fertiliser sectors. In sectors like cement, the utilisation of alternative fuels and biomass waste is crucial to reduce CO_2 emissions from combustion, while process emissions can only be mitigated through carbon capture. The same applies to the glass sector. It is not surprising that the use of fossil fuels is diminishing; however, there are specific scenarios where these fuels can still be utilised, always in combination with carbon capture and utilisation or storage techniques.

The AIDRES project provides a unique database by mapping the current, 2030 and 2050 energy requirements of **steel, chemical, cement, glass, fertiliser, and refinery** sectors, their CO_2 emissions, expenses, and this for a plethora of individual production routes. The AIDRES database serves as publicly available toolbox for energy system modellers, policy makes, students or anyone who is interested in industrial decarbonisation, to develop scenarios and pathways which can contribute to the common EU net-zero emission vision.

"The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the Commission. The Commission does not guarantee the accuracy of the data included in this study. Neither the Commission nor any person acting on the Commission's behalf may be held responsible for the use which may be made of the information contained therein."

RÉSUMÉ

Le rapport spécial du GIEC sur un réchauffement global de 1.5℃ présente des preuves irréfutables sur l'objectif de limiter le réchauffement climatique à moins de 2℃ avec des efforts à déployer pour atteindre une limite de 1.5℃, tel que formulé dans l'Accord de Paris sous l'hospice de la Convention-cadre des Nations unies sur les changements climatiques (UNFCCC). Le rapport souligne l'importance cruciale d'atteindre la neutralité des émissions mondiales de CO_2 d'ici 2050, qui est un objectif clé de l'Accord de Paris. Cet objectif est au cœur de la stratégie à long terme de l'Union européenne (UE) pour la neutralité climatique, qui propose différentes voies pour faciliter les transformations économiques et sociétales nécessaires pour atteindre la neutralité carbone au sein de l'UE d'ici 2050. La stratégie met, comme condition préalable, particulièrement l'accent sur la transition vers une économie circulaire et une utilisation efficace des ressources. Le pacte vert européen vise en conséquence à transformer l'UE en une économie moderne, rationnelle dans l'utilisation des ressources et compétitive, en dissociant la croissance économique de la consommation des ressources et en parvenant à des émissions nettes de gaz à effet de serre (GES) nulles d'ici à 2050. À cette fin, la Commission européenne a introduit le paquet "Fit-for-55", qui comprend une série de directives et de mesures visant à réduire d'au moins 55 % les émissions de gaz à effet de serre par rapport aux niveaux de 1990. Le continent est ainsi placé sur une trajectoire qui lui permettra d'atteindre l'objectif de zéro émission nette en 2050. En outre, la guerre en cours en Ukraine a renforcé la détermination de la Commission européenne à accélérer l'élimination progressive des combustibles fossiles russes, en particulier le pétrole et le gaz, et à réduire la dépendance à l'égard de ces derniers.

Pour relever ce défi et saisir l'opportunité qu'il représente, l'industrie a un rôle central à jouer. Tous les secteurs des chaînes de valeur industrielles, y compris les industries à forte intensité énergétique, doivent réduire activement leur empreinte carbone et accélérer la transition en proposant des solutions technologiques propres à un coût abordable et en développant de nouveaux modèles d'affaires. Les scénarios de l'UE indiquent que les mesures d'efficacité énergétique, l'électrification directe et indirecte, facilitée par l'utilisation de vecteurs énergétiques et de matières premières décarbonés (tels que l'hydrogène renouvelable, les carburants synthétiques et la biomasse), ainsi que la capture et l'utilisation/le stockage du carbone pour les industries à forte intensité énergétique et d'autres secteurs, seront essentiels pour parvenir à la neutralité carbone. En mettant en œuvre des mesures d'économie d'énergie, il est possible de réduire les émissions de 90 à 95 % d'ici à 2050. De cette manière, il est possible de favoriser une économie circulaire qui utilise les ressources de façon efficace et exploite les potentiels de symbiose industrielle.

Les principaux objectifs du projet AIDRES consistent à analyser et à comprendre l'efficacité, l'efficience et le coût de différentes voies innovantes pour atteindre la neutralité carbone dans les secteurs productifs de **l'acier, de la chimie, du ciment, du verre, des engrais et des raffineries** dans l'UE 27 d'ici 2030 et 2050. Cette analyse complète englobe les besoins énergétiques de ces secteurs industriels, leurs émissions de CO_2, leurs dépenses, leur répartition géographique et les synergies potentielles avec d'autres secteurs**. Les résultats de cette étude sont rassemblés dans une base de données géographique. La base de données AIDRES sert de base à la visualisation des données par le Energy and Industry Geography Lab (EIGL) du Centre Commun de Recherche (CCR) et peut être téléchargée et utilisée par le grand public, via le lien suivant :**
Base de données : https://data.jrc.ec.europa.eu/dataset/14914982-70a9-4d1d-a2fc-cdee4a1d833d
Visualisation: https://energy-industry-geolab.jrc.ec.europa.eu/
Une version simplifiée de la base de données en format EXCEL est accesible ici:

The database “Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes” (AIDRES) (europa.eu)

Cette étude vise à fournir des données fondamentales permettant de mieux comprendre les voies de décarbonisation potentielles pour les industries au sein de leurs sites ou clusters industriels respectifs dans l'Union européenne. Elle se concentre principalement sur l'analyse des options de décarbonisation telles que l'intégration des processus, l'électrification de la chaleur, l'électrification des processus, la production et l'utilisation de l'hydrogène, la capture et l'utilisation du carbone (CCU), l'utilisation de la biomasse, la capture et le stockage du carbone (CCS), parmi d'autres. Ces options sont classées et modélisées avec OSMOSE[3], en utilisant les derniers paramètres techniques et économiques spécifiques à chaque secteur et à chaque lieu, constituant ainsi le fondement de la base de données AIDRES.

Dans les études de décarbonisation industrielle, la collecte de données pose un défi, en particulier parce que les données relatives à l'énergie impliquent souvent des informations commercialement sensibles. Pour y remédier, le projet AIDRES a collaboré avec des industries privées et des fédérations sectorielles, en utilisant diverses approches pour extraire le niveau de détail requis tout en garantissant le respect des exigences de confidentialité. La stratégie de représentation des six industries a été basée sur le projet Horizon 2020 EPOS[4] de l'UE, connu sous le nom de "blueprinting", pour construire des modèles de processus représentatifs de l'industrie pour leurs principaux produits de sortie, appelés itinéraires de production actuels et futurs. Ces "blueprints" industriels facilitent le partage d'informations et la communication entre les différentes parties, permettant la diffusion de données et de connaissances sans compromettre les informations sensibles. Les "blueprints" contiennent des informations détaillées sur les flux de chaleur, de matières et d'électricité nécessaires au fonctionnement du processus, adaptées aux besoins spécifiques du projet. La consommation d'énergie et de matières premières, les coûts d'investissement, les coûts opérationnels fixes et les émissions directes de CO_2 de l'usine sont exprimés par tonne de produit.

En outre, huit scénarios ont été ajoutés a posteriori à la base de données pour chaque filière de production. Ces scénarios comprennent différentes valeurs pour les coûts opérationnels de l'électricité, de l'hydrogène, du gaz naturel et des émissions de CO_2 (ETS). En outre, différents niveaux d'intensité des émissions de CO_2 de l'électricité et de l'hydrogène pour 2030 et 2050 sont explorés. Ces paramètres variables peuvent être modifiés par l'utilisateur final sans compromettre l'intégrité des résultats du modèle.

De plus, l'étude examine et analyse la corrélation entre la demande supplémentaire dans ces secteurs industriels et les futurs sites d'énergie renouvelable au sein de l'UE. Cette cartographie est basée sur des systèmes d'information géographique (SIG) et s'appuie sur les sites industriels actuels des secteurs respectifs dans l'UE. Les informations relatives à la production de chaque site industriel proviennent de sources publiques. La cartographie est réalisée au niveau de l'usine, puis ramenée à la granularité NUTS3. Par conséquent, une cartographie complète de tous les sites industriels pertinents au sein des six secteurs industriels considérés a été réalisée.

Enfin, les filières de production individuelle actuelles et futures obtenues à partir des "blueprints" industriels sont appliqués à la production agrégée au niveau NUTS3, sur la base des paramètres de production collectés. Les résultats sont disponibles dans une base de

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[3] OSMOSE est un outil de dimensionnement de d’analyse des systèmes énergétique intégrés développé par IPESE/EPFL.

[4] Projet EPOS, financé par le programme de recherché et d’innovation Horizon2020 de l’Union Européenne dans le cadre de l’accord de financement No 679386.

données technologiquement et spatialement explicite, ainsi que dans divers rapports et feuilles de calcul.

Outre les filières de production individuelle, la base de données contient également un cas d'étude spécifique. Pour démontrer une approche potentielle à faible émission de CO_2 pour les six industries et produits à travers l'UE, deux itinéraires de production synthétiques ont été conçus: AIDRES EU mixes 2030 et 2050. Ces filières englobent une combinaison de filières de production individuelle et sont conçus pour être comparés et compris à l'échelle de l'UE. Le concept de ces filières AIDRES EU mix est introduit pour répondre à l'incertitude entourant l'itinéraire de production qui sera adopté à l'avenir pour chaque site industriel dans les NUTS3. La sélection des filières de production pour 2030 et 2050 prend en compte le scénario de référence EU Fit-for-55 MIX et les feuilles de route fournies par les associations sectorielles industrielles, si elles sont disponibles, ou celles proposées par l'équipe AIDRES, qui ont ensuite été revues et approuvées par les associations sectorielles. Il convient de noter que la filière du mix européen d'AIDRES ne vise pas à prédire l'avenir de chaque site de production, car il est peu probable que plusieurs technologies de production à faible émission de carbone soient installées sur le même site. Les utilisateurs finaux de la base de données AIDRES ont la liberté d'élaborer leurs propres scénarios au niveau NUTS2 ou NUTS3, du pays ou de l'UE en sélectionnant des filières de production individuelle pour chaque produit et secteur ou en développant un itinéraire de production mixte personnalisé.

L'exercice révèle les changements significatifs que les six industries doivent réaliser en termes de demande d'énergie et de matières premières pour atteindre les objectifs de réduction des émissions de CO_2 d'ici 2030 et 2050. Le cas d'utilisation AIDRES EU Mix montre une réduction de l'apport en énergie et en matières premières dans différents secteurs, en particulier dans le secteur des raffineries, qui connaît une diminution notable de la production d'ici 2050, principalement en raison de l'électrification des transports. Le secteur de l'acier connaît également une baisse de la demande d'énergie et de matières premières. Dans d'autres secteurs, il peut y avoir une légère augmentation ou aucun changement. Toutefois, l'aspect le plus intéressant est la transition des sources d'énergie fossiles vers les sources d'énergie renouvelables. La demande d'électricité augmente considérablement dans les six secteurs d'ici à 2050. La biomasse et l'hydrogène vert peuvent effectivement remplacer une grande partie des matières premières actuellement utilisées dans les raffineries et les industries chimiques. L'hydrogène vert joue également un rôle essentiel dans la décarbonisation des secteurs de l'acier et des engrais. Dans des secteurs comme celui du ciment, l'utilisation de combustibles alternatifs et de déchets de biomasse est essentielle pour réduire les émissions de CO_2 dues à la combustion, tandis que les émissions liées aux procédés ne peuvent être atténuées que par la séquestration du carbone. Il en va de même pour le secteur du verre. Il n'est pas surprenant que l'utilisation des combustibles fossiles diminue; cependant, il existe des scénarios spécifiques dans lesquels ces combustibles peuvent encore être utilisés, toujours en combinaison avec des techniques de capture et d'utilisation ou de stockage du carbone.

Le projet AIDRES fournit une base de données unique en cartographiant les besoins énergétiques actuels, pour 2030 et 2050, des secteurs **de l'acier, de la chimie, du ciment, du verre, des engrais et des raffineries**, leurs émissions de CO_2, leurs dépenses, et ce pour une pléthore de filières de production individuelle. La base de données AIDRES sert de boîte à outils accessible au public pour les modélisateurs de systèmes énergétiques, les décideurs politiques, les étudiants ou toute personne intéressée par la décarbonisation industrielle, afin de développer des scénarios et des voies qui peuvent contribuer à la vision commune d'émissions nettes zéro de l'UE.

1. Brief summary: AIDRES project

In recent years many studies have been published aiming to gain a better understanding of potential pathways towards carbon neutrality of various end-use sectors in general and Energy Intensive Industries in particular. But previous studies have to a large extent focused on carbon-neutrality pathways for individual sectors in isolation, based on generic processes assumptions. At the same time the successful transformation of Energy Intensive Industries will play a pivotal role if the EU Green Deal and Fit for 55 (FF55) strategies will prove successful, from an environmental and economic point of view.

The AIDRES project (Advancing industrial decarbonization by assessing the future use of renewable energies in industrial processes), builds a spatially explicit database covering future demands for renewable energy carriers (electricity, gases, liquid fuels and heat) representing future pathways for 6 energy intensive energy industrial sectors (steel, chemical, cement, glass, fertilisers and refineries) in the European Union. More specifically the AIDRES project aims to:

- Identify the magnitude of renewable energy demand for potential technological innovation paths of energy intensive industries towards carbon neutrality and more circularity, at medium (2030) and long term (2050).
- Compare effectiveness, efficiency and investment needs of technological innovation path options.
- Identify potential symbiosis with other sectors.
- Determine where resulting renewable energy demands will be located within the EU.

Work Package 1 - Systematic and comparative analyses technological innovation paths in energy intensive industrial sectors, and potential symbiosis between industries and other sectors

This WP is designed to develop models for present and future technologies applicable for the selected energy intensive industries steel, chemical, cement, glass, fertilisers and refineries within the European context. The methodology leverages on the existing (EPOS Project[5]) blueprint models for industries and construct high-level models of energy-intensive processes in the identified sectors. As a subsequent step, possibilities of industrial symbiosis between sectors and in geographical regions identified in WP2 will be evaluated. This approach will generate solutions (technological pathways) for transitioning sectors to more sustainable future operation and be documented for the years 2030 and 2050.

Work Package 2 - Mapping EU-industries renewable energy demand focuses on analysing and determining where the future demand for the associated energy inputs is located within the EU. Hence, a mapping of all relevant industrial plants for the considered sectors is carried out and forms the base of this study. Next, supporting industrial parameters will be derived at the level of industrial plants which allow WP1 to calculate energy and feedstock inputs and to identify symbiosis opportunities. The outcome is a geographical database at the level of plant location and aggregated at NUTS3 granularity; it combines information on the type of

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[5] EPOS project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 679386

installations, industrial parameters and current and future energy and material demands, production rates and GHG emissions for the defined model solutions within WP1.

The document describes the methodology used to model and characterize the industrial products in the EU (as part of WP1). Results can be consulted through the Energy and Industry Geography lab on the EU Science Hub, ia the link: https://data.jrc.ec.europa.eu/dataset/14914982-70a9-4d1d-a2fc-cdee4a1d833d

Work Package 3 - System Prefeasibility Analysis Adequacy and barrier screening concentrates on the analysis and determination of key system adequacy indicators for the future European power grid. This is achieved by integrating the AIDRES-generated electricity demand figures with existing scenarios on system development, specifically the EU Reference Scenario 2020 and the Ten-Year Network Development Plan (TYNDP) developed by ENTSO-E and ENTSOG. The projected power system, resulting from this integration, is analysed to gain insights into the expected regional self-sufficiency and the principal power system flows and barriers. This work package also offers guidance for further system assessments, thereby facilitating a comprehensive understanding of the potential challenges and opportunities in the transition towards a carbon-neutral power system in Europe.

AIDRES Project Table of Deliverables

Deliverable /Meeting	Description	Delivery date (month after the signature of the contract)	Output
WORKPACKAGE 1			
D.1.1.1-A	Inception Report, including the methodological concept for the study (draft)	M1 (4 weeks after the signature of the contract, 2 weeks after TC1)	AIDRES_D1.1.1-A_Inception Report_20210208 (DRAFT)
D.1.1.1-B	Inception Report, including comments from the kick off meeting (final)	M2 (8 weeks after the signature of the contract)	AIDRES_D1.1.1-B_Inception Report_Final_20210328
D.1.4.1	One day stakeholders workshop - Six sessions (one per sector analysed), three parallel sessions in the morning and other three in the afternoon.	M8	AIDRES_D1.4.1-A_Workshop documentation results and discussion_20211006 AIDRES_D1.4.1-B_Notes_Discussions with sectors_20210927

D.1.4.2	Draft report reflecting the methodological concept agreed upon with the EC in Task 1.1 and results of Deliverable 1.4.1	M12	AIDRES_D1.4.2-A_Methodology for EU industrial production routes_20230605 (DRAFT) AIDRES_D1.4.2-B_Methodology on Industrial Symbiosis_20230605 (DRAFT) AIDRES_D1.4.2-C Methodology for recycling streams in process industries_20230622 (DRAFT)
D3.1	Final report reflecting the methodological concept agreed upon with the EC in Task 1.1 and results of Deliverable 1.4.1	M13	AIDRES_D3.1-A_Methodology for EU industrial production routes_20230828 AIDRES_D3.1-B_Methodology on Industrial Symbiosis_20230807 AIDRES_D3.1-C Methodology for recycling streams in process industries_20230622
R1	Draft results of tasks 1.2, 1.3 & 1.4 - to be sent to the participants of the stakeholders workshop	M8 (2 weeks before the workshop)	AIDRES_R1_Stakeholder_Workshop_Upfront_Info_20210913
TC1	First telco - two weeks after start of the project	M1 (2 weeks after the signature of the contract)	AIDRES-TC01-Minutes-20201217 v1.0
KO	Kick off meeting	M2 (2 weeks after the submission of D.1.1.1 – A)	AIDRES-KOM-Minutes-2021-01-19 v1.0
WORKPACKAGE 2			
D. 2.1.1	Template of the (geo)database	M2	AIDRES_D2.1.1_GeoDB_Template_v1.0
D. 2.1.2.	Geodatabases with the first version of the quantitative results of the analysis	M8	AIDRES_D2.1.2_GeoDBDummy_Template_v2
D. 3.2	Final geodatabases	M13	AIDRES_D3.2-A_Final GeoDB_20230807 AIDRES_D3.2-B_Methodology used to map the industrial plants in the EU_20230713

			AIDRES_D3.2-C_Methodology used to map the industrial plants in the EU_Technical Description GeoDB_02052023 AIDRES_D3.2-D_AIDRES database in Excel format_20230807
WORKPACKAGE 3			
D3.4	System prefeasibility analysis report	M18	AIDRES_D3.4 and D3.5-System prefeasibility analysis report&guidance for future system assessments_20230622
D3.5	Guidance for future system assessments	M18	AIDRES_D3.4 and D3.5-System prefeasibility analysis report&guidance for future system assessments_20230622
COMMUNICATIONS & DISSEMINATION			
D.3.3	Dissemination of results in EC organised events.	M18 to M24	AIDRES_D3.3-A_Communication and dissemination_20230609 AIDRES_D3.3-B-Presentation, IEA-IETS event, Gothenburg_20230510 AIDRES_D3.3-C-Presentation, SET Plan IWG6, Brussels_20230524 AIDRES_D3.3-D-Presentation, Decarb Connect, Antwerp_20230614
FS	Two (2) to maximum three (3) Information fact sheets with main take aways of the project.	M18 to M24	AIDRES_FS-A_Factsheets_20230807 AIDRES_FS-B_Factsheets_20230807

2. How to read this report

This report aims:

- To provide insights in the used methodology and multi-layered aspect of the AIDRES model and industrial sector emissions reduction targets.
- To provide details on current and future energy and feedstock demand or inputs, for selected energy vectors, direct and selected indirect CO_2 emissions for the six industrial sectors in 2018, 2030 and 2050.
- To project investment and operational costs, related to each production route.

- To show how applying different scenarios for energy carriers, CO_2 emission and CO_2 emission intensities for electricity, natural gas and hydrogen, can determine economically optimal transformation routes.
- To illustrate a use case of the AIDRES database based on a mix of production routes across the EU for each product in the 6 sectors.
- To provide a detailed output of the used production models in the form of tables and figures.

In the Methodology, the different aspects of the AIDRES model framework are presented, including process integration, production route development and the main indicators of product costs and CO_2 emissions. Furth on, a selection of scenarios is included in the model and the concept of AIDRES EU Mix production routes is explained. The specific sector and product methodologies which are used and how they are linked towards the EU Fit-for-55 MIX scenario and industrial roadmaps, is presented in the sector specific paragraphs 4 till 9. A brief conclusion, based on the modelling results of the AIDRES EU Mix production route is provided in 10. Finally, a detailed overview of references (11) assumptions and main assumptions, including cost details (12) are provided.

3. Methodology

For the AIDRES sectors production routes, we first evaluate a so called production reference case and generate alternative production routes using process integration techniques (I. Kantor, Pouransari, and Maréchal 2018) to size the equipment of a wide range of predefined typical production routes. Production routes are characterized by their process investment, size, energy-resources consumption, direct CO_2 emissions and amounts of captured and stored CO_2. This results in a per-ton-of-product database containing energy and feedstock demand or inputs, direct emissions at the plant, amount of captured CO_2 and the associated investment.

In the second step, operating cost, total cost and total emissions - direct at the plant and selected indirect upstream emissions - are evaluated for the reference case and eight predefined EU scenarios for 2030 and 2050 (paragraph 3.5). This allows identifying production routes which can significantly reduce CO_2 emissions at the lowest total cost.

The database provides a subset of typical production routes per industrial sector with their key indicators mentioned above. These routes are mapped at NUTS3 level and can be selected afterwards by the user to create a storyline by combining single production routes for a given NUTS3 region which can be scaled up to EU level.

3.1. AIDRES model framework

The AIDRES model framework, as shown in Figure 1, consists out of several layers where key data such as production capacities and location of the main industrial production sites in the EU are gathered and combined with detailed industrial production models into a single database. The methodology that describes the spatial mapping of EU industry has been delivered as Work Package (WP) 2 of the AIDRES project. A description exists in a separate document titled: "*Methodology used to map the industrial plants in the EU – Supporting document to the industrial plants database*".

The core of the AIDRES model calculates optimal production routes (input/output) where annualised investment costs (CAPEX), fixed operational and variable operational (OPEX) costs of electricity, natural gas, hydrogen, emissions, etc. are included. The advantage of a per-ton product result is that the variable OPEX can be changed by the user of the final database, keeping the integrity of the model intact (see Figure 1). The main inputs of the model are coming from the EPOS blueprints (Partners 2022; Cervo et al. 2020; I. D. Kantor et al. 2018), scientific articles and industry references. These industrial blueprint models include details of heat, material and energy flows required for process operation. Next, a selection of reference and future production routes are modelled using ASPEN (Wikipedia, 2023), which is a widely used process simulator in the chemical industries for modelling, simulating and optimizing distillation processes, and other models where different process, built at a fit-for-purpose production rate, are integrated in a single production route. OSMOSE (Yoo et al. 2015) is used to optimize the objective function set forward, favouring lowest total production cost towards zero CO_2 emissions. The output is a solution cloud of different production routes, where those routes which meet the predefined AIDRES targets are selected. These include production solutions that can contribute to the direct CO_2 emission targets as set forward by the EU commission towards 2030 and 2050 and secondly, a pareto analysis on those solutions with the lowest CAPEX and OPEX. Important to note is that the AIDRES industrial blueprint models do not include an optimization module over the full model time horizon starting in 2018 till 2050 with an intermediate period in 2030. Moreover, the model converges where the maximum integration of processes within one industrial cluster is reached, heat recovery and material re-use is guaranteed, resulting in a single solution for all industrial sites.

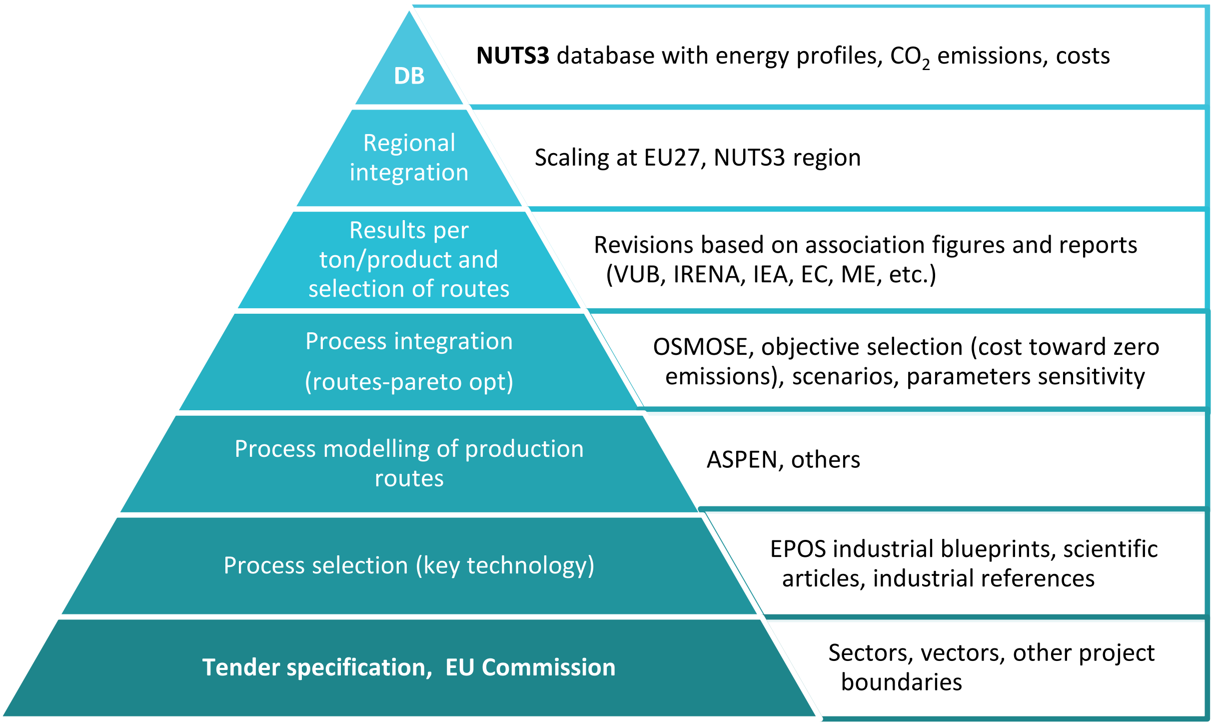


Figure 1: AIDRES WP1 gate model towards final AIDRES database.

The resulting annualized investment cost, material and energy flows, direct CO_2 emissions and captured CO_2 are expressed in “per-ton of product” unit and later integrated on NUTS3 level. In the final step, a PostgreSQL relational database is compiled and can be consulted through the JRC Energy and Industry Geography lab on the EU Science Hub.

There is no time-slicing involved in the AIDRES model, but utilisation factors are applied to the production at the NUTS3 level afterwards.

3.2. Process integration

Process integration technique (I. Kantor, Pouransari, and Maréchal 2018) is used to determine the optimal size of each process, integrated or not in a given production route, taking into account the internal use of heat/cold and waste flows while balancing the overall mass and energy flows. Each process is defined by a list of steady-state values of feed-in and feed-out energy and materials, hot and cold thermal streams requirements and the corresponding annual investment and operation cost. A simple representation of the production in -and outputs is explained in the model paragraph of each of the six industrial sectors whereas in Annex 12.7, a more detailed blueprint process superstructure is available.

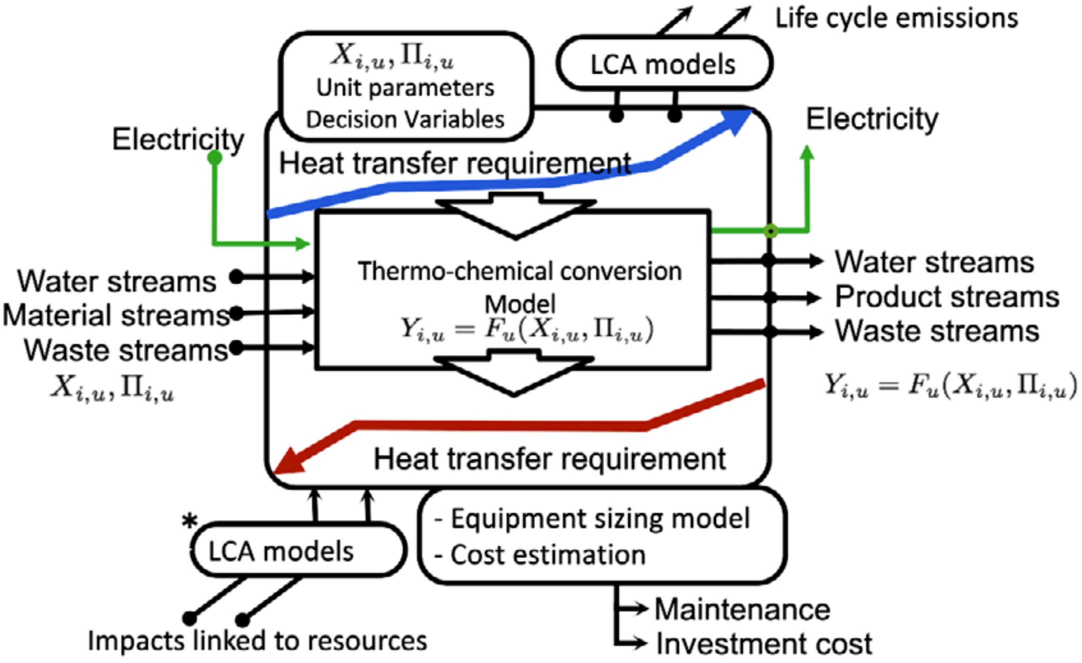


Figure 2: Resource, products and waste from a collection of process (left) integrated in production route (right).

3.3. Single production routes

Pertinent production routes are selected from the result of a parametric optimisation using various energy prices and emissions and different weights for the terms of the objective function (e.g., sum of operation cost, investment cost and impact on CO_2 emissions). In general, the selection criteria are minimising the direct emission at the plant, however in some cases, the criteria are reflecting the design of plant in the EU context (e.g., steam network design for a fertiliser plant). The resulting energy and feedstock inputs, capital cost and direct emissions at the plant are expressed per ton of product. A full overview of all parameters can be found in Table 37 (Annex 12).

3.4. Indicators

3.4.1. Capital cost (CAPEX)

An annualised investment cost is estimated for individual production routes based on published values and a typical lifetime of 40 years.

The nominal investment cost of a process (p) of Size (S) is computed by Equation 1 based on a reference cost ($CAPEX_{ref}$ [USD]) and a reference size (S_{ref}) with $f_{USD,EUR} = 0.84$, $CEPCI_{2018}$ = 596.2 and a typical α of 0.6. The bare module Cost Factor (BMC) allows to account for the direct and indirect costs (electrical systems, control, piping and engineering fees).

$$CAPEX(S)_{2018} = CAPEX(S)_{ref} \cdot f_{USD,EUR} \cdot \left(\frac{S}{S_{ref}}\right)^{\alpha} \cdot BMC \cdot \frac{CEPCI_{2018}}{CEPCI_{ref}} \quad [\mathrm{EUR}]$$

Equation 1: Actual investment for an equipment from a given reference size and investment cost at a certain time.

The investment cost of process (p) is annualised using the Equation 2 for a given lifetime (n) and an interest rate (i).

$$CAPEX(S)_{n,i} = \mathrm{CAPEX(S)} \cdot \frac{\mathrm{i} \cdot (1+\mathrm{i})^{n}}{(1+\mathrm{i})^{n-1}} \quad [\mathrm{EUR/y}]$$

Equation 2: Annualised investment cost of an equipment with a given lifetime and interest rate.

3.4.2. Operation cost (OPEX)

The annual operating cost is the sum of the prices of energy $(\dot{e})$ and feedstock material $(\dot{m})$ flows from the scenarios of

Table 1 (variable price $C_{\dot{e},\dot{m}}^{scenarios}$) and Table 43 (fixed price $C_{\dot{e},\dot{m}}^{fix}$), direct emission allowance (C_{CO_2}) (

Table 1) and operation cost for the continuous maintenance and upgrade of process of size (S_p) and the cost of carbon transport (C_{CT}) and storage (C_{CS}). In this project, we consider that the CO$_2$ in surplus is sold to the market (beverages, plastics, slaughterhouses).

$$OPEX = OPEX_{cst} + OPEX_{var} = \underbrace{\sum_{p} C_{p}^{O\&M}}_{OPEX_{cst}} + \underbrace{\sum_{\dot{e},\dot{m}} C_{\dot{e},\dot{m}} + C_{CO_2} + C_{CCS} - C_{CCU}}_{OPEX_{var}} \quad \left[\frac{EUR}{y}\right]$$

$$OPEX = \sum_{scenarios} \dot{e} \cdot C_e + \sum_{fix} \dot{e} \cdot C_e + \sum_{fix} \dot{m} \cdot C_m + \sum_{process} C_{S_p}^{O\&M} + C_{CO_2} + C_{CT} + C_{CS} \quad \left[\frac{\mathrm{EUR}}{\mathrm{y}}\right]$$

Equation 3: Annual total operating cost.

$$\Delta OPEX^{scenario}{}_{var} = Q_{p,\dot{e}} * \left(commodity\ price^{end-user} - commodity\ price^{scenario}\right) \left[\frac{EUR}{y}\right]$$

$$where\ \ Q_{p,\dot{e}:\, proces\ (p) commodity\ \ (e) intensity}$$

Equation 4: Update Operating variable cost.

3.4.3. Total cost (TOTEX)

The annual total cost (TOTEX) is the sum of the annual operation costs (OPEX) and the annualised capital costs (CAPEX).

$$TOTEX = OPEX + \sum_{\mathrm{p} \in Process} CAPEX\left(S_p\right)_{n,i} \quad \left[\frac{\mathrm{EUR}}{\mathrm{y}}\right]$$

Equation 5: Annual total production cost.

3.4.4. Emissions

The total emission is the sum of direct CO_2 emissions at the plant from waste streams and the indirect upstream emissions from resource streams. Among all the feedstock, the one representing more than 95% of indirect emissions have been retained. The sources of direct and indirect emissions are listed in Table 42 and Table 43 (Annex 12.5 and 12.6).

$$Em^{total} = Em^{direct} + Em^{indirect} \qquad [tCO_2/y]$$

Equation 6: Total emissions.

The captured emissions given by Equation 7Equation 7 are equal to a captured fraction (η^{CCS}), typically 90% of the non-biogenic and biogenic emissions.

$$Em^{CCS} = \eta^{CCS} \cdot \left(Em^{direct,non\ bio} + Em^{direct,bio}\right) \quad \left[t\frac{CO_2}{y}\right]$$

Equation 7: Captured CO_2 at the plant.

Uncaptured direct emissions from biogenic resources are not accounted ($\eta^{CCS} = 0$), however when carbon capture, transport and storage (CCS) is integrated ($\eta^{CCS} > 0$), biogenic direct emissions removed from the atmosphere are accounted negatively (Equation 8).

$$Em^{direct} = (1 - \eta^{CCS}) \cdot Em^{direct,non\ bio} - \eta^{CCS} \cdot Em^{direct,bio} \quad [tCO_2/y]$$

Equation 8: Direct emissions at the plant from biogenic and non-biogenic sources.

The profits from trading negative emissions are therefore included in the OPEX (Equation 9).

$$OPEX^{CO_2} = Em^{direct} \cdot \quad C_{CO_2} \cdot 1000 \quad [EUR/y]$$

Equation 9: Contribution of the CO_2 allowance [EUR/kg] to the operation costs.

3.5. Scenarios 2030-2050

To evaluate the impact of the different production routes, nine typical cost and emissions scenarios were considered as described in

Table 1. A reference scenario, as in 2018, and four reference scenarios for each future year 2030 and 2050. The criteria and values are selected based on EU Fit for 55 scenarios, to create a diversity of different outcomes.

The number of scenarios is restricted to eight future situations, plus one reference scenario, providing enough options for the user of the database to evaluate different combinations whilst keeping it sizeable. The scenario values can be seen as boundaries, however, additional sensitivity analysis with different values can easily be applied afterwards without having to re-run the entire AIDRES model. Limitations of energy resources availability at NUTS3 level are not taken into account and competition for resources between industrial or other sectors is also neglected, such as biomass use in the refinery and food sectors (Panoutsou and Maniatis 2021). However, the results of the AIDRES database can be independently integrated in further modelling exercises, expanding the analysis to other sectors or energy vectors.

There is a calculated output available in the AIDRES database for each production route and each scenario on NUTS3.

Table 1: Reference scenario (2018) and future EU scenarios at horizons 2030 and 2050[1].

Nr	Year	Description	€/t_{CO_2}	€/MWh electricity	kg$_{CO_2}$/MWh electricity	€/kg H_2	kg$_{CO_2}$/kg H_2	€/MWh NG
0	2018	Reference	24.8	125	230.7	1.8	8.2	24.4
1	2030	low H_2 price	150	71	120	3	0	25
2	2030	low H_2 & high NG price	150	71	120	3	0	50
3	2030	high H_2 price	150	71	120	5	0	25
4	2030	high H_2 & high NG price	150	71	120	5	0	50
5	2050	low H_2 price	350	71	0	1.5	0	35
6	2050	low H_2 & high NG	350	71	0	1.5	0	50
7	2050	high H_2 price	350	71	0	2.5	0	35
8	2050	high H_2 & high NG price	350	71	0	2.5	0	50

[1] **ETS, 150 €/tCO_2** (2030), 350 €/tCO_2 (2050) based on respective EU FF55 MIX Scenario values. Source:(European Commission 2021a), table 23, p. 148
Electricity CO_2 intensity, 120 kgCO_2/MWh (2030), '0' tCO_2/MWh (2050) based on respective Fit for 55 MIX Scenario values and agreed with EC. Source: (European Commission 2021b)
Natural gas (NG) prices 25 €/MWh (2030), 35 €/MWh (2050) based on respective Fit for 55 Scenario values. Source:(European Commission 2021a), table 20, p. 133
H_2 prices Derived from range: 2.7-5.7 €/kg (2030), 1.2-2.9 €/kg (2050). Own calculation based on technical parameters from EC Ref Scenario (07/2021). Source: (European Commission 2021b)
Electricity price, 71 €/MWh based on Fit for 55 'Mix Scenario' (2030) and EC Ref Scenario (2050); 40 €/MWh as sensitivity for regional and technology specific context. Source: (European Commission 2021b)
H_2 impact [kgCO_2/kgH2] to be assumed '0', as 'green' molecule.
H_2 based on fossil fuels (SMR process) represented in AIDRES Blueprint model.

3.6. AIDRES EU Mix production routes

One of the aims of the AIDRES database is the use of possible future single production routes, with modelled values of energy and feedstock inputs, CAPEX/OPEX, emitted CO_2 and captured CO_2 emissions, and apply them on each production site across the EU.

To illustrate how a low CO_2 emission pathway could look like for the selected EU industrial sectors and products, two synthetic production routes have been developed for 2030 and 2050: the AIDRES EU 2030 and 2050 mix routes. These production routes consist of a mix of single production routes and are to be compared and understood at European level. The concept of AIDRES EU mix routes is also introduced to account for the uncertainty which production route will be implemented in the future in each industrial site (NUTS3). Rather than applying one single production route across the European Union industrial production sites, the AIDRES EU mix routes consist of a weighted sum of production route alternatives to represent values of energy and feedstock input and CO_2 emissions. The mix of production routes (for 2030 and 2050) were defined considering the roadmaps of the industrial sector associations, if available, or proposed by the AIDRES team and submitted to the sector associations for review/approval. One practical example of why the AIDRES EU mix route does not have the ambition to forecast the future of each individual production site is that one would most likely not install multiple future low-carbon production technologies at the same site. The composition and different weights of the AIDRES EU mix routes for each sector and product can be found in paragraphs 5 to 9.

An end-user of the AIDRES database can build a specific scenario on NUTS3, 2, country or EU level by selecting single production routes per product and sector or by developing a specific mix production route as illustrated in the AIDRES EU mix routes case.

3.6.1. AIDRES Direct emission target

The AIDRES EU mix production routes are finetuned in a way to meet the EU FF55 MIX scenario emission reduction targets respectively in 2030 and 2050 as defined by the European Commission in 2021 (European Commission 2020) as in Figure 2. These targets are in line with the EU FF 55 and the EU Green deal (European Commission 2019) roadmaps.

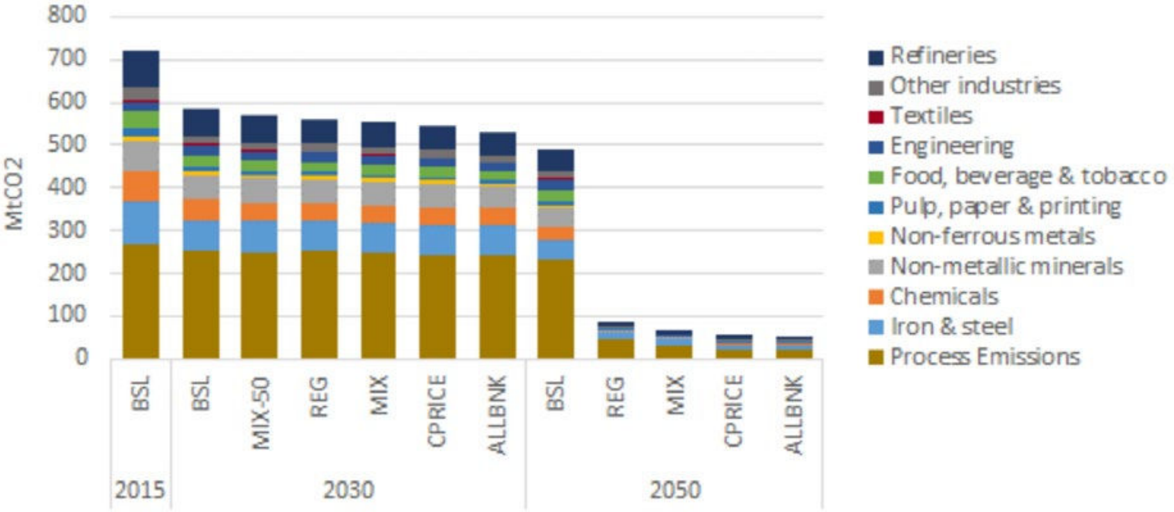


Figure 2: CO_2 emissions in industry by sector and type (sectoral emissions refer to energy-related emissions). Source: (European Commission 2020), p.80.

By including supplementary information of the EU FF55 MIX scenario of the EU 2030 Climate Target Plan (European Commission 2020), and decomposing the process emissions using data published in (European Environment Agency 2022) to define the share of the sector, a CO_2 emissions reduction target for each sector was derived as follows (Equation 10).

CO2 reduction targets

$$reduction_{t*} = \frac{(CE_{s,t} + \beta_{s,2015} \cdot PE_t)}{(CE_{s,2015} + \beta_{s,2015} \cdot PE_{2015}) \cdot (AVTE/TE_{2015})}$$

Equation 10: AIDRES Sectors CO_2 emissions reduction formula.

Where:

CE: Combustion Emissions (Source: European Commission 2021a)
PE_t: Process Emissions (Source: European Environment Agency 2022)
TE: Total emissions (Source: European Environment Agency 2022)
β: Share of sector S in process emissions (IPPU) accorinding to EEA, historical values in 2018.
s : Sector (steel, chemical, refineries, non-metallic minerals)
t : period (2030, 2050).
$AVTE$: Average total emissions 2015-2019 per sector.
BY: 2015-2019 average base year prior to the COVID-19 pandemic.

Furthermore, external reports and studies have been consulted, and partly used, to build up the AIDRES EU mix production routes, towards the EU FF55 MIX scenario emission reduction targets. Finally, the AIDRES EU production routes models and result were consulted and shared with a group of (external) industrial expert reviewers from following organisations.

- Steel: ESTEP, Arcelor Mittal
- Refinery: CONCAWE, Ineos, Dechema
- Cement: Cembureau, Febelcem, Cemex, VUB
- Glass: Institut du Verre, Glass for Europe, Dechema, VUB
- Fertiliser: Yara, Dechema
- Chemical: CEFIC, Essencia, Ineos, Dechema, VUB

Table 2: AIDRES sector specific CO_2 emission reduction targets 2030 and 2050 compared to the average of base years 2015-2019[2,3]

In $MtCO_2$	EU 27 1990 CO_2 emissions	EU 27 2015 CO_2 emissions	EU Mix 2030 CO_2 emissions	EU Mix 2050 CO_2 emissions	AIDRES EU Mix 2030 CO_2 reduction	AIDRES EU Mix 2050 CO_2 reduction
Iron & steel	254.8	168.2	133.1	21.9	**21%**	**86.3%**
Chemicals, incl. fertilizers	153.3	118.7	84.5	7.1	**29%**	**96.1%**
Non-metallic minerals, incl. glass and cement	261.4	171.4	149.3	15.1	**13%**	**93.2%**
Non-ferrous metals	23.6	18.5	15.1	1.2	19%	95.9%
Pulp, paper & printing	29.9	21.1	9.9	1.2	54%	96.2%
Food, beverage & tobacco	45.2	39	22	2	44%	97.4%
Engineering	45.9	23	22	2	5.9%	93.5%
Textiles	9.5	5	3	0.3	44.3%	96.5%
Other industries	69.3	71.4	54.9	6.3	23.5%	93.1%
Refineries	103	85.2	60.4	10.1	**28.8%**	**87.2%**

[2] Energy and process related CO_2 emissions in industry by sector and type. AIDRES EU MIX 2030 and 2050 Emission reduction % compared to base year 2015 and average reported CO_2 emissions during 2015-2019. Sources: (European Commission 2021a) and (European Environment Agency 2022)

[3] Light blue marked industrial sectors are in scope of the AIDRES model

The compilation of the AIDRES EU mix production routes for each sector follows the same methodology, as described in each sector specific model approaches and results, starting section 4 of this report.

- Definition of the AIDRES sector's specific emission reduction targets for 2030 and 2050.
- Identification of changes in product output (e.g.: refineries).
- Federation or sector decarbonization roadmaps from reports and/or literature review to define the starting EU-mix (EUmix_{2050}^{0}).
- Validation of compliance of the EUmix_{2050}^{0} with emission reduction targets by 2050.
- Adjustment of technology shares in the EUmix_{2050}^{0} to reach the desired decarbonization target by 2050, which results in $\text{EUmix}_{2050}^{AIDRES}$. This process is done based on expert judgment.
- Calculation of $\text{EUmix}_{2030}^{AIDRES}$ as a linear backward extrapolation of the share of each route starting in 2050 in such a way that it complies with the intermediate target for 2030.
- Both energy and process related CO_2 emissions are included in the AIDRES sector CO_2 emission reduction targets, shown in Table 2.

3.6.2. AIDRES EU-Mix production routes results in EU27

When applying the AIDRES EU-mix production routes on each NUTS3 aggregated production site across the EU, a transition pathway becomes visible. When comparing 2018 in Table 3 with 2050 (Table 4) results, it is possible to identify which energy and feedstock carriers can replace the existing fossil-based carriers in various energy intensive sectors. The production output for all sectors, except for the refineries, remain unchanged throughout the different model years, 2018-2030-2050.

Important to note is that these results should not be compared with national or EU wide energy balances, as the scope of the AIDRES study include certain limitations such as, the number of sectors, downstream products and the sizes of the production plants. To illustrate, the electricity consumption in the steel sector is approximately double the 45 TWh consumed by the primary and secondary steel processes combined in the AIDRES reference routes. The main reason for this disparity is that the AIDRES primary steel model concludes at the production of steel slabs, while the subsequent rolling and finishing stages require significant amounts of electricity. Also, the production capacities have been based on public available sources or own calculations based on reported emissions and products produced. However, the bottom-up nature of the AIDRES study does allows for making local projections and estimates of growth/shrinking of the expected energy and feedstock demand of the industrial sectors based on the calculated results of any given mix or single solution.The primary energy carriers that become fundamental pillars for the decarbonization are electricity, hydrogen and biomass. Results indicate that by 2050, the hydrogen and biomass consumption in AIDRES sectors might undergo a substantial transformation, transitioning from nearly negligible levels at present to a scale comparable to the current consumption of coal, coke, and natural gas, which amounts to approximately 1100 TWh. Simultaneously, electricity demand may witness a seven-fold increase, predominantly driven by the refineries and chemical sector, which are expected to grow by factors of 29 and 12, respectively. Other sectors are also projected to consume between 1.7 to 2.5 times more electricity compared to present levels.

The pronounced surge in electricity consumption within the refineries and chemical sector can be attributed to the production of e-fuels and defossilizing feedstock. It is important to emphasize that while these sectors will experience a substantial rise in their electricity consumption, the overall final product energy intensity will not exhibit such a dramatic increase. In the case of refineries, the energy intensity will only rise by 3%, whereas the chemical sector will witness a comparatively higher increase of 19%. In the AIDRES EU Mix for the chemical sector in 2050, the production routes encompass various methods. One notable component is the inclusion of approximately 30% of methanol-to-olefins (MTO) produced within the EU through co-electrolysis. This particular process would necessitate an annual electricity demand of 260TWh. Additionally, other olefins production shares consist of roughly 30% MTO derived from imported methanol, and approximately 24% obtained from biomass-based methanol produced within the EU. Whereas the AIDRES reference route for producing olefins today, is 100% naphtha based.

Table 3: AIDRES EU 2018 mix route, total energy and feedstock inputs

	[TWh/y]												
AIDRES Sector	Electricity	Hhydrogen	Alternative fuel mixture	Biomass	Coal	Biomass Waste	Coke	Crude oil	Methanol	Naphtha	Natural gas	Plastic mix	TOTAL
Cement	14		36		56	21							127
Chemical	24									555	61		640
Fertiliser	6										86		92
Glass	13	1									62		75
Refineries	15							7240			270		7525
Steel	45				464		29				3		541
TOTAL	117	1	36		520	21	29	7240		555	483		9001

Table 4: AIDRES EU 2050 mix route, total energy and feedstock inputs

	[TWh/y]												
AIDRES Sector	Electricity	Hhydrogen	Alternative fuel mixture	Biomass	Coal	Biomass Waste	Coke	Crude oil	Methanol	Naphtha	Natural gas	Plastic mix	TOTAL
Cement	26		51		13	77					2		169
Chemical	264	40		206					140	78	26		754
Fertiliser	10	49		6							21		86
Glass	33	25									16		74
Refineries	224	7		886				1207			34		2358
Steel	97	174			95		6				38	5	415
TOTAL	654	295	51	1098	108	77	6	1207	140	78	137	5	3856

In terms of direct CO_2 emission reduction and emerging energy and feedstock inputs across the six AIDRES industrial sectors, Figure 4 and Figure 5 show the results of the AIDRES EU mix routes in 2018, 2030 and 2050.

When plotting the results geographically in the EU, both magnitude and the mix of the different energy and feedstock inputs per sector are visualised across 2018 and 2050 in Figure 6. The grey backgrounds in the different countries indicate the overall emission reduction efforts, based on the mix of the sectors in each country, aligned with the AIDRES CO_2 emission reduction targets in line with the EU FF55 MIX scenario.

Following a similar approach but then looking at all the different energy and feedstock inputs and CO_2 emissions per energy vector, Figure 3, shows the results of the AIDRES EU mix routes in 2018, 2030 and 2050.

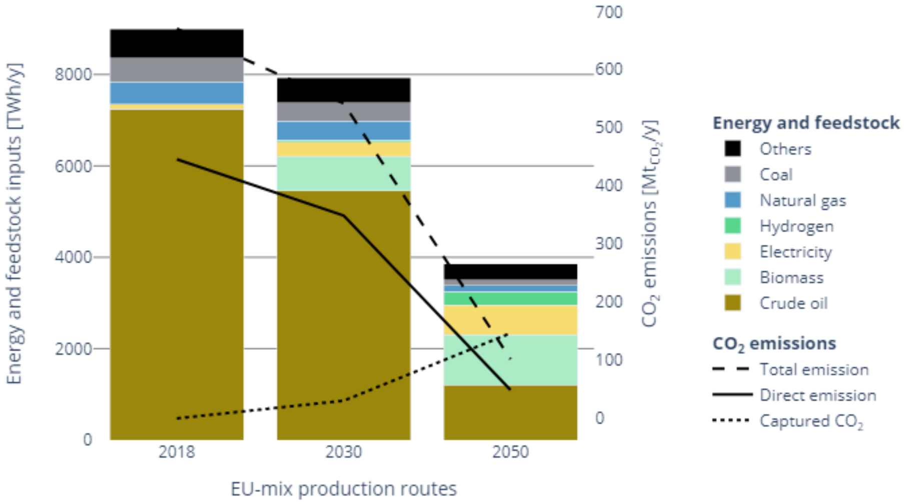


Figure 3: EU-27 energy and feedstock inputs by resources for the AIDRES EU-mix 2030-2050.

When plotting the results geographically in the EU, both magnitude and the mix of the different energy and feedstock inputs per energy vector are visualised across 2018 and 2050 in Figure 7. The grey backgrounds in the different countries indicate the overall emission reduction efforts, based on the mix of the sectors in each country, aligned with the AIDRES CO_2 emission reduction targets in line with the EU FF55 MIX scenario.

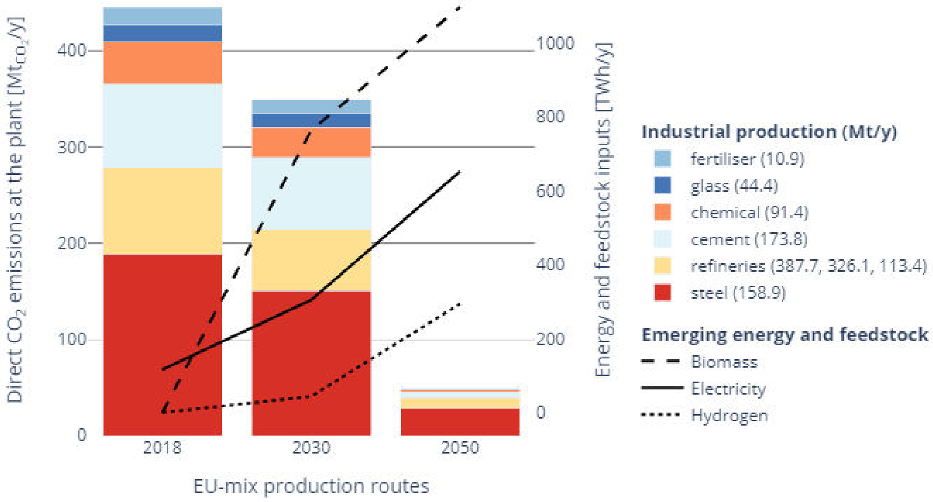


Figure 4: EU-27 direct CO_2 emissions by sector for the AIDRES EU-mix 2030-2050.

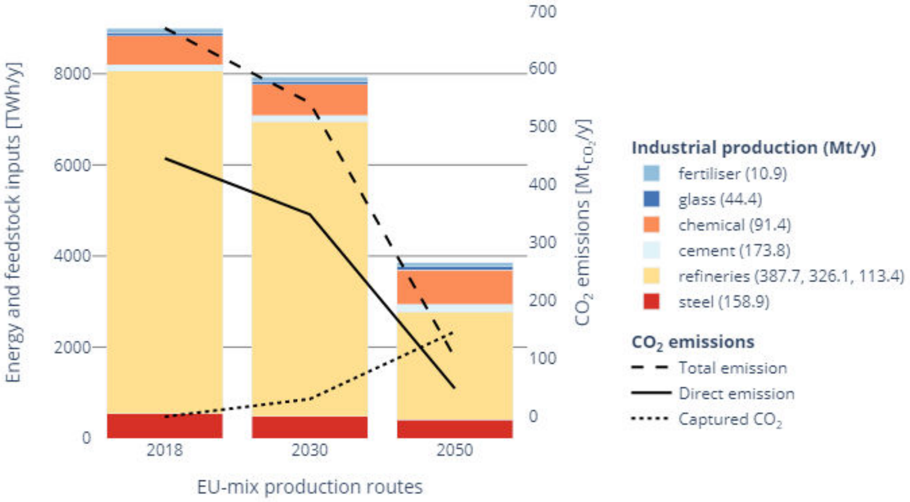
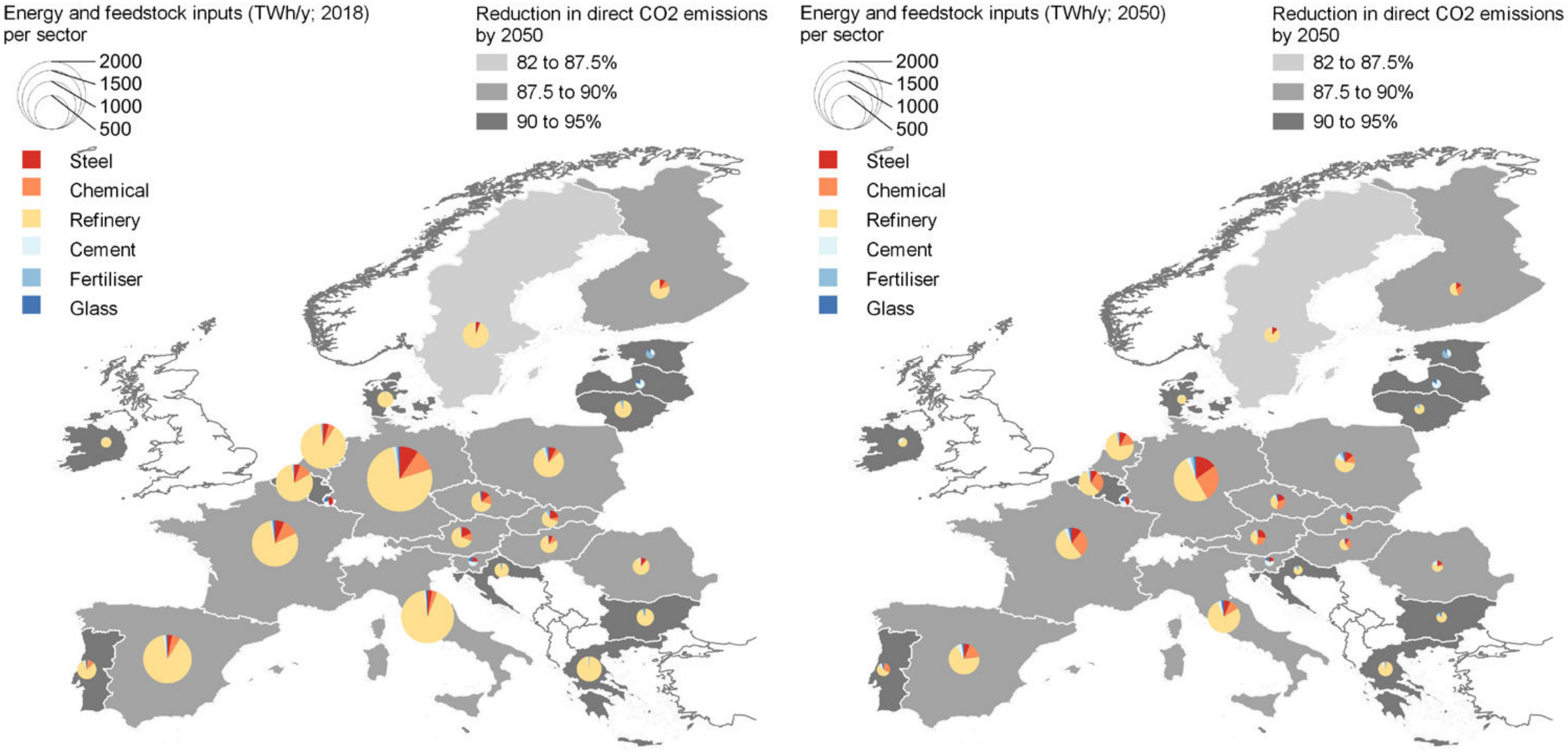


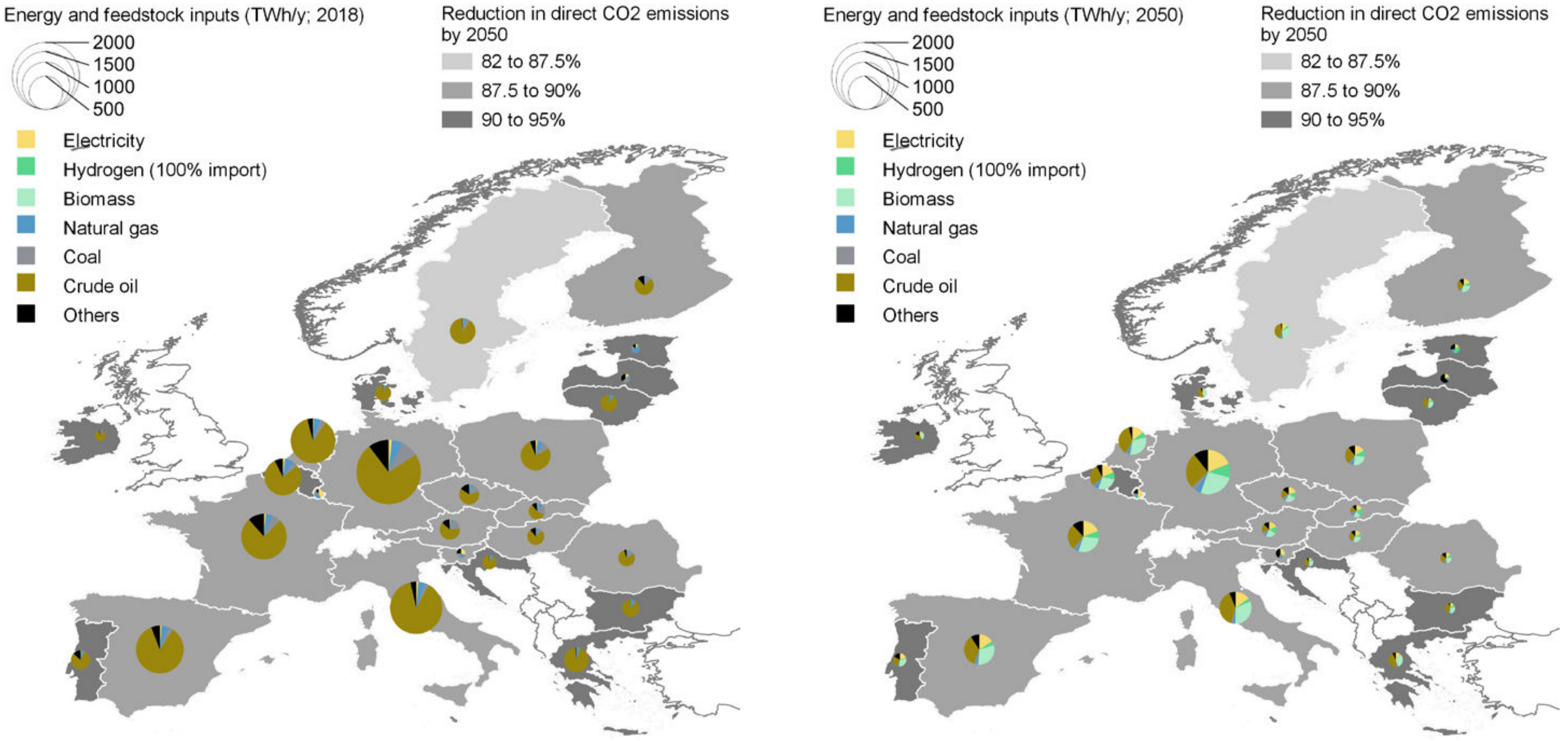
Figure 5: EU-27 energy and feedstock inputs by sector for the AIDRES EU-mix 2030-2050.



AIDRES EU-mix at horizon 2018.

AIDRES EU-mix at horizon 2050.

Figure 6: Energy feedstock and demand per sector for the AIDRES EU-mix 2018 and 2050 with direct CO_2 emissions reduction compared to AIDRES EU-mix at horizon 2050 (Remark: Sizes Pie charts for Estonia, Latvia, Luxembourg and Slovenia are doubled for readability purposes)



AIDRES EU-mix at horizon 2018.

AIDRES EU-mix at horizon 2050.

Figure 7: Energy feedstock and demand per vector for the AIDRES EU-mix 2018 and 2050 with direct CO_2 emissions reduction compared to AIDRES EU-mix at horizon 2050 (Remark: Sizes Pie charts for Estonia, Latvia, Luxembourg and Slovenia are doubled for readability purposes)

4. Steel

The steel sector –iron making, steel making and shaping– has been structured in production routes for primary steel and one route using recycled scraps and electric arc furnace (EAF) to produce secondary steel. Steel produced from primary and secondary routes has different qualities that serves different purposes. The denomination does not refer to a distinction in value.

Special types of steel and stainless steel were not further disaggregated in the model. Special types of steel are produced under request and are alloys of iron and several other materials, such as nickel and chromium. Therefore, the desegregation was done based on the following production routes: primary steel (BF-BOF) and secondary steel (EAF). This approach is aligned with the (EUROFER 2021) and (World Steel Association 2021) reports to facilitate comparison and reduce the number of products to be covered. For instance, EUROFER includes a report differentiating the production route, likewise in the AIDRES study, and another report focusses on the difference of steel quality. Both cases add up to the same annual production. Finally, the production of special steel was assumed to be included in the production of steel using the EAF route.

4.1. Model

The reference case uses a blast furnace (BF) and a Basic oxygen furnace (BOF) to produce primary steel. Alternative production routes make use of top gas recycling blast furnace (TGRBF) or waste plastic injection (WPI-BF) to replace the traditional blast furnace. TGRBF is a promising technology which can significantly reduce CO_2 emission by recycling CO and H_2 from the top gas leaving the blast furnace. The CO and H_2 content of top gasses have the potential to act as an oxygen reducing agent. Hence recirculation these gasses to the blast furnace is considered as an effective alternative to improve the BF-performance, enhance carbon and hydrogen utilisation and reduce CO_2 emissions. Other alternative primary steel production routes are replacing the BF-BOF by an electric arc furnace (EAF) or by a shaft furnace using different fuels to feed an EAF in combination with direct reduced iron or sponge iron (DRI-EAF). Monoethanolamide carbon capture (MEA) technology can be installed to capture the fumes of the different furnaces. Finally, full electrification of primary steel via molten oxide electrolysis (MOE) is a new production route with a low technology readiness level (TRL 2), using direct electrolysis, transforming iron ore towards iron and oxygen. A flow-chart of the primary and secondary steel production model is shown the steel production routes flow-chart of Figure 8.

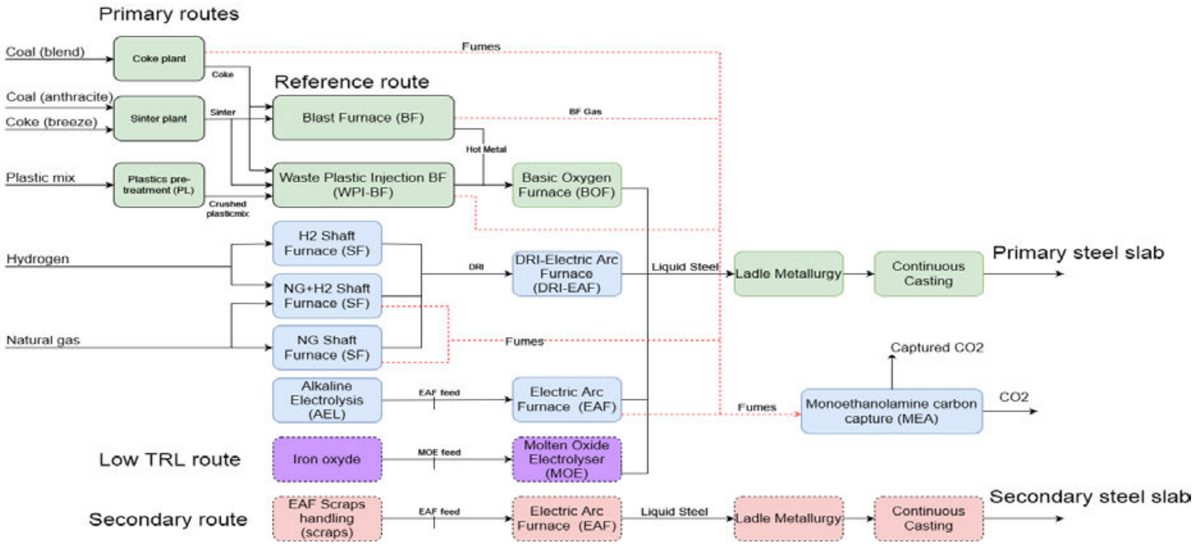


Figure 8: Steel production routes flow-chart.

An overview of steel production components which are used in the AIDRES model, is presented in Table 5 along with investment cost parameters. Reference costs for the steel industry can be found in (Dietz, Gardiner, and Scheer 2021) and (Medarac, Moya, and Somers 2020). The cost function for the carbon capture technologies is derived from methods from a 2020 CSS/U study by the Instituto de Ciencia Y Tecnologia de Carbono, Olvieda, Spain (Plaza, Martínez, and Rubiera 2020).

Table 5: Overview of AIDRES steel production processes.

Abbreviation	Component	Cost [EUR]	Size	Year	Sources
AEL	Alkaline Electrolysis	1254	1 $t_{Steel\ plate}$	2020	(Limpens et al. 2019; International Energy Agency (IEA) 2019)
BF	Blast Furnace	149	1 $t_{hot\ metal}$	2020	
scrap	EAF Scraps handling	16.8	1 $t_{Steel\ feed}$	2020	
P2H	H2 Electrolyser	2000	1 kW_{H_2}	2020	
(H2)SF	H2 Shaft Furnace	220	1 t_{DRI}	2020	(Ripke and Kopfle 2017)
(NG)SF	Natura Gas Shaft Furnace	220	1 $t_{hot\ metal}$	2020	(Sarkar et al. 2018)
(NG+H2)SF	NG+H2 Shaft Furnace	220	1 $t_{hot\ metal}$	2020	(Rechberger et al. 2020)
SP	Sinter Plant	50	1 t_{sinter}	2020	
TGRBF	Top Gas Recycling BF	149	1 $t_{hot\ metal}$	2020	(Keys, van Hout, and Daniëls 2019; Danloy, Schmöle, and van der Stel 2008; Babich et al. 2002; Stel et al. 2013)
WPI-BP	Waste Plastic Injection BF	149	1 $t_{hot\ metal}$	2020	(Minoru et al. 2009; 2014; Carpenter 2010)
BOF	Basic Oxygen Furnace	120	1 $t_{liq.\ Steel}$	2020	
CP	Coke Plant	289.4	1 t_{Coke}	2020	
DRI-EAF	DRI-Electric Arc Furnace	169	1 $t_{liq.\ Steel}$	2020	(Greene 2005a)

EAF	Electric Arc Furnace	169	1 $t_{liq.\,Steel}$	2020	(Kirschen, Badr, and Pfeifer 2011; Greene 2005b)
MOE	Molten Oxide Electrolyser	1009	1 $t_{liq.\,Steel}$	2020	
PCoal	Pulverized Coal	0.11	1 $t_{pulv.\,Coal}$	2020	
LM-CC	Continuous casting and Ladle Metallurgy	174.5	1 $t_{liq.\,Steel}$	2020	
MEA	Mono-ethanolamine carbon capture	53172000	75'240 kg_{CO_2}/h	1994	(Plaza, Martínez, and Rubiera 2020; Schmelz, Hochman, and Miller 2020; W. Zhang et al. 2016; Birat 2010; Hendriks 2012)

4.2. Primary steel

4.2.1. Production routes methodology

Based on the AIDRES EU industrial sector emission reduction targets in Table 2, the steel sector needs to reach a reduction of 20.7% by 2030 and 86.4% by 2050. The selected production routes are used to build up the AIDRES EU mix 2030 and 2050 primary steel production routes and are based on reports listed in Table 6, from ESTEP (Kempken et al. 2021), EUROFER (EUROFER 2019), IEA3 (International Energy Agency 2020). These reports mention hydrogen direct reduced iron (H-DRI) to cover for roughly 60% of the future iron and steel production in the EU. Carbon capture and use or storage (CCUS) based routes for e.g.: blast furnace-blast oxygen furnace (BF-BOF) and natural gas (NG) DRI production plants, are expected to play a role in 2050. Finally, other technologies such as the full electrification of the primary steel production process are not clearly mentioned or completely discarded in these reports. However, to acknowledge the high uncertainty but great potential of the electrification option, a small share is attributed to the AIDRES EU mixes. Guided by these reports, the AIDRES EU mix for steel consists of H-DRI as the main route, closely followed by CCUS routes, shown in Table 7.

Table 6: AIDRES EU mix 2050 primary steel production.

Report	Scenario	Primary Steel Production Mix in 2050	Estimated AIDRES direct emission reduction.
ESTEP, Decarbonization Pathways 2030 and 2050 (2021) (Kempken et al. 2021)	2050 pathway scenario "Other technologies successful"	H-DRI (36%), BF-BOF+CC (44%), IBRSR+CC (10%), Other (10%)	75%-86%
EUROFER, Low carbon roadmap pathways to a CO2-neutral European steel industry (2019) (EUROFER 2019)	Alternative pathways with CO2-free energy	Based on emission reductions: H-DRI (12%), BF-BOF+CC (3%), DRI+CC (74%), Other (10%)	82%-95%

IEA, Iron and Steel Technology Roadmap (2020) (International Energy Agency 2020)	SDS	Based on share of total production of non-EAF routes: BF-BOF (58%), BF-BOF+CC (16%), H-DRI (26%)4	33%-5

Table 7: AIDRES EU mix steel production routes categories in 2050 meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	Share 2018 [%]	Share 2030 [%]	Share 2050 [%]	Direct emissions [tCO2/t]	Direct emissions Reduction 2050 [%]
BF-BOF-MEA	CCS	18.9	0	2.4	9.4	0.79	60.5%
WPI-BOF-MEA			0	2.4	9.4	0.781	61%
MOE	Electrification	5.3	0	0.0	5.3	0	100%
(NG)DRI-EAF-MEA	Fossil-CSS	16.9	0	4.2	16.9	0.065	96.8%
(H2)DRI-EAF	Hydrogen	58.9	0	2.5	58.9	0.193	90.4%
AIDRES-EU-mix-2050	EU-mix	100.0	0	11.5	100	0.273	86.4%

AIDRES EU mix production routes for 2030 and 2050 are build up by weighing single primary steel production routes according to the previously defined emission reduction targets, explained in paragraph 3.6.1. are shown in Figure 9.

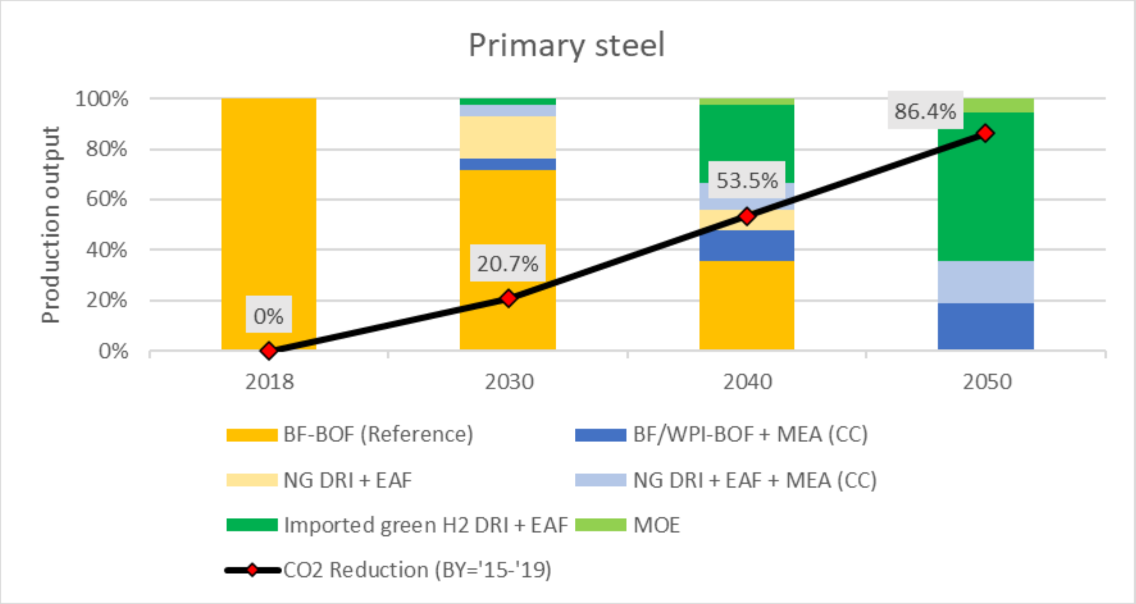


Figure 9 AIDRES EU mix production categories for primary steel towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

4.2.2. Production routes results

A selection of single primary steel production routes in 2030 and 2050 for which a set of energy vectors per ton of primary steel is modelled, is shown in Table 8a. Here we can see the consumption of coal of blast furnaces which is much higher than the consumption of coke since the coke oven plant is assumed to be within the boundaries of the sector. Nevertheless, the total energy intensity remains within the order of magnitude common for the BF-BOF (18-20 GJ/t). Both alternative production routes, H_2 without and with an electrolyser on-site (AEL), are computed and available for comparison in all scenarios. Further on, investment costs (CAPEX), direct emissions, captured emissions and the direct emissions reduction contribution, compared to the BF-BOF reference route, are calculated.

Table 8a: Energy flows, investment costs, emissions and captured CO2 per ton of primary steel.

Production route	Electricity [GJ/t]	H_2 [GJ/t]	CH4 [GJ/t]	Coal [GJ/t]	Coke [GJ/t]	Plastic Mix [GJ/t]	CAPEX [EUR/t]	Direct emiss. [tCO2/t]	CC [tCO_2/t]	Direct emiss. Reduction [%]
BF-BOF (Reference)	0.66			17.71	1.13		33	2.002		
BF-BOF-MEA	1.5		0.58	17.71	1.13		64	0.790	1.369	60.5
WPI-BOF	0.9			15.95	1.13	1.89	32	1.961		2
WPI-BOF-MEA	1.71		0.23	15.95	1.13	1.89	62	0.781	1.333	61
NG DRI-EAF	2.06		7.45	0.4			32	0.651		67.5
NG DRI-EAF-MEA	2.42		7.45	0.4			46	0.065	0.586	96.8
(NG+H2)DRI-EAF	2.06	2.95	4.99	0.4			32	0.447		77.7
(NG+H2)DRI-EAF-AEL	6.49		4.99	0.4			34	0.447		77.7
H2 DRI-EAF	2.06	11.4		0.			32	0.193		90.4
H2 DRI-EAF-AEL	19.18			0.40			40	0.193		90.4
MOE	14.34						74			100
AIDRES EU-mix-2030	1.06	0.29	1.60	13.56	0.86	0.04	35	1.588	0.089	20.7
AIDRES EU-mix-2050	2.69	6.71	1.34	3.48	0.21	0.18	42	0.273	0.354	86.4

Figure 10 shows the energy flows in [GJ/t] for each production route and Figure 47 (Annex 12.8.1) the specific investment cost in [EUR/t].

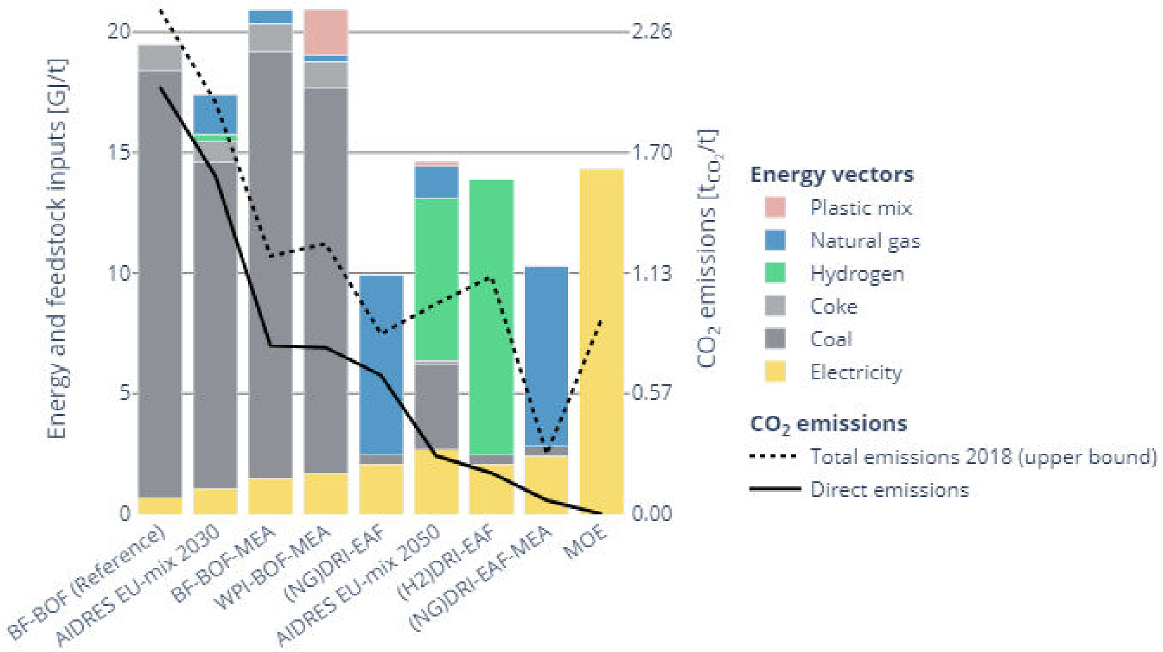


*Figure 10: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **primary steel** production routes.*

4.3. Secondary steel

4.3.1. Production route results

For secondary steel, Table 8b provides the reference and typical secondary steel production routes. Figure 48 (Annex 12.8.1) shows the specific investment cost in [EUR/t].

Table 8b: Energy flows, investment costs, emissions and captured CO_2 per ton of secondary steel.

Production route	Electricity [GJ/t]	NG [GJ/t]	Coal [GJ/t]	CAPEX [EUR/t]	Direct emiss. [tCO2/t]	CC [tCO_2/t]	Direct emiss. Reduction[%]
Scraps EAF (reference)	1.5	0.19	0.3	18	0.04	-	-
Reference	1.5	0.19	0.3	18	0.04	-	-
AIDRES EU-mix-2030	1.5	0.19	0.3	18	0.04	-	-
AIDRES EU-mix-2050	1.5	0.19	0.3	18	0.04	-	-

5. Refinery

The refinery sector featuring distillation, cracking, isomerisation, reforming, desulfurisation and Fischer-Tropsch processes, has been structured in seven routes. The refinery and Fischer-Tropsch processes are used with either a natural gas or hydrogen furnace. Carbon capture (MEA) is considered only in conjunction with the use of a natural gas furnace. The targeted product of both routes is a light liquid fuel with a lower heating value (LHV) of 42.87 MJ/kg. The LHV of the crude oil and fuels in the model are shown in Table 9. To produce one ton of light liquid fuel (LLF), 1.56 ton of crude oil is needed, which represents a LHV equivalent of 1.038 ton of Fischer-Tropsch fuel and 0.464 ton of methanol. Important to note is that the crude oil in the AIDRES model is considered as energy and feedstock inputs, rather than the energy demand as refineries are part of the transformation sector.

5.1. Model

The reference refinery (REF) without carbon capture uses crude oil to produce light liquid fuel including isomerate, heavy reformate, gasoline and gasoil or diesel (Barthe et al. 2015; Brueske et al. 2012; IPIECA 2014; M. Wang, Lee, and Molburg 2004). The biomass gasification and co-electrolysis routes are producing syngas from biomass or co-electrolysis of carbon monoxide and water. The extra carbon dioxide is separated from the syngas with a carbon capture unit (Plaza, Martínez, and Rubiera 2020; W. Zhang et al. 2016). The purified syngas is further transformed into liquid fuel with two different production routes:

- Methanol synthesis.
- Fischer-Tropsch (FT) process producing FT crude (C12, C18, C20).

Hydrogen from the market, steam methane reforming (SMR) (Salkuyeh, Saville, and MacLean 2017) and alkaline electrolysis (AEL) (Limpens et al. 2019) are competing options for the supply of hydrogen to the system. Hydrogen can be used to avoid the water gas shift reaction in the gasifier (Granacher et al. 2021).

Table 9: Lower heating values of the refineries crude and fuels.

Crude oil and fuels	LHV [kWh/kg]
Biomass	4.81
Crude oil	11.85
Fischer-Tropsch fuel	12.36
Hydrogen	33.3
Light liquid fuel	11.91
Light naphtha	12.47
Natural gas	14.5

A flow-chart of the refineries production routes and processes is shown in Figure 11.

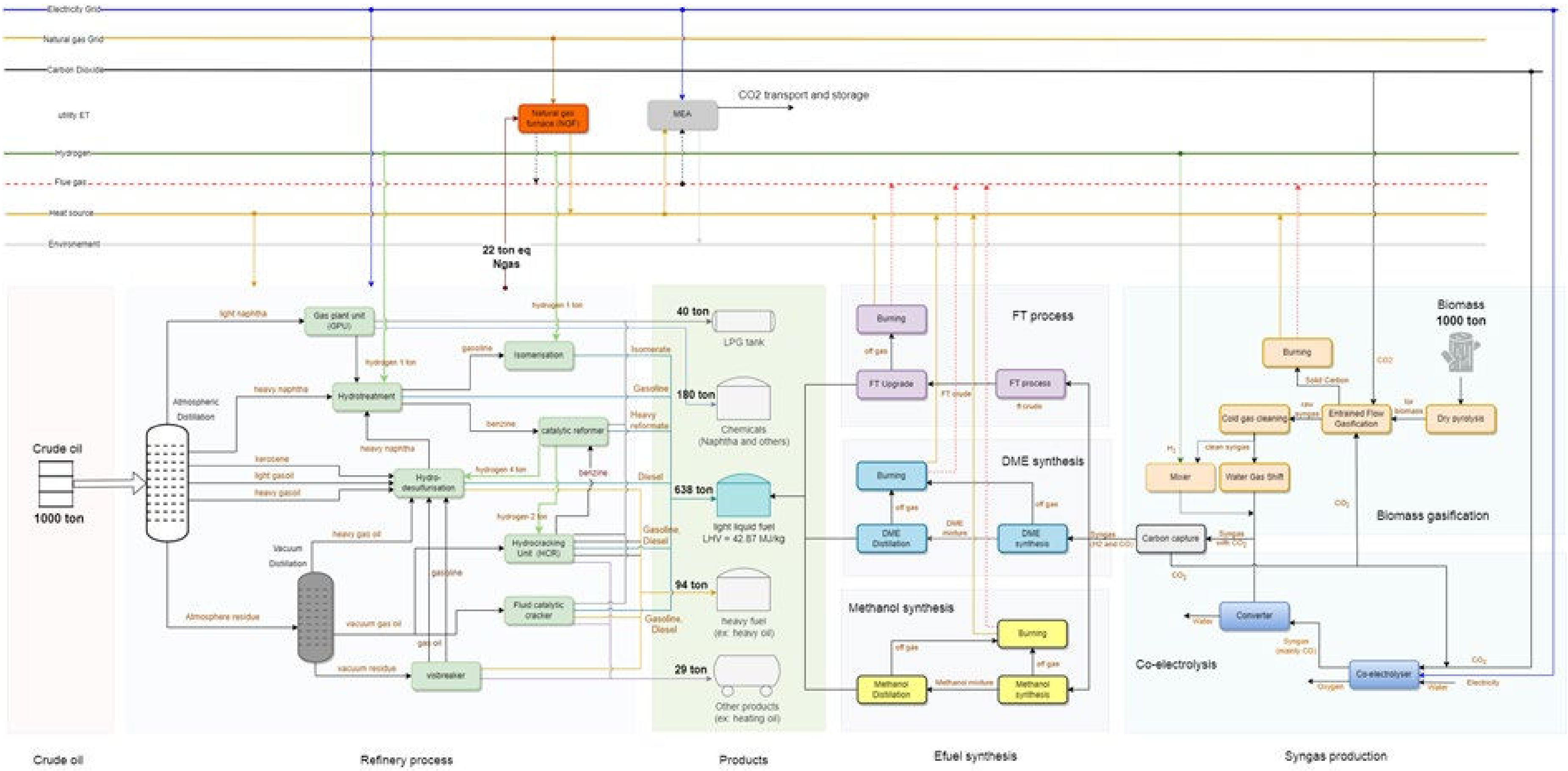


Figure 11: Refineries production routes flow-chart.

5.1.1. Co-electrolysis routes

The mass flows of the co-electrolysis routes to produce Fischer-Tropsch fuels are shown in Figure 12 and flows to produce methanol in Figure 13.

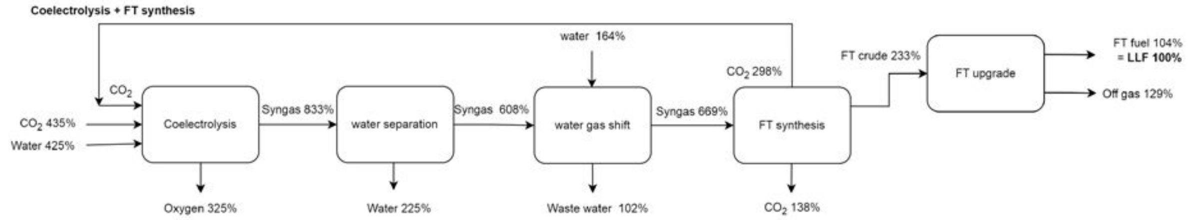


Figure 12: Co-electrolysis/Fischer-Tropsch fuels synthesis schematic (route (COEL)FT).

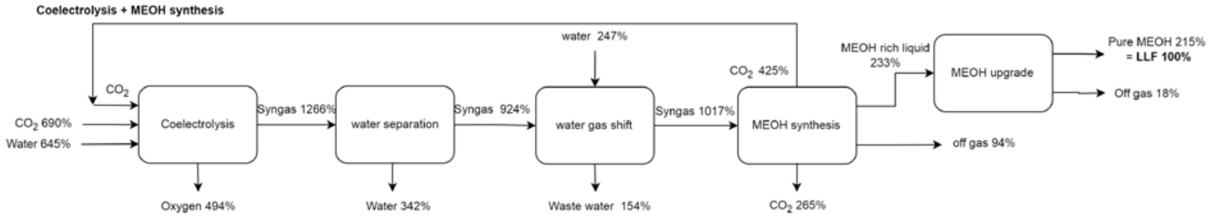


Figure 13: Co-electrolysis/methanol synthesis schematic (route (COEL)MeOH).

5.1.2. Biomass gasification routes

The mass flows of the biomass gasification route to produce Fischer-Tropsch fuels are shown in Figure 14 and using hydrogen injection instead in Figure 15.

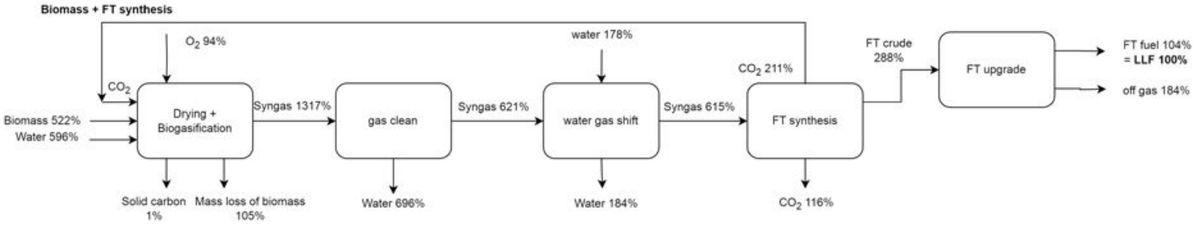


Figure 14: Biomass gasification/Fischer-Tropsch fuels synthesis schematic (route (BM)FT).

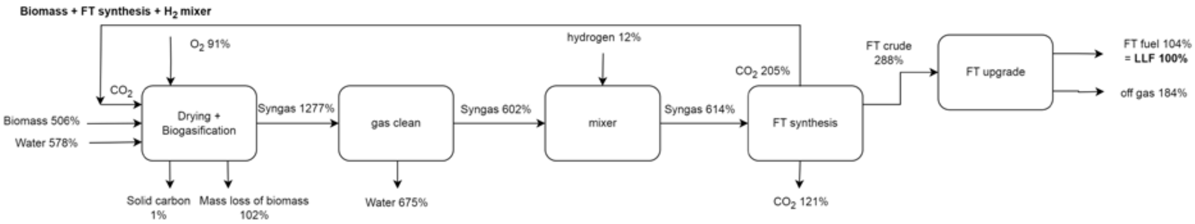


Figure 15: Biomass gasification/Fischer-Tropsch fuels synthesis with hydrogen injection schematic (route (BM+H2)FT).

Flows to produce methanol using water-gas-shift reaction are shown in Figure 16 and using hydrogen injection instead in Figure 17.

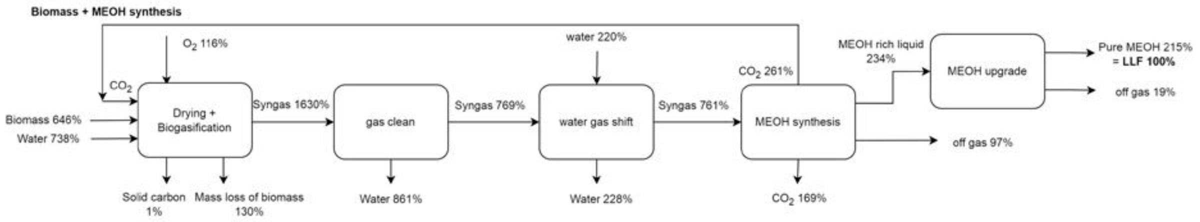


Figure 16: Biomass gasification/methanol synthesis schematic (route (BM)MeOH).

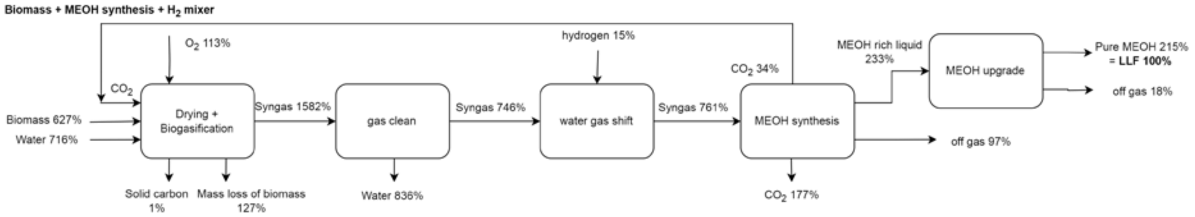


Figure 17: Biomass gasification/methanol synthesis with hydrogen injection schematic ((BM+H2)MeOH).

A list of refinery production components, which are used in the AIDRES model, are presented in Table 10 along with investment cost parameters. Reference costs for the conventional refinery industry can be found in (Jones and Pujadó 2015; Vaillancourt 2014) and for the Fischer-Tropsch process in (Peduzzi et al. 2015; Godat and Marechal 2003).

Table 10: Overview of AIDRES light liquid fuel production processes.

Abbreviation	Process	Cost [EUR]	Size	Year	Source
AEL	Alkaine Electrolysis	40	1'000 kg_{H_2}/h	2019	(Limpens et al. 2019; International Energy Agency (IEA) 2019)
Biogasi	Biomass Gasification Unit	4118	1'000 $ton_{biomass}/h$	2011	(Celebi et al. 2017; Celebi 2019)
CDU	Atmospheric Distillation Unit	2597	1'458 ton_{crude}/h	2019	
COELEC	Co-electrolysis Unit	322	18'337 kW_{elec}/h	2011	(Celebi et al. 2017; Celebi 2019; Rubio-Maya et al. 2011; L. Wang et al. 2018)
CRU	Catalytic Reforming Unit	204	1'458 ton_{crude}/h	2019	(M. Wang, Lee, and Molburg 2004)
DME	Dimethyl ether Unit	548	1'000 ton_{syngas}/h	2011	(Celebi et al. 2017; Celebi 2019)
DSV	Vacuum Distillation Unit	153	1'458 ton_{crude}/h	2019	
FCC	Fluid Catalytic Cracking	751	1'458 ton_{crude}/h	2019	
FT	Fischer-Tropsch Unit	413	1'000 ton_{syngas}/h	2011	(Celebi et al. 2017; Celebi 2019)
GPU	Gas Plant Unit	218	1'458 ton_{crude}/h	2019	
HCR	Hydrocracking Unit	192	1'458 ton_{crude}/h	2019	

HDS	Hydrodesulphurisation Unit	711	1’458 ton_{crude}/h	2019	
HDT	Hydrotreatment Unit	191	1’458 ton_{crude}/h	2019	(IPIECA 2014)
ISOM	Isomerisation Unit	172	1’458 ton_{crude}/h	2019	
MEA	Mono-ethanolamine Carbon Capture	53’172’000	75’240 kg_{CO_2}/h	2007	(Hendriks 2012)
MEOH	Methanol synthesis	816	1’000 ton_{syngas}/h	2011	(Celebi et al. 2017; Celebi 2019)
SMR	Steam Methane Reforming	1.2	1 t_{H_2}/h	2017	(Salkuyeh, Saville, and MacLean 2017)
VISB	Visbreaking Unit	240	1’458 ton_{crude}/h	2019	

5.2. Light Liquid Fuel

5.2.1. Production routes methodology

Refinery activities are heavily influenced by the decrease of fossil fuels consumption in the transport sector. This leads to a reduction in light liquid fuel production rates for 2030 and 2050 in such a way that the total production of light liquid fuels matches the expected decreasing demand, due to the deep electrification of transport, according to EU FF55 MIX scenario (European Commission 2021c) found in Figure 42, Annex 12. This leads to a decrease of light liquid fuel production, estimated from 362Mt in 2018 to 106Mt in 2050. Considering that the technology mix is strongly influenced by decisions made in the transport sector and the readiness of low carbon emission technologies, a pathway prosed in scenario 2 drafted by CONCAWE (Concawe 2021) is used as a starting point (22% fossil, 45% bio, 33% e-fuels). Such a mix makes it possible to reduce emissions by 97%, using a technology catalogue developed in the AIDRES model. However, the participation of biomass for crop-based and advance biofuels is considered to produce part of the future light liquid fuel. Therefore, CONCAWE’s proposed pathway is adjusted to reach the sector target of 85%, which is lower than the level reach with Concawe’s mix (Table 11). At the same time, the AIDRES EU mix 2030 is defined to comply with the EU REDII directive, in line with the expected role of e-fuels and biofuels in the Fit-for-55 scenarios of the European Commission. As a result, the participation of biofuels and e-fuels is reduced in 2030, and the use of market hydrogen and installation CCUS units in the reference routes is included.

Table 11: AIDRES EU mix light liquid fuel production routes categories in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct Emissions [tCO_2/t]	Emissions Reduction [%]
(BM)MeOH	Biomass	9.7	0	3.8	4.9	0	100.0
(BM)FT			0	3.8	4.9	0	100.0
(COEL)FT-MEA	E-fuel	2.9	0	0.6	1.4	0.018	92.4
(COEL)MeOH-MEA			0	0.6	1.4	0.011	95.2

REF-SMR	Reference	1.2	100	62.2	1.2	0.068	70.8
REF-SMR-MEA	Reference CCS	2.3	0	2.7	2.3	0.007	97.1
REF(H2)	Reference H_2	13.1	0	10.4	13.1	0.055	76.1
AIDRES EU-mix-2050	EU-mix	29.2	100	84.1	29.2	0.030	87.2

AIDRES EU mix production routes for 2030 and 2050 are build up by weighting single light liquid fuel production routes according to the previously defined emission reduction targets, explained in paragraph 3.6.1. are shown in Figure 18.

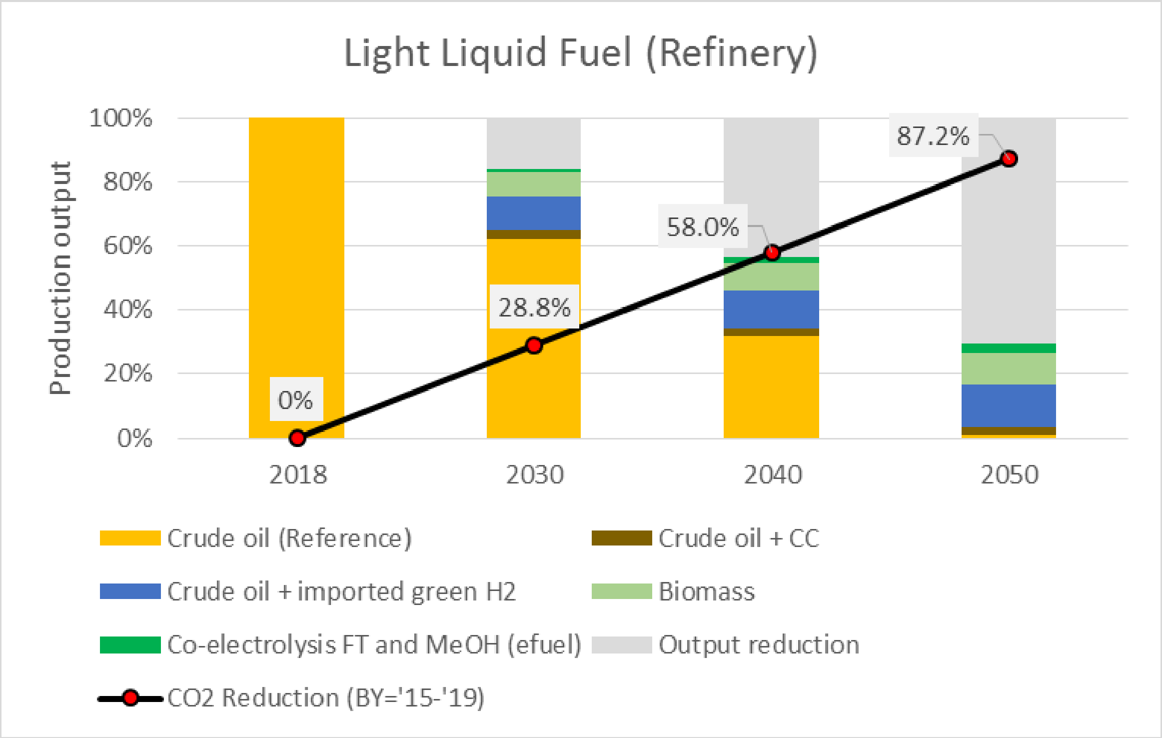


Figure 18:AIDRES EU mix production categories for light liquid fuel towards 2050, decreased output in grey, meeting EU FF55 MIX scenario derived emission reduction targets.

5.2.2. Production route results

For light liquid fuel, Table 12 shows the reference and light liquid fuel production routes.

Table 12: Energy flows, investment costs, emissions and captured CO_2 per ton of light liquid fuel.

Production route	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	Biomass [GJ/t]	Crude oil [GJ/t]	CAPEX [EUR/t]	Direct emiss. [tCO2/t]	Captured emiss. [tCO2/t]	Emiss. Reduction [%]
REF-SMR	0.14		2.51		67.23	44	0.231		
REF(H2)	0.14	0.51	1.73		67.23	44	0.189		18.2
REF(H2)-MEA	0.25	0.51	1.73		67.23	44	0.019	0.170	91.

REF-SMR-MEA	0.27		2.51		67.23	45	0.023	0.208	9
(BM)FT	3.06			85.27		193			100
(BM+H2)FT	2.96	15.91		82.56		78			100
(BM+H2)FT-AEL	26.86			82.56		89			100
(BM)FT-MEA	3.41			85.27		193	-1.667	1.667	821.6
(BM+H2)FT-MEA	3.30	15.91		82.56		79	-1.729	1.729	848.5
(BM+H2)FT-AEL-MEA	27.20			82.56		90	-1.729	1.729	848.5
(BM)MeOH	4.34			84.08		201			100
(BM+H2)MeOH	4.24	15.69		81.40		88			100
(BM+H2)MeOH-AEL	27.80			81.40		99			100
(BM)MeOH-MEA	4.56			84.08		201	-1.176	1.176	609.1
(BM+H2)MeOH-MEA	4.47	15.69		81.40		88	-1.236	1.236	635.1
(BM+H2)MeOH-AEL-MEA	28.03			81.40		99	-1.236	1.236	635.1%
(COEL)FT	58.72					755	0.602		-160.6
(COEL)FT-MEA	59.06					755	0.060	0.542	74
(COEL)MeOH	59.22					755	0.385		-66.7
(COEL)MeOH-MEA	59.43					755	0.038	0.346	83.5
AIDRES EU-mix-2030	1.31	0.02	2.28	5.60	61.72	65	0.211	0.007	8.5
AIDRES EU-mix-2050	13.76	0.07	1.19	22.83	34.71	238	0.124	0.095	46.4

Figure 19 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 49 (Annex 12.8.2) the specific investment cost in [EUR/t]. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

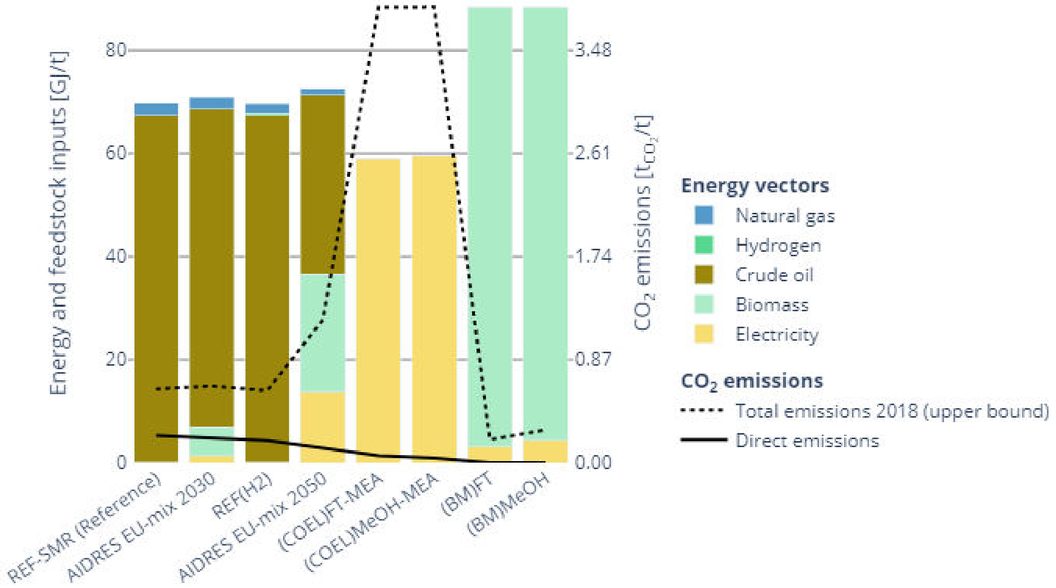


*Figure 19: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **light liquid fuel production** routes.*

6. Cement

The cement sector has been modelled with a production route (raw mill, kiln, calcination, product mill) using dry kiln and coal as reference production route and an alternative route using calcination process to produce Limestone Calcined Clay Cement (LC3).

Six types of cement have been modelled however, no distinction is made on NUTS3 level between these different types. Portland cement II (BV325R with a clinker-to-cement ratio of 70%, is considered as the AIDRES EU reference and LC3 as a future alternative (best case). Portland cement I or cl425R, is a conservative type of cement with a clinker-to-cement ratio of 95% and has one of the highest CO_2 emissions (worst case). The composition of the different cement types is given in Table 13.

Table 13: Composition of modelled cement types.

Resources	Type I	Type II	Type III	Type IV	Type V	LC3
Clinker	95%	70%	65%	67%	45%	50%
Gypsum	4%	4%		6.4%	6.4%	4%
Gypsum (scrap)	1%	1%		1.6%	1.6%	1%
Lignite ash		25%	5%			
Blast furnace slag			25%		45%	
Fly ash and scrubber sludge			5%		2%	
Limestone				25%		15%
Calcinated clay						30%
Total	100%	100%	100%	100%	100%	100%

6.1. Model

In cement manufacturing, about 60% CO_2 is emitted during the calcination process and the remaining 40% originates from fuel consumption.

The conventional cement production route uses a dry kiln, cement, coal (54%), alternative fuels mixture (30%) and biomass waste (BMW) (16%) to produce Portland cement type II with 70% clinker-to-cement ratio (Table 15). The flue gases from a conventional cement plant contains 20-25% CO_2.

Besides Mono-ethanolamine (MEA) carbon capture technology, Calcium looping seems to emerge as the most promising carbon capture technology in the sector.

Alternative production routes replace coal by alternative fuel mixture (AFM) and BMW with integrated MEA or calcium looping (CaL) carbon capture. Furthermore, in some production routes oxy-combustion with carbon capture and a novel calcination process to produce Limestone Calcined Clay Cement (LC3) is used. The latter is a new type of cement with a lower CO_2 footprint based on calcined clay. Through research and testing, LC3 aims at becoming a standard and mainstream general-use product in the global cement market (Pillai et al. 2019).

Different calcination modes exist, e.g., rotary kiln (soak calcination) and flash gas suspension calciner. The latter is chosen for this model as its product presents a clinker substitution rate of 30-40%, due to significantly higher reactivity of the calcined clay with cement, whereas the soak calcination product can only substitute 15-25%. Other advantages are no grinding requirement required after the calciner and reduced CAPEX by 75% compared with the rotary kiln production route. The calcination step involves mainly two reactions: drying of the clay at around 100°C and a metakaolin reaction between 400 and 600°C, producing steam as by-product. A flow-chart of the cement production routes and processes is shown in Figure 20.

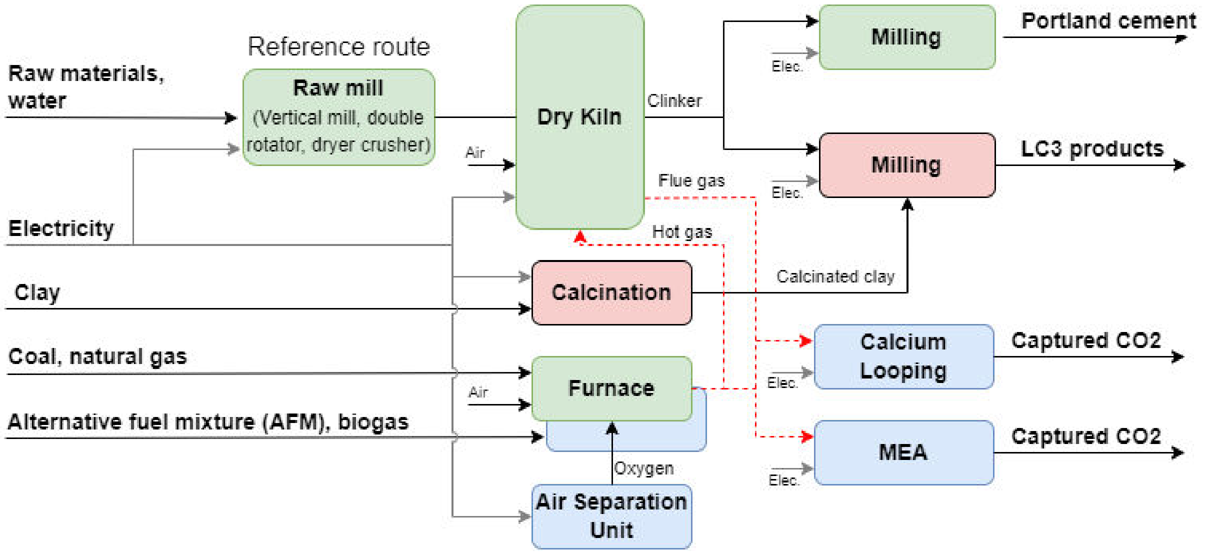


Figure 20: Cement production routes flow-chart.

A list of cement production components used in the AIDRES model is presented in Table 14 along with investment cost parameters. Reference costs for the cement industry can be found in (Atmaca and Yumrutaş 2014) and for carbon capture (Edoardo De Lena et al. 2019; Hassan, Douglas, and Croiset 2007).

Table 14: Overview of AIDRES cement production processes

Abbreviation	Process	Cost [EUR]	Size	Year	Source
CaL	Calcium looping	202.3	136 t_{CO_2}/h	2019	(Plaza, Martínez, and Rubiera 2020; Limpens et al. 2019; International Energy Agency (IEA) 2019; Edoardo De Lena et al. 2019; Rodriguez et al. 2009; Cormos, Cormos, and Petrescu 2017; Atsonios et al. 2015; Ozcan, Ahn, and Brandani 2013; E. De Lena et al. 2017)
MEA	Mono-ethanolamine Carbon Capture	53’172’000	75’240 kg_{CO_2}/h	2007	(W. Zhang et al. 2016; Birat 2010; Hendriks 2012; Hassan, Douglas, and Croiset 2007; European Cement Research Academy 2017)
KCC	Kaolinite clay calcination	8.65	34 $t_{clinker}/h$	2019	(Edoardo De Lena et al. 2019; Teklay et al. 2014; Bishnoi 2020; Almenares et al. 2017)
DPK	Dry process kilns	28.09	103 $t_{clinker}/h$	2014	(Atmaca and Yumrutaş 2014)

CGM	Cement grinding mill	18.61	75 $t_{cement\ product}/h$	2014	(Atmaca and Yumrutaş 2014)
RMDR	Raw mill double rotator	33.1	150 $t_{raw\ meal}/h$	2014	(Atmaca and Yumrutaş 2014)
RMDC	Raw mill dryer crusher	33.1	150 $t_{raw\ meal}/h$	2014	(Atmaca and Yumrutaş 2014)
VRMR	Vertical raw mill roller	33.1	150 $t_{raw\ meal}/h$	2014	(Atmaca and Yumrutaş 2014)
ASU	Air separation unit	27’900’000.0	24 t_{O2}/h	2002	(Banaszkiewicz, Chorowski, and Gizicki 2014)

6.2. Portland Cement II and LC3

6.2.1. Production routes methodology

The cement industry is characterised by the fact that two-thirds of its CO_2 emissions are process related. In other words, even if the heat demand is fully decarbonized, there will still be emissions in the production process that must be addressed. To achieve deep decarbonization levels, the sector heavily relies on carbon capture technologies. CEMBUREAU’s 2050 roadmap (CEMBUREAU 2020) outlines direct and indirect actions to reduce the CO_2 emission per ton of cement. While direct actions such as CCUS, clinker-to-cement ratio, and fuel switching are important, the expected CO_2 emission reduction ranges between 280-440 kg_{CO_2}/t_{cement}, representing a reduction of 56%. CEMBUREAU also considers indirect actions such as carbon neutral transport, concrete mix, CO_2 capture by buildings, among others, which are better covered in Life Cycle Assessment analysis and therefore left outside the scope of the AIDRES project and subsequent scenarios.

CEMBUREAU’s roadmap identifies CCUS and fuel switching as key measures to reduce CO_2 emissions per ton of cement. These measures are estimated to achieve an emission reduction in 2050 of approximately 82%, with a 75% share for CCUS production routes and a 25% for fuel switch routes. However, since deep decarbonization levels cannot be achieved through fuel switching alone, a combination of CCUS, fuel switching, and novel products is more likely to be the path forward. In the AIDRES EU cement mix, fuel switching involves replacing fossil fuels with alternative fossil fuel mixtures and biomass waste, coupled with CCUS for 95% of cement production in the by 2050. This leaves roughly 5% of cement production not coupled to a CCUS technology.

Table 15: AIDRES EU mix cement production routes categories in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
CEM2-(Coal)CaL	CCS	7	0	0.5	3.5	0.086	82.7
CEM2-(Coal)Oxy-CaL			0	0.5	3.5	0.083	83.3
CEM2-(Afm)MEA	CCS + alt.fuel	78.5	0	1.5	10.7	0.129	74.1
CEM2-(Afm)CaL			0	1.5	10.7	0.088	82.3
CEM2-(Afm)Oxy-CaL			0	1.5	10.7	0.075	84.9
CEM2-(BMW)MEA			0	1.6	11.6	-0.308	161.8
CEM2-(BMW)CaL			0	1.6	11.6	-0.188	137.7
CEM2-(BMW)Oxy-MEA			0	1.6	11.6	0.02	96
CEM2-(BMW)Oxy-CaL			0	1.6	11.6	0.014	97.2

LC3-(Coal)CaL	LC3	5.0	0	0.1	0.5	0.065	87
LC3-(NG)MEA			0	0.1	0.5	0.082	83.5
LC3-(NG)CaL			0	0.1	0.5	0.057	88.6
LC3-(NG)Oxy-CaL			0	0.1	0.5	0.066	86.8
LC3-(Afm)MEA			0	0.1	0.5	0.098	80.3
LC3-(Afm)CaL			0	0.1	0.5	0.067	86.6
LC3-(Afm)Oxy-MEA			0	0.1	0.5	0.068	86.4
LC3-(Afm)Oxy-CaL			0	0.1	0.5	0.056	88.8
LC3-(BMW)Oxy-MEA			0	0.1	0.5	0.01	98
LC3-(BMW)Oxy-CaL			0	0.1	0.5	0.004	99.2
CEM2-(Coal)	Reference	9.5	54	47.1	5.1	0.524	-5.2
CEM2-(Afm)			30	26.2	2.9	0.535	-7.4
CEM2-(BMW)			16	14	1.5	0.342	31.4
AIDRES EU-mix	EU-mix	100	100	100	100	0.034	93.2

AIDRES EU mix cement production routes are obtained by weighing single production routes. Starting from the reference case, the proposed mixed routes are equally distributed within categories having direct emission reduction targets by 2050 allowing to reach 93.2% reduction by 2050 (Table 15 and Figure 21). The biomass waste ratio in the alternative fuel is projected to be 20% in 2030 and can go up to 50% in 2050. In the AIDRES model, the production routes are using either coal, alternative fossil fuels or biomass waste. Various mixed solutions could be added by weighing the ratio of the different fuels in Table 15.

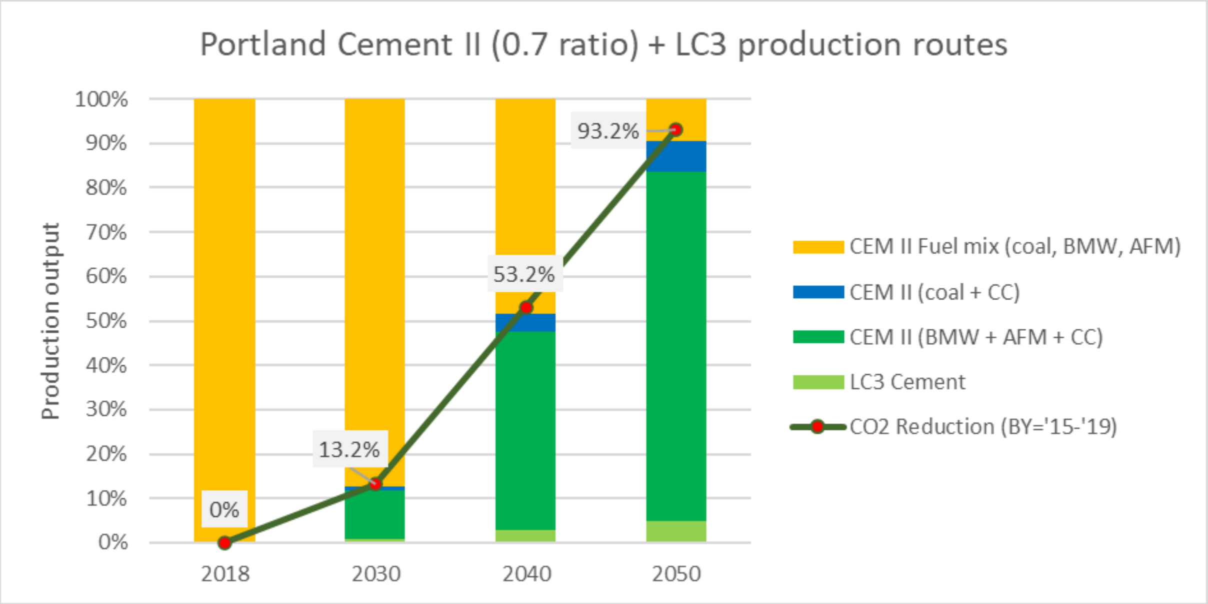


Figure 21: AIDRES EU mix production categories for cement towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets.

6.2.2. Production route results

For cement, Table 16 gives a reference and the typical future production routes.

Table 16: Energy flows, investment costs, emissions and captured CO_2 per ton of Portland cement II and LC3.

Production route	Electricity [GJ/t]	Coal [GJ/t]	Natural gas [GJ/t]	Alternative fuel mixture [GJ/t]	Biomass waste [GJ/t]	CAPEX [EUR/t]	Direct emissions [tCO_2/t]]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
2018 reference mix	0.29	1.15		0.74	0.44	3	0.498		
CEM2-(Coal)	0.29	2.13				3	0.524		-5.2
CEM2-(Coal)MEA	0.62	4.01				5	0.137	0.548	72.5
CEM2-(Coal)CaL	0.47	2.13				21	0.086	0.438	82.7
CEM2-(Coal)Oxy-MEA	0.69	3.09				4	0.108	0.629	78.3
CEM2-(Coal)Oxy-CaL	0.57	2.15				15	0.083	0.533	83.3
CEM2-(NG)	0.29		2.16			3	0.463		7.1
CEM2-(NG)MEA	0.56		3.69			4	0.110	0.439	77.9
CEM2-(NG)CaL	0.45		2.16			19	0.076	0.387	84.7
CEM2-(NG)Oxy-MEA	0.77		3.14			5	0.113	0.676	77.3
CEM2-(NG)Oxy-CaL	0.62		2.18			16	0.087	0.565	82.5
CEM2-(Afm)	0.29			2.46		3	0.535		-7.4
CEM2-(Afm)MEA	0.60			3.86		5	0.129	0.516	74.1
CEM2-(Afm)CaL	0.47			2.46		22	0.088	0.448	82.3
CEM2-(Afm)Oxy-MEA	0.58			3.05		4	0.092	0.485	81.5
CEM2-(Afm)Oxy-CaL	0.51			2.46		15	0.075	0.457	84.9
CEM2-(BMW)	0.29				2.77	3	0.342		31.4
CEM2-(BMW)MEA	0.69				4.47	5	-0.308	0.650	161.8
CEM2-(BMW)CaL	0.51				2.77	25	-0.188	0.530	137.7
CEM2-(BMW)Oxy-MEA	0.65				3.16	4	0.020	0.706	96
CEM2-(BMW)Oxy-CaL	0.58				2.77	16	0.014	0.665	97.2
LC3-(Coal)	0.30	1.81				3	0.399		19.9
LC3-(Coal)MEA	0.55	3.25				4	0.104	0.417	79.1
LC3-(Coal)CaL	0.44	1.81				17	0.065	0.334	87.0
LC3-(Coal)Oxy-MEA	0.61	2.50				4	0.081	0.483	83.7
LC3-(Coal)Oxy-CaL	0.52	1.82				12	0.063	0.414	87.4
LC3-(NG)	0.30		1.84			3	0.347		30.3
LC3-(NG)MEA	0.50		2.99			4	0.082	0.329	83.5
LC3-(NG)CaL	0.42		1.84			15	0.057	0.291	88.6
LC3-(NG)Oxy-MEA	0.67		2.54			4	0.085	0.521	82.9
LC3-(NG)Oxy-CaL	0.57		1.85			12	0.066	0.442	86.8
LC3-(Afm)	0.30			2.13		3	0.411		17.5
LC3-(Afm)MEA	0.54			3.12		4	0.098	0.391	80.3
LC3-(Afm)CaL	0.44			2.13		17	0.067	0.344	86.6
LC3-(Afm)Oxy-MEA	0.52			2.46		4	0.068	0.367	86.4
LC3-(Afm)Oxy-CaL	0.47			2.13		12	0.056	0.352	88.8
LC3-(BMW)	0.30				2.40	3	0.244		51

LC3-(BMW)MEA	0.60				3.62	5	-0.256	0.500	151.4
LC3-(BMW)CaL	0.47				2.40	21	-0.171	0.415	134.3
LC3-(BMW)Oxy-MEA	0.57				2.56	4	0.010	0.545	98
LC3-(BMW)Oxy-CaL	0.53				2.40	12	0.004	0.532	99.2
AIDRES EU-mix-2030	0.32	1.03	0.00	0.78	0.61	4	0.433	0.071	13.2
AIDRES EU-mix-2050	0.54	0.27	0.03	1.06	1.59	12	0.034	0.501	93.2

Figure 22 and Figure 23 show the energy flows in [GJ/t] for Portland cement II and LC3 routes of the AIDRES EU mix and Figure 50 and Figure 51 (Annex 0) the specific investment cost in [EUR/t].

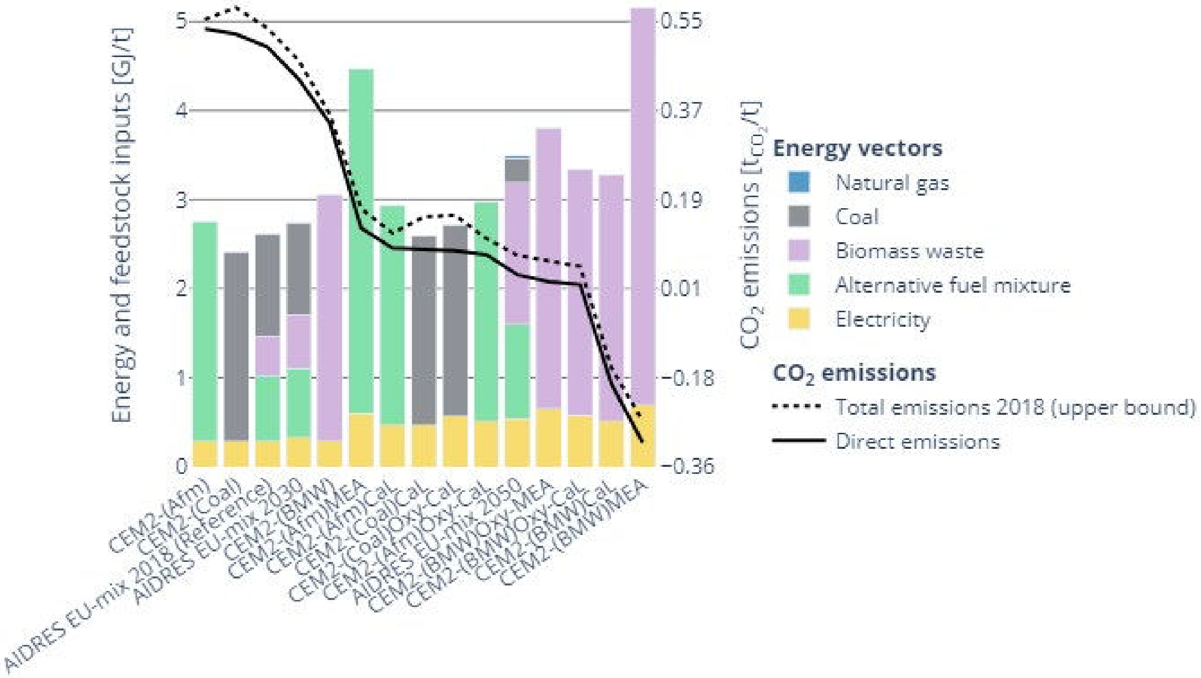


*Figure 22: Energy and feedstock flows [GJ/t] and emissions [tCO_2/t] for **Portland cement II** production routes.*

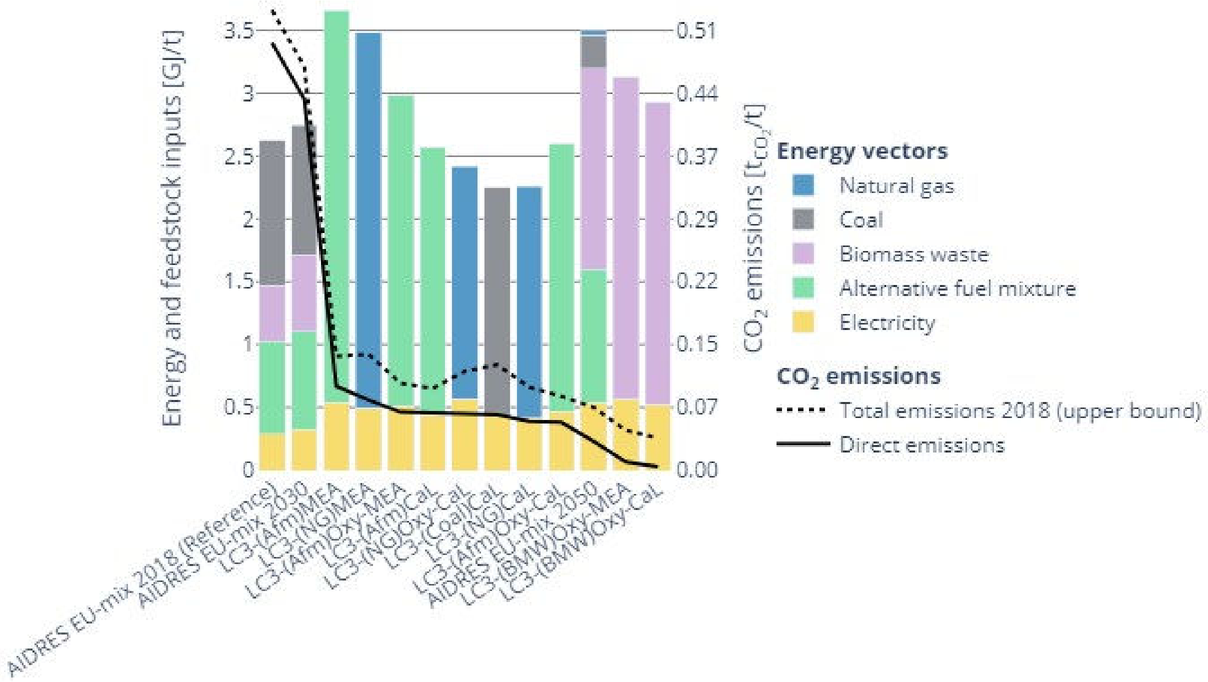


*Figure 23: Energy and feedstock flows [GJ/t], direct and total 2018 emissions [tCO2/t] for **LC3** production routes.*

7. Glass

The glass sector has been structured in production routes using either natural gas (reference production route), hydrogen or electric furnaces with or without carbon capture technology. Hydrogen can be produced on site by an alkaline electrolyser (AEL) or purchased on the market.

7.1. Model

Fibre glass consists out of roughly 10% of the total output whereas most glass products are container or hollow (60%) and flat glass (30%). The high temperature requirements of the process are limiting the available options. Natural gas (NG) or hydrogen (H_2) can be used to satisfy the heating demand. Electric melting furnaces have also been considered with an efficiency of 93% and a cost based on equipment recently installed. A flow-chart of the glass production routes and processes is shown in Figure 24.

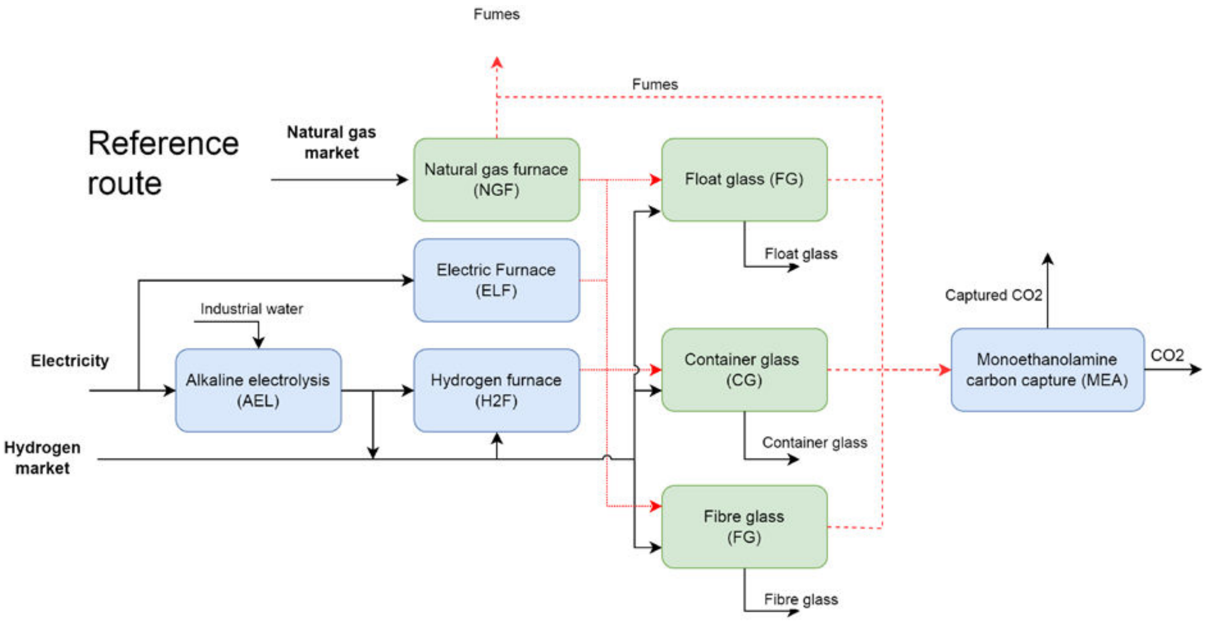


Figure 24: Glass production routes flow-chart.

A list of glass production components, which are used in the AIDRES model, is presented in Table 17 along with investment cost parameters. Reference costs for the glass industry can be found in a study of Scalet et al. (2013). Carbon capture (MEA) and furnaces processes are computed based on studies from Plaza, Martínez, and Rubiera (2020) and Schorcht et al. (2013).

Table 17: Overview of AIDRES glass production processes.

Abbreviation	Process	Cost [EUR]	Size	Year	Source
AEL	Alkaline Electrolysis	329	1 kW_{H_2}	2020	(Limpens et al. 2019; International Energy Agency (IEA) 2019)
Container	container glass plant	26.5	1 $t_{container}$	2016	(Usbeck, Pflieger, and Sun 2011)
ELF	EL Furnace	4890	1 kW	2020	
Fibre	Fibre glass plant	22.7	1 t_{fibre}	2016	(Usbeck, Pflieger, and Sun 2011)
Float	Float glass plant	26.5	1 t_{float}	2004	(Usbeck, Pflieger, and Sun 2011)
MEA	Mono-ethanolamine carbon capture	53’172’000	75’240 kg_{CO_2}/h	1994	(Hendriks 2012)

7.2. Container glass

7.2.1. Production routes methodology

The European glass federations and their reports, which were consulted several times during the AIDRES project, did not provide a straightforward starting point. For instance, Glass for Europe suggests that up to 75% of production emissions can be reduced by switching to carbon-free energy, while implementing CCUS can further reduce emissions by up to 93% (Glass for Europe 2020). Similarly, the European Container Glass Federation (FEVE) emphasizes the importance of decarbonizing furnaces by exploring the use of hydrogen, electricity, and biomass (FEVE 2023). As a result, the sector has embarked on innovative solutions and pilot projects that allow for partial or full electrification of furnaces (FEVE 2020). In alignment with the glass sector federations mentioned above, companies are starting to explore partial electrification of furnaces and other processes when suitable (AGC and Saint-Gobain 2023).

Although federations and companies do not offer a definitive production route or a mix of technologies for 2050, it is important to note that up to 25% of emissions are due to raw materials, or so-called process emissions. Therefore, applying carbon capture is necessary to achieve emissions reductions beyond 75%. Since there is no preference for technologies in the consulted reports, the starting point was defined as a technology-agnostic even distribution. Meaning, the same participation of each technology category: CCUS, hydrogen and electricity. Nonetheless, the CCUS category includes the implementation of carbon capture units along with fuel switching. With this even-distribution approach the emission reduction target of 2050 lands at 93%. The share of the CCUS production routes is slightly increased in such a way to reach the emissions reduction target of 2050, while maintaining the share of hydrogen and electricity at the same level, which is in line with the partial electrification pathways, currently explored in the glass sector.

Table 18: AIDRES EU mix container glass production routes categories in 2050.

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction[%]
NG-CC	CCS	73.4	0	3.5	24.5	0.011	96.7
H2-CC			0	3.5	24.5	0.002	99.4
Electricity-CC			0	3.5	24.5	0.002	99.4
Electricity	Electrification	13.3	0	1.9	13.3	0.073	78.4
H_2	Hydrogen	13.3	0	1.9	13.3	0.073	78.4
AIDRES EU-mix-2050	EU-mix	100	0	14.1	100	0.023	93.2

AIDRES EU mix container glass production routes are obtained by weighing single production routes. Starting from the reference cases, the proposed mixed routes are equally distributed within similar production categories meeting direct emission reduction targets by 2050 allowing to reach a global 93.2% reduction by 2050 (Table 18 and Figure 25).

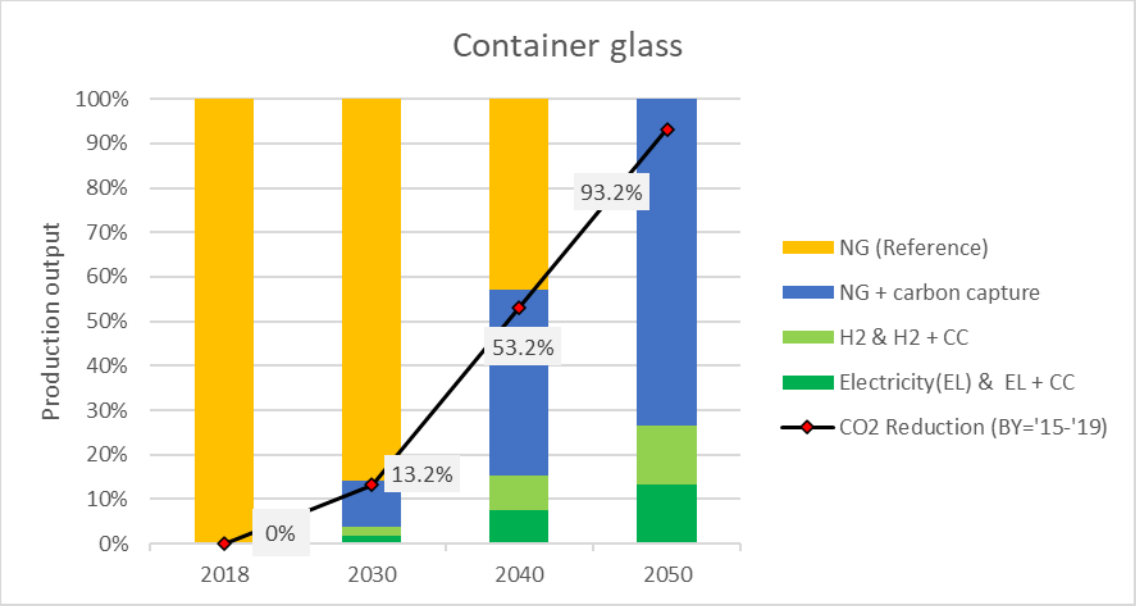


Figure 25: AIDRES EU mix production categories for container glass towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets.

7.2.2. Production route results

For container glass, Table 19 gives the reference and the typical production routes. Figure 26 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 52 (Annex 0) the specific investment cost in [EUR/t].

Table 19: Energy flows, investment costs, emissions and captured CO_2 per ton of container glass.

Production routes	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	CAPEX [EUR/t]	Direct emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
NG (REF)	1.07	0.04	4.73	53	0.338		
NG-CC	1.13	0.04	4.73	55	0.011	0.097	96.7
H_2	1.07	5.04		55	0.073		78.4
H_2-CC	1.08	5.04		55	0.002	0.021	99.4
H_2-AEL	8.64			68	0.073		78.4
H_2-AEL-CC	8.65			68	0.002	0.021	99.4
Electricity	5.09	0.04		50	0.073		78.4
Electricity -CC	5.10	0.04		51	0.002	0.021	99.4
AIDRES EU-mix-2030	1.29	0.31	4.23	53	0.294	0.005	13.2
AIDRES EU-mix-2050	2.61	1.93	1.16	53	0.023	0.034	93.2

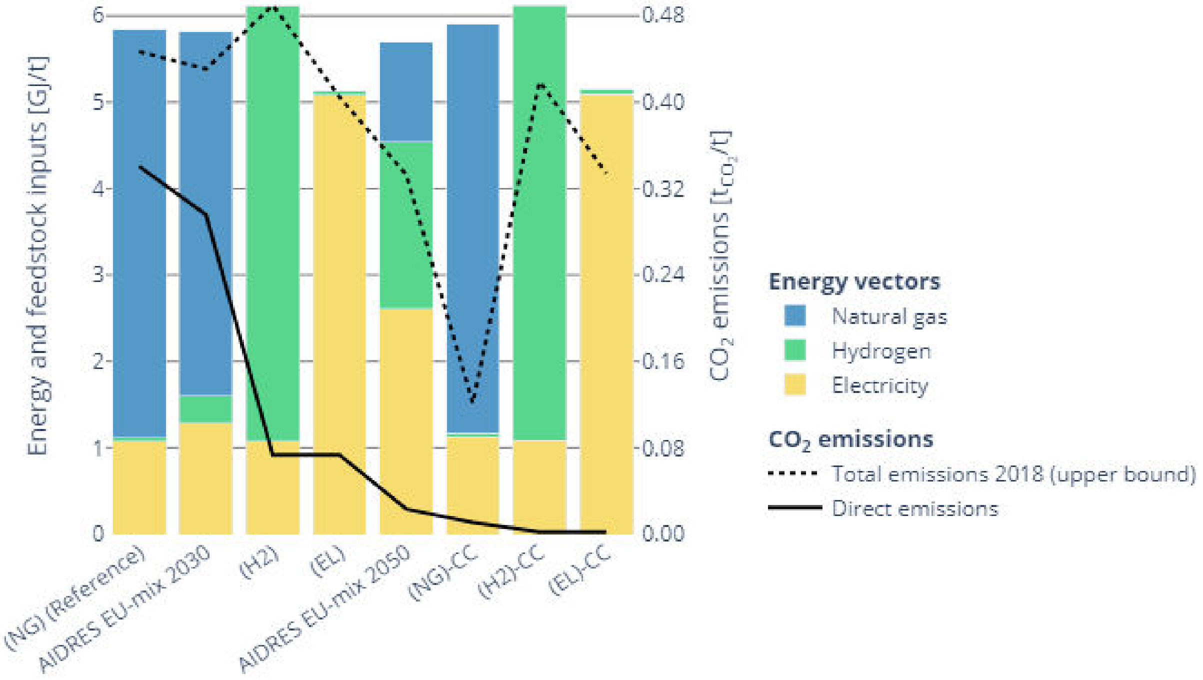


*Figure 26: Energy and feedstock flows [GJ/t] and emissions [tCO2/t] for **container glass** production routes.*

7.3. Flat glass

7.3.1. Production routes methodology

AIDRES EU Mix flat glass production routes are obtained by weighting single production routes. Starting from the reference case, the proposed mixed routes are equally distributed within similar production categories meeting direct emission reduction targets by 2050 allowing to reach a global 93.2% reduction by 2050 (Table 20 and Figure 27).

Table 20: AIDRES EU mix flat glass production routes categories in 2050 meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
NG-CC	CCS	86.1	0	4.1	28.7	0.016	96.7
H2-CC			0	4.1	28.7	0.006	98.8
Electricity-CC			0	4.1	28.7	0.006	98.8
Electricity	Electrification	6.9	0	1	6.9	0.182	62.6
H_2	Hydrogen	6.9	0	1	6.9	0.182	62.6
AIDRES EU-mix-2050	EU-mix	100	0	14.1	100	0.033	93.2

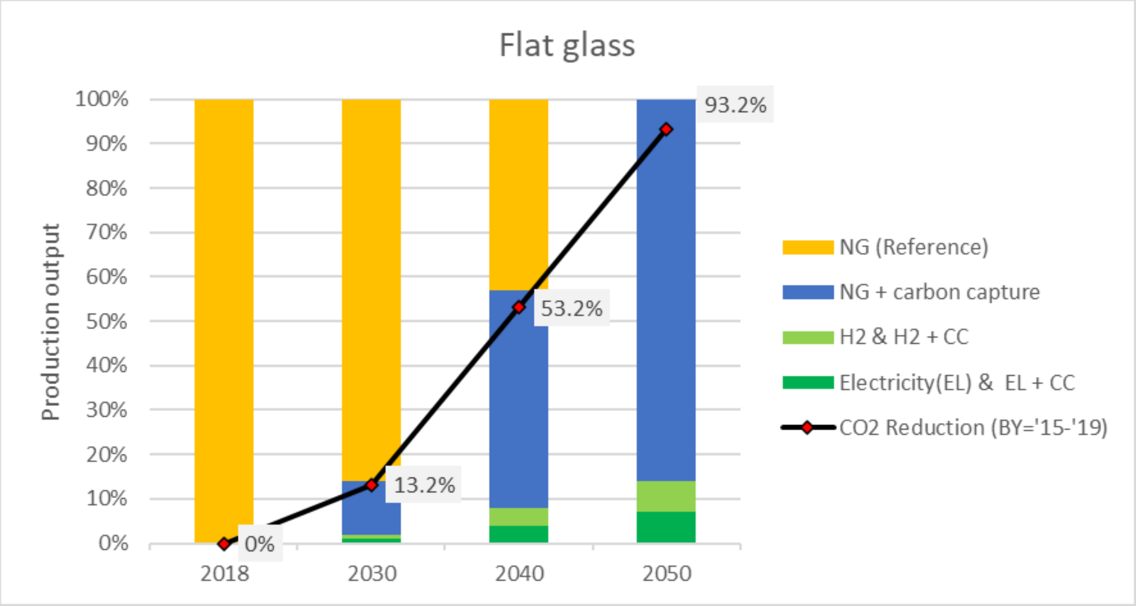


Figure 27: AIDRES EU mix production categories for flat glass towards 2050, meeting EU F55 MIX scenario derived emission reduction targets.

7.3.2. Production route results

For flat glass, Table 21 gives the reference and the typical production routes. Figure 28 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 53 (Annex 0) the specific investment cost in [EUR/t].

Table 21: Energy flows, investment costs, emissions and captured CO_2 per ton of flat glass.

Production routes	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
NG (REF)	0.80	0.04	5.43	61	0.487		
NG-CC	0.88	0.04	5.43	64	0.016	0.14	96.7
H_2	0.80	5.78		63	0.182		62.6
H_2-CC	0.83	5.78		64	0.006	0.052	98.8
H_2-AEL	9.48			78	0.182		62.6
H_2-AEL-CC	9.51			79	0.006	0.052	98.8
Electricity	5.41	0.04		58	0.182		62.6
Electricity -CC	5.44	0.04		59	0.006	0.052	98.8
AIDRES EU-mix-2030	1.04	0.33	4.88	61	0.423	0.01	13.2
AIDRES EU-mix-2050	2.49	2.09	1.56	62	0.033	0.07	93.2

The energy resource per ton of product is given in Figure 28. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

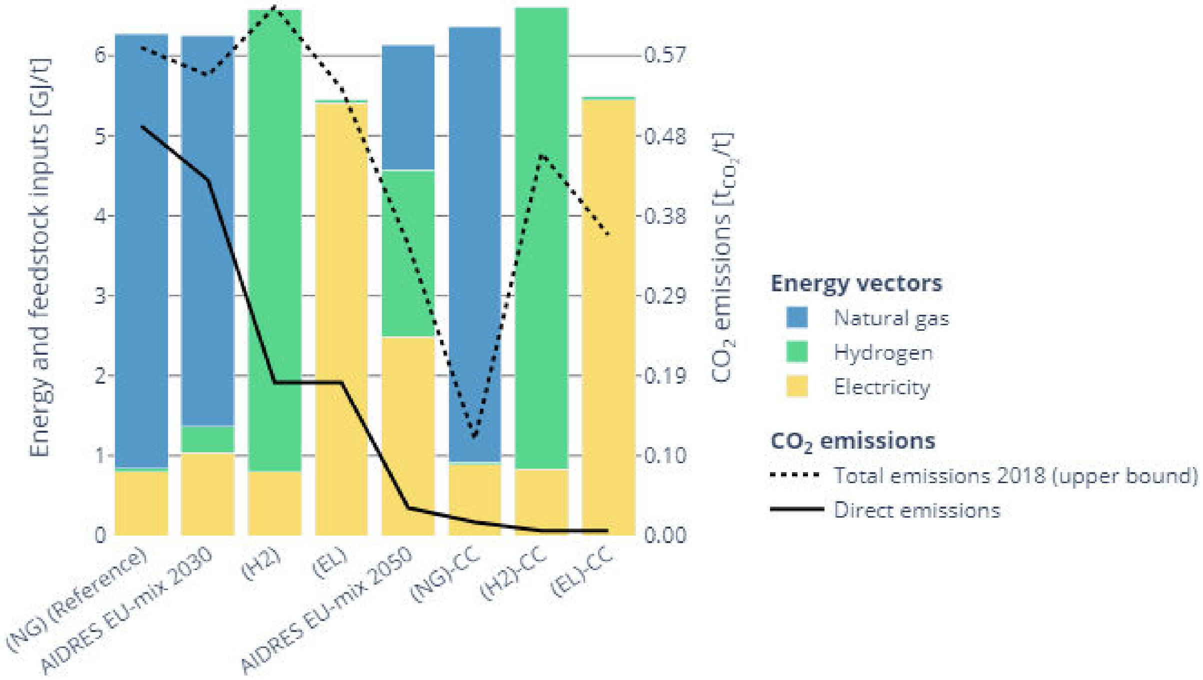


*Figure 28: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **flat glass** production routes.*

7.4. Fibre glass

7.4.1. Production routes methodology

AIDRES EU Mix fibre production routes are obtained by weighting single production routes. Starting from the reference case, the proposed mixed routes are equally distributed within similar production categories meeting direct emission reduction targets by 2050 allowing to reach a global 93.2% reduction by 2050 (Table 22 and Figure 29).

Table 22: AIDRES EU mix fibre glass production routes categories in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
(NG)-CC	CCS	85.2	0	4.0	28.4	0.020	96.8
(H2)-CC			0	4.0	28.4	0.007	98.9
(EL)-CC			0	4.0	28.4	0.007	98.9
(H2)	Hydrogen	14.8	0	2.1	14.8	0.227	64.2
EU-mix-2050	EU-mix	100	0	14.1	100	0.043	93.2

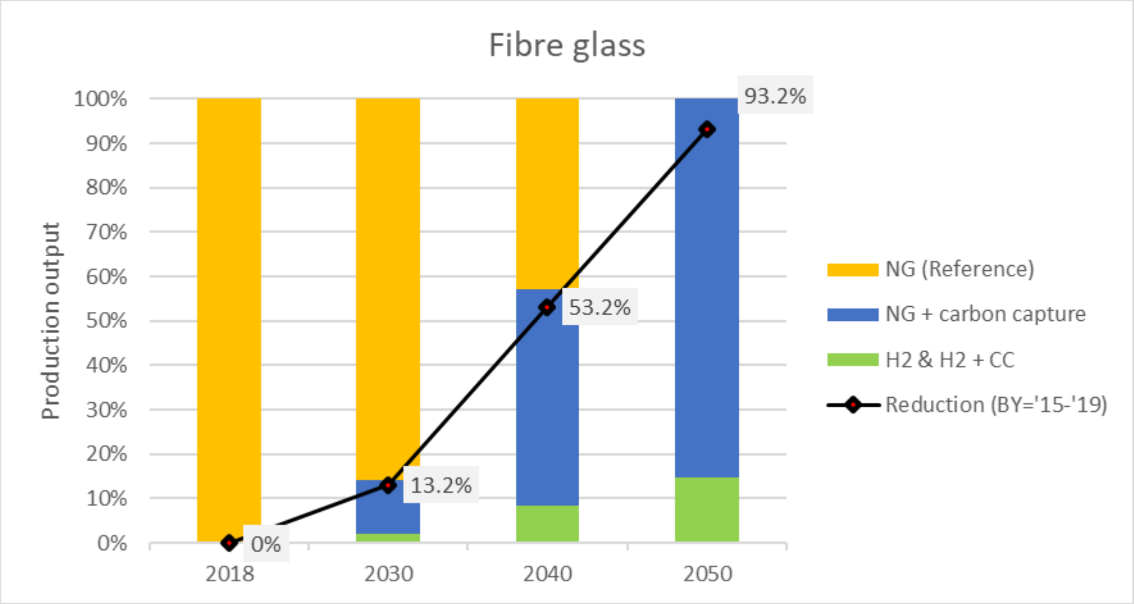


Figure 29: AIDRES EU mix production categories for fibre glass towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets.

7.4.2. Production route results

For fibre glass, Table 23 gives the reference and the typical production routes. Figure 30 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 54 (Annex 0) the specific investment cost in [EUR/t].

Table 23: Energy flows, investment costs, emissions and captured CO_2 per ton of fibre glass.

Production routes	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
NG (REF)	2.16	0.04	7.24	80	0.634		
NG-CC	2.27	0.04	7.24	84	0.020	0.183	96.8
H_2	2.16	7.17		77	0.227		64.2
H_2-CC	2.20	7.17		79	0.007	0.066	98.9
H_2-AEL	12.92			96	0.227		64.2
H_2-AEL-CC	12.96			97	0.007	0.066	98.9
Electricity	7.89	0.04		71	0.227		64.2
Electricity -CC	7.93	0.04		72	0.007	0.066	98.9
AIDRES EU-mix-2030	2.40	0.48	6.51	80	0.551	0.013	13.2
AIDRES EU-mix-2050	3.84	3.12	2.06	78	0.043	0.089	93.2

The energy resource per ton of product is given in Figure 30. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

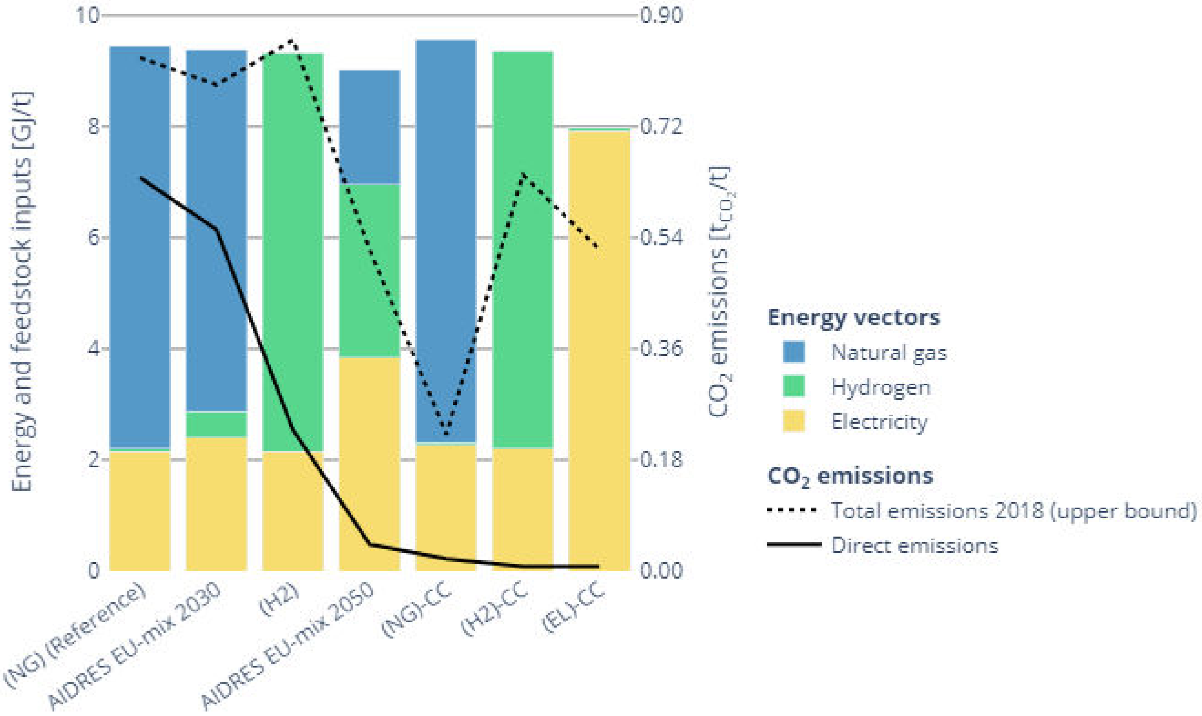


*Figure 30: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **fibre glass** production routes.*

8. Fertiliser

The fertiliser sector has been structured in four routes to produce ammonia, ammonia + urea and ammonia + urea + nitric acid. The production routes are using either natural gas with and without carbon capture, biomass or electricity.

8.1. Model

The reference production route is a conventional natural gas-based ammonia production plants (Figure 31), which is equipped with efficient energy integration networks able to recover the waste heat available throughout the chemical system (Daniel Flórez-Orrego et al. 2020). Alternative routes use biomass gasification or nitrogen and hydrogen (H2)NH3 for replacing methane in the integrated ammonia production plant (Daniel Flórez-Orrego, Maréchal, and de Oliveira Junior 2019). Hydrogen is either produced at the plan using alkaline electrolyser (AEL) or imported from the market. In both cases, mechanical vapor recompression (MVR) can be integrated to recycle waste heat, thus lowering the natural gas demand and direct emissions.

Hydrogen is either coming from the market: grey and green hydrogen (Table 24) or alternatively produced on-site by alkaline electrolysis (AEL).

Ammonia process emissions is a particular case where CO_2 used for urea, which is captured by necessity from the SMR syngas, is accounted as direct emissions at the plant and not as captured CO_2 (CSS). The CO_2 in surplus from the gas purification unit is send to the market e.g.: beverages, plastics, slaughterhouses and accounted as direct emission. The routes integrating diethanolamine carbon capture of CO_2 from the gas purification unit are labelled with (DEA), while the routes with CCS on the furnace using mono-ethanolamine carbon capture are labelled with (MEA).

Accounting and mitigation of the greenhouse gas emissions effects of nitrogen dioxide (NO_2) for the nitric acid production routes is out of the scope of the AIDRES project.

A flow-chart of the fertiliser production routes and processes is shown in Figure 31.

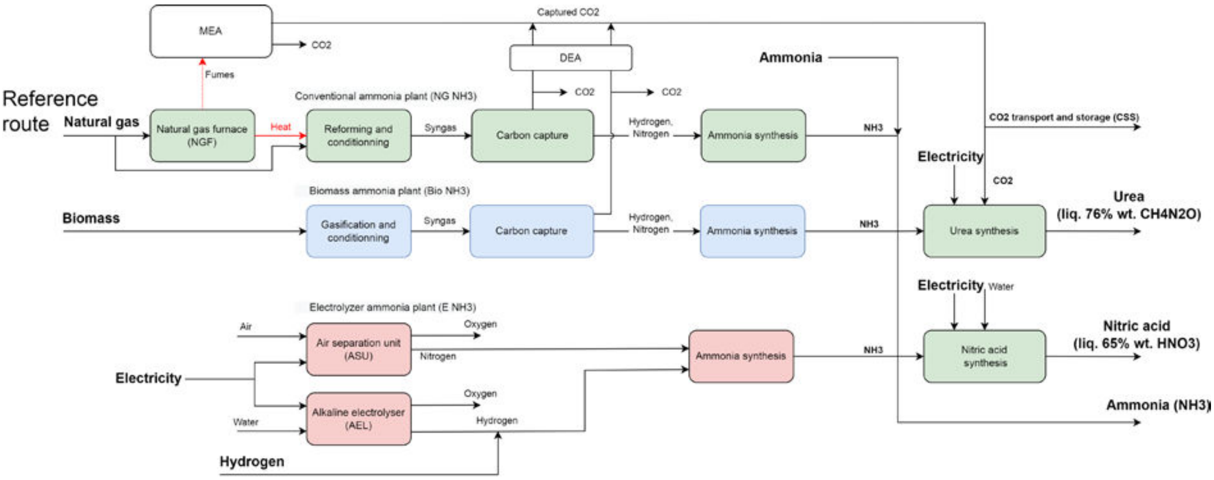


Figure 31: Fertiliser production routes flow-chart

The AIDRES ammonia production routes and scenarios options in the perspective of CO_2-emission reduction of hydrogen feedstock for 2030 in Europe (Ausfelder, Herrmann, and López González 2022), are given in Figure 46 (Annex 12.7.4), are given in Table 24.

Table 24: Technology options of ammonia production routes and scenarios in AIDRES.

Production route	Scenario 0	Scenarios 1-8
(NG) NH_3	grey H_2	grey H_2
(NG) NH_3-MVR	grey H_2	grey H_2
(NG) NH_3-MEA	blue H_2	blue H_2
(NG) NH_3-MVR-MEA	blue H_2	blue H_2
(NG) NH_3-MEA-DEA	blue H_2	blue H_2
(NG) NH_3-MVR-DEA	blue H_2	blue H_2
(NG) NH_3-MVR-MEA-DEA	blue H_2	blue H_2
(H_2) NH_3	yellow H_2	green H_2
(H_2) NH_3-AEL	yellow H_2, produced on-site	green H_2, produced on-site
(BM) NH_3	green H_2	green H_2
(BM) NH_3-DEA	green H_2, negative emissions	green H_2, negative emissions

A list of fertiliser production components, which are used in the AIDRES model, is presented in

Table 25 along with investment cost parameters. Reference costs for the fertiliser industry can be found in (D. Flórez-Orrego 2018; Bartels 2008; Arora et al. 2017; Domingos et al. 2021).

The CAPEX is modelled for the whole the plant (syngas production unit, gas purification unit, ammonia conversion, steam network and cooling). A study from the IEA (International Energy Agency 2021) reveals a large spread in investment costs for this type plants (Figure 45, Annex 12.7.4). In our approach, the bare module cost, accounting for the steam network of ammonia, nitric acid and urea plants, has been selected from the worst-case scenarios (BM=2).

Table 25: Overview of AIDRES fertiliser production processes

Abbreviation	Process	Cost [EUR]	Size	Year	Source
Bio NH3	Ammonia plant biomass	1’861’500’000	48 t_{NH_3}/h	2018	(D. Flórez-Orrego 2018)
CoolEl	Cooling tower	15.1	1 KW_{th}	2008	
WSU	Ammonia plant electrolyser	2’000	1.0 kW	2008	(Ball and Weeda 2016)
HNO_3	Nitric acid plant	216’600’000	57 t_{HNO_3}/h	2020	(Luck 2021)
MEA	Mono-ethanolamine Carbon Capture	53’172’000	75’240 kg_{CO_2}/h	2007	(Hendriks 2012)
MVR	Mechanical vapor recompression	integrated			
NG NH3	Ammonia plant conventional	613’200’000	41.60 t_{NH_3}/h	2008	(Bartels 2008)
RefrEl	Refrigerator	5’000’000	25’000 KW_{th}	2013	
STNU	Steam network	integrated			
UREA	Urea plant	56’100’000	58 t_{urea}/h	1981	(Daniel Flórez-Orrego and de Oliveira Junior 2017; World Bank Group, n.d.; H. Zhang et al. 2021)

8.2. Ammonia

8.2.1. Production routes methodology

Fertiliser products included in AIDRES are ammonia and derivatives as a separate industrial sector, though often fertilisers are part of the chemical sector. The decarbonization alternatives strongly depend on the ammonia production route. Heat demand in the production of derivatives might also be replaced with low-carbon energy sources. This leads to three main options to decarbonize ammonia and satisfy the heat demand in fertilisers production, being CCUS (blue ammonia), low carbon hydrogen (green ammonia) or sustainable biomass-based ammonia.

The IEA estimates that hydrogen will dominate future ammonia production, accounting for roughly 70% of the production in EU. The remaining 30% is covered by the traditional SMR route, partially coupled with CCUS, and pyrolysis (International Energy Agency 2021). In the same report, the role of biomass is limited for the global production mix. However, biomass alternatives are being explored, which could make it possible to see this production route in selected EU countries with access to sustainable biomass. The technology mixed defined by IEA renders an emissions reduction of 86%, which is still below the AIDRES sector target of 96%. To meet the AIDRES chemical and fertiliser sectors emission reduction target, different weights were given to H_2 based production routes.

Table 26: AIDRES EU mix ammonia production routes categories in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
(BM)NH3	Biomass	5	0	1.5	5	0	100
(NG) NH_3-DEA	CCS	23	0	1.8	5.8	0.322	81.5
(NG) NH_3-MEA-DEA			0	1.8	5.8	0.04	97.7
(NG) NH_3-MVR-DEA			0	1.8	5.8	0.202	88.4
(NG) NH_3-MVR-MEA-DEA			0	1.8	5.8	0.02	98.9
(H2) NH_3	Hydrogen	70	0	21.4	70	0	100
(NG)N NH_3H3	Reference	2	100	70	2	1.742	0
AIDRES EU-mix-2050	EU-mix	100	100	100	100	0.068	96.1

AIDRES mixed ammonia production routes are obtained by weighing single production routes. Starting from the reference case, the proposed mixed routes are equally distributed within categories having direct emission reduction targets by 2050 allowing to reach a global 96% reduction by 2050 (

Table 26 and Figure 32).

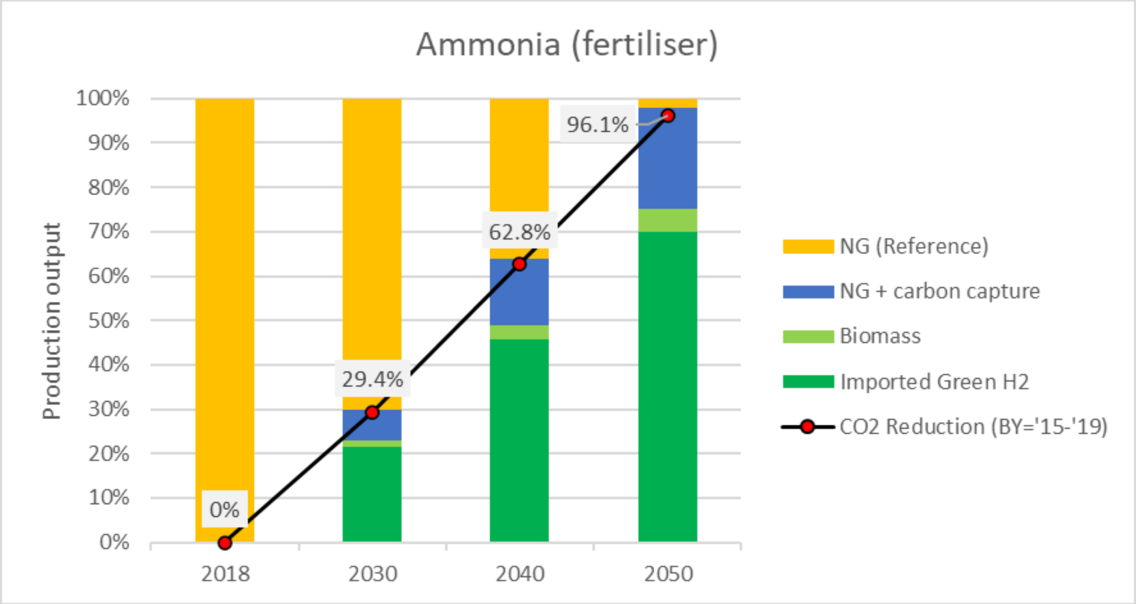


Figure 32: AIDRES EU mix production categories for ammonia towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

8.2.2. Production route results

In a conventional plant, ammonia is produced from a mixture of nitrogen and hydrogen in a stoichiometric proportion of 3:1 from water, natural gas and air.

Table 27 gives the ammonia reference and the typical production routes. Figure 33 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 55 (Annex 0) the specific investment cost in [EUR/t].

Table 27: Energy flows, investment costs, emissions and captured CO_2 per ton of ammonia.

Production route	Electricity [GJ/t]y	Hydrogen [GJ/t]y	Natural gas [GJ/t]y	Biomass [GJ/t]y	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
(NG) NH3-REF	2.08		28.33		127	1.742		
(NG) NH3-MEA	2.16		29.69		255	1.46	0.359	16.2
(NG) NH3-DEA	2.08		28.33		127	0.322	1.42	81.5
(NG) NH3-MEA-DEA	2.16		29.69		255	0.04	1.779	97.7
(NG) NH3-MVR	2.14		26.19		104	1.622		6.9
(NG) NH3-MVR-MEA	2.58		26.19		162	1.440	0.182	17.3
(NG) NH3-MVR-DEA	2.14		26.19		104	0.202	1.420	88.4
(NG) NH3-MVR-MEA-DEA	2.58		26.19		162	0.020	1.602	98.9
(BM) NH3	4.46			40.52	170			100
(BM) NH3-DEA	4.46			40.52	170	-2.557	2.557	246.8
(H_2) NH3	3.40	23.06			577			100
(H_2) NH3-AEL	38.03				704			100

AIDRES EU-mix-2030	2.41	4.94	21.77	0.62	227	1.229	0.11	29.4
AIDRES EU-mix-2050	3.16	16.14	6.91	2.03	452	0.068	0.358	96.1

The energy resource per ton of product are given in Figure 33. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

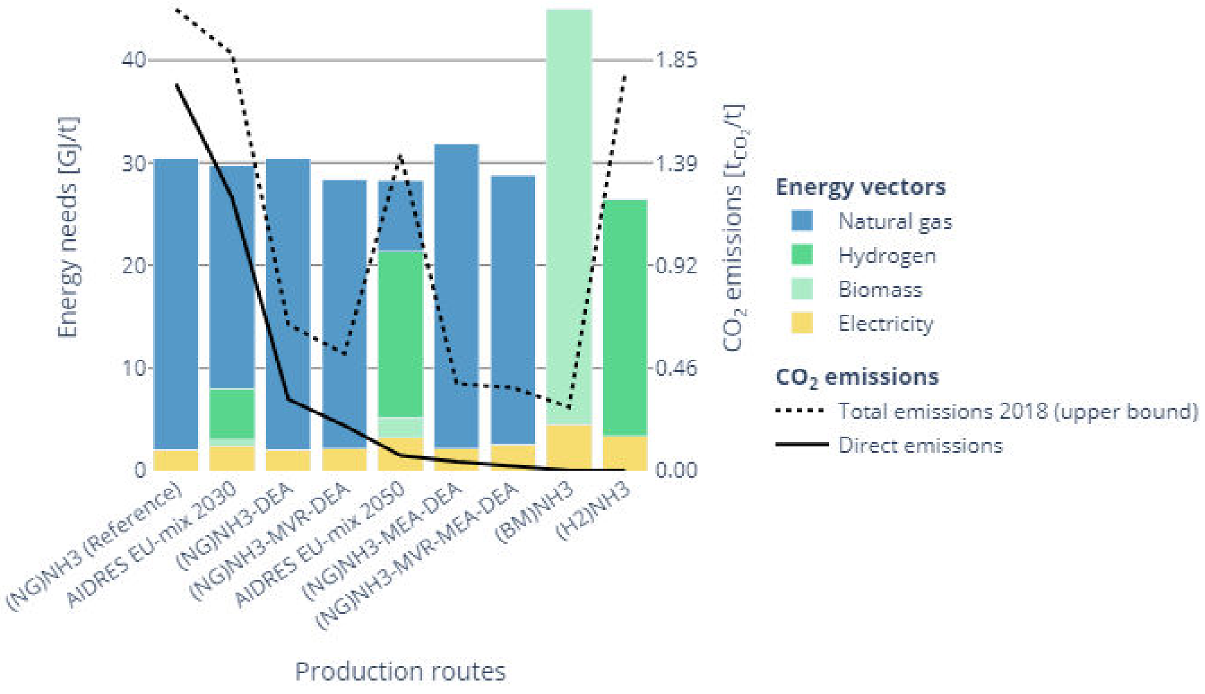


*Figure 33: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **ammonia** production routes.*

8.3. Urea

8.3.1. Production route results

For urea, Table 28 gives the reference and the typical production routes.

Table 28: Energy flows, investment costs, emissions and captured CO_2 per ton of urea.

Production route	Electricity [GJ/t]y	Hydrogen [GJ/t]y	Natural gas [GJ/t]y	Biomass [GJ/t]y	Ammonia [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
(NG) Urea-REF	0.82		14.88			33	0.186		
(NG) Urea-MEA	0.90		14.86			66	0.082	0.103	55.9
(NG) Urea-DEA	0.82		14.88			33	0.116	0.07	37.6
(NG) Urea-MEA-DEA	0.90		14.86			66	0.011	0.173	94.1
(BM) Urea	1.74			22.99		11			100
(BM) Urea-DEA	1.74			22.99		11	-1.451	1.451	880.1

(H$_2$) Urea	2.	13.09				11			100
(H$_2$) Urea-AEL	21.65					83			100
(NH$_3$) Urea	0.07				10.73	11			100

8.4. Nitric acid

8.4.1. Production route results

For nitric acid, Table 29 gives the reference and the typical production routes.

Table 29: Energy flows, investment costs, emissions and captured CO$_2$ per ton of urea.

Production route	Electricity [GJ/t]y	Hydrogen [GJ/t]y	Natural gas [GJ/t]y	Biomass [GJ/t]y	Ammonia [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO$_2$/t]	Captured CO$_2$ [tCO$_2$/t]	Direct emissions reduction [%]
(NG) HNO$_3$			6.5			30	0.409		
(NG) HNO$_3$-DEA			6.5			30		0.409	100
(BM) HNO$_3$				11.66		30			100
(BM) HNO$_3$-DEA				11.66		30	-0.736	0.736	280
(H$_2$) HNO$_3$		6.64				30			100
(H$_2$) HNO$_3$-AEL	9.27					67			100
(NH$_3$) HNO3					5.44	30			100
AIDRES EU-mix-2030		0.8	5.2	0.93		30	0.289	0.039	29.4
AIDRES EU-mix-2050		2.61	2.26	3.03		30	0.016	0.126	96.1

9. Chemical

The chemicals sector in the EU is highly complex and encompassing bulk chemical manufacturing, especially chemicals for the pharmaceutical industry and plastics production. This part of the study considers the production of three main products: olefins, polyethylene and poly-ethyl-acetate. The olefins include ethylene, propylene and other olefins products. Ethylene is an intermediate in the production of poly-ethyl-acetate and polyethylene. The production of methanol from biomass and co-electrolysis are two pathways considered in the model

9.1. Model

Three different routes are considered to produce olefins: naphtha, for the reference route, and methanol synthetized from either renewable green biomass gasification or from the co-electrolysis of carbon dioxide and water.

The reference case for the chemical sector uses light naphtha (LN) to produce Poly-ethyl-acetate (PE), ethylene and Propylene. The alternative route (LN+EL) uses an electrical furnace to provide heat for the naphtha cracking, thus avoiding direct emissions from combustion.

Methanol is either imported from the market in the form of grey methanol from steam reforming process or is produced in the EU from biomass (BM-MeOH) or by co-electrolysis (COEL-MeOH) using CO_2 from the market. One burner is included for the off-gas during the methanol synthesis and upgrading process. Crude methanol is directly fed into a methanol-to-olefin reactor with oxygen (Hannula and Arpiainen 2015). Four products are then recovered: ethylene, butene, propylene and other olefins (Xiang et al. 2015). The model is designed for a production of 600 kt of ethylene per year.

Polyethylene (PE) production is modelled using four main units: preheating of the reactant's ethylene, hydrogen used as chain-transfer agent and nitrogen, to 70°C. In the next step, the polymerisation of ethylene in a slurry takes place, followed by recycling of unreacted liquid and gas reagents. Finally the intermediate product is quenched with water followed by extrusion (Falcke et al. 2017; Jeremic 2014; Maraschin 2005). The model was designed for a production of 25 tonnes of polyethylene per hour.

Ethyl-acetate is produced via the esterification of carboxylic acids (Riemenschneider and Bolt 2005). This is a process simulation whereby ethylene is reacted with acetic acid at 170°C to produce 15 tonnes per hour of ethyl-acetate. Following the initial reaction, the hot gases are cooled down to room temperature before being send to a separation section which consists of two flash drums in series to extract the unreacted ethylene from the hot gases and recycle it to a preheating unit. The acid is then recovered from the products and recycled. The product is purified and later polished to remove light and medium hydrocarbons. The light hydrocarbons are stripped of acetaldehyde and recycled whereas both the high and medium hydrocarbons are disregarded following heat exchange with other cooling process streams. Finally, ethanol and water are recovered from the water rich stream exiting purification and recycled. All process conditions are based on the blueprint model developed by (Cervo et al. 2020). The polymerization reaction requires cooling water and the injection of cold feedstock into the reactor to control temperatures between 150 and 200°C at pressures from 13 to 83 bar.

A flow-chart of the chemical production routes and processes is shown in Figure 34.

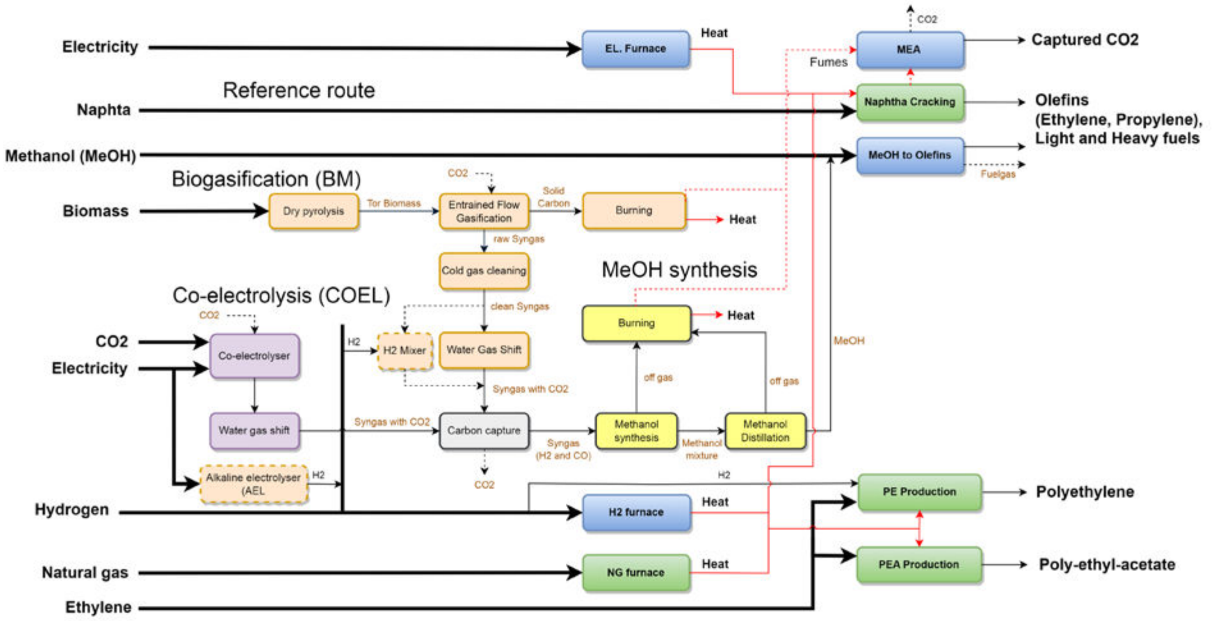


Figure 34: Chemical production routes flow-chart.

A list of chemical production components, which are used in the AIDRES model, is presented in Table 30 along with investment cost parameters. Reference costs for the chemical industry can be found in (Hannula and Arpiainen 2015; Yang and You 2017; EUROPEAN COMMISSION 2007; Šulgan, Labovský, and Labovská 2020). Cost function for the carbon capture technology (MEA) is derived from a method of (Plaza, Martínez, and Rubiera 2020).

Table 30: Overview of AIDRES chemical production processes.

Abbreviation	Process	Cost [EUR]	Size	Year	Source
MTO	Methanol to olefins	173’400’000	33’120 $kg_{ethylene}/h$	2013	(Hannula and Arpiainen 2015; Xiang et al. 2015)
MEA	Mono-ethanolamine carbon capture	53’117’988	75’261 kg_{CO_2}/h	2007	(Hendriks 2012)
NTO	Naphtha cracking	1’042’800’000	125’000 $kg_{ethylene}/h$	2017	(LASSC, n.d.)
PE	Polyethylene production	118’440’000	34’247 kg_{PE}/h	2007	(Falcke et al. 2017; Cervo 2020; Harding et al. 2007)
PEA	Polyethyl acetate production	8’324’400	880 kg_{PEA}/h	2020	(Hong Thuy et al. 2011)
Efuel-MEA	Mono-ethanolamine Carbon Capture	53’172’000	75’240 kg_{CO_2}/h	2011	(Plaza, Martínez, and Rubiera 2020; W. Zhang et al. 2016; Birat 2010)
Biogasi	Biomass Gasification Unit	4118	1’000 $ton_{biomass}/h$	2011	(Celebi et al. 2017; Celebi 2019)
COELEC	Co-electrolysis Unit	322	18’337 kW_{elec}/h	2011	(Celebi et al. 2017; Celebi 2019; Rubio-Maya et al. 2011; L. Wang et al. 2018)
FT	Fischer-Tropsch Unit	413	1’000 ton_{syngas}/h	2011	(Celebi et al. 2017; Celebi 2019)
MEOH	Methanol synthesis	816	1’000 ton_{syngas}/h	2011	(Celebi et al. 2017; Celebi 2019)

9.2. Olefins

9.2.1. Production routes methodology

The chemical sector in AIDRES consists of olefins, polymers and inorganics. Since olefins are linked to polymers, it was assumed the starting point for the definition of the chemical sector. In 2022, BloombergNEF (2022) published a study to decarbonize the petrochemical sector. This report identifies CCUS (41%), electrification of crackers (36%), methanol as feedstock (21%), bio-naphtha (1.5%) and others as part of the future global high-value chemicals production. Using this mix of technologies with AIDRES model results, the sector reaches an emissions reduction of 91%. Therefore, to reach the challenging target of the sector (96%), it was necessary to adjust the participation of each technology, reducing the share of CCUS and increasing the biomass and methanol alternatives, as each of these alternatives alone can go up to 100% or 94% of decarbonization levels respectively.

Table 31: AIDRES EU mix olefins production routes categories in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
(BM-MeOH) O	Biomass	23.7	0	3.6	11.9	0.000	100.0
(BM+H2-MeOH) O			0	3.6	11.9	0.000	100.0
(COEL-MeOH) O-MEA	Methanol (co-electrolysis)	31.1	0	9.5	31.1	0.059	93.9
(MeOH) O-MEA	Methanol (market)	31.1	0	9.5	31.1	0.015	98.4
(LN) O-MEA	Naphtha (CCS)	8.1	0	2.5	8.1	0.111	88.5
(LN+EL) O	Naphtha (electrification)	5.9	0	1.8	5.9	0.000	100.0
AIDRES EU-mix-2050	EU-mix	100.0	0	30.6	100.0	0.032	96.7

AIDRES EU mix production routes are obtained by weighing single production routes. Starting from the olefins reference case, the proposed mixed routes are equally distributed within categories having direct emission reduction targets by 2050 allowing to reach a global 96% reduction by 2050 (Table 31 and Figure 35).

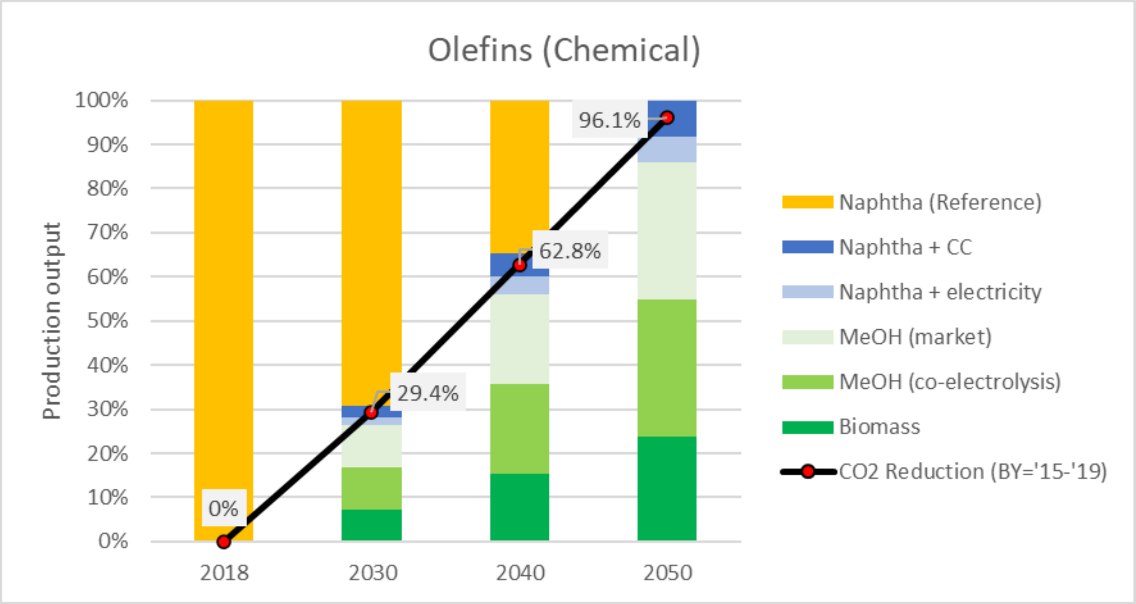


Figure 35: AIDRES EU mix production categories for olefins towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

9.2.2. Production route results

For olefins, Table 32 gives the reference and the typical production routes. Figure 36 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 56 (Annex 0) the specific investment cost in [EUR/t]. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

Table 32: Energy flows, investment costs, emissions and captured CO_2 per ton of olefins.

Production route	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	Naphtha [GJ/t]	Methanol [GJ/t]	Biomass [GJ/t]	CAPEX [EUR/t]	Direct emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
(LN) O (REF)	1.06			60.52			55	0.967		
(LN) O-MEA	2.68		2.61	60.52			88	0.111	1.002	88.5
(LN+EL) O	37.5			60.52			55			100
(MeOH) O	0.66				49.01		17	0.147		84.8
(MeOH) O-MEA	0.74				49.01		17	0.015	0.132	98.4
(BM-MeOH) O	5.62					96.08	246			100
(BM-MeOH)O-MEA	5.96					96.08	247	1.476	1.476	252.6
(BM+H_2-MeOH) O	5.51	17.93				93.02	117			100

(BM+H_2-MeOH) O-AEL	32.44					93.02	163			100
(BM+H_2-MeOH) O-MEA	5.85	17.93				93.02	118	-1.545	1.545	259.8
(BM+H_2-MeOH) O-MEA-AEL	32.77					93.02	164	-1.545	1.545	259.8
(COEL-MeOH) O	68.34						880	0.586		39.4
(COEL-MeOH) O-MEA	68.66						881	0.059	0.528	93.9
EU-mix-2030	8.50	0.65	0.07	44.59	4.67	6.86	140	0.681	0.088	29.6
EU-mix-2050	25.35	2.13	0.21	8.52	15.25	22.41	333	0.032	0.287	96.7

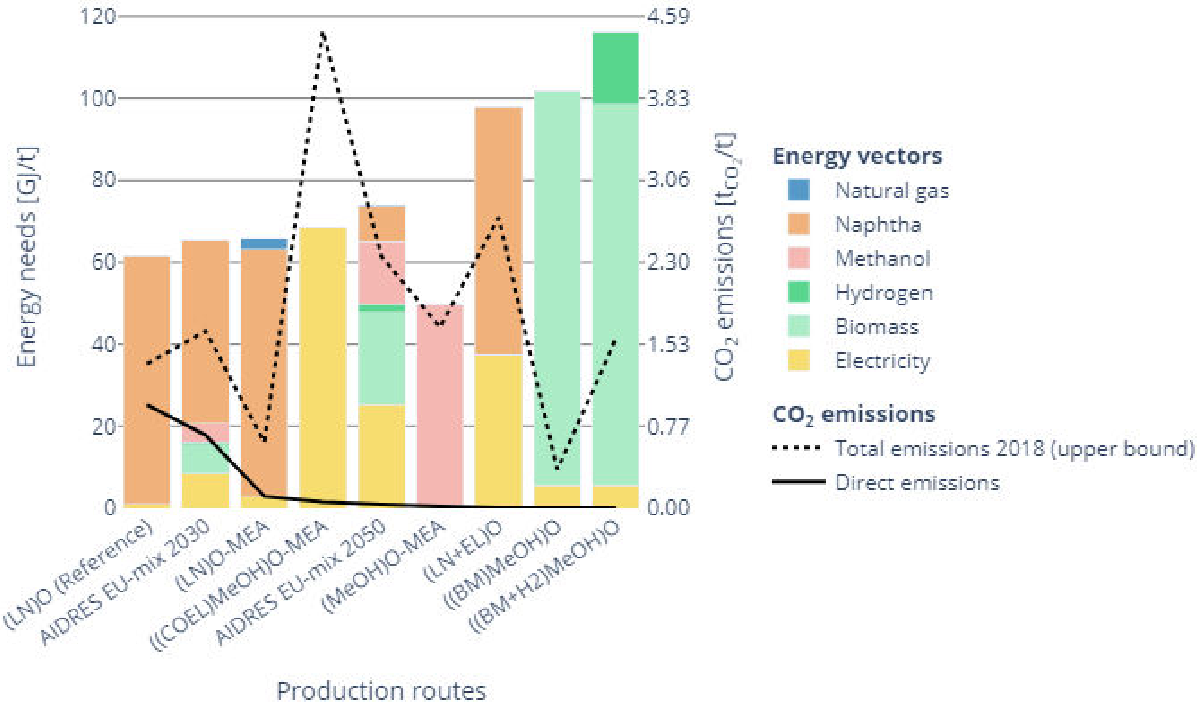


*Figure 36: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **olefins** production routes.*

9.3. Polyethylene

9.3.1. Production routes methodology

AIDRES mix production routes are obtained by weighing single production routes. Starting from the polyethylene reference case, the proposed mixed routes are equally distributed within categories having direct emission reduction targets by 2050 allowing to reach a global 96% reduction by 2050 (Table 33 and Figure 37).

Table 33: AIDRES EU mix production categories for polyethylene in 2050, meeting EU FF55 MIX scenario derived emission reduction targets

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
(NG)PE-MEA	CCS	31.3	0	9.6	31.3	0.002	87.5
(Electricity) PE	Electrification	34.4	0	10.5	34.4	0	100
(H_2) PE	Hydrogen	34.4	0	10.5	34.4	0	100
AIDRES EU-mix-2050	EU-mix	100.0	0	30.6	100.0	0.001	96.1

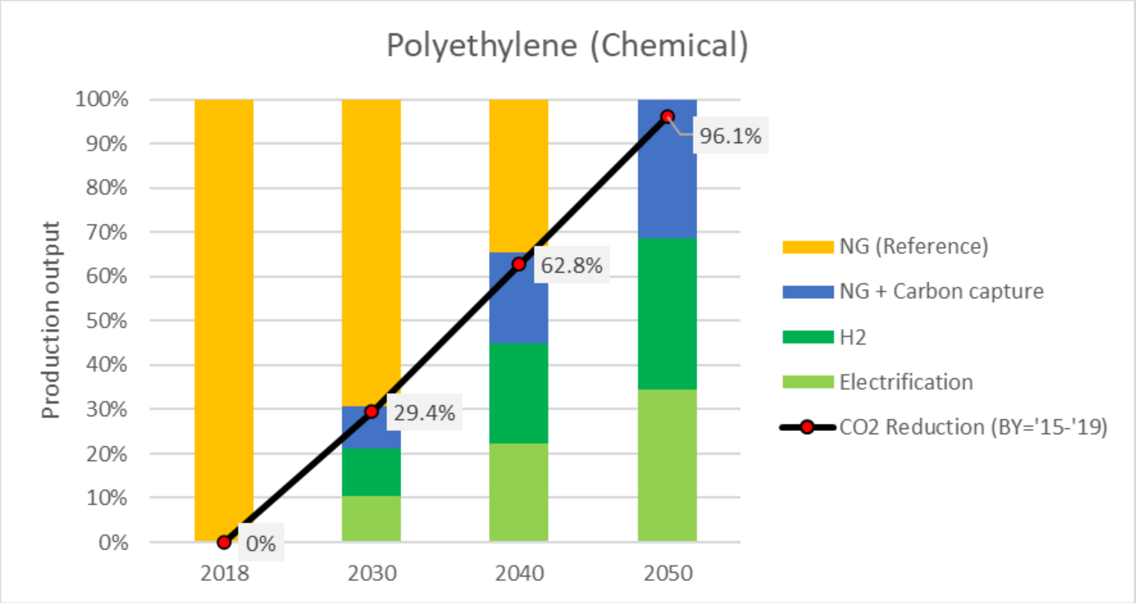


Figure 37: AIDRES EU mix production categories for polyethylene towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

9.3.2. Production route results

Polyethene has a small impact on energy demand, as it implies an exothermic reaction. However, it is very relevant for chemicals and plastic markets. Table 34 gives the reference and the typical production routes. Figure 38 shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 57 (Annex 0) the specific investment cost in [EUR/t].

Table 34: Specific energy flows, investment costs, emissions and captured CO_2 per ton of polyethylene.

Polyethene production route	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
(NG) PE-REF	0.49	0.01	0.29	37	0.016		
(NG) PE-MEA	0.50	0.01	0.30	37	0.002	0.015	87.5
(H_2) PE	0.49	0.31		37			100
(H_2) PE-AEL	0.96			38			100
(Electricity) PE	0.75	0.01		37			100
EU-mix-2030	0.52	0.04	0.23	37	0.011	0.001	29.4
EU-mix-2050	0.58	0.11	0.10	37	0.001	0.005	96.1

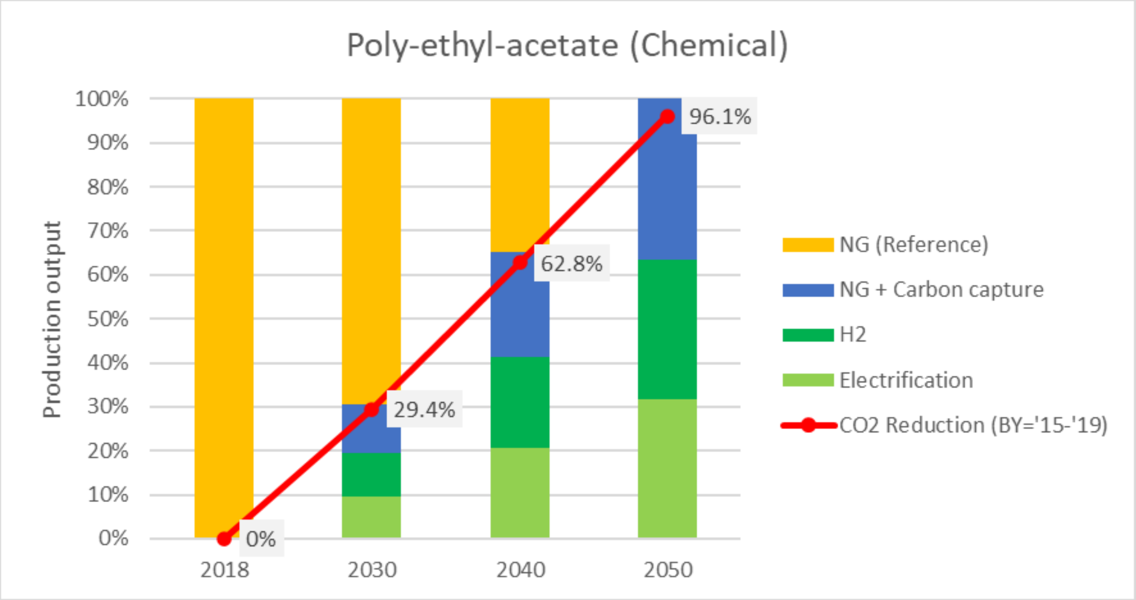


Figure 38: AIDRES EU mix production categories for polyethylene towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

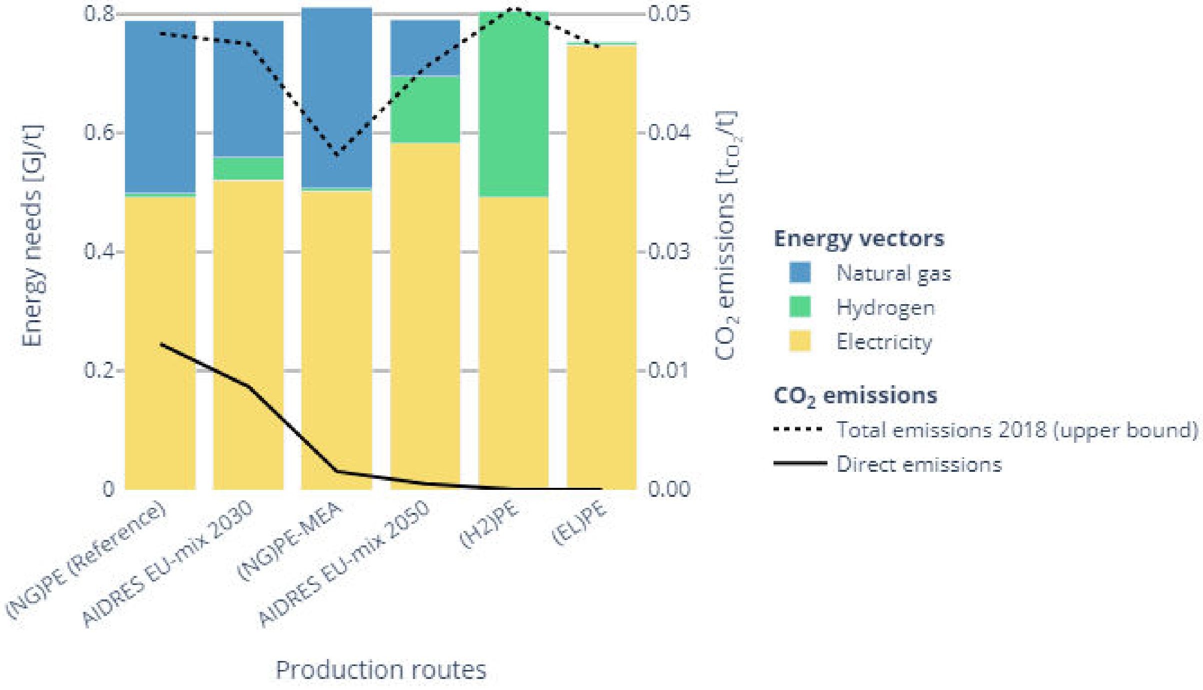


*Figure 39: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for **polyethylene** production routes.*

9.4. Poly-ethyl-acetate

9.4.1. Production routes methodology

AIDRES mix production routes are obtained by weighting single production routes. Starting from the poly-ethyl-acetate reference case, the proposed mixed routes are equally distributed within categories having direct emission reduction targets by 2050 allowing to reach a global 96% reduction by 2050 (Table 35 and Figure 40).

Table 35: Energy flows, investment costs, emissions and captured CO_2 per ton of poly-ethyl-acetate.

Route	Category	Target 2050 [%]	2018 [%]	2030 [%]	2050 [%]	Direct emissions [tCO2/t]	Direct emissions reduction [%]
(NG) PEA-MEA	CCS	36.6	0	11.2	36.6	0.049	89.3
(EL) PEA	Electrification	31.7	0	9.7	31.7	0	100
(H2) PEA	Hydrogen	31.7	0	9.7	31.7	0	100
AIDRS EU-mix-2050	EU-mix	100	0	30.6	100	0.018	96.1

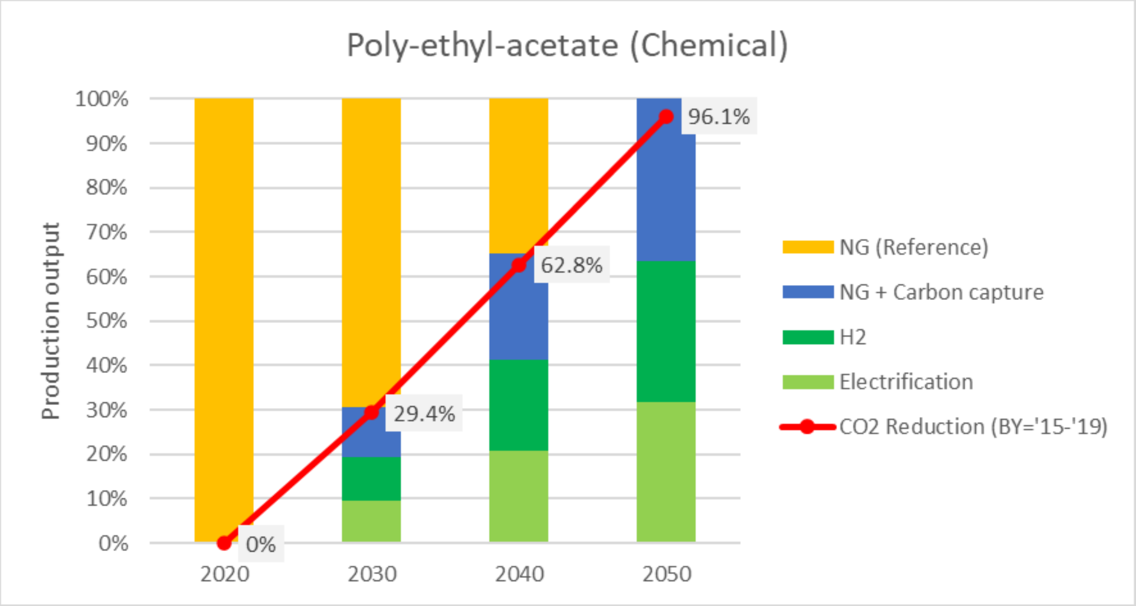


Figure 40: AIDRES EU mix production categories for poly-ethyl-acetate towards 2050, meeting EU FF55 MIX scenario derived emission reduction targets

9.4.2. Production route results

For poly-ethyl-acetate, Table 36 gives the reference and the typical production routes. Figure 41: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for poly-ethyl-acetate production routes. shows the energy flows in [GJ/t] for each production route of the AIDRES EU-mix and Figure 58 (Annex 0) the specific investment cost in [EUR/t].

Table 36: Energy flows, investment costs, emissions and captured CO_2 per ton of poly-ethyl-acetate.

Poly-ethyl-acetate production route	Electricity [GJ/t]	Hydrogen [GJ/t]	Natural gas [GJ/t]	CAPEX [EUR/t]	Direct Emissions [tCO_2/t]	Captured CO_2 [tCO_2/t]	Direct emissions reduction [%]
(NG) PEA-REF	1.30		8.16	112	0.459		
(NG) PEA-MEA	1.57		8.76	120	0.049	0.443	89.3
(H_2) PEA	1.30	8.64		115			100
(H_2)PEA-AEL	14.27			137			100
(Electricity) PEA	8.54			111			100
EU-mix-2030	2.03	0.84	6.65	113	0.324	0.050	29.4
EU-mix-2050	3.69	2.74	3.21	116	0.018	0.162	96.1

The energy resource per ton of product is given in Figure 41. The direct emissions line is the lowest bound of the emissions, while the total emissions in 2018 represents the upper bound, accounting in particular for the emissions from the electricity grid.

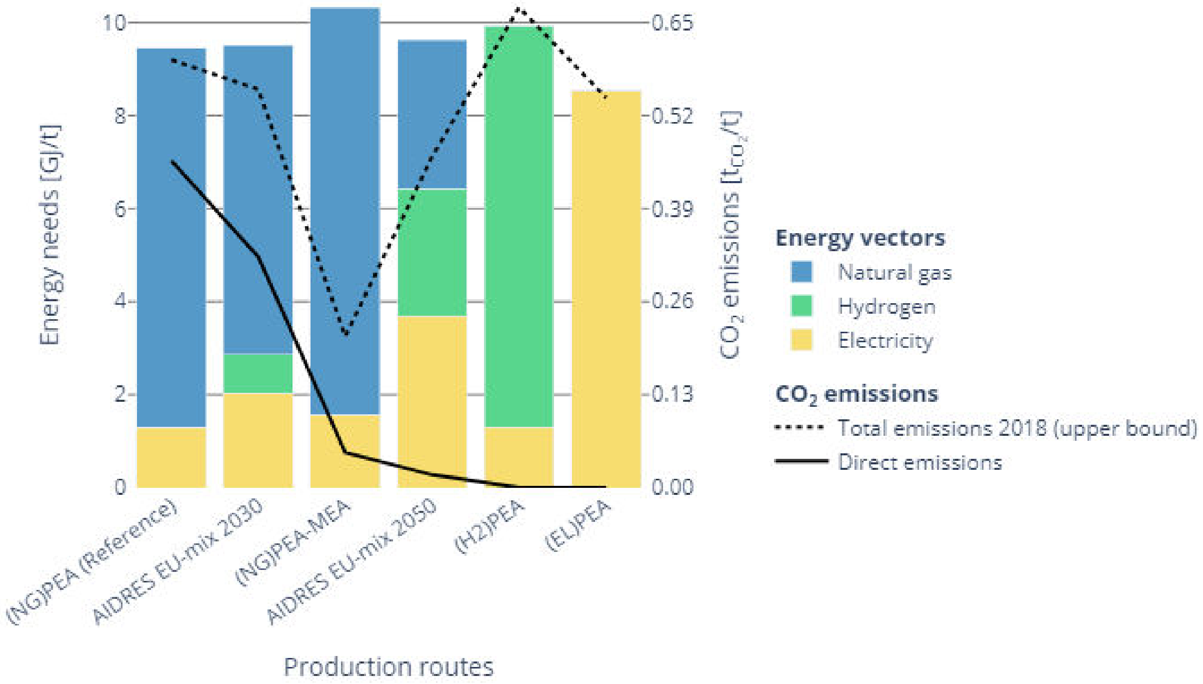


Figure 41: Energy and feedstock inputs flows [GJ/t] and emissions [tCO2/t] for poly-ethyl-acetate production routes.

10. Conclusion

Meeting the European Union's climate targets in 2030 and 2050 for energy intensive industries requires an ambitious shift from existing production methods to novel or disruptive technologies. Increasing the energy efficiency of existing and future manufacturing processes by means of e.g., process integration techniques, is a first obvious, but limited, exercise that can help industries finding ways to reduce their energy demand. Next, electrification of industrial heat and processes, when applicable, is preferable due to its efficiency, relatively straightforward way to decarbonise and because of the maturity of renewable energy generation technologies such as wind and solar power. Biomass can play an important role in providing certain qualities of heat and feedstock, under the condition that it can be sustainably sourced. In some cases, hydrogen can be used as alternative energy and feedstock source. CO_2 emissions which cannot be avoided, can be captured and either stored or reused.

In the transition towards a sustainable and low-carbon future, several key trends and developments are expected to shape the energy and feedstock landscape by 2050:

- **Substantial reduction in energy and feedstock inputs**: there is a projected decrease of 57% in overall energy and feedstock inputs between 2018 and 2050. This reduction primarily stems from decreased refinery output.
- **Surge in renewable electricity demand:** By 2050, there will be a sharp increase in renewable electricity demand up to seven times current levels, depending on degree of electrification of the industry. Refineries and the chemical sector stand out in the increase of electricity consumption.
- **Growing role of biomass in chemical and refinery sectors**: Methanol is expected to replace naphtha as a vital feedstock for the refineries and chemical sectors. Biomass gasification is therefore expected to play a significant role in those sectors by 2050.
- **Use of alternative fuels**: The cement sector is likely to adopt sustainable practices by relying on biomass waste and alternative fuel mixtures, along with carbon capture technologies such as oxy-fuel combustion and calcium looping.
- **Emergence of green hydrogen**: Green hydrogen is poised to become a crucial energy vector for multiple sectors including steel, fertilizer, and chemicals.
- **Decline of coal, natural gas and crude oil**: While there will be a significant decline in the use of coal and natural gas, however these fossil fuels may still have a role in certain sectors, especially when combined with carbon capture technologies. This approach aims to mitigate emissions while utilizing existing infrastructure.

To achieve the transition towards industrial decarbonisation, the following strategies should be considered:

- **Presence and accessibility of renewable energy sources** will be crucial for the development of renewable electricity and biomass-based production routes within regions or areas. Adequate planning for these resources, both in terms of time and in relation with other sectors such as transport, building, which also heavily rely on these RES, is paramount.
- **Concerted collaboration across industrial sectors and regions** is needed for the elaboration of multi energy strategies and partnerships for the penetration of renewable electricity and biomass. The EU industry, being very geographically dispersed, also

must rely and smartly plan on the transition of infrastructure, to gain speed in implementation and cost competitiveness in a globalised market.

- **Development of cost-competitive technologies** is required to reduce waste and exploit cross-sectorial synergies, such as carbon capture and the production of methanol and electro-fuels from CO_2. This includes all process across the value chain of these molecules besides the production, such as transport, terminals and conversion.
- **Industrial and regional symbiosis** is essential for enhancing efficiency and reducing waste. Strategic coordination of energy and material flows involves the integration of renewable electricity and biomass into industrial processes, the utilisation of waste heat and the exploration of synergies and flexibilities.
- **Open exchange of knowledge and data** across the EU and globally should be promoted and the study extended to consider additional downstream products (aromatics, ethanol) and integrate furthers energy intensive sectors such as the pulp and paper and the power generation industries.

Finally, The AIDRES EU mix routes are not the only pathways which can be constructed from the AIDRES database. In fact, a virtual unlimited number of different combinations of different production routes across the EU and at specific NUTS3 locations can be simulated, using the publicly available AIDRES database. Additional parameters, which are not available in the AIDRES model, such as grid infrastructure, electricity pricing zones, H2/NG-infrastructure, availability of biomass, local decisions, etc. might result in more relevant and feasible selections of production routes for a given NUTS3 region and lead to a different EU mix.

The AIDRES database serves as input for data visualisation by the Energy and Industry Geography Lab (EIGL) of the Joint Research Centre (JRC) and is made available for download and use by the general public, at this link:
Database: https://data.jrc.ec.europa.eu/dataset/14914982-70a9-4d1d-a2fc-cdee4a1d833d.
Visualisation: https://energy-industry-geolab.jrc.ec.europa.eu/

A simplified version of the database in EXCEL format can be found here:
The database “Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes” (AIDRES) (europa.eu)

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12. Annex

12.1. AIDRES database, main energy, emissions and cost parameters.

Table 37: Overview of the energy and feedstock inputs, capital cost and direct emissions parameters at the production route level included in the database, and as expressed per ton of product

Type	Parameter	Description	Unit
Feedstock and energy inputs	Electricity [GJ/t]	Electricity per ton of product energy consumption in PJ pear y	GJ/t
	Alternative fuel mixture [GJ/t]	Alternative fuel mixture per ton of product energy consumption	GJ/t
	Biomass [GJ/t]	Biomass per ton of product energy consumption	GJ/t
	Biomass waste [GJ/t]	Biomass waste per ton of product energy consumption	GJ/t
	Coal [GJ/t]	Coal per ton of product energy consumption	GJ/t
	Coke [GJ/t]	Coke per ton of product energy consumption	GJ/t
	Crude oil [GJ/t]	Crude oil per ton of product energy consumption	GJ/t
	Hydrogen [GJ/t]	Hydrogen per ton of product energy consumption	GJ/t
	Methanol [GJ/t]	Methanol per ton of product energy consumption	GJ/t
	Ammonia [GJ/t]	Ammonia per ton of product energy consumption	GJ/t
	Naphtha [GJ/t]	Naphtha per ton of product energy consumption	GJ/t
	Natural gas [GJ/t]	Natural gas per ton of product energy consumption	GJ/t
	Plastic mix [GJ/t]	Plastic mix per ton of product energy consumption	GJ/t
Emission parameters	Direct emission [tCO_2/t]	Direct per ton of product CO2 emissions at the plant	tCO_2/t
	Total emission [tCO_2/t]	Direct at the plant and indirect upstream per ton of product CO2 emissions	tCO_2/t
	Direct emission reduction [%]	Direct emission reduction	%
	Total emission reduction [%]	Total emission reduction	%
	Captured CO_2 [tCO_2/t]	Captured CO_2 at the plant per ton of product (production process and fumes)	tCO_2/t
Cost parameters	totex [EUR/t]	per ton of product total expenditure (TOTEX)	EUR/t
	opex var [EUR/t]	per ton of product operation expenditure from the energy consuption	EUR/t
	CO_2 allowance [EUR/t]	per ton of product CO_2 allowance	EUR/t
	opex cst [EUR/t]	per ton of product constant operation expenditure (OPEX)	EUR/t
	opex [EUR/t]	per ton of product operation expenditure (OPEX)	EUR/t
	capex [EUR/t]	per ton of product capital expenditure (CAPEX)	EUR/t

12.2. CO_2 emissions in industry, EU Reference scenario

Table 38: CO_2 emissions in industry by sector and type (sectoral emissions refer to energy-related emissions). Source: (European Commission 2020). AIDRES MIX 2030 and 2050 Emission reduction % compared to either base year 2015 or an average during 2015-2019.

	BSL			MIX		AIDRES BY=2015		AIDRES BY=2015-2019	
In $MtCO_2$	2015	2030	2050	2020	2030	2030	2050	2030	2050
Iron & steel	168.2	136.8	104.4	21.9	133.1	21%	87%	21%	86%
Chemicals	118.7	90.9	71.2	7.1	84.5	29%	94%	29%	96%
Non-metallic minerals	171.4	155.5	133.9	15.1	149.3	13%	91%	13%	93%
Non-ferrous metals	18.5	15.6	13.5	1.2	15.1	19%	93%	19%	96%
Pulp, paper & printing	21.1	11.5	10.5	1.2	9.9	53%	94%	54%	96%
Food, beverage & tobacco	39.0	26.0	24.0	2.0	22.0	42%	94%	44%	97%
Engineering	23.0	23.0	26.0	2.0	22.0	6%	92%	0%	0%
Textiles	5.0	3.0	2.0	0.0	3.0	43%	95%	0%	0%
Other industries	71.0	58.0	53.0	6.0	55.0	23%	91%	24%	93%
Refineries	85.0	65.0	49.0	10.0	60.0	29%	88%	28%	85%

12.3. Energy consumption in transport, EU Fit for 55 Scenario

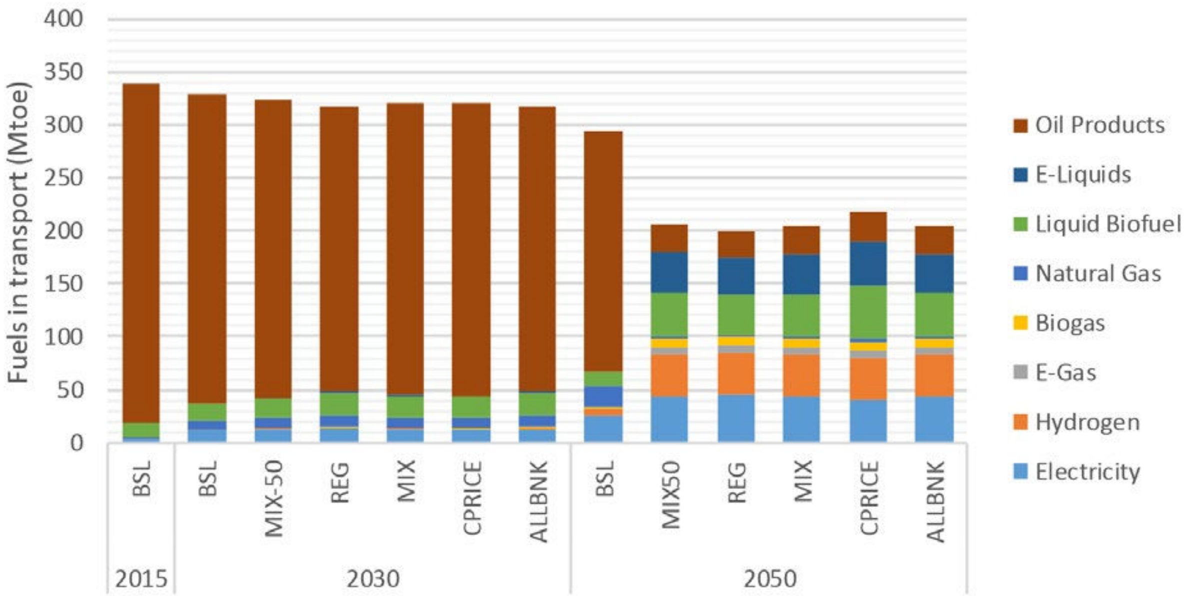

Figure 42: Energy consumption in transport (incl. international aviation and maritime) in the EU. Source: (European Commission 2020), p.76.

Table 39: Energy consumption of fuels in transport, including international aviation and maritime in the EU (excluding inland navigation). Source: (European Commission 2021c).

Fuels excluding inland navigation	2015	2030	2050	2030	2030	2050
Electricity	4	11	25	11	12	43
Hydrogen	0	0	7	0	1	40
E-Gas	0	0	0	0	0	6

Biogas	0	0	1	0	1	8
Natural Gas	2	9	21	9	10	2
Liquid Biofuel	13	16	13	16	20	41
E-Liquids	0	0	0	0	1	38
Oil Products	320	293	227	293	276	27
TOTAL	339	330	294	330	321	205

Table 40: Euro balance, Transport final energy consumption. Source: (Eurostat 2023).

In Mtoe	2015	2016	2017	2018	2019	2020
Liquefied petroleum gases	6.0	6.0	6.0	6.0	6.0	5
Aviation gasoline	0.1	0.1	0.1	0.1	0.1	0
Motor gasoline (excluding biofuel portion)	64.0	65.0	65.0	65.0	67.0	57
Kerosene-type jet fuel (excluding biofuel portion)	40.0	42.0	45.0	47.0	48.0	21
Gas oil and diesel oil (excluding biofuel portion)	184.0	190.0	193.0	192.0	193.0	171
Fuel oil	32.0	33.0	35.0	36.0	35.0	29
TOTAL	326.0	336.0	343.0	346.0	349.0	284

Note: In AIDRES, 16 Mt of 1th generation biofuels are added to the total amount in the base year 2018. AIDRES does not have a specific production model for ethanol.

12.4. Energy and feedstock

Table 41: AIDRES energy vectors and feedstock by industrial sector.

Sector	Energy and feedstock
Steel	Alloy, Anthracite, Argon, BF Dust and Sludge, Blast, BOF Dust and Sludge, Burnt lime, Coal blend, Coal steel, Coke breeze, Compressed Air, Coolant Scraps, Dolomite, Gas, Graphite electrode, Hydrogen, Industrial water, Iron Ore, Iron Pellet, Lime, Limestone, Lump Ore, Natural gas, Nitrogen, Other additives, Oxygen, Plastic mix, Recycled materials, Recycled Steel, Refractory lining, Scales, Sinter fines, Sludge, Steam, Steel Scraps,
Refineries	Biomass, CO_2, Crude oil, Demineralised water, Hydrogen, Steam, Natural gas, Water,
Cement	Alternative fuel mixture (AFM), Air, Blast furnace slag, Clay, Coal quality 1, Compressed Air, Propylene glycol, Gyps, Industrial water, Limestone, Sand, Scrap gyps, Sludge cement,
Glass	Coal, Cullet ext, Cullet int, Dolomite, Feldspar, Hydrogen, Limestone, NaCl, NaSO4, Natural gas, Nitrogen, Oxygen, Sand, Slag, Soda, Water,
Fertiliser	Biomass, CO_2, Hydrogen, Natural gas, Water,
Chemical	Acetic acid pure, Biomass, CO_2, Ethylene pure, Hydrogen, Industrial water, Light naphtha, Natural gas, Water,

12.5. Direct (SCOPE 1) emission sources

Table 42: Direct sources of emissions.

Emission source	Process	Quality	Units
Blast furnace gas (BFG)	Blast furnace	0.45980	kg/kg$_{BFG}$
Blast furnace fumes (BFF)	Blast furnace	0.32000	kg/kg$_{BFF}$
Blast furnace gas (BFG)	Blast furnace WPI	0.45980	kg/kg$_{BFG}$
Blast furnace fumes (BFF)	Blast furnace WPI	0.32000	kg/kg$_{BFF}$
Blast oxygen furnace gas (BOFG)	Basic Oxygen Furnace	0.23760	kg/kg$_{BOFG}$
Coke oven gas (COG)	Coke Plant	0.32000	kg/kg$_{COG}$
Coke pant fumes (CPF)	Coke Plant	0.32000	kg/kg$_{CPF}$
Blast furnace gas (BFG)	Top Gas Recycling Blast furnace	0.45980	kg/kg$_{BFG}$
Shaft furnace gas (CFG)	NG Shaft Furnace	0.29330	kg/kg$_{SFG}$
Shaft furnace gas (CFG)	NG+H2 Shaft Furnace	0.19550	kg/kg$_{SFG}$
Shaft furnace gas (CFG)	H2 Shaft Furnace	0.07350	kg/kg$_{SFG}$
Electric arc furnace fumes (EAFF)	EAF furnace DRI, EAF Scraps	0.32000	kg/kg$_{EAFF}$
Coke pulverisation fumes (CPF)	Coke pulverization	0.32000	kg/kg$_{CPF}$
Clinker	(Pre-calcination)	0.43000	kg/kg$_{Clinker}$
Clinker fumes (CF)	Dry Kiln (Clinkerization process)	0.06849	kg/kg$_{CF}$
Coal	Furnace - coal	2.52000	kg/kg$_{Coal}$
Natural gas (ng)	Furnace - natural gas	1.99000	kg/kg$_{ng}$
Biogas (bg)	Furnace - biogas	1.61000	kg/kg$_{bg}$
Alternative fuel mixture (Afm)	Furnace - alternative fuel mixture	0.55000	kg/kg$_{Afm}$
Mill flue gas (MFG)	Ball mill, Double rotator, Dry crusher, Vertical mill	0.10000	kg/kg$_{MFG}$
Natural gas (ng) combustion	Natural gas furnace	2.75000	kg/kg$_{ng}$
Naphtha cracking	Naphtha cracking	0.96700	kg/kg$_{Olefins}$
Fuel gas combustion	Methanol to olefins - Fuel gas	0.23000	kg/kg$_{Olefins}$
Flue gas combustion	Methanol to olefins - Flue gas	0.12900	kg/kg$_{Olefins}$
Container glass	Glass container	0.07300	kg/kg$_{container}$
Fibre glass	Glass fibre	0.22700	kg/kg$_{fibre}$
Flat glass	Glass float	0.18200	kg/kg$_{float}$
Ammonia production from natural gas	Ammonia production from natural gas	1.42000	kg/kg$_{NH_3}$
Ammonia production from biomass	Ammonia production from biomass	2.55700	kg/kg$_{NH_3}$

12.6. Resources, LHV, indirect emissions and prices

Table 43: Lower heating values, indirect upstream emissions and prices of the energy vector and feedstock.

Energy and feedstock	LHV [kWh/kg]	Indirect emissions [kgCO2/kg]	Cost	
Alternative fuel mixture (AFM)	6.13	0.008	8.4	EUR/t
Air	-	-	0	EUR/t
Biogas	8.33	0.000	0.07	EUR/kWh
Blast furnace slag	-	-	75	EUR/t
Clay	-	-	15	EUR/t
Coal quality 1	8.19	0.349	62	EUR/t
Compressed Air	-	-	2037	EUR/t
Electricity	-	scenarios	scenarios	EUR/kWh
Fly ash and scrubber sludge	-	-	4.5	EUR/t
Propylene glycol	-	-	880.6	EUR/t
Gyps	-	-	20	EUR/t
Industrial water	-	-	0	EUR/t
Lignite ash	-	-	5	EUR/t

Lignite ash	-	-	5	EUR/t
Limestone	-	-	20	EUR/t
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Oxygen	-	-	60.7	EUR/t
Sand	-	-	4.5	EUR/t
Scrap gyps	-	-	5	EUR/t
Sludge cement	-	-	0.1	EUR/t
Acetic acid pure	-	-	0	EUR/t
Biomass	4.81	0.000	57	EUR/t
CO2	-	-	scenarios	EUR/kg
Electricity	-	scenarios	scenarios	EUR/kWh
Ethylene pure	-	-	0	EUR/t
Hydrogen	33.30	scenarios	scenarios	EUR/kg
Industrial water	-	-	0	EUR/t
Light naphtha	12.47	0.232	390.3	EUR/t
Methanol	5.53	0.661	410	EUR/t
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Oxygen	-	-	60.7	EUR/t
Water	-	-	0.08	EUR/t
Biomass	4.81	0.000	57	EUR/t
CO2	-	-	scenarios	EUR/kg
Electricity	-	scenarios	scenarios	EUR/kWh
Hydrogen	33.30	scenarios	scenarios	EUR/kg
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Water	-	-	0.08	EUR/t
Coal	-	-	65	EUR/t
Cullet ext	-	-	59.1	EUR/t
Cullet int	-	-	0	EUR/t
Dolomite	-	-	140	EUR/t
Electricity	-	scenarios	scenarios	EUR/kWh
Feldspar	-	-	58.8	EUR/t
Hydrogen	33.30	scenarios	scenarios	EUR/kg
Limestone	-	-	20	EUR/t
NaCl	-	-	150	EUR/t
NaSO4	-	-	97.1	EUR/t
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Nitrogen	-	-	33.9	EUR/t
Oxygen	-	-	60.7	EUR/t
Sand	-	-	4.5	EUR/t
Slag	-	-	75	EUR/t
Soda	-	-	201	EUR/t
Water	-	-	0.08	EUR/t
Biomass	4.81	0.000	57	EUR/t
CO2	-	-	scenarios	EUR/kg
Crude oil	11.85	0.232	370	EUR/t
Demineralised water	-	-	0.5	EUR/t
Electricity	-	scenarios	scenarios	EUR/kWh
Hydrogen	33.30	scenarios	scenarios	EUR/kg
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Steam	-	-	35	EUR/t
Water	-	-	0.08	EUR/t
Alloy	-	-	1500	EUR/t
Anthracite	9.01	0.349	160	EUR/t
Argon	-	-	375	EUR/t
BF Dust and Sludge	-	-	0	EUR/t
Blast	-	-	1.10	EUR/t
BOF Dust and Sludge	-	-	0	EUR/t
Burntlime	-	-	115	EUR/t
Coal blend	8.19	0.349	125	EUR/t
Coal steel	6.67	0.349	125	EUR/t
Coke breeze	8.86	0.000	52	EUR/t
Compressed Air	-	-	2037	EUR/t
Coolant Scraps	-	-	290	EUR/t
Dolomite	-	-	140	EUR/t
Electricity	-	scenarios	scenarios	EUR/kWh
Gas	-	-	0	EUR/t

Graphite electrode	-	-	11679	EUR/t
Hydrogen	33.30	scenarios	scenarios	EUR/kg
Industrial water	-	-	0	EUR/t
Iron Ore	-	-	57	EUR/t
Iron Pellet	-	-	97	EUR/t
Lime	-	-	140	EUR/t
Limestone	-	-	20	EUR/t
Lump Ore	-	-	20	EUR/t
Natural gas	14.50	scenarios	scenarios	EUR/kWh
Nitrogen	-	-	33.9	EUR/t
Other additives	-	-	15	EUR/t
Oxygen	-	-	60.7	EUR/t
Plastic mix	8.61	1.389	300	EUR/t
Recycled materials	-	-	0	EUR/t
Recycled Steel	-	-	0	EUR/t
Refractory lining	-	-	300	EUR/t
Scales	-	-	0	EUR/t
Sinter fines	-	-	0	EUR/t
Sludge	-	-	0	EUR/t
Steam	-	-	12	EUR/t
Steel Scraps	-	-	295	EUR/t

Table 44: Sources of indirect upstream emissions

Resource	Process
Alternative fuel mixture (AFM)	Combustion Furnace
Biogas	Combustion Furnace
Coal quality 1	Combustion Furnace
Electricity	Kaolinite clay calcination, Vertical raw mill roller, Cement grinding mill, Cryogenic air separation unit, Raw mill dryer crusher, Mono-ethanolamine Carbon Capture, Dry process kilns, Raw mill double rotator, Calcium looping
Natural gas	Combustion Furnace
Biomass	Biomass gasification, Biomass-to-methanol
Electricity	Refrigerator, Biomass-to-methanol, Polymerization (Polyethylene), Naphtha-to-olefins, Alkaline electrolyser, Naphtha-to-olefins electric, FT fuel synthesis, Methanol-to-olefins, Co-electrolysis, Mono-ethanolamine Carbon Capture, Mono-ethanolamine carbon capture, EL Furnace, Biomass gasification, Polymerization (Poly-ethyl-acetate), Methanol synthesis
Hydrogen	H2 Furnace, Polymerization (Polyethylene), Biomass gasification
Light naphtha	Naphtha-to-olefins electric, Naphtha-to-olefins
Methanol	Methanol-to-olefins
Natural gas	NG Furnace
Biomass	Ammonia plant biomass, Biomass Furnace
Electricity	Refrigerator, Mechanical vapor recompression, Ammonia plant electrolyser, Ammonia plant conventional, Nitric acid plant, Cooling tower, Air separation unit, Steam network, Ammonia plant biomass, Refrigerator biomass, Mono-ethanolamine Carbon Capture, Urea plant, Refrigerator conventional, Alkaline electrolyser

Hydrogen	Ammonia plant electrolyser
Natural gas	Natural gas Furnace, Ammonia plant conventional
Electricity	Container glass, Alkaline electrolyser, Fibre glass, Mono-ethanolamine carbon capture, EL Furnace, Flat glass
Hydrogen	H2 Furnace, Fibre glass, Container glass, Flat glass
Natural gas	NG Furnace
Biomass	Biomass gasification (DME), Biomass gasification (FT and MEOH)
Crude oil	Atmospheric Distillation
Electricity	Isomerisation, Atmospheric Distillation, Fischer-Tropsch plant, Vacuum Distillation, Hydrocracking, Hydrotreatment, Hydrodesulphurisation, Visbreaking, Electrolyser, Biomass gasification (DME), Co-electrolysis, Gas Plant, Biomass gasification (FT and MEOH), Mono-ethanolamine Carbon Capture, DME synthesis, Fluid Catalytic Cracking, Catalytic Reforming, Methanol synthesis
Hydrogen	Isomerisation, Hydrocracking, Hydrotreatment, Hydrodesulphurisation, Biomass gasification (DME), Biomass gasification (FT and MEOH)
Natural gas	NG Combustion Furnace, Steam methane reforming
Anthracite	Sinter Plant
Coal blend	Coke Plant
Coal steel	Electric Arc Furnace, DRI-Electric Arc Furnace, Pulverized Coal
Coke breeze	Sinter Plant
Electricity	Electric Arc Furnace, NG Shaft Furnace, DRI(NG) carbon capture, (H2)SF carbon capture, H2 Shaft Furnace, Alkaline electrolyser, Blast furnace, NG+H2 Shaft Furnace, Plastics pre-treatment for BF, Ladle Metal. & Cont. Casting, Waste Plastic Injection BF, (NG+H2)SF carbon capture, Molten Oxide Electrolyser, Vacuum Pressure Swing Adsorption, Pulverized Coal, Mono-ethanolamine carbon capture, Basic Oxygen Furnace, Sinter Plant, Coke Plant, Top Gas Recycling BF, DRI-Electric Arc Furnace
Hydrogen	NG+H2 Shaft Furnace, H2 Shaft Furnace
Natural gas	NG Shaft Furnace, Electric Arc Furnace, NG+H2 Shaft Furnace, DRI-Electric Arc Furnace
Plastic mix	Plastics pre-treatment for BF

12.7. Description of the production routes

12.7.1. Steel

Primary steel

Table 45: Description of the primary steel production routes.

Production route	Process
BF-BOF	Blast furnace,Coke Plant,Rolling Mill,Sinter Plant,Basic Oxygen Furnace,Ladle Metal. & Cont. Casting,Pulverized Coal

BF-BOF-MEA	Blast furnace,Coke Plant,Rolling Mill,Sinter Plant,Basic Oxygen Furnace,Ladle Metal. & Cont. Casting,Pulverized Coal,Mono-ethanolamine carbon capture
WPI-BOF	Coke Plant,Rolling Mill,Sinter Plant,Basic Oxygen Furnace,Ladle Metal. & Cont. Casting,Pulverized Coal,Plastics pre-treatment for BF,Waste Plastic Injection BF
WPI-BOF-MEA	Coke Plant,Rolling Mill,Sinter Plant,Basic Oxygen Furnace,Ladle Metal. & Cont. Casting,Pulverized Coal,Plastics pre-treatment for BF,Waste Plastic Injection BF,Mono-ethanolamine carbon capture
(NG)DRI-EAF	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, NG Shaft Furnace
(NG)DRI-EAF-MEA	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, NG Shaft Furnace, DRI(NG) carbon capture, Mono-ethanolamine carbon capture
(NG+H2)DRI-EAF	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, NG+H2 Shaft Furnace
(NG+H2)DRI-EAF-AEL	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, NG+H2 Shaft Furnace, Alkaline electrolyser
(H2)DRI-EAF	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, H2 Shaft Furnace
(H2)DRI-EAF-AEL	Rolling Mill, Ladle Metal. & Cont. Casting, DRI-Electric Arc Furnace, H2 Shaft Furnace, Alkaline electrolyser
MOE	Rolling Mill, Ladle Metal. & Cont. Casting, Molten Oxide Electrolyser

Secondary steel

Table 46: Description of the primary steel production routes.

Production route	Process
Scraps EAF	Rolling Mill, Ladle Metal. & Cont. Casting, EAF Scraps handling, Electric Arc Furnace

12.7.1. Refineries

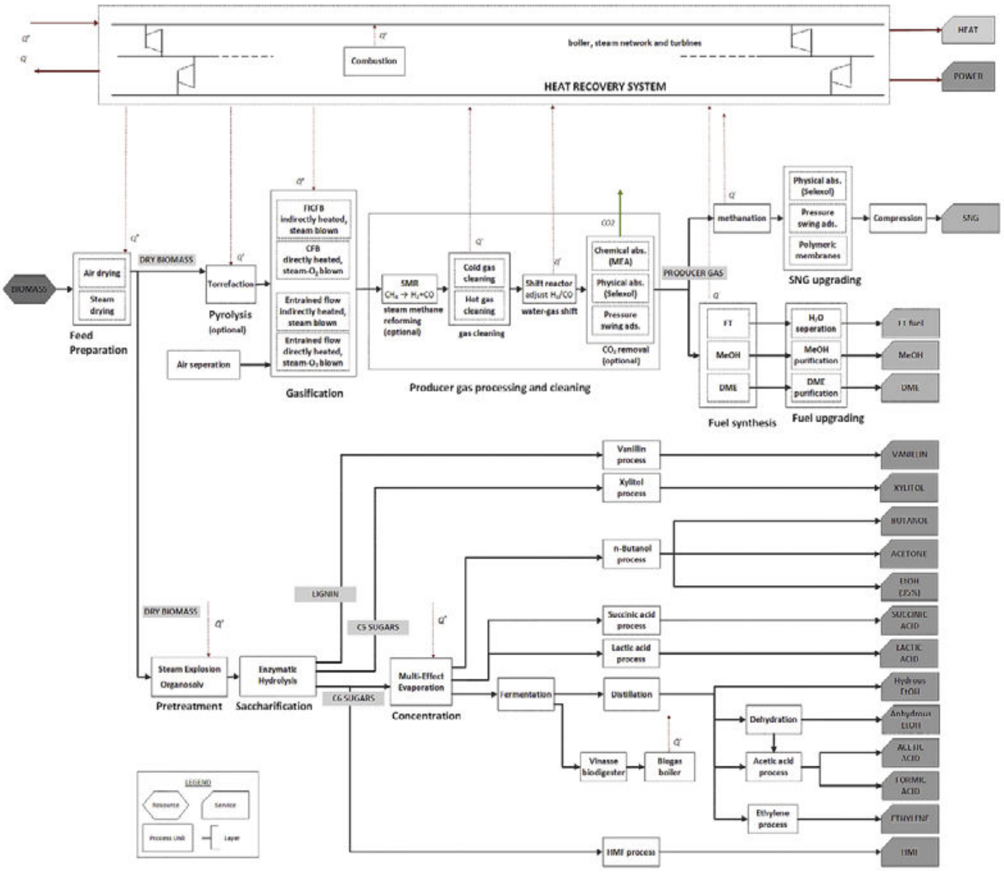

Figure 43: Superstructure of the biomass plant integrated in the AIDRES refineries blueprint model for the production of FT fuel and MeOH. Source: (Celebi et al. 2017).

Light liquid fuel

Table 47: Description of the light liquid fuel production routes.

Production route	Process
REF-SMR	Atmospheric Distillation, Gas Plant, Catalytic Reforming, Vacuum Distillation, Fluid Catalytic Cracking, Hydrocracking, Hydrodesulphurisation, Hydrotreatment, Isomerisation, Visbreaking, Water Cooling, NG Combustion Furnace, Refinery products, Steam methane reforming
REF(H2)	Atmospheric Distillation, Gas Plant, Catalytic Reforming, Vacuum Distillation, Fluid Catalytic Cracking, Hydrocracking, Hydrodesulphurisation, Hydrotreatment, Isomerisation, Visbreaking, Water Cooling, NG Combustion Furnace, Refinery products
REF(H2)-MEA	Atmospheric Distillation, Gas Plant, Catalytic Reforming, Vacuum Distillation, Fluid Catalytic Cracking, Hydrocracking, Hydrodesulphurisation, Hydrotreatment, Isomerisation, Visbreaking, Water Cooling, NG Combustion Furnace, Refinery products, Mono-ethanolamine Carbon Capture
REF-SMR-MEA	Atmospheric Distillation, Gas Plant, Catalytic Reforming, Vacuum Distillation, Fluid Catalytic Cracking, Hydrocracking, Hydrodesulphurisation, Hydrotreatment, Isomerisation, Visbreaking, Water Cooling, NG Combustion Furnace, Refinery products, Mono-ethanolamine Carbon Capture, Steam methane reforming
(BM)FT	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM+H2)FT	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM+H2)FT-AEL	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Electrolyser, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM)FT-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Mono-ethanolamine Carbon Capture, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM+H2)FT-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Mono-ethanolamine Carbon Capture, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM+H2)FT-AEL-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Water Cooling, Mono-ethanolamine Carbon Capture, Electrolyser, Biomass gasification (FT and MEOH), Fischer-Tropsch plant
(BM)MeOH	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(BM+H2)MeOH	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(BM+H2)MeOH-AEL	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Electrolyser, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(BM)MeOH-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Mono-ethanolamine Carbon Capture, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(BM+H2)MeOH-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Mono-ethanolamine Carbon Capture, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(BM+H2)MeOH-AEL-MEA	Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis, Water Cooling, Mono-ethanolamine Carbon Capture, Electrolyser, Biomass gasification (FT and MEOH), Fischer-Tropsch plant, Methanol synthesis
(COEL)FT	Co-electrolysis, Fischer-Tropsch plant, Water Cooling, Co-electrolysis, Fischer-Tropsch plant
(COEL)FT-MEA	Co-electrolysis, Fischer-Tropsch plant, Water Cooling, Mono-ethanolamine Carbon Capture, Co-electrolysis, Fischer-Tropsch plant
(COEL)MeOH	Co-electrolysis, Methanol synthesis, Water Cooling, Co-electrolysis, Methanol synthesis
(COEL)MeOH-MEA	Co-electrolysis, Methanol synthesis, Water Cooling, Mono-ethanolamine Carbon Capture, Co-electrolysis, Methanol synthesis

12.7.2. Cement

Table 48: Description of the Portland cement production routes.

Production route	Process
CEM2-(Coal)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace
CEM2-(Coal)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Mono-ethanolamine Carbon Capture
CEM2-(Coal)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Calcium looping
CEM2-(Coal)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Mono-ethanolamine Carbon Capture
CEM2-(Coal)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Calcium looping
CEM2-(NG)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace

CEM2-(NG)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Mono-ethanolamine Carbon Capture
CEM2-(NG)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Calcium looping
CEM2-(NG)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Mono-ethanolamine Carbon Capture
CEM2-(NG)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Calcium looping
CEM2-(Afm)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Air cooling
CEM2-(Afm)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Mono-ethanolamine Carbon Capture
CEM2-(Afm)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Calcium looping, Air cooling
CEM2-(Afm)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Mono-ethanolamine Carbon Capture
CEM2-(Afm)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Calcium looping, Air cooling
CEM2-(BMW)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Air cooling
CEM2-(BMW)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Mono-ethanolamine Carbon Capture
CEM2-(BMW)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Calcium looping, Air cooling
CEM2-(BMW)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Mono-ethanolamine Carbon Capture
CEM2-(BMW)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Calcium looping, Air cooling

Table 49: Description of the limestone calcined clay production routes.

Production route	Process
LC3-(Coal)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination
LC3-(Coal)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(Coal)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Calcium looping
LC3-(Coal)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(Coal)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Calcium looping
LC3-(NG)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination
LC3-(NG)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(NG)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Calcium looping
LC3-(NG)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(NG)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Calcium looping
LC3-(Afm)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Air cooling
LC3-(Afm)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(Afm)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Calcium looping, Air cooling
LC3-(Afm)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(Afm)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Calcium looping, Air cooling
LC3-(BMW)	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Air cooling
LC3-(BMW)MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture
LC3-(BMW)CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Kaolinite clay calcination, Calcium looping, Air cooling
LC3-(BMW)Oxy-MEA	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Mono-ethanolamine Carbon Capture

LC3-(BMW)Oxy-CaL	Dry process kilns, Raw mill double rotator, Cement grinding mill, Combustion Furnace, Cryogenic air separation unit, Kaolinite clay calcination, Calcium looping, Air cooling

12.7.3. Glass

Container glass

Table 50: Description of the container glass production routes.

Production route	Process
(NG)	Container glass, Air, NG Furnace
(NG)-CC	Container glass, Air, NG Furnace, Mono-ethanolamine carbon capture
(H2)	Container glass, Air, H2 Furnace
(H2)-CC	Container glass, Air, H2 Furnace, Mono-ethanolamine carbon capture
(H2)-AEL	Container glass, Air, H2 Furnace, Alkaline electrolyser
(H2)-AEL-CC	Container glass, Air, H2 Furnace, Mono-ethanolamine carbon capture, Alkaline electrolyser
(EL)	Container glass, Air, EL Furnace
(EL)-CC	Container glass, Air, Mono-ethanolamine carbon capture, EL Furnace
EU-mix-2018	Air, Container glass, NG Furnace

Flat glass

Table 51: Description of the flat glass production routes.

Production route	Process
(NG)	Flat glass,Air,NG Furnace
(NG)-CC	Flat glass,Air,NG Furnace,Mono-ethanolamine carbon capture
(H2)	Flat glass,Air,H2 Furnace
(H2)-CC	Flat glass,Air,H2 Furnace,Mono-ethanolamine carbon capture
(H2)-AEL	Flat glass,Air,H2 Furnace,Alkaline electrolyser
(H2)-AEL-CC	Flat glass,Air,H2 Furnace,Mono-ethanolamine carbon capture,Alkaline electrolyser
(EL)	Flat glass,Air,EL Furnace
(EL)-CC	Flat glass,Air,Mono-ethanolamine carbon capture,EL Furnace

Fibre glass

Table 52: Description of the fibre glass production routes.

Production route	Process
(NG)	Fibre glass,Air, NG Furnace
(NG)-CC	Fibre glass,Air, NG Furnace,Mono-ethanolamine carbon capture
(H2)	Fibre glass,Air,H2 Furnace
(H2)-CC	Fibre glass,Air,H2 Furnace,Mono-ethanolamine carbon capture
(H2)-AEL	Fibre glass,Air,H2 Furnace, Alkaline electrolyser
(H2)-AEL-CC	Fibre glass,Air,H2 Furnace,Mono-ethanolamine carbon capture,Alkaline electrolyser
(EL)	Fibre glass,Air, EL Furnace
(EL)-CC	Fibre glass,Air,Mono-ethanolamine carbon capture,EL Furnace

12.7.4. Fertilizer

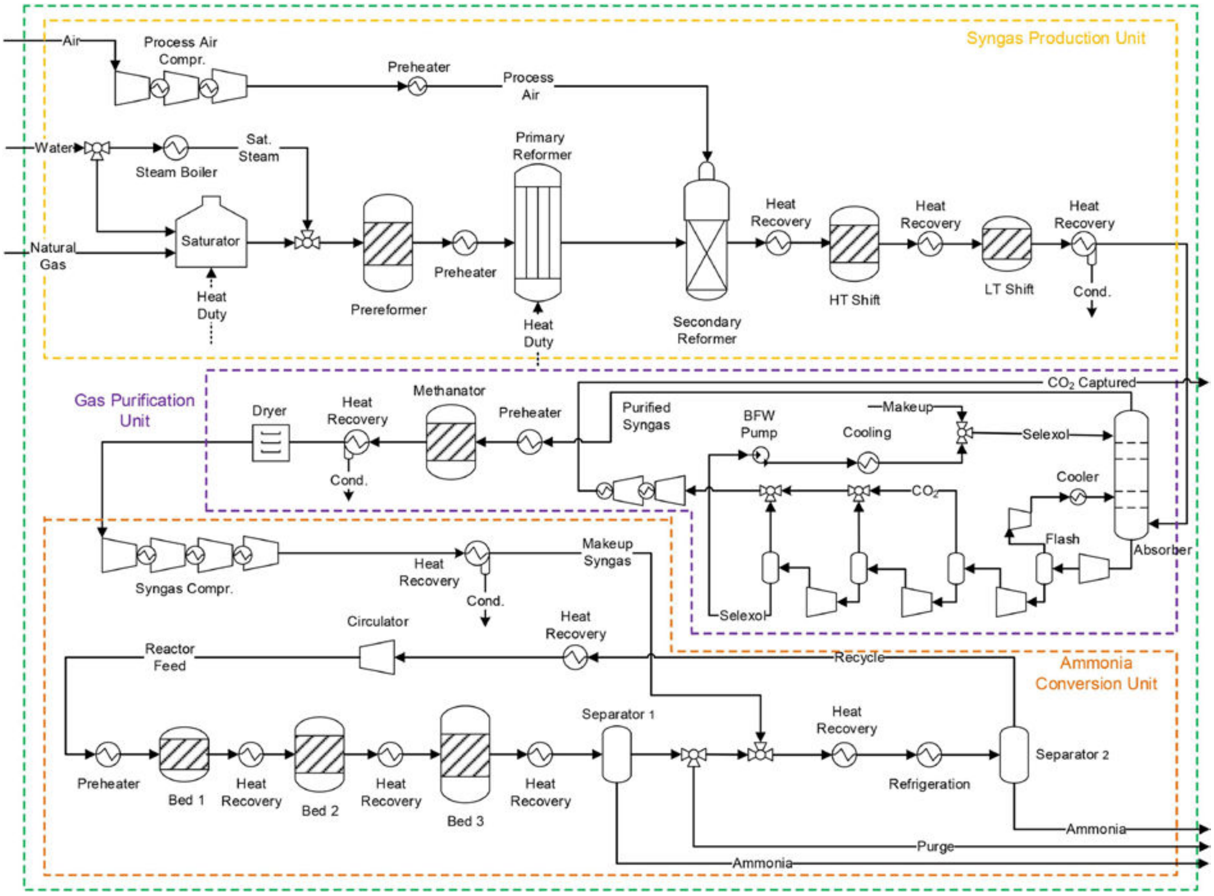

Figure 44: Superstructure integrated in the AIDRES blueprint model for the production of ammonia. Source: (Daniel Flórez-Orrego, Maréchal, and de Oliveira Junior 2019).

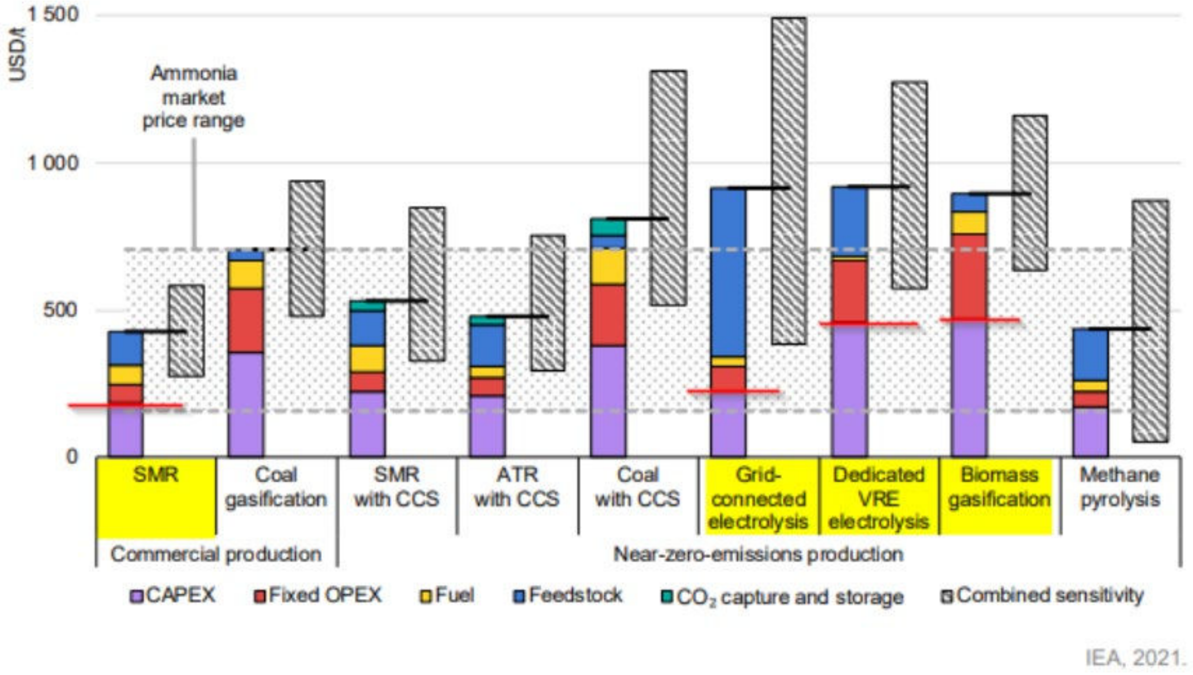

Figure 45: Simplified levelized cost of ammonia production for commercial and near-zero-emission production routes in 2020. Source: (International Energy Agency 2021).

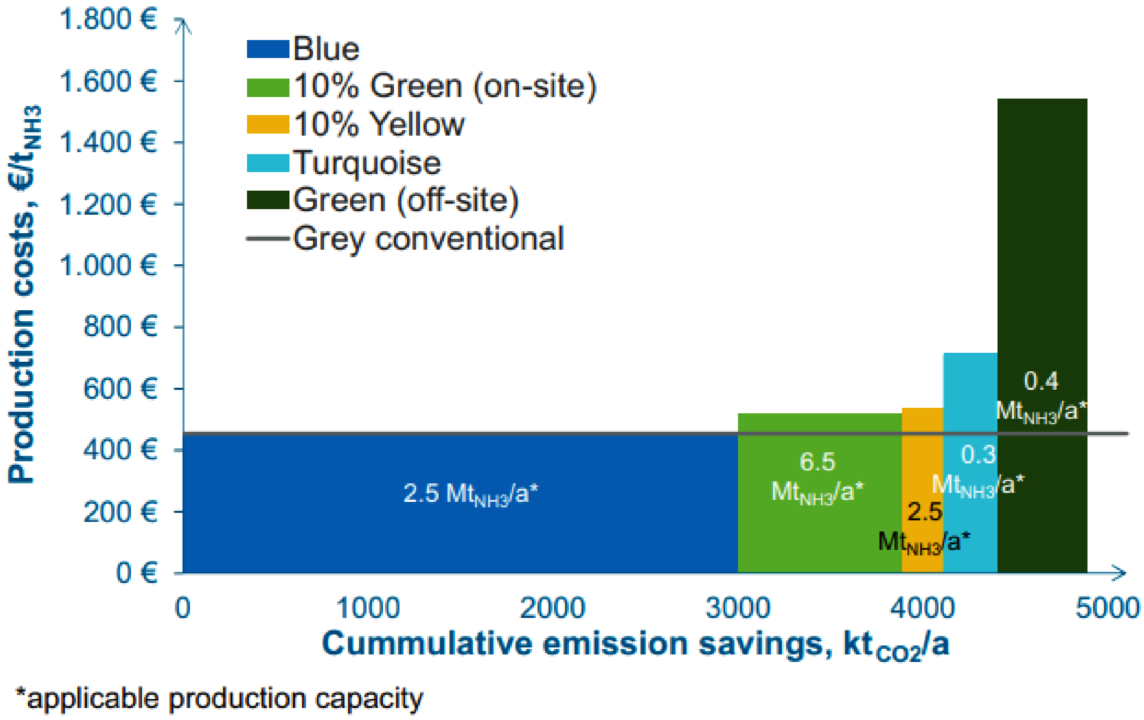

Figure 46: Production costs per ton ammonia of different technologies vs emission savings in 2030. Source: (Ausfelder, Herrmann, and López González 2022).

Ammonia

Table 53: Description of the ammonia production routes.

Production route	Process
(NG)NH3	Refrigerator conventional,Ammonia plant conventional,Cooling tower,Natural gas Furnace
(NG)NH3-MEA	Refrigerator conventional,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mono-ethanolamine Carbon Capture
(NG)NH3-DEA	Refrigerator conventional,Ammonia plant conventional,Cooling tower,Natural gas Furnace
(NG)NH3-MEA-DEA	Refrigerator conventional,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mono-ethanolamine Carbon Capture
(NG)NH3-MVR	Refrigerator conventional,Steam network,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mechanical vapor recompression
(NG)NH3-MVR-MEA	Refrigerator conventional,Steam network,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mechanical vapor recompression,Mono-ethanolamine Carbon Capture
(NG)NH3-MVR-DEA	Refrigerator conventional,Steam network,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mechanical vapor recompression
(NG)NH3-MVR-MEA-DEA	Refrigerator conventional,Steam network,Ammonia plant conventional,Cooling tower,Natural gas Furnace,Mechanical vapor recompression,Mono-ethanolamine Carbon Capture
(BM)NH3	Refrigerator conventional,Steam network,Ammonia plant biomass,Cooling tower
(BM)NH3-DEA	Refrigerator conventional,Steam network,Ammonia plant biomass,Cooling tower
(H2)NH3	Refrigerator conventional,Ammonia plant electrolyser,Cooling tower,Air separation unit
(H2)NH3-AEL	Refrigerator conventional,Ammonia plant electrolyser,Cooling tower,Air separation unit,Alkaline electrolyser
AIDRES EU-mix-2018	Cooling tower,Natural gas Furnace,Ammonia plant conventional,Refrigerator conventional
AIDRES EU-mix-2030	Air separation unit,Ammonia plant biomass,Cooling tower,Ammonia plant electrolyser,Mono-ethanolamine Carbon Capture,Mechanical vapor recompression,Natural gas Furnace,Ammonia plant conventional,Refrigerator conventional,Steam network
AIDRES EU-mix-2040	Air separation unit,Ammonia plant biomass,Cooling tower,Ammonia plant electrolyser,Mono-ethanolamine Carbon Capture,Mechanical vapor recompression,Natural gas Furnace,Ammonia plant conventional,Refrigerator conventional,Steam network
AIDRES EU-mix-2050	Air separation unit,Ammonia plant biomass,Cooling tower,Ammonia plant electrolyser,Mono-ethanolamine Carbon Capture,Mechanical vapor recompression,Natural gas Furnace,Ammonia plant conventional,Refrigerator conventional,Steam network

Urea

Table 54: Description of the urea production routes.

Production route	Process
(NG)Urea	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Natural gas Furnace, Urea plant
(NG)Urea-MEA	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Natural gas Furnace, Mono-ethanolamine Carbon Capture, Urea plant
(NG)Urea-DEA	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Natural gas Furnace, Urea plant
(NG)Urea-MEA-DEA	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Natural gas Furnace, Mono-ethanolamine Carbon Capture, Urea plant
(BM)Urea	Refrigerator conventional, Steam network, Ammonia plant biomass, Cooling tower, Urea plant
(BM)Urea-DEA	Refrigerator conventional, Steam network, Ammonia plant biomass, Cooling tower, Urea plant
(H2)Urea	Refrigerator conventional, Ammonia plant electrolyser, Cooling tower, Air separation unit, Urea plant
(H2)Urea-AEL	Refrigerator conventional, Ammonia plant electrolyser, Cooling tower, Air separation unit, Alkaline electrolyser, Urea plant
(NH3)Urea	Cooling tower, Urea plant

Nitric acid

Table 55: Description of the nitric acid production routes.

Production route	Process
(NG)HNO3	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Nitric acid plant
(NG)HNO3-DEA	Refrigerator conventional, Steam network, Ammonia plant conventional, Cooling tower, Nitric acid plant
(BM)HNO3	Refrigerator conventional, Steam network, Ammonia plant biomass, Cooling tower, Nitric acid plant
(BM)HNO3-DEA	Refrigerator conventional, Steam network, Ammonia plant biomass, Cooling tower, Nitric acid plant
(H2)HNO3	Refrigerator conventional, Steam network, Ammonia plant electrolyser, Cooling tower, Air separation unit, Nitric acid plant
(H2)HNO3-AEL	Refrigerator conventional, Steam network, Ammonia plant electrolyser, Cooling tower, Air separation unit, Alkaline electrolyser, Nitric acid plant
(NH3)HNO3	Steam network, Cooling tower, Nitric acid plant

12.7.5. Chemical

Olefins

Table 56: Description of the olefins production routes.

Production route	Process
(LN)O	Air cooling, Refrigerator, Naphtha-to-olefins, Naphtha-to-olefins electric
(LN)O-MEA	NG Furnace, Refrigerator, Mono-ethanolamine carbon capture, Naphtha-to-olefins
(LN+EL)O	Air cooling, Refrigerator, Naphtha-to-olefins, Naphtha-to-olefins electric
(MeOH)O	Air cooling, Methanol-to-olefins
(MeOH)O-MEA	Air cooling, Mono-ethanolamine carbon capture, Methanol-to-olefins
((BM)MeOH)O	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis
((BM)MeOH)O-MEA	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Mono-ethanolamine carbon capture, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis, Mono-ethanolamine Carbon Capture
((BM+H2)MeOH)O	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis
((BM+H2)MeOH)O-AEL	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Alkaline electrolyser, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis
((BM+H2)MeOH)O-MEA	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Mono-ethanolamine carbon capture, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis, Mono-ethanolamine Carbon Capture
((BM+H2)MeOH)O-MEA-AEL	Biomass gasification, FT fuel synthesis, Methanol synthesis, Air cooling, EtOAc-water cooling, Mono-ethanolamine carbon capture, Alkaline electrolyser, Methanol-to-olefins, Biomass gasification, FT fuel synthesis, Methanol synthesis, Mono-ethanolamine Carbon Capture
((COEL)MeOH)O	Co-electrolysis, Methanol synthesis, Air cooling, EtOAc-water cooling, Methanol-to-olefins, Co-electrolysis, Methanol synthesis
((COEL)MeOH)O-MEA	Co-electrolysis, Methanol synthesis, Air cooling, EtOAc-water cooling, Mono-ethanolamine carbon capture, Methanol-to-olefins, Co-electrolysis, Methanol synthesis, Mono-ethanolamine Carbon Capture

Polyethylene

Table 57: Description of the polyethylene production routes.

Production route	Process
(NG)PE	Polymerization (Polyethylene), NG Furnace, Air cooling, Water cooling
(NG)PE-MEA	Polymerization (Polyethylene), NG Furnace, Air cooling, Water cooling, Mono-ethanolamine carbon capture
(H2)PE	Polymerization (Polyethylene), H2 Furnace, Air cooling, EtOAc-water cooling
(H2)PE-AEL	Polymerization (Polyethylene), H2 Furnace, Air cooling, EtOAc-water cooling, Alkaline electrolyser
(EL)PE	Polymerization (Polyethylene), Air cooling, EtOAc-water cooling, EL Furnace
AIDRES EU-mix-2018	Air cooling, NG Furnace, Polymerization (Polyethylene), Water cooling
AIDRES EU-mix-2030	Air cooling, EL Furnace, EtOAc-water cooling, H2 Furnace, Mono-ethanolamine carbon capture, NG Furnace, Polymerization (Polyethylene), Water cooling
AIDRES EU-mix-2050	Air cooling, EL Furnace, EtOAc-water cooling, H2 Furnace, Mono-ethanolamine carbon capture, NG Furnace, Polymerization (Polyethylene), Water cooling

Poly-ethyl-acetate

Table 58: Description of the poly-ethyl-acetate production routes.

Production route	Process
(NG)PEA	Polymerization (Poly-ethyl-acetate), NG Furnace, Air cooling, EtOAc-water cooling
(NG)PEA-MEA	Polymerization (Poly-ethyl-acetate), NG Furnace, Air cooling, EtOAc-water cooling, Mono-ethanolamine carbon capture

(H2)PEA	Polymerization (Poly-ethyl-acetate), H2 Furnace, Air cooling, EtOAc-water cooling
(H2)PEA-AEL	Polymerization (Poly-ethyl-acetate), H2 Furnace, Air cooling, EtOAc-water cooling, Alkaline electrolyser
(EL)PEA	Polymerization (Poly-ethyl-acetate), Air cooling, EtOAc-water cooling, EL Furnace
AIDRES EU-mix-2018	Air cooling, EtOAc-water cooling, NG Furnace, Polymerization (Poly-ethyl-acetate)
AIDRES EU-mix-2030	Air cooling, EL Furnace, EtOAc-water cooling, H2 Furnace, Mono-ethanolamine carbon capture, NG Furnace, Polymerization (Poly-ethyl-acetate)
AIDRES EU-mix-2050	Air cooling, EL Furnace, EtOAc-water cooling, H2 Furnace, Mono-ethanolamine carbon capture, NG Furnace, Polymerization (Poly-ethyl-acetate)

12.8. Scenario integration

12.8.1. Steel

Primary steel

CAPEX

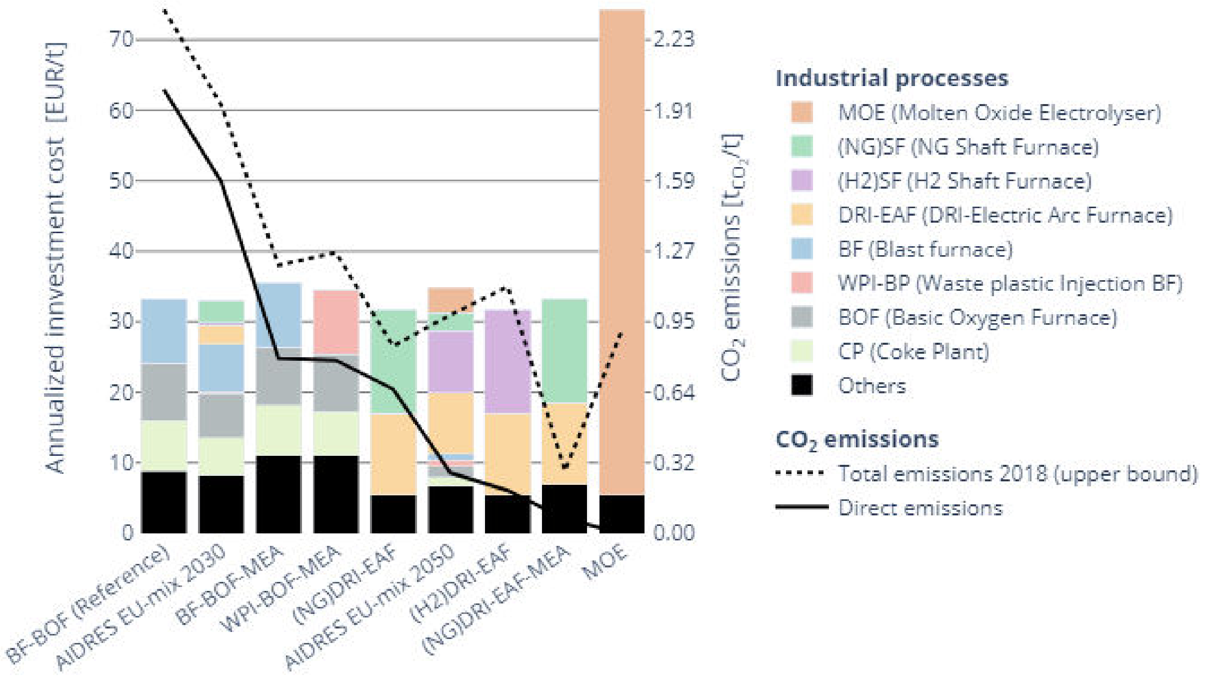

Figure 47: Specific investment cost of the primary steel AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of primary steel for the scenarios 2018-2050 (Table 1) are given in Table 59.

Table 59: Operating cost for the primary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
BF-BOF-REF	494	735	735	735	735	1136	1136	1136	1136
BF-BOF-MEA		574	578	574	578	733	736	733	736
WPI-BOF		764	764	764	764	1156	1156	1156	1156
WPI-BOF-MEA		605	606	605	606	762	763	762	763
(NG)DRI-EAF		440	492	440	492	591	622	591	622
(NG)DRI-EAF-MEA		359	411	359	411	393	424	393	424
(NG+H2)DRI-EAF		466	501	515	550	533	553	557	578
(NG+H2)DRI-EAF-AEL		480	514	480	514	583	604	583	604
(H2)DRI-EAF		605	605	795	795	501	501	596	596
(H2)DRI-EAF-AEL		657	657	657	657	696	696	696	696
MOE		506	506	506	506	506	506	506	506
EU-mix-2030		659	670	664	675				
EU-mix-2050						529	535	585	591

TOTEX

The annual total cost (TOTEX) per ton of primary steel for the scenarios 2018-2050 (

Table 1) are given in Table 60.

Table 60: Total cost for the primary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
BF-BOF-REF	527	768	768	768	768	1169	1169	1169	1169
BF-BOF-MEA		638	642	638	642	797	800	797	800
WPI-BOF		796	796	796	796	1188	1188	1188	1188
WPI-BOF-MEA		667	668	667	668	824	825	824	825
(NG)DRI-EAF		472	524	472	524	623	654	623	654
(NG)DRI-EAF-MEA		405	457	405	457	439	470	439	470
(NG+H2)DRI-EAF		498	533	547	582	565	585	589	610
(NG+H2)DRI-EAF-AEL		514	548	514	548	617	638	617	638
(H2)DRI-EAF		637	637	827	827	533	533	628	628
(H2)DRI-EAF-AEL		697	697	697	697	736	736	736	736
MOE		580	580	580	580	580	580	580	580
EU-mix-2030		694	705	699	710				
EU-mix-2050						572	577	628	633

Total emission

The total emission per ton of primary steel for the scenarios 2018-2050 (

Table 1) are given in Table 61.

Table 61: Total emissions for the primary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
BF-BOF-REF	2.36	2.34	2.34	2.34	2.34	2.32	2.32	2.32	2.32
BF-BOF-MEA		1.16	1.16	1.16	1.16	1.11	1.11	1.11	1.11
WPI-BOF		2.37	2.37	2.37	2.37	2.34	2.34	2.34	2.34
WPI-BOF-MEA		1.21	1.21	1.21	1.21	1.16	1.16	1.16	1.16
(NG)DRI-EAF		0.78	0.78	0.78	0.78	0.71	0.71	0.71	0.71

(NG)DRI-EAF-MEA	0.21	0.21	0.21	0.21	0.13	0.13	0.13	0.13
(NG+H2)DRI-EAF	0.56	0.56	0.56	0.56	0.49	0.49	0.49	0.49
(NG+H2)DRI-EAF-AEL	0.71	0.71	0.71	0.71	0.49	0.49	0.49	0.49
(H2)DRI-EAF	0.27	0.27	0.27	0.27	0.20	0.20	0.20	0.20
(H2)DRI-EAF-AEL	0.84	0.84	0.84	0.84	0.20	0.20	0.20	0.20
MOE	0.48	0.48	0.48	0.48	0.00	0.00	0.00	0.00
EU-mix-2030	1.88	1.88	1.88	1.88				
EU-mix-2050					0.35	0.35	0.35	0.35

Secondary steel

CAPEX

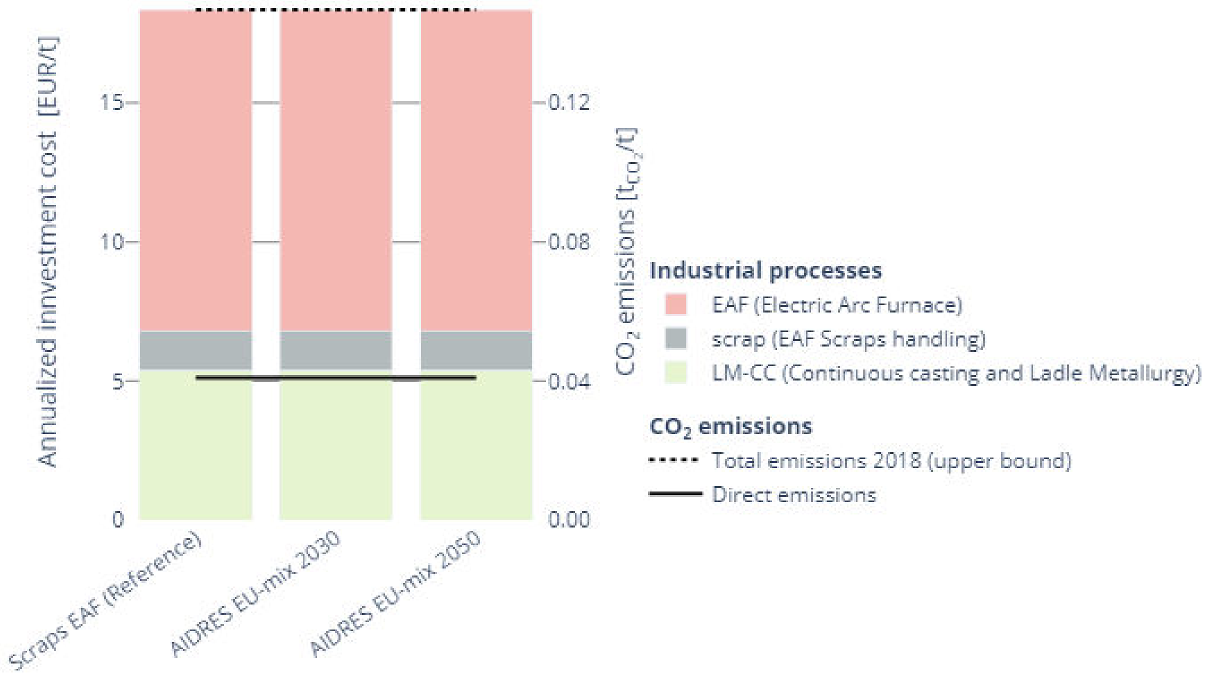

Figure 48: Specific investment cost of the secondary steel AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of product for the scenarios 2018-2050 (

Table 1) are given in Table 62.

Table 62: Operating cost for the secondary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
Scraps EAF-REF	531	514	515	514	515	522	523	522	523
EU-mix-2030		514	515	514	515				
EU-mix-2050						522	523	522	523

TOTEX

The annual total cost (TOTEX) per ton of product for the scenarios 2018-2050 (

Table 1) are given in Table 63.

Table 63: Total cost for the secondary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
Scraps EAF-REF	549	532	533	532	533	540	541	540	541
EU-mix-2030		532	533	532	533				
EU-mix-2050						540	541	540	541

Total emission

The total emission per ton of secondary steel for the scenarios 2018-2050 (

Table 1) are given in Table 64.

Table 64: Total emissions for the secondary steel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
12. Scraps EAF-REF	0.14	0.1	0.1	0.1	0.1	0.05	0.05	0.05	0.05
3. EU-mix-2030		0.1	0.1	0.1	0.1				
5. EU-mix-2050						0.05	0.05	0.05	0.05

12.8.2. Refineries

Light liquid fuel

CAPEX

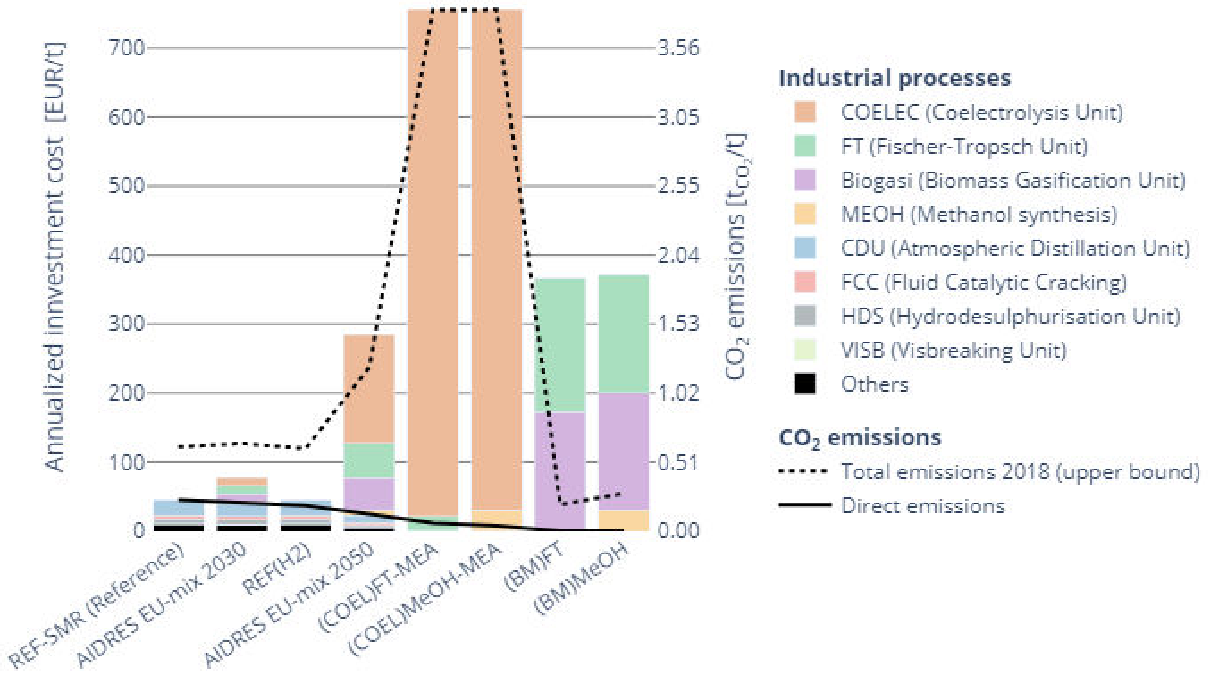

Figure 49: Specific investment cost of the light liquid fuel AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of secondary steel for the scenarios 2018-2050 (

Table 1) are given in Table 65.

Table 65: Operating cost for the light liquid fuel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
REF-SMR-REF	623	650	667	650	667	703	714	703	714
REF(H2)		643	655	652	664	680	687	684	691
REF(H2)-MEA		619	631	627	639	621	628	625	633
REF-SMR-MEA		620	638	620	638	632	642	632	642
(BM)FT		388	388	388	388	388	388	388	388
(BM+H2)FT		774	774	1039	1039	574	574	707	707
(BM+H2)FT-AEL		847	847	847	847	847	847	847	847
(BM)FT-MEA		142	142	142	142	-192	-192	-192	-192
(BM+H2)FT-MEA		518	518	783	783	-27	-27	106	106
(BM+H2)FT-AEL-MEA		591	591	591	591	245	245	245	245
(BM)MeOH		412	412	412	412	412	412	412	412
(BM+H2)MeOH		792	792	1054	1054	595	595	726	726
(BM+H2)MeOH-AEL		864	864	864	864	864	864	864	864
(BM)MeOH-MEA		238	238	238	238	3	3	3	3
(BM+H2)MeOH-MEA		609	609	870	870	165	165	296	296
(BM+H2)MeOH-AEL-MEA		681	681	681	681	433	433	433	433
(COEL)FT		1432	1432	1432	1432	1552	1552	1552	1552
(COEL)FT-MEA		1354	1354	1354	1354	1366	1366	1366	1366
(COEL)MeOH		1416	1416	1416	1416	1493	1493	1493	1493
(COEL)MeOH-MEA		1366	1366	1366	1366	1374	1374	1374	1374
EU-mix-2030		645	660	645	661				
EU-mix-2050						761	766	762	767

TOTEX

The annual total cost (TOTEX) per ton of secondary steel for the scenarios 2018-2050 (

Table 1) are given in Table 66.

Table 66: Total cost for the light liquid fuel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
REF-SMR-REF	667	694	711	694	711	747	758	747	758
REF(H2)		687	699	696	708	724	731	728	735
REF(H2)-MEA		663	675	671	683	665	672	669	677
REF-SMR-MEA		665	683	665	683	677	687	677	687
(BM)FT		581	581	581	581	581	581	581	581
(BM+H2)FT		852	852	1117	1117	652	652	785	785
(BM+H2)FT-AEL		936	936	936	936	936	936	936	936
(BM)FT-MEA		335	335	335	335	1	1	1	1
(BM+H2)FT-MEA		597	597	862	862	52	52	185	185
(BM+H2)FT-AEL-MEA		681	681	681	681	335	335	335	335
(BM)MeOH		613	613	613	613	613	613	613	613
(BM+H2)MeOH		880	880	1142	1142	683	683	814	814

(BM+H2)MeOH-AEL		963	963	963	963	963	963	963	963
(BM)MeOH-MEA		439	439	439	439	204	204	204	204
(BM+H2)MeOH-MEA		697	697	958	958	253	253	384	384
(BM+H2)MeOH-AEL-MEA		780	780	780	780	532	532	532	532
(COEL)FT		2187	2187	2187	2187	2307	2307	2307	2307
(COEL)FT-MEA		2109	2109	2109	2109	2121	2121	2121	2121
(COEL)MeOH		2171	2171	2171	2171	2248	2248	2248	2248
(COEL)MeOH-MEA		2121	2121	2121	2121	2129	2129	2129	2129
EU-mix-2030		710	726	710	726				
EU-mix-2050						999	1003	999	1004

Total emission

The total emission per ton of secondary steel for the scenarios 2018-2050 (

Table 1) are given in Table 67.

Table 67: Total emissions for the light liquid fuel production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
REF-SMR-REF	0.62	0.62	0.62	0.62	0.62	0.61	0.61	0.61	0.61
REF(H2)		0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
REF(H2)-MEA		0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
REF-SMR-MEA		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
(BM)FT		0.10	0.10	0.10	0.10	0.00	0.00	0.00	0.00
(BM+H2)FT		0.10	0.10	0.10	0.10	0.00	0.00	0.00	0.00
(BM+H2)FT-AEL		0.90	0.90	0.90	0.90	0.00	0.00	0.00	0.00
(BM)FT-MEA		-1.55	-1.55	-1.55	-1.55	-1.67	-1.67	-1.67	-1.67
(BM+H2)FT-MEA		-1.62	-1.62	-1.62	-1.62	-1.73	-1.73	-1.73	-1.73
(BM+H2)FT-AEL-MEA		-0.82	-0.82	-0.82	-0.82	-1.73	-1.73	-1.73	-1.73
(BM)MeOH		0.14	0.14	0.14	0.14	0.00	0.00	0.00	0.00
(BM+H2)MeOH		0.14	0.14	0.14	0.14	0.00	0.00	0.00	0.00
(BM+H2)MeOH-AEL		0.93	0.93	0.93	0.93	0.00	0.00	0.00	0.00
(BM)MeOH-MEA		-1.02	-1.02	-1.02	-1.02	-1.18	-1.18	-1.18	-1.18
(BM+H2)MeOH-MEA		-1.09	-1.09	-1.09	-1.09	-1.24	-1.24	-1.24	-1.24
(BM+H2)MeOH-AEL-MEA		-0.30	-0.30	-0.30	-0.30	-1.24	-1.24	-1.24	-1.24
(COEL)FT		2.56	2.56	2.56	2.56	0.60	0.60	0.60	0.60
(COEL)FT-MEA		2.03	2.03	2.03	2.03	0.06	0.06	0.06	0.06
(COEL)MeOH		2.36	2.36	2.36	2.36	0.38	0.38	0.38	0.38
(COEL)MeOH-MEA		2.02	2.02	2.02	2.02	0.04	0.04	0.04	0.04
EU-mix-2030		0.61	0.61	0.61	0.61				
EU-mix-2050						0.32	0.32	0.32	0.32

12.8.3. Cement

Portland Cement II (BV325R)

CAPEX

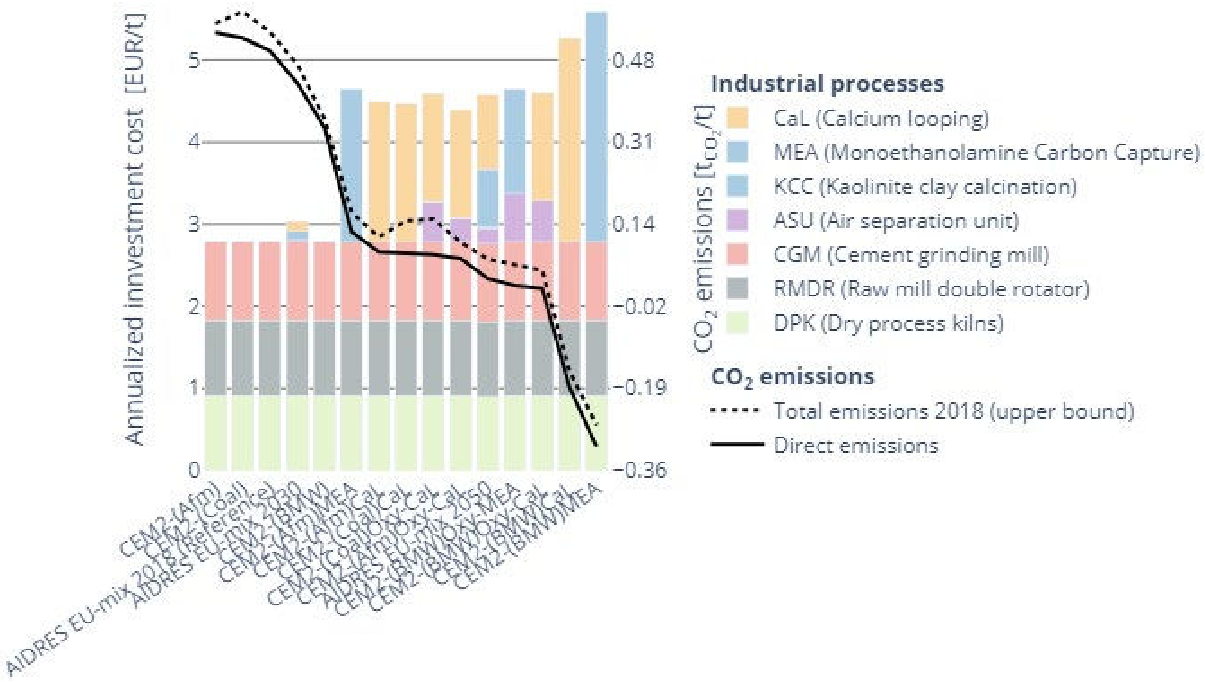

Figure 50: Specific investment cost of the Portland cement II routes of the AIDRES EU-mix.

OPEX

The annual operating cost per ton of Portland cement II for the scenarios 2018-2050 (Table 1) are given in Table 68.

Table 68: Operating cost for the Portland cement II production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018-REF	53								
CEM2-(Coal)	55	117	117	117	117	221	221	221	221
CEM2-(Coal)MEA		73	73	73	73	101	101	101	101
CEM2-(Coal)CaL		61	61	61	61	79	79	79	79
CEM2-(Coal)Oxy-MEA		70	70	70	70	92	92	92	92
CEM2-(Coal)Oxy-CaL		62	62	62	62	78	78	78	78
CEM2-(NG)		113	128	113	128	212	221	212	221
CEM2-(NG)MEA		76	102	76	102	109	124	109	124
CEM2-(NG)CaL		65	80	65	80	86	95	86	95
CEM2-(NG)Oxy-MEA		82	104	82	104	113	127	113	127
CEM2-(NG)Oxy-CaL		70	85	70	85	93	103	93	103
CEM2-(Afm)	47	110	110	110	110	217	217	217	217
CEM2-(Afm)MEA		56	56	56	56	81	81	81	81
CEM2-(Afm)CaL		54	54	54	54	71	71	71	71

CEM2-(Afm)Oxy-MEA		51	51	51	51	70	70	70	70
CEM2-(Afm)Oxy-CaL		49	49	49	49	64	64	64	64
CEM2-(BMW)	54	93	93	93	93	161	161	161	161
CEM2-(BMW)MEA		10	10	10	10	-51	-51	-51	-51
CEM2-(BMW)CaL		26	26	26	26	-12	-12	-12	-12
CEM2-(BMW)Oxy-MEA		56	56	56	56	60	60	60	60
CEM2-(BMW)Oxy-CaL		54	54	54	54	57	57	57	57
EU-mix-2030		102	102	102	102				
EU-mix-2050						58	59	58	59

TOTEX

The annual total cost (TOTEX) per ton of product for the scenarios 2018-2050 (

Table 1) are given in Table 69.

Table 69: Total cost for the Portland cement II production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018	56								
CEM2-(Coal)	58	120	120	120	120	224	224	224	224
CEM2-(Coal)MEA		78	78	78	78	106	106	106	106
CEM2-(Coal)CaL		82	82	82	82	100	100	100	100
CEM2-(Coal)Oxy-MEA		74	74	74	74	96	96	96	96
CEM2-(Coal)Oxy-CaL		77	77	77	77	93	93	93	93
CEM2-(NG)		116	131	116	131	215	224	215	224
CEM2-(NG)MEA		80	106	80	106	113	128	113	128
CEM2-(NG)CaL		84	99	84	99	105	114	105	114
CEM2-(NG)Oxy-MEA		87	109	87	109	118	132	118	132
CEM2-(NG)Oxy-CaL		86	101	86	101	109	119	109	119
CEM2-(Afm)	50	113	113	113	113	220	220	220	220
CEM2-(Afm)MEA		61	61	61	61	86	86	86	86
CEM2-(Afm)CaL		76	76	76	76	93	93	93	93
CEM2-(Afm)Oxy-MEA		55	55	55	55	74	74	74	74
CEM2-(Afm)Oxy-CaL		64	64	64	64	79	79	79	79
CEM2-(BMW)	57	96	96	96	96	164	164	164	164
CEM2-(BMW)MEA		15	15	15	15	-46	-46	-46	-46
CEM2-(BMW)CaL		51	51	51	51	13	13	13	13
CEM2-(BMW)Oxy-MEA		60	60	60	60	64	64	64	64
CEM2-(BMW)Oxy-CaL		70	70	70	70	73	73	73	73
EU-mix-2030		107	107	107	107				
EU-mix-2050						71	71	71	71

Total emission

The total emission per ton of Portland cement II for the scenarios 2018-2050 (

Table 1) are given in Table 70.

Table 70: Total emissions for the Portland cement II production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018	0.54								
CEM2-(Coal)	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56
CEM2-(Coal)MEA		0.22	0.22	0.22	0.22	0.20	0.20	0.20	0.20
CEM2-(Coal)CaL		0.14	0.14	0.14	0.14	0.12	0.12	0.12	0.12
CEM2-(Coal)Oxy-MEA		0.18	0.18	0.18	0.18	0.16	0.16	0.16	0.16
CEM2-(Coal)Oxy-CaL		0.14	0.14	0.14	0.14	0.12	0.12	0.12	0.12
CEM2-(NG)		0.49	0.49	0.49	0.49	0.48	0.48	0.48	0.48
CEM2-(NG)MEA		0.16	0.16	0.16	0.16	0.14	0.14	0.14	0.14
CEM2-(NG)CaL		0.11	0.11	0.11	0.11	0.09	0.09	0.09	0.09
CEM2-(NG)Oxy-MEA		0.16	0.16	0.16	0.16	0.14	0.14	0.14	0.14
CEM2-(NG)Oxy-CaL		0.12	0.12	0.12	0.12	0.10	0.10	0.10	0.10
CEM2-(Afm)	0.55	0.55	0.55	0.55	0.55	0.54	0.54	0.54	0.54
CEM2-(Afm)MEA		0.15	0.15	0.15	0.15	0.13	0.13	0.13	0.13
CEM2-(Afm)CaL		0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09
CEM2-(Afm)Oxy-MEA		0.11	0.11	0.11	0.11	0.09	0.09	0.09	0.09
CEM2-(Afm)Oxy-CaL		0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08
CEM2-(BMW)	0.36	0.35	0.35	0.35	0.35	0.34	0.34	0.34	0.34
CEM2-(BMW)MEA		-0.29	-0.29	-0.29	-0.29	-0.31	-0.31	-0.31	-0.31
CEM2-(BMW)CaL		-0.17	-0.17	-0.17	-0.17	-0.19	-0.19	-0.19	-0.19
CEM2-(BMW)Oxy-MEA		0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02
CEM2-(BMW)Oxy-CaL		0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01
EU-mix-2030		0.46	0.46	0.46	0.46				
EU-mix-2050						0.04	0.04	0.04	0.04

Limestone Calcined Clay product (LC3)

CAPEX

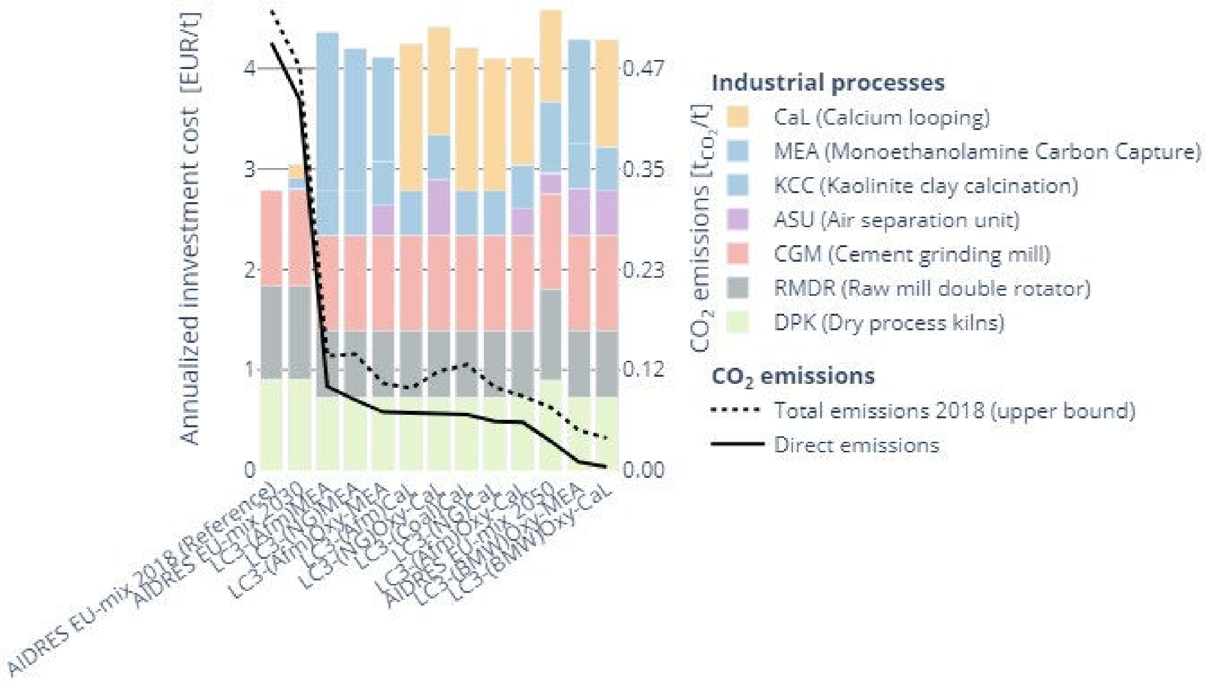

Figure 51: Specific investment cost of the LC3 AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of the limestone calcined clay for the scenarios 2018-2050 (

Table 1) are given in Table 71.

Table 71: Operating cost for the limestone calcined clay production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018	53								
LC3-(Coal)		98	98	98	98	178	178	178	178
LC3-(Coal)MEA		65	65	65	65	86	86	86	86
LC3-(Coal)CaL		56	56	56	56	69	69	69	69
LC3-(Coal)Oxy-MEA		62	62	62	62	79	79	79	79
LC3-(Coal)Oxy-CaL		56	56	56	56	69	69	69	69
LC3-(NG)		95	108	95	108	170	178	170	178
LC3-(NG)MEA		68	88	68	88	92	105	92	105
LC3-(NG)CaL		59	72	59	72	75	83	75	83
LC3-(NG)Oxy-MEA		72	90	72	90	96	107	96	107
LC3-(NG)Oxy-CaL		64	76	64	76	82	90	82	90
LC3-(Afm)		93	93	93	93	175	175	175	175
LC3-(Afm)MEA		51	51	51	51	70	70	70	70
LC3-(Afm)CaL		49	49	49	49	63	63	63	63
LC3-(Afm)Oxy-MEA		47	47	47	47	61	61	61	61
LC3-(Afm)Oxy-CaL		46	46	46	46	57	57	57	57
LC3-(BMW)		78	78	78	78	127	127	127	127
LC3-(BMW)MEA		14	14	14	14	-37	-37	-37	-37
LC3-(BMW)CaL		26	26	26	26	-9	-9	-9	-9

LC3-(BMW)Oxy-MEA		51	51	51	51	53	53	53	53
LC3-(BMW)Oxy-CaL		51	51	51	51	51	51	51	51
EU-mix-2030		102	102	102	102				
EU-mix-2050						58	59	58	59

TOTEX

The annual total cost (TOTEX) per ton of the limestone calcined clay for the scenarios 2018-2050 (

Table 1) are given in Table 72.

Table 72: Total cost for the limestone calcined clay production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018	56								
LC3-(Coal)		101	101	101	101	181	181	181	181
LC3-(Coal)MEA		69	69	69	69	90	90	90	90
LC3-(Coal)CaL		73	73	73	73	86	86	86	86
LC3-(Coal)Oxy-MEA		66	66	66	66	83	83	83	83
LC3-(Coal)Oxy-CaL		68	68	68	68	81	81	81	81
LC3-(NG)		98	111	98	111	173	181	173	181
LC3-(NG)MEA		72	92	72	92	96	109	96	109
LC3-(NG)CaL		74	87	74	87	90	98	90	98
LC3-(NG)Oxy-MEA		76	94	76	94	100	111	100	111
LC3-(NG)Oxy-CaL		76	88	76	88	94	102	94	102
LC3-(Afm)		96	96	96	96	178	178	178	178
LC3-(Afm)MEA		55	55	55	55	74	74	74	74
LC3-(Afm)CaL		66	66	66	66	80	80	80	80
LC3-(Afm)Oxy-MEA		51	51	51	51	65	65	65	65
LC3-(Afm)Oxy-CaL		58	58	58	58	69	69	69	69
LC3-(BMW)		81	81	81	81	130	130	130	130
LC3-(BMW)MEA		19	19	19	19	-32	-32	-32	-32
LC3-(BMW)CaL		47	47	47	47	12	12	12	12
LC3-(BMW)Oxy-MEA		55	55	55	55	57	57	57	57
LC3-(BMW)Oxy-CaL		63	63	63	63	63	63	63	63
EU-mix-2030		107	107	107	107				
EU-mix-2050						71	71	71	71

Total emission

The total emission per ton of the limestone calcined clay for the scenarios 2018-2050 (

Table 1) are given in Table 73.

Table 73: Total emissions for the limestone calcined clay production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
EU-mix-2018	0.54								
LC3-(Coal)		0.44	0.44	0.44	0.44	0.43	0.43	0.43	0.43
LC3-(Coal)MEA		0.18	0.18	0.18	0.18	0.16	0.16	0.16	0.16
LC3-(Coal)CaL		0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10
LC3-(Coal)Oxy-MEA		0.14	0.14	0.14	0.14	0.12	0.12	0.12	0.12

LC3-(Coal)Oxy-CaL		0.11	0.11	0.11	0.11	0.09	0.09	0.09	0.09
LC3-(NG)		0.37	0.37	0.37	0.37	0.36	0.36	0.36	0.36
LC3-(NG)MEA		0.12	0.12	0.12	0.12	0.10	0.10	0.10	0.10
LC3-(NG)CaL		0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07
LC3-(NG)Oxy-MEA		0.13	0.13	0.13	0.13	0.10	0.10	0.10	0.10
LC3-(NG)Oxy-CaL		0.10	0.10	0.10	0.10	0.08	0.08	0.08	0.08
LC3-(Afm)		0.42	0.42	0.42	0.42	0.41	0.41	0.41	0.41
LC3-(Afm)MEA		0.12	0.12	0.12	0.12	0.10	0.10	0.10	0.10
LC3-(Afm)CaL		0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07
LC3-(Afm)Oxy-MEA		0.09	0.09	0.09	0.09	0.07	0.07	0.07	0.07
LC3-(Afm)Oxy-CaL		0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06
LC3-(BMW)		0.25	0.25	0.25	0.25	0.24	0.24	0.24	0.24
LC3-(BMW)MEA		-0.24	-0.24	-0.24	-0.24	-0.26	-0.26	-0.26	-0.26
LC3-(BMW)CaL		-0.16	-0.16	-0.16	-0.16	-0.17	-0.17	-0.17	-0.17
LC3-(BMW)Oxy-MEA		0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01
LC3-(BMW)Oxy-CaL		0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
EU-mix-2030		0.46	0.46	0.46	0.46				
EU-mix-2050						0.04	0.04	0.04	0.04

12.8.4. Glass

Container glass

CAPEX

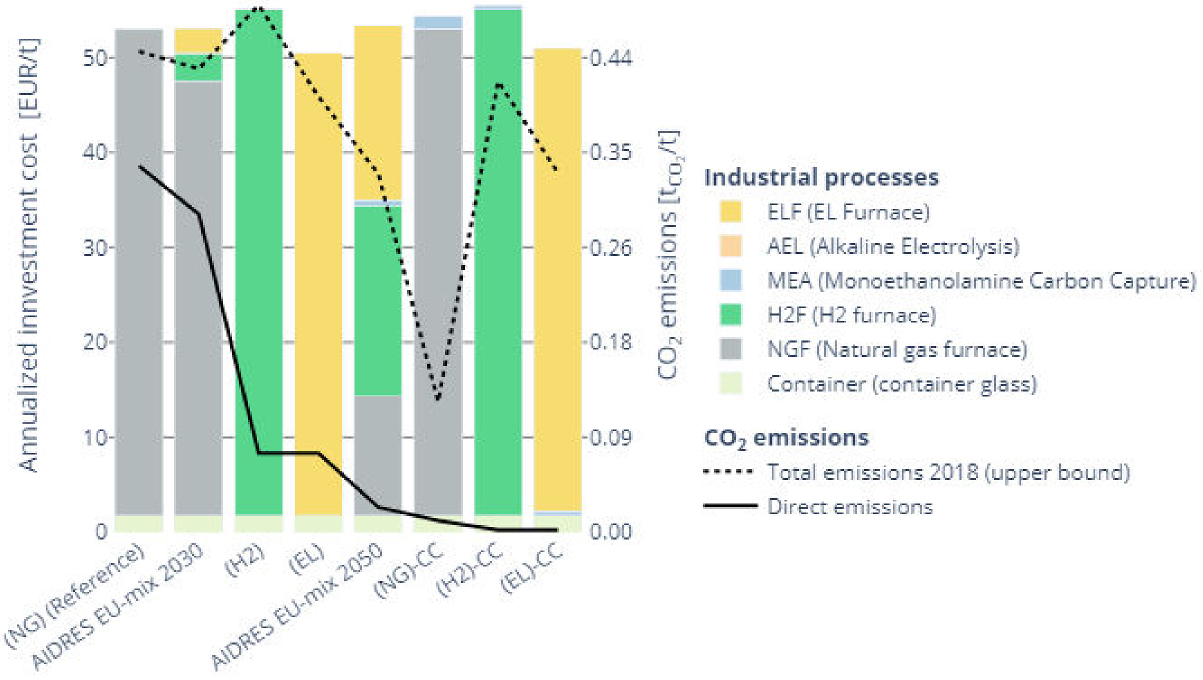

Figure 52: Specific investment cost of the container glass AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of container glass for the scenarios 2018-2050 (

Table 1) are given in Table 74.

Table 74: Operating cost for the container glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	184	211	244	212	245	291	311	292	311
(NG)-CC		163	196	164	197	178	198	178	198
(H2)		263	263	347	347	215	215	257	257
(H2)-CC		253	253	337	337	190	190	232	232
(H2)-AEL		287	287	287	287	301	301	301	301
(H2)-AEL-CC		276	276	276	276	277	277	277	277
(EL)		218	218	218	218	232	232	232	232
(EL)-CC		207	207	208	208	207	207	207	207
EU-mix-2030		212	241	217	246				
EU-mix-2050						200	205	216	221

TOTEX

The annual total cost (TOTEX) per ton of container glass for the scenarios 2018-2050 (

Table 1) are given in Table 75.

Table 75: Total cost for the container glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	237	264	297	265	298	344	364	345	364
(NG)-CC		218	251	219	252	233	253	233	253
(H2)		318	318	402	402	270	270	312	312
(H2)-CC		308	308	392	392	245	245	287	287
(H2)-AEL		355	355	355	355	369	369	369	369
(H2)-AEL-CC		344	344	344	344	345	345	345	345
(EL)		268	268	268	268	282	282	282	282
(EL)-CC		258	258	259	259	258	258	258	258
EU-mix-2030		265	294	270	299				
EU-mix-2050						254	258	270	274

Total emission

The total emission per ton of container glass for the scenarios 2018-2050 (

Table 1) are given in Table 76.

Table 76: Total emissions for the container glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	0.44	0.41	0.41	0.41	0.41	0.37	0.37	0.37	0.37
(NG)-CC		0.08	0.08	0.08	0.08	0.04	0.04	0.04	0.04
(H2)		0.11	0.11	0.11	0.11	0.07	0.07	0.07	0.07
(H2)-CC		0.04	0.04	0.04	0.04	0.00	0.00	0.00	0.00
(H2)-AEL		0.36	0.36	0.36	0.36	0.07	0.07	0.07	0.07
(H2)-AEL-CC		0.29	0.29	0.29	0.29	0.00	0.00	0.00	0.00

(EL)		0.24	0.24	0.24	0.24	0.07	0.07	0.07	0.07
(EL)-CC		0.17	0.17	0.17	0.17	0.00	0.00	0.00	0.00
EU-mix-2030		0.37	0.37	0.37	0.37				
EU-mix-2050						0.03	0.03	0.03	0.03

Flat glass

CAPEX

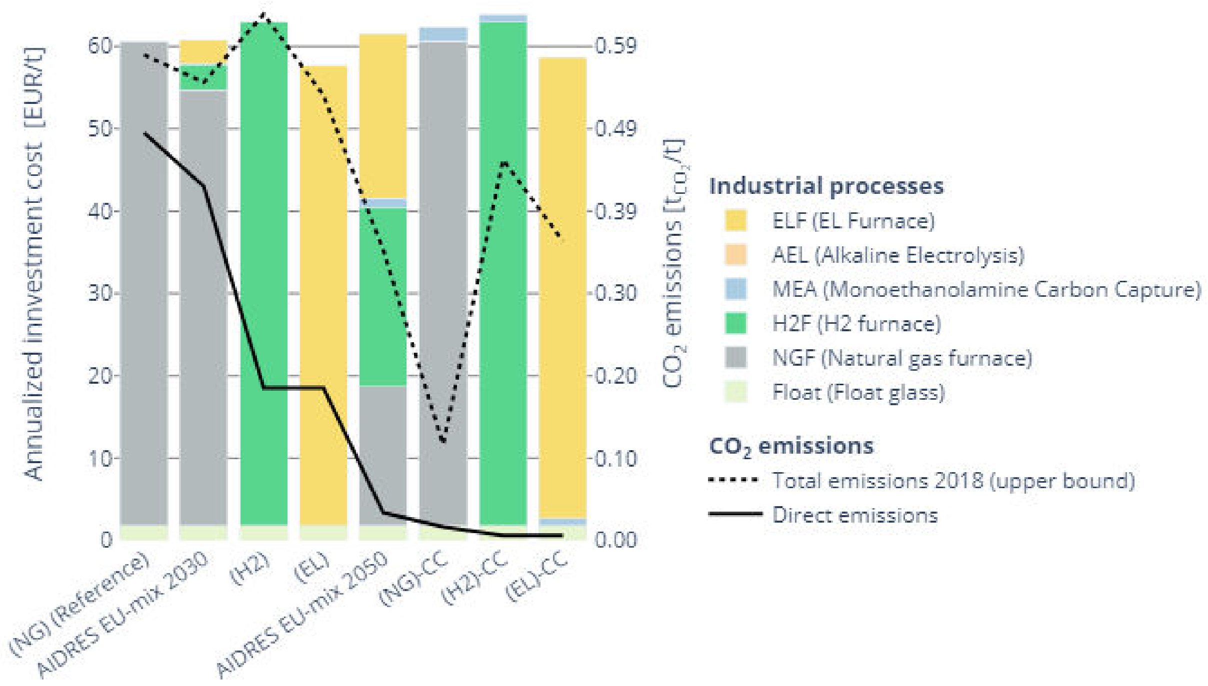

Figure 53: Specific investment cost of the flat glass AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of flat glass for the scenarios 2018-2050 (Table 1) are given in Table 77.

Table 77: Operating cost for the flat glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	162	213	250	214	251	325	347	325	348
(NG)-CC		144	182	145	182	162	184	162	185
(H2)		273	273	369	369	237	237	285	285
(H2)-CC		247	247	343	343	176	176	224	224
(H2)-AEL		299	299	299	299	336	336	336	336
(H2)-AEL-CC		274	274	274	274	275	275	275	275
(EL)		220	220	221	221	256	256	256	256
(EL)-CC		194	194	195	195	195	195	195	195
EU-mix-2030		211	245	217	251				
EU-mix-2050						187	194	205	211

TOTEX

The annual total cost (TOTEX) per ton of flat glass production for the scenarios 2018-2050 (

Table 1) are given in Table 78.

Table 78: Total cost for the flat glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	223	274	311	275	312	386	408	386	409
(NG)-CC		208	246	209	246	226	248	226	249
(H2)		336	336	432	432	300	300	348	348
(H2)-CC		311	311	407	407	240	240	288	288
(H2)-AEL		377	377	377	377	414	414	414	414
(H2)-AEL-CC		353	353	353	353	354	354	354	354
(EL)		278	278	279	279	314	314	314	314
(EL)-CC		253	253	254	254	254	254	254	254
EU-mix-2030		272	306	278	312				
EU-mix-2050						249	256	267	273

Total emission

The total emission per ton of flat glass production for the scenarios 2018-2050 (

Table 1) are given in Table 79.

Table 79: Total emissions for the flat glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	0.58	0.55	0.55	0.55	0.55	0.53	0.53	0.53	0.53
(NG)-CC		0.08	0.08	0.08	0.08	0.05	0.05	0.05	0.05
(H2)		0.21	0.21	0.21	0.21	0.18	0.18	0.18	0.18
(H2)-CC		0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01
(H2)-AEL		0.50	0.50	0.50	0.50	0.18	0.18	0.18	0.18
(H2)-AEL-CC		0.32	0.32	0.32	0.32	0.01	0.01	0.01	0.01
(EL)		0.36	0.36	0.36	0.36	0.18	0.18	0.18	0.18
(EL)-CC		0.19	0.19	0.19	0.19	0.01	0.01	0.01	0.01
EU-mix-2030		0.49	0.49	0.49	0.49				
EU-mix-2050						0.04	0.04	0.04	0.04

Fibre glass

CAPEX

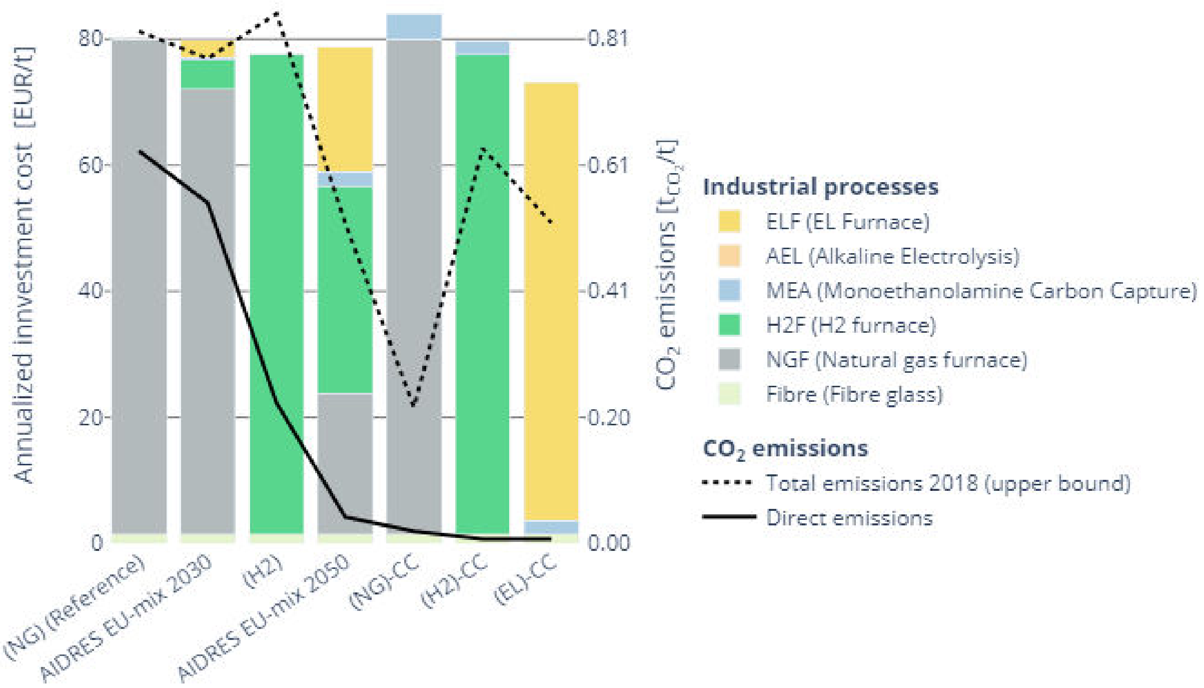

Figure 54: Specific investment cost of the fibre glass AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of fibre glass production for the scenarios 2018-2050 (

Table 1) are given in Table 80.

Table 80: Operating cost for the fibre glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	231	280	330	280	331	426	456	426	457
(NG)-CC		190	240	190	241	213	243	214	244
(H2)		347	347	466	466	302	302	362	362
(H2)-CC		314	314	434	434	226	226	286	286
(H2)-AEL		379	379	379	379	425	425	425	425
(H2)-AEL-CC		347	347	347	347	349	349	349	349
(EL)		281	281	282	282	326	326	326	326
(EL)-CC		249	249	250	250	250	250	250	250
EU-mix-2030		278	323	286	331				
EU-mix-2050						240	249	267	275

TOTEX

The annual total cost (TOTEX) per ton of fibre glass production for the scenarios 2018-2050 (

Table 1) are given in Table 81.

Table 81: Total cost for the fibre glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	311	360	410	360	411	506	536	506	537
(NG)-CC		274	324	274	325	297	327	298	328
(H2)		424	424	543	543	379	379	439	439
(H2)-CC		393	393	513	513	305	305	365	365
(H2)-AEL		475	475	475	475	521	521	521	521
(H2)-AEL-CC		444	444	444	444	446	446	446	446
(EL)		352	352	353	353	397	397	397	397
(EL)-CC		321	321	322	322	322	322	322	322
EU-mix-2030		357	402	365	410				
EU-mix-2050						319	327	345	353

Total emission

The total emission per ton of fibre glass for the scenarios 2018-2050 (

Table 1) are given in Table 82.

Table 82: Total emissions for the fibre glass production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)-REF	0.83	0.76	0.76	0.76	0.76	0.69	0.69	0.69	0.69
(NG)-CC		0.15	0.15	0.15	0.15	0.07	0.07	0.07	0.07
(H2)		0.30	0.30	0.30	0.30	0.23	0.23	0.23	0.23
(H2)-CC		0.08	0.08	0.08	0.08	0.01	0.01	0.01	0.01
(H2)-AEL		0.66	0.66	0.66	0.66	0.23	0.23	0.23	0.23
(H2)-AEL-CC		0.44	0.44	0.44	0.44	0.01	0.01	0.01	0.01
(EL)		0.49	0.49	0.49	0.49	0.23	0.23	0.23	0.23
(EL)-CC		0.27	0.27	0.27	0.27	0.01	0.01	0.01	0.01
EU-mix-2030		0.68	0.68	0.68	0.68				
EU-mix-2050						0.06	0.06	0.06	0.06

12.8.5. Fertilizer

Ammonia

CAPEX

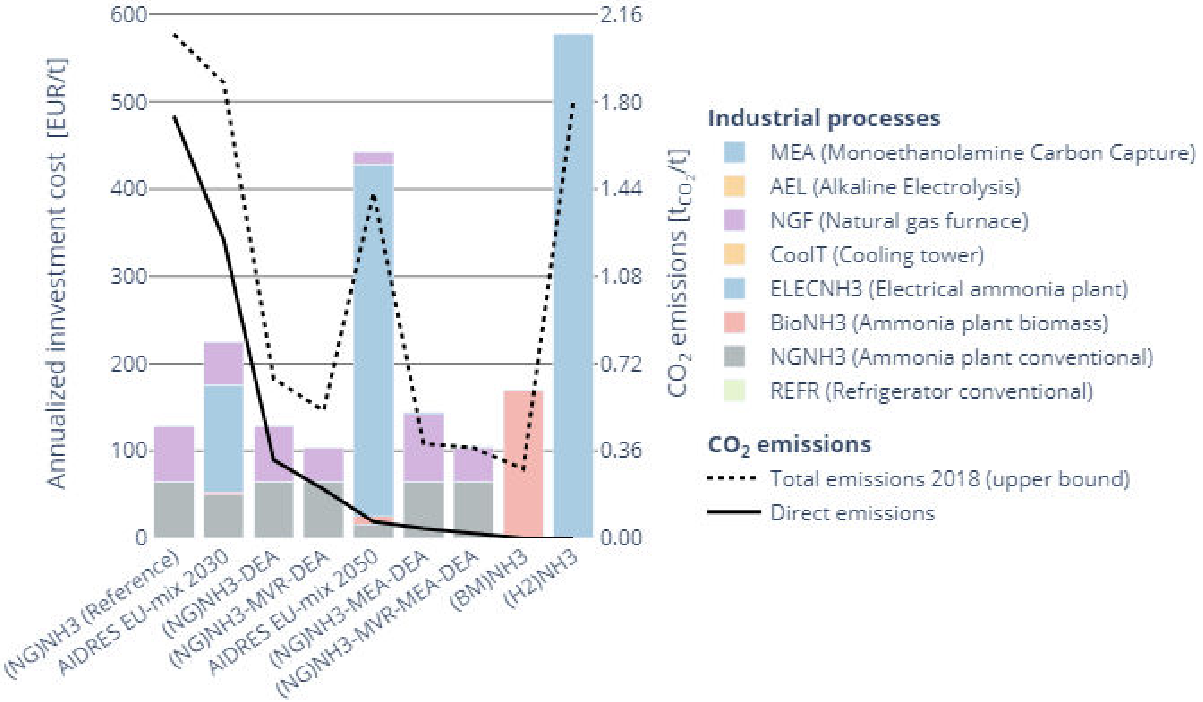

Figure 55: Specific investment cost of the ammonia AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of ammonia for the scenarios 2018-2050 (

Table 1) are given in Table 83.

Table 83: Operating cost for the ammonia production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)NH3-REF	307	499	696	499	696	926	1044	926	1044
(NG)NH3-MEA		468	674	468	674	842	966	842	966
(NG)NH3-DEA		286	483	286	483	429	547	429	547
(NG)NH3-MEA-DEA		255	461	255	461	345	469	345	469
NG)NH3-MVR		467	649	467	649	864	974	864	974
(NG)NH3-MVR-MEA		449	631	449	631	810	919	810	919
(NG)NH3-MVR-DEA		254	436	254	436	367	477	367	477
(NG)NH3-MVR-MEA-DEA		236	418	236	418	313	422	313	422
(BM)NH3		222	222	222	222	222	222	222	222
(BM)NH3-DEA		-162	-162	-162	-162	-673	-673	-673	-673
(H2)NH3		644	644	1029	1029	356	356	548	548
(H2)NH3-AEL		750	750	750	750	750	750	750	750
EU-mix-2030		509	660	591	743				

EU-mix-2050						362	391	497	526

TOTEX

The annual total cost (TOTEX) per ton of ammonia for the scenarios 2018-2050 (

Table 1) are given in Table 84.

Table 84: Total cost for the ammonia production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)NH3-REF	434	626	823	626	823	1053	1171	1053	1171
(NG)NH3-MEA		723	929	723	929	1097	1221	1097	1221
(NG)NH3-DEA		413	610	413	610	556	674	556	674
(NG)NH3-MEA-DEA		510	716	510	716	600	724	600	724
(NG)NH3-MVR		571	753	571	753	968	1078	968	1078
(NG)NH3-MVR-MEA		611	793	611	793	972	1081	972	1081
(NG)NH3-MVR-DEA		358	540	358	540	471	581	471	581
(NG)NH3-MVR-MEA-DEA		398	580	398	580	475	584	475	584
(BM)NH3		392	392	392	392	392	392	392	392
(BM)NH3-DEA		8	8	8	8	-503	-503	-503	-503
(H2)NH3		1221	1221	1606	1606	933	933	1125	1125
(H2)NH3-AEL		1454	1454	1454	1454	1454	1454	1454	1454
EU-mix-2030		735	887	818	969				
EU-mix-2050						814	843	949	978

Total emission

The total emission per ton of ammonia for the scenarios 2018-2050 (

Table 1) are given in Table 85.

Table 85: Total emissions for the ammonia production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)NH3-REF	2.08	2.01	2.01	2.01	2.01	1.95	1.95	1.95	1.95
(NG)NH3-MEA		1.74	1.74	1.74	1.74	1.67	1.67	1.67	1.67
(NG)NH3-DEA		0.59	0.59	0.59	0.59	0.53	0.53	0.53	0.53
(NG)NH3-MEA-DEA		0.32	0.32	0.32	0.32	0.25	0.25	0.25	0.25
(NG)NH3-MVR		1.88	1.88	1.88	1.88	1.81	1.81	1.81	1.81
(NG)NH3-MVR-MEA		1.71	1.71	1.71	1.71	1.63	1.63	1.63	1.63
(NG)NH3-MVR-DEA		0.46	0.46	0.46	0.46	0.39	0.39	0.39	0.39
(NG)NH3-MVR-MEA-DEA		0.29	0.29	0.29	0.29	0.21	0.21	0.21	0.21
(BM)NH3		0.15	0.15	0.15	0.15	0.00	0.00	0.00	0.00
(BM)NH3-DEA		-2.41	-2.41	-2.41	-2.41	-2.56	-2.56	-2.56	-2.56
(H2)NH3		0.11	0.11	0.11	0.11	0.00	0.00	0.00	0.00
(H2)NH3-AEL		1.27	1.27	1.27	1.27	0.00	0.00	0.00	0.00
EU-mix-2030		1.47	1.47	1.47	1.47				
EU-mix-2050						0.12	0.12	0.12	0.12

12.8.6. Chemical

Olefins

CAPEX

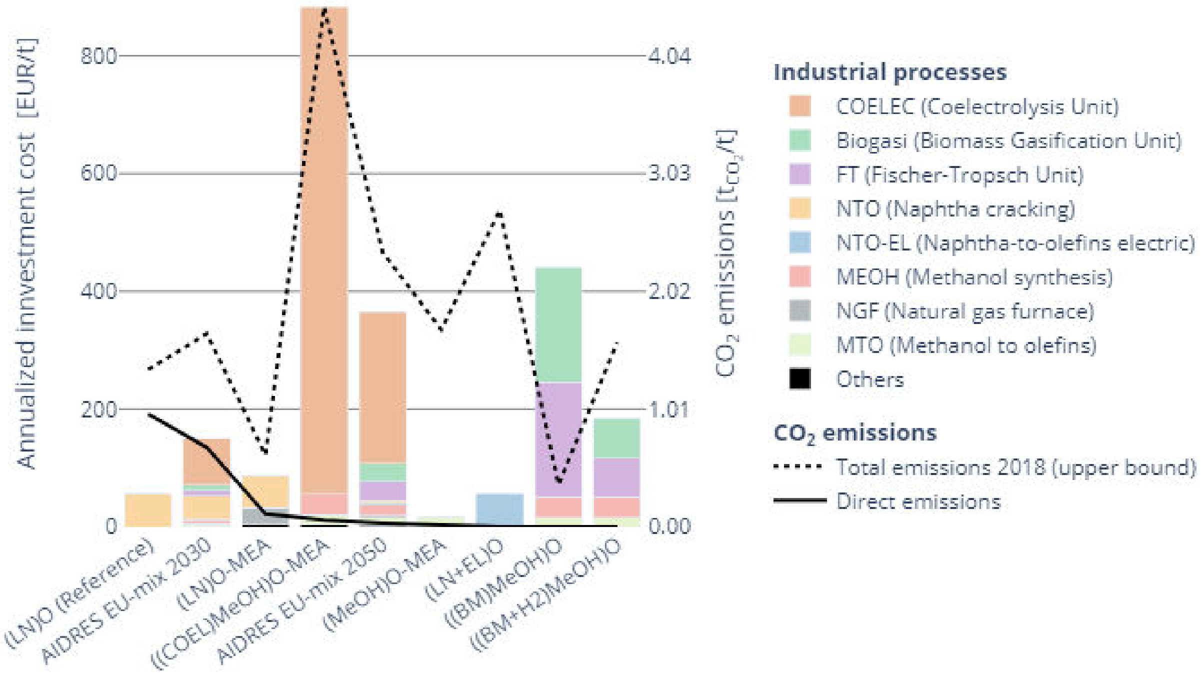

Figure 56: Specific investment cost of the olefins AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of olefins for the scenarios 2018-2050 (

Table 1) are given in Table 86.

Table 86: Operating cost for the olefin production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(LN)O-REF	587	692	692	692	692	886	886	886	886
(LN)O-MEA		614	632	614	632	643	654	643	654
(LN+EL)O		1266	1266	1266	1266	1266	1266	1266	1266
(MeOH)O		1045	1045	1045	1045	1074	1074	1074	1074
(MeOH)O-MEA		1027	1027	1027	1027	1030	1030	1030	1030
((BM)MeOH)O		427	427	427	427	427	427	427	427
((BM)MeOH)O-MEA		213	213	213	213	-83	-83	-83	-83
((BM+H2)MeOH)O		864	864	1163	1163	640	640	789	789
((BM+H2)MeOH)O-AEL		946	946	946	946	946	946	946	946
((BM+H2)MeOH)O-MEA		639	639	938	938	105	105	255	255
((BM+H2)MeOH)O-MEA-AEL		721	721	721	721	412	412	412	412
((COEL)MeOH)O		1561	1561	1561	1561	1679	1679	1679	1679
((COEL)MeOH)O-MEA		1489	1489	1489	1489	1500	1500	1500	1500

AIDRES EU-mix-2030		805	806	816	816				
AIDRES EU-mix-2050						1041	1042	1059	1060

TOTEX

The annual total cost (TOTEX) per ton of olefins for the scenarios 2018-2050 (Table 1) are given in Table 87.

Table 87: Total cost for the olefins production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(LN)O-REF	642	747	747	747	747	941	941	941	941
(LN)O-MEA		702	720	702	720	731	742	731	742
(LN+EL)O		1321	1321	1321	1321	1321	1321	1321	1321
(MeOH)O		1062	1062	1062	1062	1091	1091	1091	1091
(MeOH)O-MEA		1044	1044	1044	1044	1047	1047	1047	1047
((BM)MeOH)O		673	673	673	673	673	673	673	673
((BM)MeOH)O-MEA		460	460	460	460	164	164	164	164
((BM+H2)MeOH)O		981	981	1280	1280	757	757	906	906
((BM+H2)MeOH)O-AEL		1109	1109	1109	1109	1109	1109	1109	1109
((BM+H2)MeOH)O-MEA		757	757	1056	1056	223	223	373	373
((BM+H2)MeOH)O-MEA-AEL		885	885	885	885	576	576	576	576
((COEL)MeOH)O		2441	2441	2441	2441	2559	2559	2559	2559
((COEL)MeOH)O-MEA		2370	2370	2370	2370	2381	2381	2381	2381
AIDRES EU-mix-2030		945	946	956	956				
AIDRES EU-mix-2050						1374	1375	1392	1392

Total emission

The total emission per ton of olefins for the scenarios 2018-2050 (Table 1) are given in Table 88.

Table 88: Total emissions for the olefins production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(LN)O-REF	1.35	1.32	1.32	1.32	1.32	1.28	1.28	1.28	1.28
(LN)O-MEA		0.53	0.53	0.53	0.53	0.44	0.44	0.44	0.44
(LN+EL)O		1.56	1.56	1.56	1.56	0.31	0.31	0.31	0.31
(MeOH)O		1.80	1.80	1.80	1.80	1.77	1.77	1.77	1.77
(MeOH)O-MEA		1.67	1.67	1.67	1.67	1.64	1.64	1.64	1.64
((BM)MeOH)O		0.19	0.19	0.19	0.19	0.00	0.00	0.00	0.00
((BM)MeOH)O-MEA		-1.28	-1.28	-1.28	-1.28	-1.48	-1.48	-1.48	-1.48
((BM+H2)MeOH)O		0.18	0.18	0.18	0.18	0.00	0.00	0.00	0.00
((BM+H2)MeOH)O-AEL		1.08	1.08	1.08	1.08	0.00	0.00	0.00	0.00
((BM+H2)MeOH)O-MEA		-1.35	-1.35	-1.35	-1.35	-1.54	-1.54	-1.54	-1.54
((BM+H2)MeOH)O-MEA-AEL		-0.45	-0.45	-0.45	-0.45	-1.54	-1.54	-1.54	-1.54

((COEL)MeOH)O		2.86	2.86	2.86	2.86	0.59	0.59	0.59	0.59
((COEL)MeOH)O-MEA		2.35	2.35	2.35	2.35	0.06	0.06	0.06	0.06
AIDRES EU-mix-2030		1.35	1.35	1.35	1.35				
AIDRES EU-mix-2050						0.58	0.58	0.58	0.58

Polyethylene

CAPEX

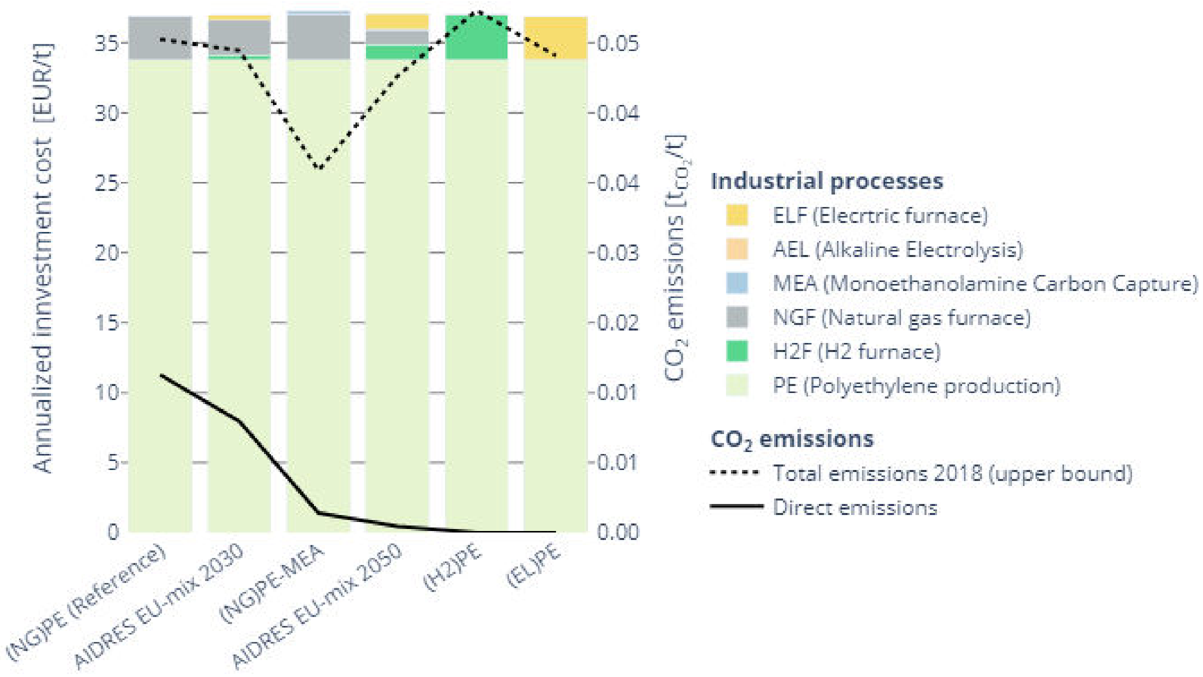

Figure 57: Specific investment cost of the polyethylene AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of polyethylene for the scenarios 2018-2050 (

Table 1) are given in Table 89.

Table 89: Operating cost for the polyethylene production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)PE-REF	970	964	966	964	966	968	969	968	969
(NG)PE-MEA		962	965	963	965	964	965	964	965
(H2)PE		968	968	973	973	964	964	966	966
(H2)PE-AEL		969	969	969	969	969	969	969	969
(EL)PE		965	965	965	965	965	965	965	965
EU-mix-2030		965	966	965	967				
EU-mix-2050						964	964	965	965

TOTEX

The annual total cost (TOTEX) per ton of polyethylene for the scenarios 2018-2050 (

Table 1) are given in Table 90.

Table 90: Total cost for the polyethylene production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)PE-REF	1007	1001	1003	1001	1003	1005	1006	1005	1006
(NG)PE-MEA		999	1002	1000	1002	1001	1002	1001	1002
(H2)PE		1005	1005	1010	1010	1001	1001	1003	1003
(H2)PE-AEL		1007	1007	1007	1007	1007	1007	1007	1007
(EL)PE		1002	1002	1002	1002	1002	1002	1002	1002
EU-mix-2030		1002	1003	1002	1004				
EU-mix-2050						1001	1001	1002	1002

Total emission

The total emission per ton of polyethylene for the scenarios 2018-2050 (

Table 1) are given in Table 91.

Table 91: Total emissions for the polyethylene production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)PE-REF	0.05	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
(NG)PE-MEA		0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
(H2)PE		0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
(H2)PE-AEL		0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00
(EL)PE		0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
EU-mix-2030		0.03	0.03	0.03	0.03				
EU-mix-2050						0.00	0.00	0.00	0.00

Poly-ethyl-acetate

CAPEX

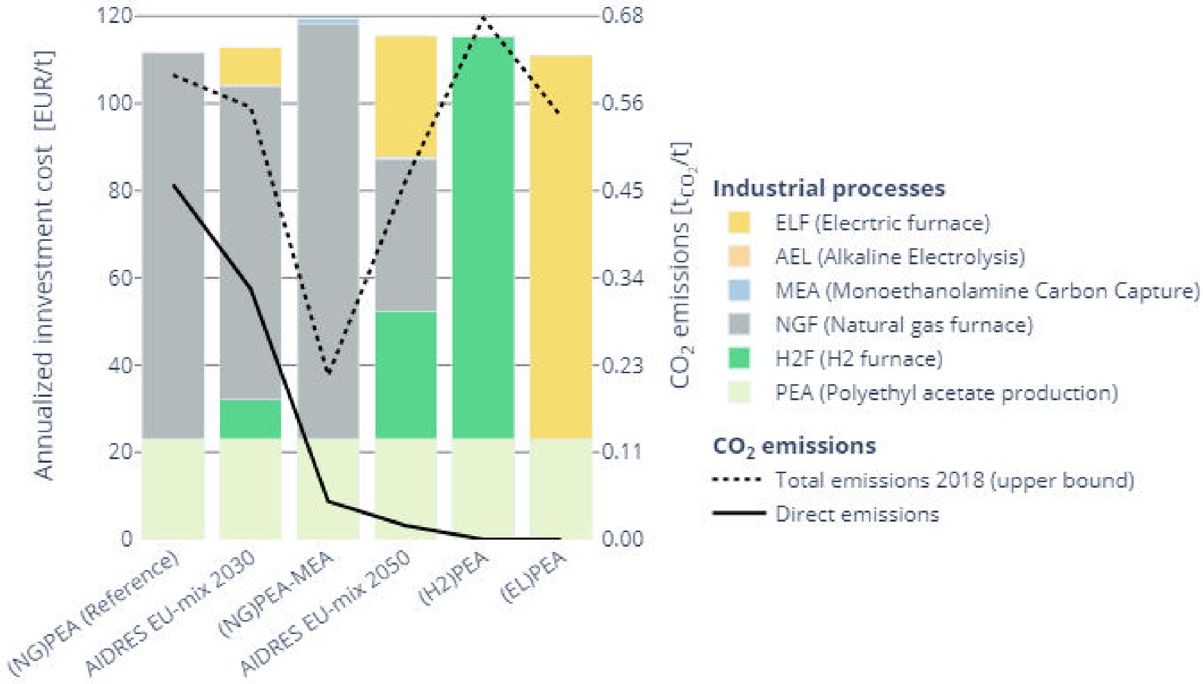

Figure 58: Specific investment cost of the poly-ethyl-acetate AIDRES production routes and EU-mix.

OPEX

The annual operating cost per ton of poly-ethyl-acetate for the scenarios 2018-2050 (

Table 1) are given in Table 92.

Table 92: Operating cost for the poly-ethyl-acetate production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)PEA-REF	1107	1147	1203	1147	1203	1261	1295	1261	1295
(NG)PEA-MEA		1095	1155	1095	1155	1129	1165	1129	1165
(H2)PEA		1237	1237	1381	1381	1129	1129	1201	1201
(H2)PEA-AEL		1277	1277	1277	1277	1277	1277	1277	1277
(EL)PEA		1164	1164	1164	1164	1164	1164	1164	1164
EU-mix-2030		1151	1197	1165	1211				
EU-mix-2050						1140	1153	1163	1176

TOTEX

The annual total cost (TOTEX) per ton of poly-ethyl-acetate for the scenarios 2018-2050 (

Table 1) are given in Table 93.

Table 93: Total cost for the poly-ethyl-acetate production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8

(NG)PEA-REF	1219	1259	1315	1259	1315	1373	1407	1373	1407
(NG)PEA-MEA		1215	1275	1215	1275	1249	1285	1249	1285
(H2)PEA		1352	1352	1496	1496	1244	1244	1316	1316
(H2)PEA-AEL		1414	1414	1414	1414	1414	1414	1414	1414
(EL)PEA		1275	1275	1275	1275	1275	1275	1275	1275
EU-mix-2030		1264	1311	1278	1324				
EU-mix-2050						1256	1269	1278	1292

Total emission

The total emission per ton of poly-ethyl-acetate for the scenarios 2018-2050 (Table 1) are given in Table 94.

Table 94: Total emissions for the poly-ethyl-acetate production routes and scenarios.

Route	0	1	2	3	4	5	6	7	8
(NG)PEA-REF	0.6	0.56	0.56	0.56	0.56	0.52	0.52	0.52	0.52
(NG)PEA-MEA		0.16	0.16	0.16	0.16	0.11	0.11	0.11	0.11
(H2)PEA		0.04	0.04	0.04	0.04	0.00	0.00	0.00	0.00
(H2)PEA-AEL		0.48	0.48	0.48	0.48	0.00	0.00	0.00	0.00
(EL)PEA		0.28	0.28	0.28	0.28	0.00	0.00	0.00	0.00
EU-mix-2030		0.44	0.44	0.44	0.44				
EU-mix-2050						0.04	0.04	0.04	0.04

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