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AIDRES: A database for the decarbonisation of the heavy industry in Europe

Luc Girardin[a], Juan David Correa-Laguna[b], Joris Valee[b], Shivom Sharma[a], Daniel Florez-Orrego[a], Meire Ribeiro-Domingos[a], Rafael Castro-Amoedo[a], Yi Zhao[a], Julia Granacher[a], Marie Jones[a], Francisco Mendez Alva[e], Wim Clymans[c], Ivan Kantor[d], Frank Meinke-Hubeny[b] and François Maréchal[a]

[a] École Polytechnique Fédérale de Lausanne, Industrial Process and Energy Systems Engineering (IPESE-EPFL), Sion, Switzerland, luc.girardin@epfl.ch
[b] VITO-Energyville, Mol, Belgium, joris.valee@vito.be
[c] VITO NV, Unit SEB - Smart Energy & Built Environment, Mol, Belgium, wim.clymans@vito.be
[d] Concordia University, Chemical and Materials Engineering, St. Catherine W., Canada, ivan.kantor@concordia.ca
[e] Ghent University. Faculty of Engineering and Architecture, Gent, Belgium, Francisco.MendezAlva@UGent.be

Abstract:
The AIDRES database aims to support the long-term objective of a fully integrated industrial strategy in the EU-27, providing a service to the European Commission and a catalogue for industries to understand the effectiveness, efficiency and cost of potential innovation pathways for achieving carbon neutral processes in the steel, chemical, cement, glass, fertilizers and refineries sectors by 2050. The approach considers the geographical distribution of the annual production of key products quantified at EU-NUTS3 regional level. Process integration techniques are used to generate and evaluate the reference and future optimal production routes, providing a quantitative, technical and multi-criteria estimate of energy demand in Europe's major industrial sectors. Decarbonisation of the production considers routes achieving (i) substitution of less energy intensive products, (ii) electrification of the production, (iii) use of oxy-combustion, (iv) carbon capture transport and storage, (v) use of alternative fuels and (vi) biomass. This results in a per-ton-of-product database containing energy demand, direct emissions at the plant, amount of captured CO_2 and the associated investment and operation costs. Scenarios 2018-2050 for the energy prices, indirect upstream emissions, CO_2 allowance and production shift are considered to foreseen the operation expenditure and total emissions. Finally, the per-ton database is scaled-up at the NUTS3 level by the regional production capacity. The application of the database is demonstrated at the EU level for the analysis of the present and future evolution of selected heavy industrial sectors, reaching a direct emission reduction between 90-95% compared with 2015-2019 average.

Keywords:
industrial processes, heavy industry, decarbonisation, renewable energies, process integration, database.

1. Introduction

The European Green Deal [7] and aims to transform the EU into a modern, resource efficient and competitive economy while making Europe the first climate neutral continent with a 2050 climate neutrality target. To reach this ambitious goal, an economical and societal transformation process is required. Europe's energy intensive industries (EIIs), especially the sectors steel, chemical, cement, glass, fertiliser and refineries, are today an integral part, if not the foundation, of the European economy and have therefore a leading role to play in this transition. To make this transition successful, unprecedented levels of industrial investments are required while the market actors face at the same time increasing global competition.

Previous studies for a carbon neutral industrial strategy [30] and [8] were developed in close collaboration with industrial representatives to define a realistic solution space for this ambitious transition. Valuable insights are provided in these studies, identifying and quantifying in an aggregated format the steps to the envisioned 90-95% emissions reductions by 2050 for EIIs, compared to 1990 levels.

Building from many collaborative experiences with private industries, industrially representative process models have been developed in the H2020 project EPOS[23] to build, so-called blueprints. Validated by industrial sector associations, industrial blueprints provide details of energy and material requirements of the processes, using average or obfuscated values to avoid disclosure of confidential data. Described in greater detail in [4] and [18], this approach allows for data and knowledge to be shared outside of an organization without

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disclosing sensitive information.

The AIDRES project is providing the next level of necessary data to develop a sharper picture of potential pathways for industries at their respective sites or industrial clusters in Europe. This study is focused on the analysis of decarbonisation options such as further energy efficiency measures, further process integration, electrification of heat for processes, electrification of processes, production and use of hydrogen, use of biomasse, electricity from carbon neutral sources, Carbon Capture and Utilization (CCU) and Carbon Capture, transport and Storage (CCS) among others.

2. Approach

2.1. Blueprint model integration

Blueprints include details of heat, electricity and material flows as well as the annual investment and operation cost required for process operation. Process integration technique [17] is used to determine the optimal size of each process in typical production route, taking into account the internal use of heat/cold streams while balancing the overall material and energy resource, product and waste flows.

For production routes integrating carbon capture, transport and storage (CCS), the captured emissions (Em^{CCS}) given by (1) are equal to a fraction (η^{CCS}), typically 90%, of the non biogenic and biogenic emissions. Uncaptured direct emissions (2) from biogenic resources are not accounted ($\eta^{CSS} = 0$) but when carbon capture, transport and storage (CCS) is integrated ($\eta^{CCS} > 0$), biogenic direct emissions removed from the atmosphere are accounted negatively. The profits from trading negative emissions are therefore included in the OPEX.

$$Em^{CCS} = \eta^{CCS} \cdot (Em^{direct,non\ bio} + Em^{direct,bio}) \qquad [t_{CO_2}/y] \qquad (1)$$

$$Em^{direct} = (1 - \eta^{CCS}) \cdot Em^{direct,non\ bio} - \eta^{CCS} \cdot Em^{direct,bio} \qquad [t_{CO_2}/y] \qquad (2)$$

2.2. Per ton of product results

Pertinent production routes are selected form the result of a parametric optimisation [32] using various energy prices and emissions and different weight for the terms of the objective function (sum of operation cost, investment cost and impact/emissions). In general, the selection criteria is minimising the direct emission at the plant, however in some cases, the criteria is reflecting the plant's design in the EU context (e.g. steam network design for fertilizer plant). The resulting mass/energy flows, capital cost and direct emissions at the plant are expressed per ton of product.

2.3. AIDRES EU Mix production routes

The concept of EU mix routes is introduced to account for the uncertainty which emerges from the unknown of future production methods for each individual industrial site (NUTS3). Rather than applying one single production route across the European Union industrial production sites, the AIDRES EU mix routes can be considered as a balanced hypothetical alternative to represent values of energy and feedstock input and CO_2 emissions, without merit to actual industrial transition plans. The AIDRES EU Mix 2030 and 2050 production routes (3) are build up by weighting single production routes per ton results (r_i) according to the emission reduction targets. The integration of the mix to the mapped production sites at NUTS3 level are to be compared and understood at European level.

$$mix = \sum_{i \in routes} w_i \cdot r_i \text{ with } \sum_{i \in routes} w_i = 1 \text{ and } w_i \leq 1 \qquad \text{[t/t] or [€/t]} \qquad (3)$$

The AIDRES mix are done in a way to meet the MIX EU Reference Scenario emission reduction targets in 2030 and 2050, as defined by the European Commission in 2021 [6] in line with the Fit for 55 and the EU Green deal roadmap [7].

2.4. Scenarios integration

To evaluate the impact of the different production routes, nine typical cost and emissions scenarios 2018-2030-2050, given in Table 1, have been considered. The criteria and values were selected based on EU reference scenarios, to create a diversity of different outcomes. The amount of scenarios was restricted to eigth plus a reference scenario to keep the number of modeled solutions under control. The values can be seen as boundaries and sensitivity with different values can easily be done afterwards without having to re-run the AIDRES model. The AIDRES model does not take limitations of resource availability into account and does not consider competition for the resource, such as biomass [22], between and with other sectors (e.g. food). The scenarios are aligned with the EC Fit for 55 [9]. In the AIDRES database, there is a record available for all AIDRES production routes on NUTS3 and this for every scenario.

Table 1: AIDRES reference scenario 2018 and future EU scenarios at horizons 2030 and 2050.

			CO_2	Electricity		Hydrogen		Natural gas
	Horizon	Scenarios	[€/kg_{CO_2}]	[€/kWh]	[kg_{CO_2}/kWh]	[€/kg]	[kg_{CO_2}/kg]	[€/kWh]
0	2018	Reference	0.025	0.125	0.231	1.8	8.2	0.024
1	2030	low H_2 price	0.150	0.071	0.120	3.0	0.0	0.025
2	2030	low H_2 & high NG price	0.150	0.071	0.120	3.0	0.0	0.050
3	2030	high H_2 price	0.150	0.071	0.120	5.0	0.0	0.025
4	2030	high H_2 & high NG price	0.150	0.071	0.120	5.0	0.0	0.050
5	2050	low H_2 price	0.350	0.071	0.000	1.5	0.0	0.035
6	2050	low H_2 & high NG	0.350	0.071	0.000	1.5	0.0	0.050
7	2050	high H_2 price	0.350	0.071	0.000	2.5	0.0	0.035
8	2050	high H_2 & high NG price	0.350	0.071	0.000	2.5	0.0	0.050

2.5. Regional integration

The single and mixed production scenarios per ton of product results (r_i [t/t] or [€/t]) are scaled-up at regional level (4) considering the annual production ($p_{NUTS3,i}$ $[t/y]$) in each NUTS3 region.

$$R_{NUTS3,i} = \sum r_i \cdot \left(p_{NUTS3,i}\right) \qquad \text{[t/y] or [€/y]} \qquad (4)$$

The aggregated annual production of the EIIs at EU level is given in Table 2.

Table 2: NUTS3 annual production aggregated at EU level for the AIDRES industrial sectors in [t/y].

Sector	Product [t/y]	2018	2030	2050
Cement	Cement	173'836	173'836	173'836
Chemical	Polyethylene	31'584	31'584	31'584
	poly-ethyl-acetate	25'920	25'920	25'920
	Olefins	36'956	36'956	36'956
Fertiliser	Ammonia	10'928	10'928	10'928
Glass	Container glass	32'256	32'256	32'256
	Fibte Glass	2'100	2'100	2'100
	Flat glass	10'072	10'072	10'072
Refineries	Light-liquid-fuel	360'543	306'268	104'674
Steel	primary	93'144	93'144	93'144
	secondary	65'709	65'709	65'709

3. Industrial production route

3.1. Cement sector

The cement sector (raw mill, kiln, calcination, product mill) has been structured with production routes using dry kiln and coal and alernative route using calcination process to produce Limestone Calcined Clay Cement (LC3).

Six types of cement have been modeled however, no distinction is made in the EU-NUTS3 level and we have therefore considered Portland cement II (BV325R with a clinker-to-cement ratio of 70%) as the reference and Calcined clay product (LC3) as a future alternative (best case). Portland cement I (cI425R) 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).

In cement manufacturing, about 60% CO_2 comes from calcination process, and remaining 40% comes from fuel consumption.

The conventional route uses dry kiln, cement, coal(54%), alternative fuels mixture(30%) and biomass waste (BMW) to produce Portland cement type II with 70% clinker-to-cement ratio. The flue gases from a conventional cement plant contains 20-25% CO_2. Beside Monoethanolamine (MEA) Capture technology, Calcium looping seems to emerge as the most promising carbon capture technology in the sector.

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Alternative production routes (a) replace coal by alternative fuel mixture (AFM) and biomass waste (BMW), (b) integrate monoethanolamine amine (MEA) or calcium looping (CaL) carbon capture, (c) use oxy-combustion with carbon capture and (d) use calcination process to produce Limestone Calcined Clay Cement (LC3), 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 [24].

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 clinker subsitution 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 to the rotary kiln option. The calcination step involves mainly 2 reactions : drying of the clay (at around 100°C), and metakaolin reaction between 400 and 600°C, producing water (gaseous) as by-product.

3.2. Chemical sector

The chemical sector in Europe is highly complex, encompassing bulk chemical manufacturing, especially chemicals for the pharmaceutical industry and plastics production. This work considers the production of three main products: poly-ethyl-acetate, polyethylene and olefins. Olefins includes 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 coelectrolysis is considered as well for the production of olefins.

Three different routes are considered for the production of olefins: (a) naphtha for the reference route and methanol synthetized either from (b) renewable green biomass gasification or (c) 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), Etylene and Propylene. The alternative route (LN+EL) uses an electrical furnace to provide heat for naphta cracking, thus avoiding direct emissions from combustion.

Methanol is either imported from the market (grey methanol from steam reforming process) or produced from biomass ((BM)MeOH) or coelectrolysis ((COEL)MeOH) using CO_2 from the market. One burner is included for offgas from methanol synthesis and upgrading. Crude methanol is directly fed to a methanol-to-olefin reactor with oxygen [14]. Four products are then recovered: ethylene, butene, propylene and other olefins [31]. The model was designed for a production of 600 ktonnes of ethylene per year.

Polyethylene (PE) production is modelled using four main units: preheating of the reactants (ethylene, hydrogen used as chain-transfer agent and nitrogen) to 70°C; polymerization of ethylene in a slurry; recycle of unreacted liquid and gas reagents to finishing step; and quenching with water followed by extrusion [10, 16, 20]. The model was designed for a production of 25'000 kilos of polyethylene per hour.

Ethyl-acetate is produced via the esterification of carboxylic acids [26]. A process whereby ethylene is reacted with acetic acid at 170°C to produce 15 tonnes per hour of ethyl acetate is simulated. Following reaction, the hot gases are cooled down to room temperature before being send to the separation section which consists of two flash drum in series to extract the unreacted ethylene from the hot gases and recycle it to the preheating unit. The acid is then recovered from the products and recycled. The product is purified and latter 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 cooled 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 [3]. 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.

3.3. Fertilizer sector

The fertiliser sector has been structured in four routes for the production of ammonia, ammonia plus urea and ammonia plus urea plus nitric acid. The production routes use either natural gas with and without carbon capture, biomass or electricity.

The reference production route is a conventional natural gas-based ammonia production plants which is equipped with efficient energy integration networks able to recover the waste heat available throughout the chemical system [12]. Alternative routes use biomass gasification or nitrogen and hydrogen (H2)NH3 for replacing methane in the integrated ammonia production plant [11]. 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 1 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 emission 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 (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 monoethanolamine carbon capture are labelled with (MEA).

Accounting and mitigation of the green house gas emission effect of NO_2 for the nitric acid production routes is out of the scope of the AIDRES project.

3.4. Glass sector

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

Fibre glass consists out of roughly 10% of the total whereas majority of the glass products are container or hollow (60%) and flat glass (30%).

The high temperature requirement of the process is limiting the available options. Natural gas (NG) or Hydrogen (H_2) can be used to satisfy the heating demand. Electric melting furnaces are also been considered with an efficiency of 85% and a cost based on equipment recently installed.

3.5. Refineries sector

The Refineries sector (Distillation, Cracking, Isomerisation, Reforming Desulfurisation and Fischer-Tropsch process) has been structured in seven routes. The refinery and Fischer-Tropsch process are used with either 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 (LHV = 42.87 MJ/kg). To produce 1 ton of light liquid fuel (LLF), 1.56 ton of crude oil is needed, which represents an LHV equivalent of 1.038 $ton_{eq_{LLF}}$ of Fischer-Tropsch fuel and 0.464 $ton_{eq_{LLF}}$ of methanol.

The reference refineries (REF) uses crude oil to produce, without carbon capture, light liquid fuel (LHV = 42.87 MJ/kg) including isomerate, heavy reformate, gasoline and gasoil (diesel) [1, 2, 15, 28].

Two routes (Biomass gasification and co-electrolysis) are producing syngas from biomass or co-electrolysis of CO_2 and water. The extra Carbon dioxide is separated from the syngas with a carbon capture unit [25, 33]. 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) [27] and Alkaine Electrolysis [19] (AEL) are competing options for the supply of hydrogen to the system. Hydrogen can indeed be used to avoid the water gas shift reaction in the gasifier [13].

3.6. Steel sector

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 from primary and secondary production routes have different quality that serves different purpose. 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 it is an alloy of iron and several other materials (such as nickel and chromium). Therefore, the desegregation was done based on the production route: primary steel (BF-BOF) and secondary steel (EAF). This approach is aligned with EUROFER [5] and World Steel reports [29] to facilitate comparison and reduce the number of products to be covered. For instance, EUROFER includes a report differentiating the production route, as it is done in AIDRED, and another report by 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 with EAF.

The reference case uses a blast furnace (BF) and a Basic oxygen furnace (BOF) to produce primary steel.

Alternative routes make use of (i) top gas Recycling blast furnace (TGRBF) or (ii) waste plastic injection BF to replace the BF. TGRBF is a promising technology to significantly reduce the CO_2 emission by recycling CO and H_2 from the top gas leaving the blast furnace (BF). CO and H_2 content of top gas has a potential to act as reducing gas elements, and hence their recirculation to the BF is considered as an effective alternative to improve the BF performance, enhance utilization of Carbon and hydrogen, and reduce CO_2 emission.

Other alternative for primary steel production routes are (iii) replacing the BF-BOF by an electric arc furnace (EAF) or (iv) by shaft furnaces using different fuels to feed an EAF with direct reduced iron (DRI-EAF). The use of molten oxyde electrolyser (v) is a route with low technology readiness level (TRL). Finally (vi) monoethanolamine carbon capture (MEA) can be used on the fumes of the different furnaces.

The consumption of coal of blast furnaces is much higher than the consumption of coke since the coke oven

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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 alternatives, H_2 without and with electrolyzer on-site (AEL) are computed and available for comparison in all scenarios.

4. Results

A subset of the full AIDRES database, giving the specific energy flows, investment costs, emissions and captured CO_2 per ton of product for the routes of the AIDRES EU-mix 2018-2050, is reported in Table 3 of appendix A. The AIDRES EU-mix, shown in Figure 1 comply with the emission reduction targets for 2030 and 2050 based on the MIX EU Reference Scenario [6] in line with Fit for 55 and the EU Green deal [7]. The corresponding energy demand, aggregated at the EU level are reported in Figure 2. The map of Figure 3 shows the energy and direct emissions reduction, aggregated at country scale, for the AIDRES EU-mix at horizon 2050.

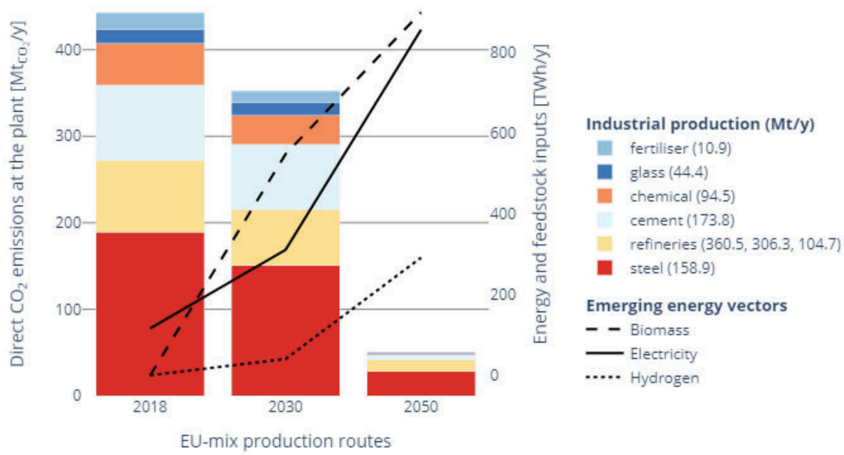
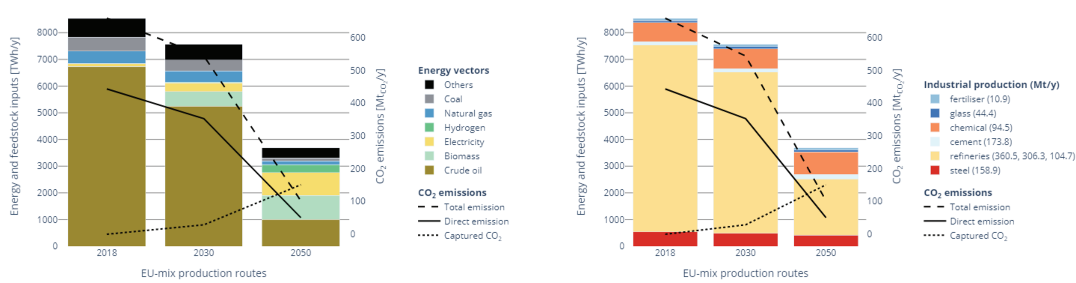


Figure 1: EU-27 EIIs direct emission at the plant [Mt_{CO_2}/y] and emerging energy vectors [TWh/y] AIDRES EU mix production routes meeting EU reference MIX scenario derived emission reduction targets.



(a) Energy and feedstock inputs by vectors.

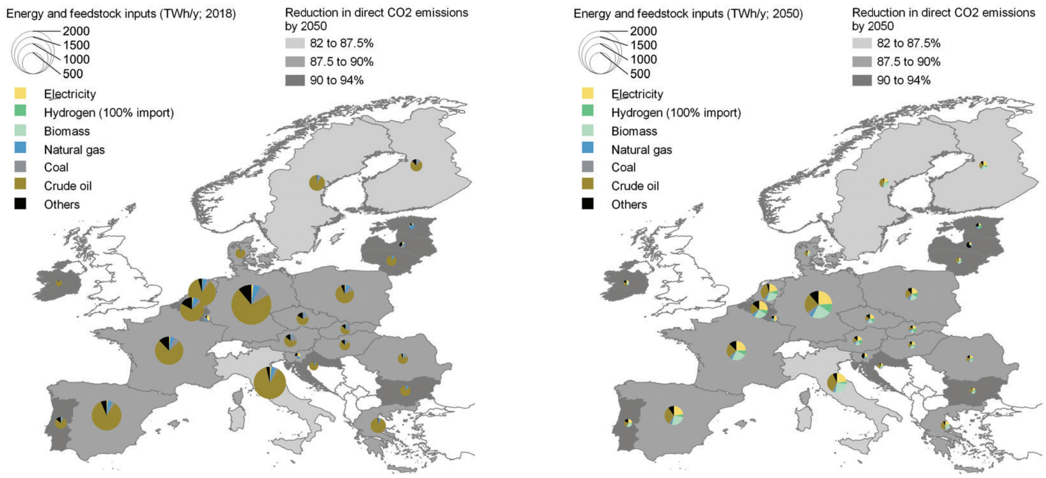
(b) Energy and feedstock inputs by sectors.

Figure 2: EU-27 EIIs energy and feedstock inputs flows [TWh/y], direct and total 2018 emissions [Mt_{CO_2}/y] for AIDRES EU mix production routes meeting EU reference MIX scenario derived emission reduction targets.

5. Conclusion

This paper presents a publicly available database for the decarbonisation of the heavy industry in Europe in line with other databases of energy intensive industries, such as EU ETS. The concept of AIDRES EU mix routes has been introduced to account for the uncertainty which emerges from the unknown of future production methods for each individual industrial site (NUTS3).

According to the AIDRES EU-EIIs decarbonisation pathway, the overall energy and feedstock inputs are expected to decrease by 57% by 2050, mainly due to the reduced refinery output, while the renewable electricity



(a) AIDRES reference 2018.

(b) AIDRES EU-mix 2050.

Figure 3: Map of the energy and feedstock inputs flows [Twh/y] for the AIDRES EU-mix 2018 and 2050 with direct CO_2 emissions reduction [%] by 2050. Scales of Luxembourg, Estonia, Latvia and Slovenia x 3.

demand will see a sharp increase by a factor of three by 2030. Biomass could play a crucial role in the chemical and refinery sectors in the future, while methanol will replace naphtha as a vital feedstock for the chemical sector. The usage of green hydrogen is moreover expected to become essential in the steel, fertilizer, and chemical sectors. The cement industry will have to rely on a mixture of biomass waste and alternative fuels, combined with carbon capture technologies such as oxy-fuel combustion and calcium looping. Although there will be a strong decline in coal and natural gas usage, they can still have a role in some sectors combined with carbon capture technologies.

However, the AIDRES EU mix routes are not the only pathways toward the decarbonisation of the heavy industry in Europe. A virtual unlimited number of different combinations of different production routes, across the EU and at specific NUTS3 locations, can indeed be simulated using the publicly available AIDRES database.

The AIDRES database has already been applied to develop regional and sectoral approaches to identify potential industrial symbiosis initiatives, highlighting the optimization potential of symbiotic profiles and recommending the inclusion of additional sectors such as paper and power plants [21]. The proposed format can be used in future studies and model applications by EU institutions, such as the Directorate-General for Energy (DG ENER) and the Joint Research Centre (JRC).

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Appendix A Per ton results of the AIDRES single and EU-mix production routes.

Table 3: Per ton of product energy flows [GJ/t], investment costs [€/t], direct emissions and captured CO_2 [t_{CO_2}/t] for AIDRES single and EU mix [%] production routes.

Products	Production routes	Electricity [GJ/t]	AFM [GJ/t]	Biomass [GJ/t]	Biomass waste [GJ/t]	Coal [GJ/t]	Coke [GJ/t]	Crude oil [GJ/t]	Hydrogen [GJ/t]	Methanol [GJ/t]	Naphtha [GJ/t]	Natural gas [GJ/t]	Plastic mix [GJ/t]	Capex [EUR/t]	Direct emission [tCO2/t]	Captured CO2 [tCO2/t]	Direct em. reduction [%]	Mix 2018 [%]	Mix 2030 [%]	Mix 2050 [%]
Cement reference	**AIDRES EU-mix-2018**	**0.29**	**0.74**		**0.44**	**1.15**								**3**	**0.498**			**100.0**		
Portland cement II	CEM2-(Coal)	0.29				2.13								3	0.524		-5.2	54.0	47.1	5.1
	CEM2-(Coal)CaL	0.47				2.13								21	0.086	0.438	82.7		0.5	3.5
	CEM2-(Coal)Oxy-CaL	0.57				2.15								15	0.083	0.533	83.3		0.5	3.5
	CEM2-(AFM)	0.29	2.46											3	0.535		-7.4	30.0	26.2	2.9
	CEM2-(AFM)MEA	0.60	3.86											5	0.129	0.516	74.1		1.5	10.7
	CEM2-(AFM)CaL	0.47	2.46											22	0.088	0.448	82.3		1.5	10.7
	CEM2-(AFM)Oxy-CaL	0.51	2.46											15	0.075	0.457	84.9		1.5	10.7
	CEM2-(BMW)	0.29			2.77									3	0.342		31.4	16.0	14.0	1.5
	CEM2-(BMW)MEA	0.69			4.47									5	-0.308	0.650	161.8		1.6	11.6
	CEM2-(BMW)CaL	0.51			2.77									25	-0.188	0.530	137.7		1.6	11.6
	CEM2-(BMW)Oxy-MEA	0.65			3.16									4	0.020	0.706	96.0		1.6	11.6
	CEM2-(BMW)Oxy-CaL	0.58			2.77									16	0.014	0.665	97.2		1.6	11.6
Limestone calcined clay	LC3-(Coal)CaL	0.44				1.81								17	0.065	0.334	87.0		0.1	0.5
	LC3-(NG)MEA	0.50										2.99		4	0.082	0.329	83.5		0.1	0.5
	LC3-(NG)CaL	0.42										1.84		15	0.057	0.291	88.6		0.1	0.5
	LC3-(NG)Oxy-CaL	0.57										1.85		12	0.066	0.442	86.8		0.1	0.5
	LC3-(AFM)MEA	0.54	3.12											4	0.098	0.391	80.3		0.1	0.5
	LC3-(AFM)CaL	0.44	2.13											17	0.067	0.344	86.6		0.1	0.5
	LC3-(AFM)Oxy-MEA	0.52	2.46											4	0.068	0.367	86.4		0.1	0.5
	LC3-(AFM)Oxy-CaL	0.47	2.13											12	0.056	0.352	88.8		0.1	0.5
	LC3-(BMW)Oxy-MEA	0.57			2.56									4	0.010	0.545	98.0		0.1	0.5
	LC3-(BMW)Oxy-CaL	0.53			2.40									12	0.004	0.532	99.2		0.1	0.5
	AIDRES EU-mix-2030	0.32	0.78		0.61	1.03						0.00		4	0.433	0.071	13.2		100.0	
	AIDRES EU-mix-2050	0.54	1.06		1.59	0.27						0.03		12	0.034	0.501	93.2			100.0
Polyethylene	**(NG)PE**	**0.49**							**0.01**			**0.29**		**37**	**0.016**			**100.0**	**69.4**	
	(NG)PE-MEA	0.50							0.01			0.30		37	0.002	0.015	87.5		9.6	31.3
	(H2)PE	0.49							0.31					37			100.0		10.5	34.4
	(EL)PE	0.75							0.01					37			100.0		10.5	34.4
	AIDRES EU-mix-2018	0.49							0.01			0.29		37	0.016			100.0		
	AIDRES EU-mix-2030	0.52							0.04			0.23		37	0.011	0.001	29.4		100.0	
	AIDRES EU-mix-2050	0.58							0.11			0.10		37	0.001	0.005	96.1			100.0
Poly-ethyl-acetate	**(NG)PEA**	**1.30**										**8.16**		**112**	**0.459**			**100.0**	**69.4**	
	(NG)PEA-MEA	1.57										8.76		120	0.049	0.443	89.3		11.2	36.6
	(H2)PEA	1.30							8.64					115			100.0		9.7	31.7
	(EL)PEA	8.54												111			100.0		9.7	31.7
	AIDRES EU-mix-2030	2.03							0.84			6.65		113	0.324	0.050	29.4		100.0	
	AIDRES EU-mix-2050	3.69							2.74			3.21		116	0.018	0.162	96.1			100.0

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Table 3: Per ton of product energy flows [GJ/t], investment costs [€/t], direct emissions and captured CO_2 [t_{CO_2}/t] for AIDRES single and EU mix [%] production routes.

Products	Production routes	Electricity [GJ/t]	AFM [GJ/t]	Biomass [GJ/t]	Biomass waste [GJ/t]	Coal [GJ/t]	Coke [GJ/t]	Crude oil [GJ/t]	Hydrogen [GJ/t]	Methanol [GJ/t]	Naphtha [GJ/t]	Natural gas [GJ/t]	Plastic mix [GJ/t]	Capex [EUR/t]	Direct emission [tCO2/t]	Captured CO2 [tCO2/t]	Direct em. reduction [%]	Mix 2018 [%]	Mix 2030 [%]	Mix 2050 [%]
Olefins	**(LN)O**	**1.06**									**60.52**			**55**	**0.967**			**100.0**	**69.4**	
	(LN)O-MEA	2.68									60.52	2.61		88	0.111	1.002	88.5		2.5	8.1
	(LN+EL)O	37.50									60.52			55			100.0		1.8	5.9
	(MeOH)O-MEA	0.74								49.01				17	0.015	0.132	98.4		9.5	31.1
	((BM)MeOH)O	5.62		96.08										246			100.0		3.6	11.9
	((BM+H2)MeOH)O	5.51		93.02					17.93					117			100.0		3.6	11.9
	((COEL)MeOH)O-MEA	68.66												881	0.059	0.528	93.9		9.5	31.1
	AIDRES EU-mix-2030	8.50		6.86					0.65	4.67	44.59	0.07		140	0.681	0.088	29.6		100.0	
	AIDRES EU-mix-2050	25.35		22.41					2.13	15.25	8.52	0.21		333	0.032	0.287	96.7			100.0
Ammonia	(NG)NH3	2.08										28.33		127	1.742			100.0	70.0	2.0
	(NG)NH3-DEA	2.08										28.33		127	0.322	1.420	81.5		1.8	5.8
	(NG)NH3-MEA-DEA	2.16										29.69		255	0.040	1.779	97.7		1.8	5.8
	(NG)NH3-MVR-DEA	2.14										26.19		104	0.202	1.420	88.4		1.8	5.8
	(NG)NH3-MVR-MEA-DEA	2.58										26.19		162	0.020	1.602	98.9		1.8	5.8
	(BM)NH3	4.46		40.52										170			100.0		1.5	5.0
	(H2)NH3	3.40							23.06					577			100.0		21.4	70.0
	AIDRES EU-mix-2030	2.41		0.62					4.94			21.77		227	1.229	0.110	29.4		100.0	
	AIDRES EU-mix-2050	3.16		2.03					16.14			6.91		452	0.068	0.358	96.1			100.0
Nitric-acid	**(NG)HNO3**											**6.50**		**30**	**0.409**			**100.0**	**76.6**	**23.7**
	(NG)HNO3-DEA											6.50		30		0.409	100.0		3.4	11.0
	(BM)HNO3			11.66										30			100.0		4.6	15.0
	(BM)HNO3-DEA			11.66										30	-0.736	0.736	280.0		3.4	11.0
	(H2)HNO3								6.64					30			100.0		12.0	39.3
	AIDRES EU-mix-2030			0.93					0.80			5.20		30	0.289	0.039	29.4		100.0	
	AIDRES EU-mix-2050			3.03					2.61			2.26		30	0.016	0.126	96.1			100.0
Urea	**(NG)Urea**	**0.82**										**14.88**		**33**	**0.186**			**100.0**	**69.3**	
	(NG)Urea-MEA	0.90										14.86		66	0.082	0.103	55.9		2.7	8.9
	(BM)Urea	1.74		22.99										11			100.0		14.0	45.6
	(H2)Urea	2.00							13.09					11			100.0		14.0	45.6
	AIDRES EU-mix-2030	1.12		3.21					1.83			10.72		28	0.131	0.003	29.5		100.0	
	AIDRES EU-mix-2050	1.78		10.48					5.96			1.32		16	0.007	0.009	96.1			100.0
Container glass	**(NG)**	**1.07**							**0.04**			**4.73**		**53**	**0.338**			**100.0**	**85.9**	
	(NG)-CC	1.13							0.04			4.73		55	0.011	0.097	96.7		3.5	24.5
	(H2)	1.07							5.04					55	0.073		78.4		1.9	13.3
	(H2)-CC	1.08							5.04					55	0.002	0.021	99.4		3.5	24.5
	(EL)	5.09							0.04					50	0.073		78.4		1.9	13.3
	(EL)-CC	5.10							0.04					51	0.002	0.021	99.4		3.5	24.5
	AIDRES EU-mix-2030	1.29							0.31			4.23		53	0.294	0.005	13.2		100.0	
	AIDRES EU-mix-2050	2.61							1.93			1.16		53	0.023	0.034	93.2			100.0

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Products	Production routes	Electricity [GJ/t]	AFM [GJ/t]	Biomass [GJ/t]	Biomass waste [GJ/t]	Coal [GJ/t]	Coke [GJ/t]	Crude oil [GJ/t]	Hydrogen [GJ/t]	Methanol [GJ/t]	Naphtha [GJ/t]	Natural gas [GJ/t]	Plastic mix [GJ/t]	Capex [EUR/t]	Direct emission [tCO2/t]	Captured CO2 [tCO2/t]	Direct em. reduction [%]	Mix 2018 [%]	Mix 2030 [%]	Mix 2050 [%]
Fibre glass	**(NG)**	**2.16**							**0.04**			**7.24**		**80**	**0.634**			**100.0**	**85.9**	
	(NG)-CC	2.27							0.04			7.24		84	0.020	0.183	96.8		4.0	28.4
	(H2)	2.16							7.17					77	0.227		64.2		2.1	14.8
	(H2)-CC	2.20							7.17					79	0.007	0.066	98.9		4.0	28.4
	(EL)-CC	7.93							0.04					72	0.007	0.066	98.9		4.0	28.4
	AIDRES EU-mix-2030	2.40							0.48			6.51		80	0.551	0.013	13.2		100.0	
	AIDRES EU-mix-2050	3.84							3.12			2.06		78	0.043	0.089	93.2			100.0
Flat glass	**(NG)**	**0.80**							**0.04**			**5.43**		**61**	**0.487**			**100.0**	**85.9**	
	(NG)-CC	0.89							0.04			5.43		64	0.016	0.140	96.7		4.1	28.7
	(H2)	0.80							5.78					63	0.182		62.6		1.0	6.9
	(H2)-CC	0.83							5.78					64	0.006	0.052	98.8		4.1	28.7
	(EL)	5.41							0.04					58	0.182		62.6		1.0	6.9
	(EL)-CC	5.44							0.04					59	0.006	0.052	98.8		4.1	28.7
	AIDRES EU-mix-2030	1.04							0.33			4.88		61	0.423	0.010	13.2		100.0	
	AIDRES EU-mix-2050	2.49							2.09			1.56		62	0.033	0.070	93.2			100.0
Light liquid fuel	**REF-SMR**	**0.14**						**67.23**				**2.51**		**44**	**0.231**			**100.0**	**88.4**	**37.7**
	REF(H2)	0.14						67.23	0.51			1.73		44	0.189		18.2		3.4	14.0
	(BM)FT	3.06		85.27										193			100.0		3.3	13.5
	(BM)MeOH	4.34		84.08										201			100.0		3.3	13.5
	(COEL)FT-MEA	59.06												755	0.060	0.542	74.0		0.8	10.7
	(COEL)MeOH-MEA	59.43												755	0.038	0.346	83.5		0.8	10.7
	AIDRES EU-mix-2030	1.31		5.60				61.72	0.02			2.28		65	0.211	0.007	8.5		100.0	
	AIDRES EU-mix-2050	13.76		22.83				34.71	0.07			1.19		238	0.124	0.095	46.4			100.0
Primary steel	**BF-BOF**	**0.66**				**17.71**	**1.13**							**33**	**2.002**			**100.0**	**71.6**	
	BF-BOF-MEA	1.50				17.71	1.13					0.58		64	0.790	1.369	60.5		2.4	9.4
	WPI-BOF-MEA	1.71				15.95	1.13					0.23	1.89	62	0.781	1.333	61.0		2.4	9.4
	(NG)DRI-EAF	2.06				0.40						7.45		32	0.651		67.5		16.9	
	(NG)DRI-EAF-MEA	2.42				0.40						7.45		46	0.065	0.586	96.8		4.2	16.9
	(H2)DRI-EAF	2.06				0.40			11.40					32	0.193		90.4		2.5	58.9
	MOE	14.34												74			100.0			5.3
	AIDRES EU-mix-2030	1.06				13.56	0.86		0.29			1.60	0.04	35	1.588	0.089	20.7		100.0	
	AIDRES EU-mix-2050	2.69				3.48	0.21		6.71			1.34	0.18	42	0.273	0.354	86.4			100.0
Secondary steel	**Scraps EAF**	**1.50**				**0.30**						**0.19**		**18**	**0.040**			**100.0**	**100.0**	**100.0**

AIDRES reference 2018 in bold.

AFM: Alternative fuel mixture, **BM**: Biomass, **BMW**: Biomass Waste, **BOF**: Basic oxygen furnace (BOF), **CaL**: Calcium looping carbon capture, **CEM2**: Portland cement II - clinker-to-cement ratio of 70%, **COEL**: Co-electrolysis process for syngas production, **DEA**: Diethanolamine carbon capture, **DRI**: Direct Reduced Iron electric arc furnace, **EAF**: Electric Arc Furnace, **EIIs**: Europe's energy intensive industries, **EL**: Electrical furnace, **FT**: Fischer-Tropsch process, **HNO3**: Nitric acid production, **LC3**: Limestone Calcined Clay Cement - clinker-to-cement ratio of 50%, **LN**: Naphtha ctacking, **MEA/CC**: Monoethanolamine carbon capture, **MeOH**: Methanol, **MOE**: Molten oxide electrolyser, **MVR**: Mechanical vapor recompression, **NG**: Natural gas, **NG+H2**: Natural gas and hydrogen mix shaft furnace, **NH3**: Ammonia production, **NUTS**: Nomenclature of Territorial Units for Statistics, **O**: Olefins production, **Oxy**: Oxycombustion, **PE**: Polyethylene production, **PEA**: Poly-ethyl-acetate production, **REF**: Conventionnal crude oil refinning, **Scraps EAF**: EAF Scraps handling (recycling/secondary route), **WPI**: Waste plastic injection blast furnace.

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