AIDRES

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

Methodology on Industrial Symbiosis

-

Supporting the energy transition at industrial clusters

(D3.1)

Written by Mendez Alva F., van Eetvelde G., Valee J., Correa Laguna J., Clymans W., Girardin L., Meinke-Hubeny F.

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Contact: Eric Lecomte

E-mail: eric.lecomte@*ec.europa.eu*

European Commission
B-1049 Brussels

Authors :

Francisco Mendez Alva ; Ghent University (UGent)
Greet van Eetvelde ; Ghent University (UGent)

Contributors :

Joris Valee ; Energyville | Vlaamse Flemish Institute for Technological Research (VITO)
Juan Correa Laguna ; Energyville | Flemish Institute for Technological Research (VITO)
Wim Clymans ; Flemish Institute for Technological Research (VITO)
Frank Meinke-Hubeny ; Energyville | Flemish Institute for Technological Research (VITO)
Luc Girardin ; École Polytechnique Fédérale de Lausanne (EPFL)

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EXECUTIVE SUMMARY

This report describes circular economy practices and in particular the potential for industrial symbioses (IS) in six energy-intensive industry sectors (steel, refinery, cement, chemical, glass and fertiliser), **using the AIDRES EU reference (2018) and 2050 Mix route** as a use case. The focus is on reducing energy consumption, raw material usage, CO_2 emissions, and overall costs through synergies between industries in five different clusters. A circular economy is based on the principles of reducing the need for materials and energy, reusing products and by-products, recycling waste streams, and recovering energy from waste. The four "R" strategies (reduce, reuse, recycle, and recover) are linked to specific outcomes in this report.

The steel sector, both as supplier and consumer, has reported synergies with the cement and chemicals sector, and with urban districts. The refinery sector, similarly, has ongoing interactions with the power, steel, and chemicals sector. The cement sector, known for its energy, material and waste recovery capabilities, has reported synergies with the steel, energy and chemicals sector, as well as with urban districts. The glass sector, as supplier and consumer, has reported exchanges with the construction, energy and steel sector. Finally. the fertiliser sector, primarily a consumer, has synergies with refining, metal production and paper industries.

The AIDRES database, including production capacities of large EU industrial installations (>20M), aggregated on NUTS3, is utilised to analyse regions with high potential for IS applied to the six industrial sectors. The presence of these sectors varies across Europe, with certain regions showing higher production capacities than others. The steel, cement and glass sectors have a wide geographically distribution, while fertiliser and refining sectors have a more concentrated geo-footprint. The potential for industrial symbiosis depends on the density and diversity of sectors within a region. Some regions have significant potential for IS across multiple sectors, while other areas have limited options due to physical restrictions (such as dispersion, distance or type of resources). This study aimed at answering the demand for more circularity and finding drivers to advance cross-sectoral industrial symbiosis. The report includes the assessment of future technology models, matchmaking criteria, and the identification of synergies for integration. By quantifying critical resources for symbiosis, such as captured CO_2 for infrastructure mutualisation, symbiosis options are expanded. The impact of symbiosis is assessed qualitatively at industrial cluster level, considering factors such as lower energy demand, raw materials, CO_2 emissions, and total expenditure (TOTEX).

Five selected clusters are examined as use cases to illustrate the potential for symbiosis and expected impact. The clusters are: **Belgium/Antwerp, France/Fos-sur-Mer, Spain/Asturias, Poland /Częstochowski and Bulgaria/Varna**. For each cluster, the profile, transition analysis, and qualitative assessment of symbiosis is presented. The analysis initiates with selecting a region based on a set of symbiosis criteria and the AIDRES database is used to generate maps and gather baseline information. The energy demand and carbon emission profiles of the clusters are characterised using the AIDRES EU Mix production routes, aiming for sector specific CO2 emission targets towards 2050.

Based on the sectors present in each cluster and selected production routes, symbiosis options are suggested using the IS case base. Key areas include material and energy flows shared by

multiple processing units, sector blueprints, and the four R's circular strategies. Additional symbiosis cases are suggested based on the EPOS[1,2] IS generic cases matrix.

The impact of symbiosis on the clusters depends on factors such as feedstock need, excess heat, demand response options, and specific site information**. Potential synergies include heat and biomass logistics, shared renewable energy sourcing, CO2 and hydrogen infrastructure mutualisation**, and the possibility of negative emissions projects. The highest impact for symbiosis is expected to **result in decreasing TOTEX, energy demand, and raw materials**.

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

[2] PHD Thesis, Mendez Alva, F. Industrial symbiosis enabling resource circularity and climate neutrality in the process industry, https://biblio.ugent.be/publication/01GMSTA27PB9ACYZ4JRKH2EVZP

Résumé

Ce rapport décrit les pratiques de l'économie circulaire et en particulier le potentiel des symbioses industrielles (SI) dans six secteurs industriels à forte consommation d'énergie (acier, raffinerie, ciment, l'industrie chimique, verre et engrais), **en utilisant la filière de référence AIDRES EU (2018) et celle du Mix 2050 comme cas d'étude**. L'accent est mis sur la réduction de la consommation d'énergie, de l'utilisation des matières premières, des émissions de CO2 et des coûts globaux par l'exploitation des synergies entre cinq différentes grappes industrielles. Le principe d'économie circulaire appliqué est basé sur la réduction des besoins en matériaux et en énergie, la réutilisation des produits et des sous-produits, le recyclage des flux de déchets et la récupération de l'énergie produite à partir des déchets. La stratégie des quatre "R" (réduction, réutilisation, recyclage et récupération) se rattache aux résultats spécifiques du rapport.

Le secteur de l'acier, à la fois fournisseur et consommateur, dispose d'un potentiel de synergie avec les secteurs du ciment et de la chimie, ainsi qu'avec les quartiers urbains. De même, le secteur des raffineries a des interactions permanentes avec les secteurs de l'électricité, de l'acier et de la chemie. Le secteur du ciment, connu pour ses capacités de récupération de l'énergie, des matériaux et des déchets, dispose d'un potentiel de synergies avec les secteurs de l'acier, de l'énergie et de la chimie, ainsi qu'avec les districts urbains. Le secteur du verre, en tant que fournisseur et consommateur, dispose d'un potentiel d'échanges avec les secteurs de la construction, de l'énergie et de l'acier. Enfin, le secteur des engrais, essentiellement consommateur, présente des synergies avec les secteurs du raffinage, de la métallurgie et du papier.

La base de données AIDRES, qui contient les capacités de production des grandes installations industrielles de l'UE (>20M), agrégées au niveau des NUTS3, est utilisée pour analyser les régions présentant un potentiel élevé de SI appliquées aux six secteurs industriels. La présence de ces secteurs varie en Europe, certaines régions affichant des capacités de production plus élevées que d'autres. Les secteurs de l'acier, du ciment et du verre ont une large dispersion géographique, tandis que les secteurs des engrais et du raffinage ont une empreinte géographique plus concentrée. Le potentiel de symbiose industrielle dépend de la densité et de la diversité des secteurs au sein d'une région. Certaines régions disposent d'un potentiel important pour les SI dans plusieurs secteurs, tandis que d'autres zones ont des options limitées en raison de restrictions physiques (telles que la dispersion, la distance ou le type de ressources). Cette étude vise à répondre à la demande pour plus de circularité en identifiant les moteurs du développement de la symbiose industrielle intersectorielle. Le rapport comprend l'évaluation des futurs modèles technologiques et des critères d'appariement, ainsi que l'identification des synergies d'intégration. La quantification des ressources critiques pour la symbiose, telles que le CO2 capturé pour la mutualisation des infrastructures, permet d'élargir les options de symbiose. L'impact de la symbiose est évalué qualitativement au niveau des grappes industrielles, en tenant compte de facteurs tels que la réduction de la demande d'énergie, des matières premières, des émissions de CO2 et des dépenses totales (TOTEX).

Cinq clusters industriels sélectionnés sont examinés en tant que cas d'étude pour illustrer le potentiel de symbiose et l'impact attendu. Il s'agit des clusters suivants : Belgique/Anvers, France/Fos-sur-Mer, Espagne/Asturies, Pologne/Częstochowski et Bulgarie/Varna. Pour chaque cluster, le profil, l'analyse de la transition et l'évaluation qualitative de la symbiose sont présentés. L'analyse commence par la sélection d'une région sur la base d'un ensemble de critères de symbiose et la base de données AIDRES est utilisée pour générer des cartes et rassembler des informations de base. La demande énergétique et les profils d'émissions de carbone des clusters sont caractérisés à l'aide des filières de production AIDRES EU Mix,

dans le but d'atteindre des objectifs d'émissions de CO2 spécifiques à chaque secteur à l'horizon 2050.

Sur la base des secteurs présents dans chaque cluster et des filières de production sélectionnées, des options de symbiose sont suggérées à l'aide de solutions de SI de base. Les domaines clés comprennent les flux de matières et d'énergie partagés par de multiples unités de traitement, les plans sectoriels et les stratégies circulaires des quatre "R". D'autres cas de symbiose sont suggérés sur la base de la matrice des cas de SI génériques EPOS34.

L'impact de la symbiose sur les clusters dépend de facteurs tels que les besoins en matières premières, l'excès de chaleur, les options de réponse à la demande et les informations spécifiques au site. Les synergies potentielles comprennent la distribution de chaleur et de biomasse, le partage des sources d'énergie renouvelable, la mutualisation des infrastructures de CO2 et d'hydrogène, et la possibilité de projets à émissions négatives. L'impact le plus important de la symbiose devrait se traduire par une diminution du TOTEX ainsi que de la demande en énergie et en matières premières.

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 decarbonisation 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[3]) 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 installations, industrial parameters and current and future energy and material demands, production rates and GHG emissions for the defined model solutions within WP1.

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

The document describes the methodology used to model and characterise 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.

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.

2. Aim of this report

The AIDRES project considers energy and material synergies among energy-intensive industries to include present and future industrial symbiosis (IS) cases as a circular economy strategy. Although the impact of IS includes the reduction of carbon emission directly by the substitution of material with lower emissions, most reductions on emissions impact scope 3 more than scope 1 and 2. Therefore the impact of IS in the AIDRES database is not as high as when including scope 3 impact.

This report aims:

- To provide the context of industrial symbiosis per sector (IS sector profiles).
- To give an overview of industrial clusters in Europe according to the AIDRES database.
- To provide insights on the potential for the symbiosis of selected regions using the AIDRES database.

The report includes:

- A brief description of methodology based on the EPOS project.
- An analysis per sector in terms of synergy streams, partnering sectors and regions.
- An exploratory ranking of NUTS3 regions industrial clusters based on its potential for symbiosis.
- Five NUTS3 region analyses for IS as **use cases of the AIDRES database.**
- Overall conclusions and future research directions.
- Appendixes with a full list of potential cross-sectoral synergies (six sectors) and industrial clusters (across Europe).

The report builds on the outcome of WP2 (industrial site location) and WP1 (sector models and future technology selections). Therefore, additional details can be consulted in the AIDRES final report.

Critical boundaries settings for IS implicit in the AIDRES project:

- Industrial sectors are preselected and defined: cement, chemical, fertiliser, glass, refinery, and steel.
- The baseline for comparison/reference is 2018 (pre-COVID).
- The time horizon towards carbon neutrality for selected industries is 2050 and aims at sector-specific direct emissions, between 85% and 96%, compared to 2018 as described in the AIDRES methodology for EU industrial production routes Report used to model industrial production routes
- Green hydrogen is assumed to be available and accessible in 2050, adding scenarios at different prices for affordability.
- Climate-neutral electricity is considered available, accessible, and affordable in 2050.

- Production in the studied process sectors is regarded constant except for refineries, in which a one-third reduction in light liquid fuel production is assumed in 2050.
- Fossil feedstock (naphtha and crude oil) used in the chemical and refinery sectors are considered energy carriers to define part of the energy demand of a cluster.
- Externalities, such as the COVID crisis, energy crisis or war situations, are understood to impact the transition of process industry towards climate and resource neutrality in 2050.

All figures in section 4 of the report (cluster cases) are produced using the AIDRES database. The production routes and consequent figures are selected to illustrate the insight capabilities implicit in the database. The cluster cases are NOT intended to be seen as roadmaps for the clusters, as to this purpose the involvement of local stakeholders is essential.

3. Industrial symbiosis and circular economy

The basic circular economy (CE) principle is to close loops by reusing, recycling or recovering waste streams (materials/energies) across society and encourage their use as new resources either locally or in other industries, sectors, districts, applications, etc. Moreover, when embedding circularity in a future climate and resource neutral economy, the 4th R of the ladder of Lansink, introduced in 1979 [1], is added as basic principle: reducing the need for materials and energies at the source (Figure 1).

Reduce

Avoids fossil-based energy or materials by replacing fuel and feedstock with low/zero-carbon alternatives or by using new technologies. This refers to both future product and technology lists per sector to directly reduce energy and resources.

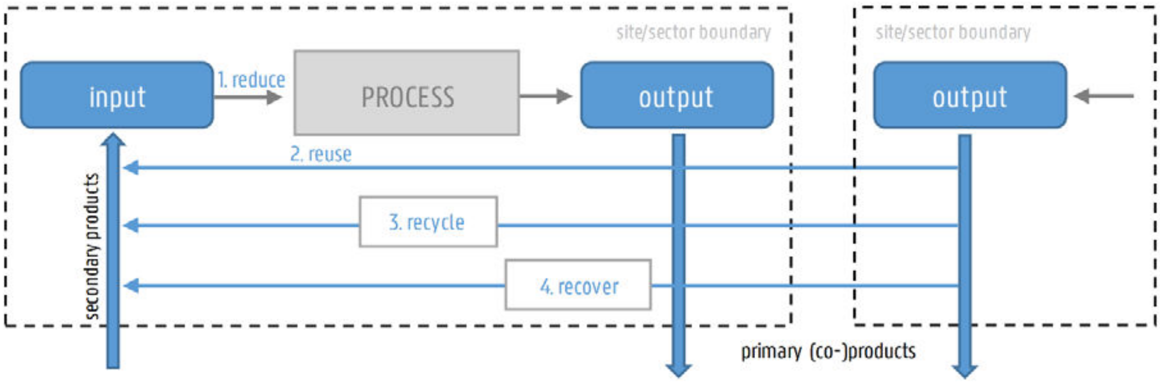

Figure 1 The 4Rs circular strategy embedded in process industry symbiosis using an input-output model of an industrial sector blueprint. Blue arrows indicate flow options within and across blueprints. Grey frames indicate flows that require processing.

Reuse

To give a second life to end- or by-products which refers to secondary resources used as direct input (symbiosis database).

Recycle

To reprocess material waste streams into recycled resources and refers to end-of-life waste products (solid, liquid or gas) available for reuse after treatment.

Recover

Converts energy waste streams to provide heat, power or fuel refers to energy cascading (heat, power or fuel).

Industrial symbiosis (IS) drives the circular economy. IS can be articulated for each of the 4Rs, however most cases are traditionally associated to R2 (the reuse of waste and by products) and R3 (energy recovery across sectors). Each of the 4Rs strategies is related to an outcome in the project (Figure 2). R1 relates to the new production routes selected to reduce fossil fuel and carbon emissions, having implication in the database and description of the tech models in the final report (mixed routes 2050 in the WP1 database). R2 relates to the cross-sectoral connection of energy and material flows (IS), having implication for the database as depending on the sector present in each NUSTS3 region, specific flows are selected (the full list of flow per section is included in the appendix of this report). R3 relates to secondary production of steel, glass and plastic, with reporting implications about the potential and trends (R3 report on recycling). Finally, R4 is related to incineration of waste stream in cement kilns, having implications for regional synergies among industries (the full list of waste material as alternative fuels is included in the appendix A of this report).

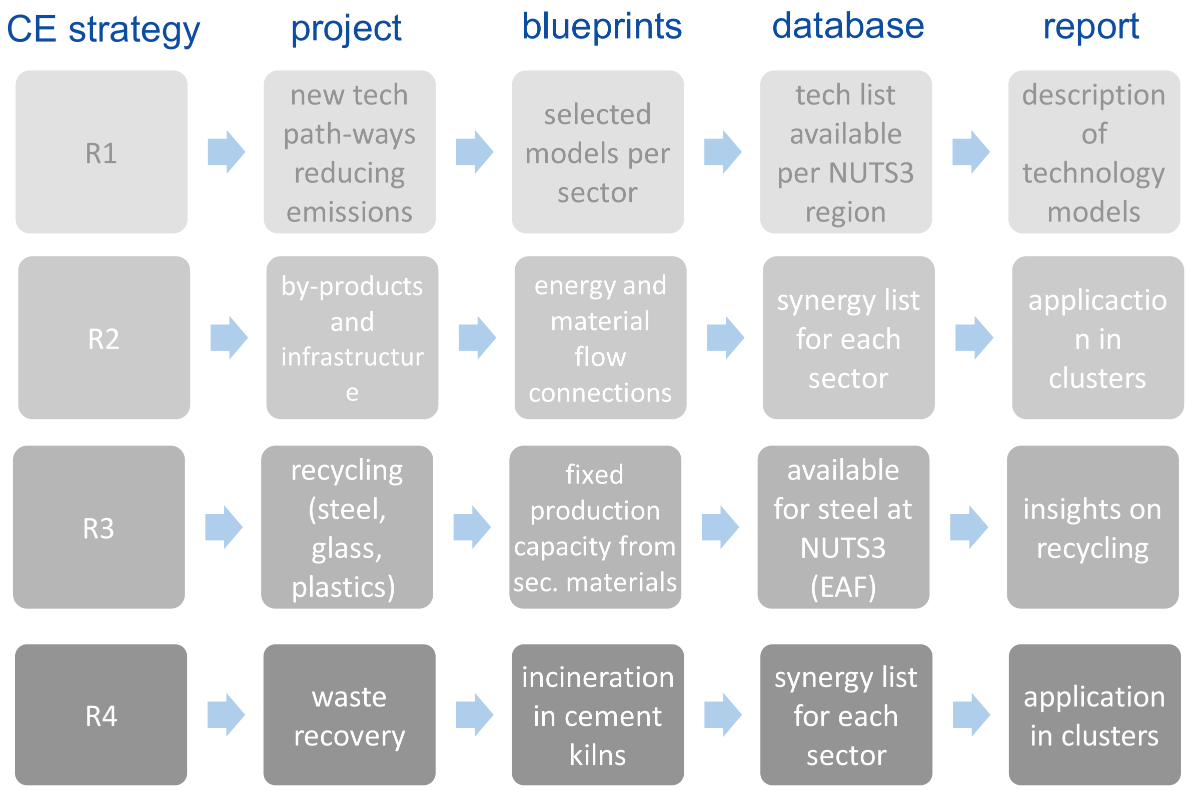

Figure 2 Circular Economy strategies in the AIDRES project

4. IS overview per sector

Industrial symbiosis is considered a corner stone in the transition towards a circular economy and climate neutrality goals in energy intensive industries. The establishment of collaboration and synergies across sector is the essence of IS [2], [3].

IS in the AIDRES project buildings from proven methodologies developed in EU projects & Energy and Cluster Management (ECM) research on industrial symbiosis (Figure 3):

- H2020 EPOS project: LESTS surveys, generic cases, and matchmaking criteria for blueprints.
- H2020 SPIRE projects MAESTRI and SCALER, EPOS (IS databases).

Specific tools are used per time horizon. In 2030, the situation is more about the replication of successful cases, while the 2050 situation is more influenced by synergies involving new technologies in different sectors.

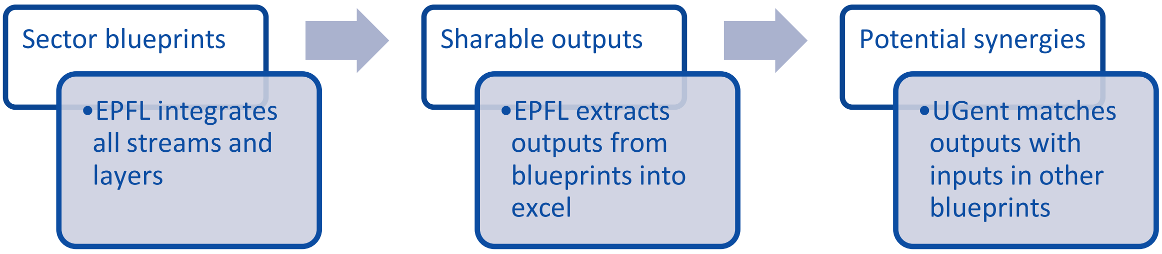

Figure 3 Matchmaking methodology (adapted from the EPOS project)

2018 (baseline situation)

- ECM IS database [4]
  - 276 synergies collected from 3 databases MAESTRI, SCALER and EPOS
  - Synergies comprising at least one AIDRES sector
- ECM case-base building from EPOS matchmaking criteria [5]
  - Fertiliser, refinery, and glass added using EPOS criteria
  - Classification of cases according to the CE-IS frame

2050 (future situation)

- Future technology model per sector
  - Matchmaking layers in new production routes using EPOS criteria [5]
  - Generic cases for options common to all sectors [6]

In the following subsection, an overview per sector is provided and the full list of IS cases is available in Appendix A.

4.1. Steel

The steel sector has mostly a supplier in symbiosis, with an inclination towards valorisation of waste and energy with other industrial sectors. The sector has reported synergies with cement, chemical and urban district sectors [4].

The steel sector, as a supplier, valorises mainly waste and energy for symbiosis, having reported synergies with cement, chemical and non-ferrous metals production [4]. A total of 44 synergies was selected to assess integration in the AIDRES modelling task (Appendix Table 24). The most relevant synergies for the future are related to the supply of hydrogen from electrolysers and furnace gases, oxygen from electrolysis by-product and CO_2 (joint infrastructure for capturing at scale).

The steel sector, as a consumer, valorises waste and energy for symbiosis, having reported synergies mostly with urban districts, power supply and chemical sectors [4]. A total of 44 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 25). The most relevant synergies are the consumption of electricity, providing flexibility to the grid with electrolysers and hydrogen or oxygen production in clusters (joint infrastructure).

The steel sector has a presence in 107 NUTS3 regions (Figure 4). The average production per region is 4 Mt/y. There is maximum primary steel production of 12.8 Mt/y in region DEA12 ('Duisburg, Kreisfreie Stadt', Germany), a German region along the Rhine River with the largest inland port ('Duisburg-Ruhrorter Häfen'), with also a high presence of the chemical sector.

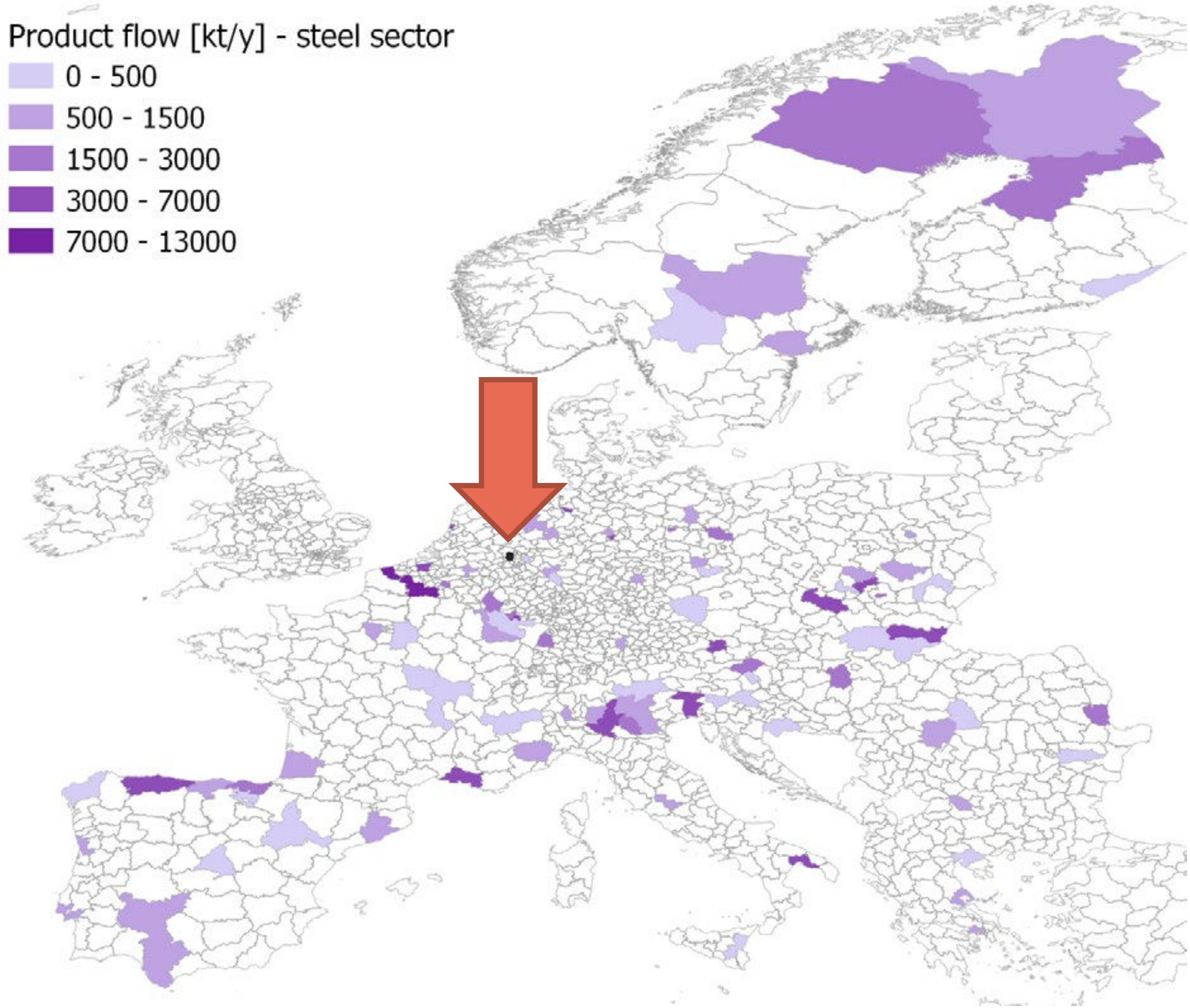

Figure 4 Steel sector capacity production across Europe, with region DEA12 in Germany with the highest production capacity (from AIDRES database).

The steel sector has a limited IS potential when setting the boundaries at NUTS3 regions. The average number of AIDRES sectors in a NUTS3 with steel production is two. Around 52% of the regions with steel production has no detected symbiosis options, but this is probably due to the restriction of AIDRES sectors in the selected regions. Over 20% of steel-producing regions has the potential to establish IS with three or four other sectors. Steel production shares regions that can be connected to the chemical sector (Figure 14), which is promising for future integration potential.

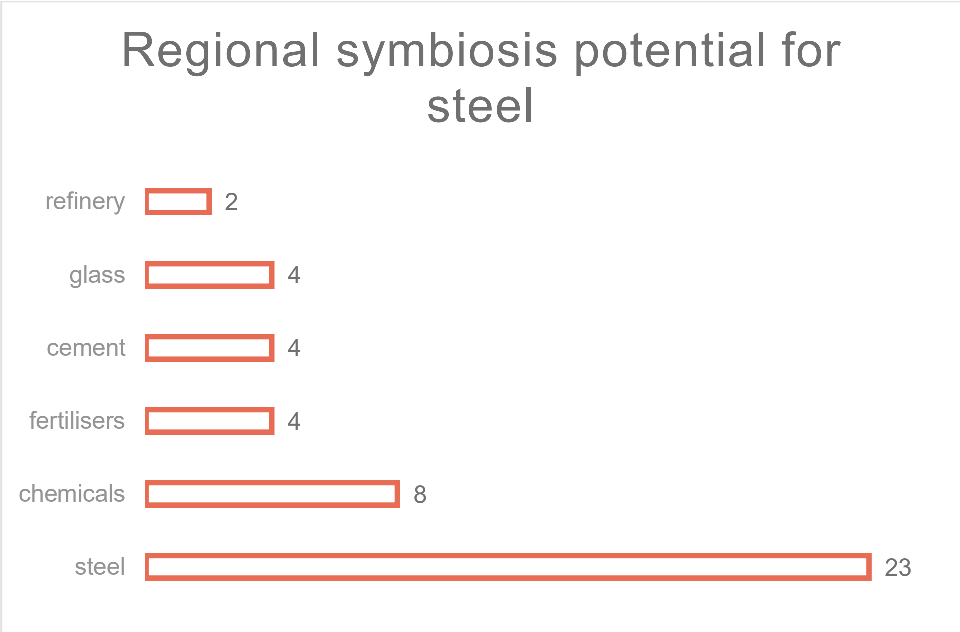

Figure 5 Number of NUTS3 regions with steel production added with other AIDRES sector's production

4.2. Refinery

Refineries have supplier and consumer roles in symbiosis, with an inclination towards valorisation of energy and by-products with other industrial sectors. The sector has reported synergies with the power supply, chemical and steel sectors [4].

The refining sector, as a consumer, valorises energy, by-products and waste in symbiosis, having reported synergies mostly with power supply, steel and non-metal production sectors [4]. A total of 21 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 22). Relevant symbiosis for the future is related to CO_2 for Fischer-Tropsch synthetic fuels (FT fuels), biomass and hydrogen (electrolysis infrastructure).

The refining sector, as a supplier, valorises mainly energy and by-products for symbiosis, having reported synergies with the power supply, chemical, and non-ferrous metal production [4]. A total of 27 synergies was selected to assess integration in the AIDRES modelling task (Appendix Table 23), including future prospective toward carbon and heat networks.

The refining sector has a presence in 68 NUTS3 regions. The average processing per region is 9 Mt/y of crude oil. There is maximum refining production of 56.2 Mt/y in region NL33C ('Groot-Rijnmond', Netherlands), the port of Rotterdam region, with also chemical production (1.3 Mt/y).

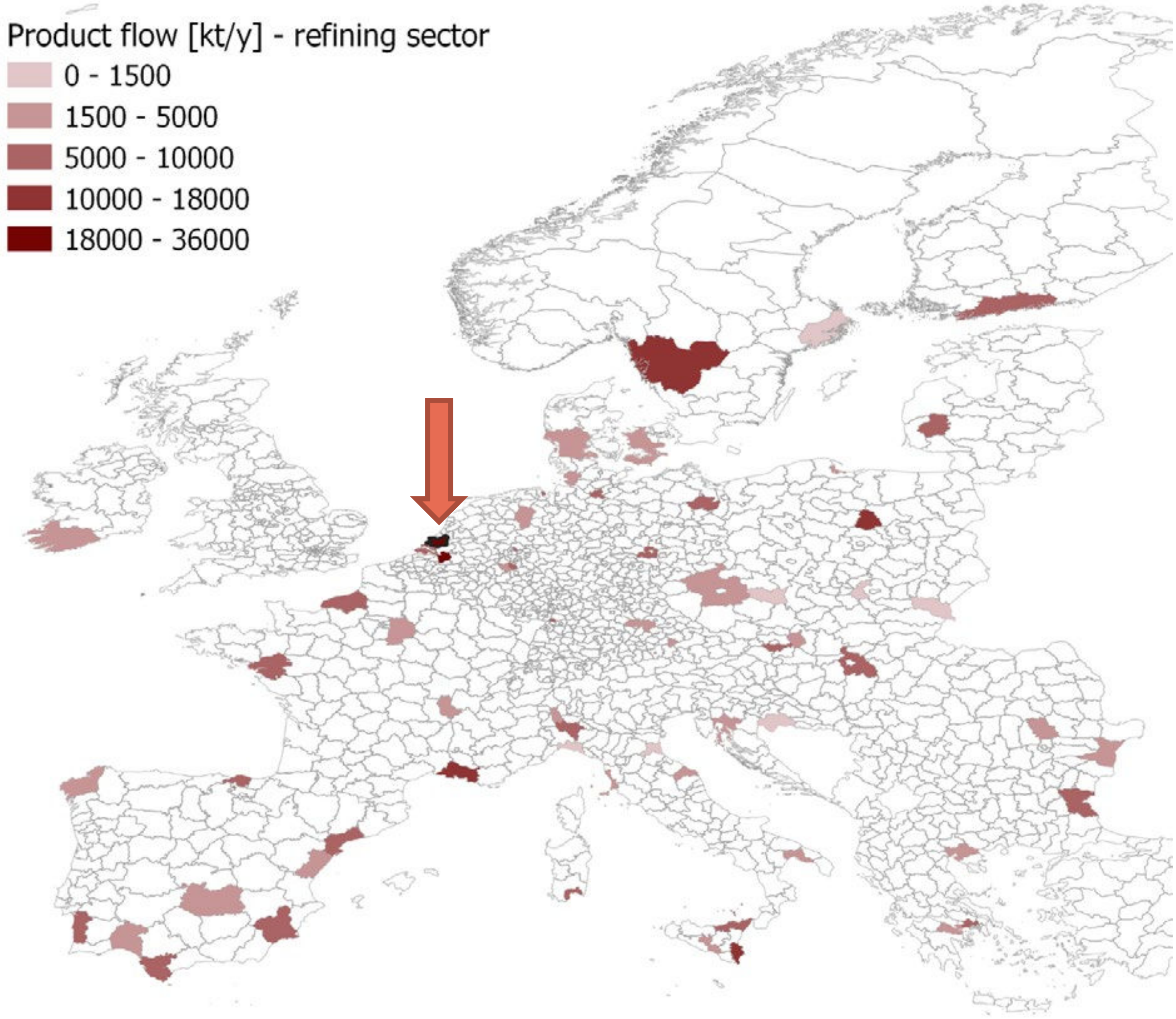

Figure 6 Refining sector capacity production across Europe, with region NL33C in the Netherlands with the highest production capacity (from AIDRES database).

Refineries have symbiosis partners in most regions. The average number of AIDRES sectors in a NUTS3 with refining production is 2.1. Around 28% of the regions has only refining production (no symbiosis), and 8.8% of refining producing regions has the potential to establish IS with three others. Refining production shares regions mainly with chemical (Figure 15) and cement (Figure 9).

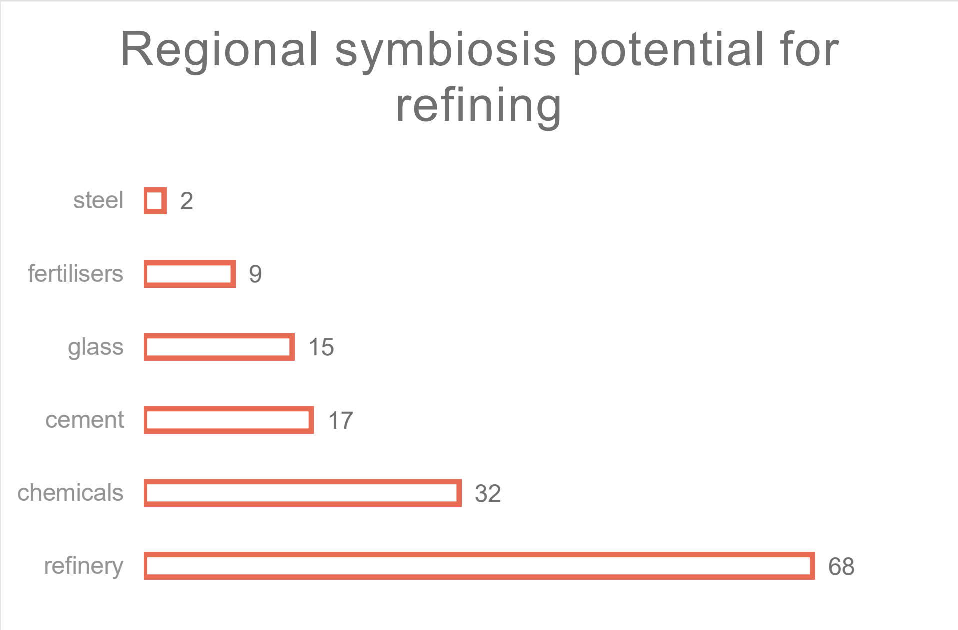

Figure 7 Number of NUTS3 regions with refining production added with other AIDRES sectors

4.3. Cement

The cement sector has high relevance for symbiosis as a consumer of underused resources, related to the high capability of energy and material recovery inherent to the manufacturing process of cement [4]. Most of the synergies are related to material recovery based on waste, followed by the energy synergies where alternative fuels are frequent. Such internal capability leaves little space for supplying underused resources to other industries. However, a main issue of cement production is the CO_2 emissions from non-combustion processes. The potential of such abundant underused resources is being explored in several pilot projects [7].

The cement sector, as a consumer, valorises waste and energy for symbiosis, having reported synergies mostly with steel, energy supply, urban districts and chemical sectors [4]. A total of 29 synergies are selected to assess integration in the AIDRES modelling task (Appendix A). The most relevant future synergies proposed are related to shared renewable electricity infrastructure, added with oxygen and hydrogen from different sectors. The use of oxyfuels takes advantage of oxygen as a by-product in electrolysers, in new steel production technology or from a (green) power plant [8]. The traditional synergy of making use of alternative fuels such as biomass and other materials with high calorific value, is also envisioned for the corresponding cement products. However, only green hydrogen or climate-neutral biomass would contribute to the reduction of net carbon emissions.

The cement sector, as a supplier, valorises energy and by-products for symbiosis, having reported synergies with the energy supply, steel and chemical sectors [4]. The most relevant future synergies are related to the use of CO_2 rich streams for utilisation and storage. A total of 17 synergies was selected to assess integration in the AIDRES modelling task (Appendix A: Table 15).

The cement sector has a spread presence in 162 NUTS3 regions (Figure 9). The average production per region is 1 Mt/y. There is a maximum cement production capacity of 4.7 Mt/y in region PL722 (Sandomiersko-jędrzejowski, Poland), a Polish cement corridor that includes glass production (0.2 MT/y).

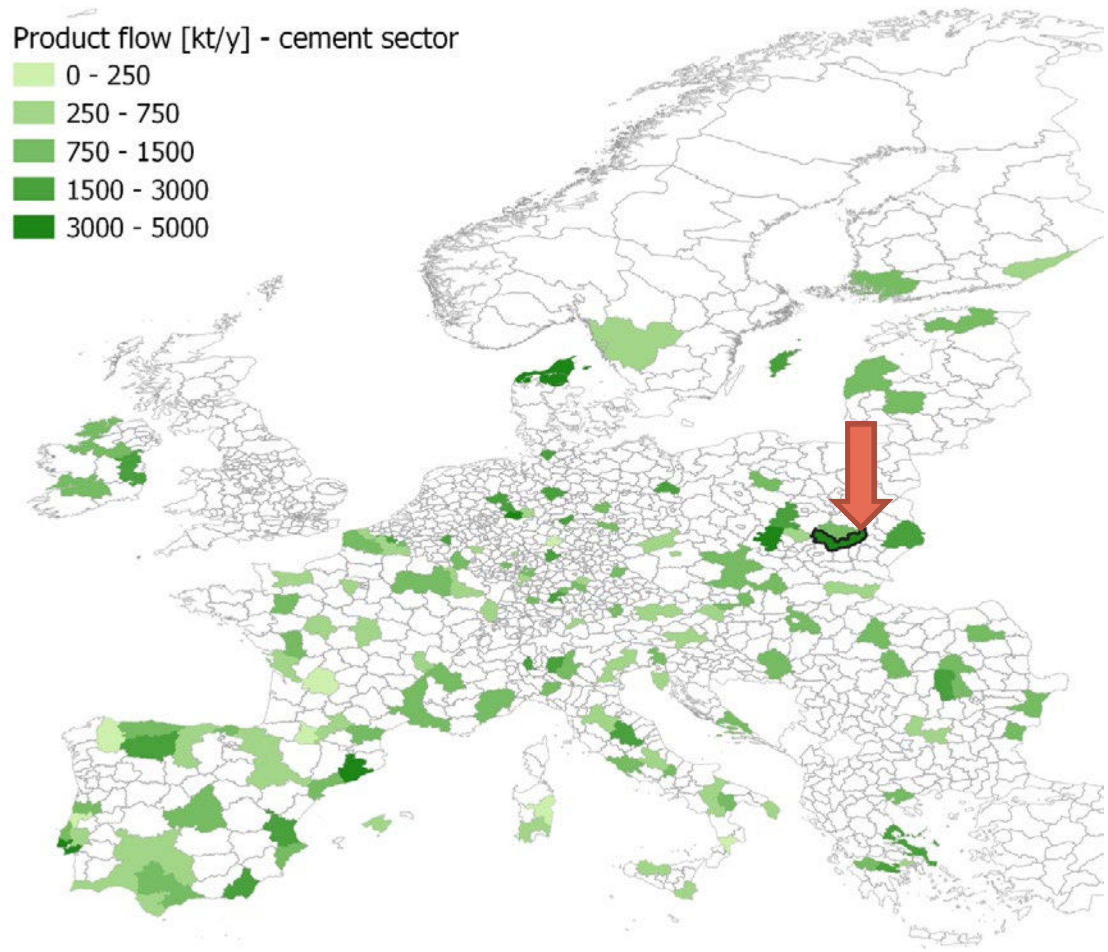

Figure 8 Cement sector capacity production across Europe, with region PL722 in Poland with the highest production capacity (from the AIDRES database).

The cement sector has a wider distribution of production sites compared with other sectors, which reduces its potential for IS. The average number of AIDRES sectors in a NUTS3 with cement production is 1.5 out of 6. Around 55% of the regions with cement production have no symbiosis options due to the lack of other AIDRES sectors in the same region. Resulting in only 5% of cement-producing regions having a potential to establish IS with three other sectors at maximum sector diversity. Glass is the sector with the most frequent production in cement-producing regions, specifically 48 NUTS3 regions (Figure 11), promising significant IS potential between cement and glass production. Although primary steel production is present in only four regions where there is cement production, the primary steel production capacity in each region is high, leading to a high potential for symbiosis with cement.

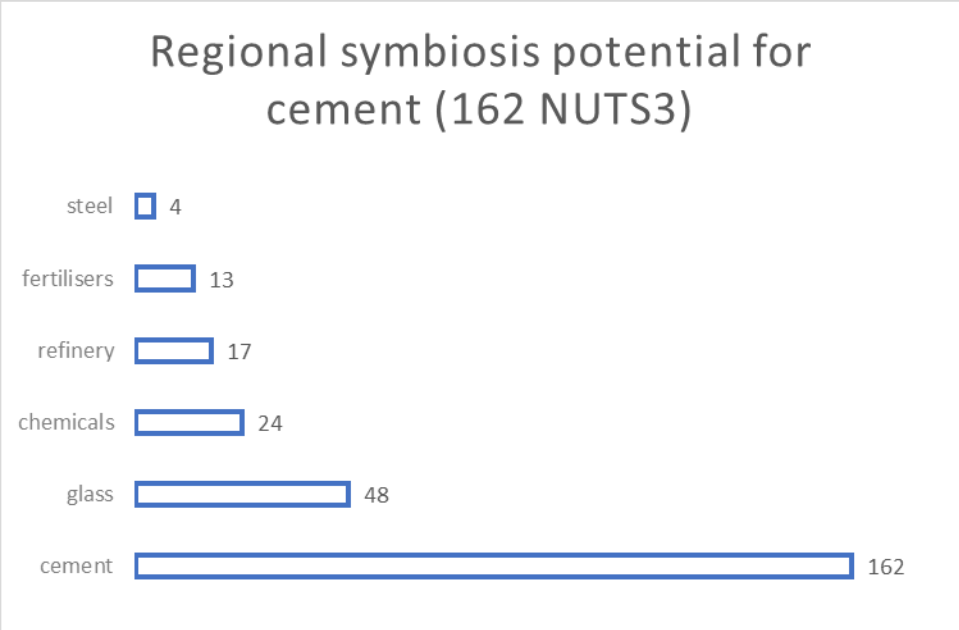

Figure 9 Number of NUTS3 regions with cement production added with other sectors' production

4.4. Glass

The glass sector both play supplier and consumer roles in IS, with an inclination towards the valorisation of by-products and energy with other industrial sectors. The sector has reported synergies with the construction, energy supply and steel sectors [4].

The glass sector, as a supplier, valorises mainly by-products and energy for symbiosis, having reported synergies with construction and food-producing sectors [4]. A total of 5 synergies was selected to assess integration in the AIDRES modelling task (Appendix Table 20), all related to heat valorisation.

The glass sector, as a consumer, valorises waste and by-products for symbiosis, having reported synergies mainly with the power supply and steel sectors [4]. A total of 19 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 21). The most relevant synergies for the future are related to renewable electricity, hydrogen, and oxygen consumption. These synergies can help in establishing a common infrastructure for carbon capture and electrolysis to produce hydrogen which can be used in refurbished furnaces.

The glass sector has a presence in 190 NUTS3 regions. The average production per region is 234 kt/y. There is maximum glass production of 1.1 Mt/y in region PT16F ('Região de Leiria', Portugal), a Portuguese port region, where also cement (0.02Mt/y) is produced.

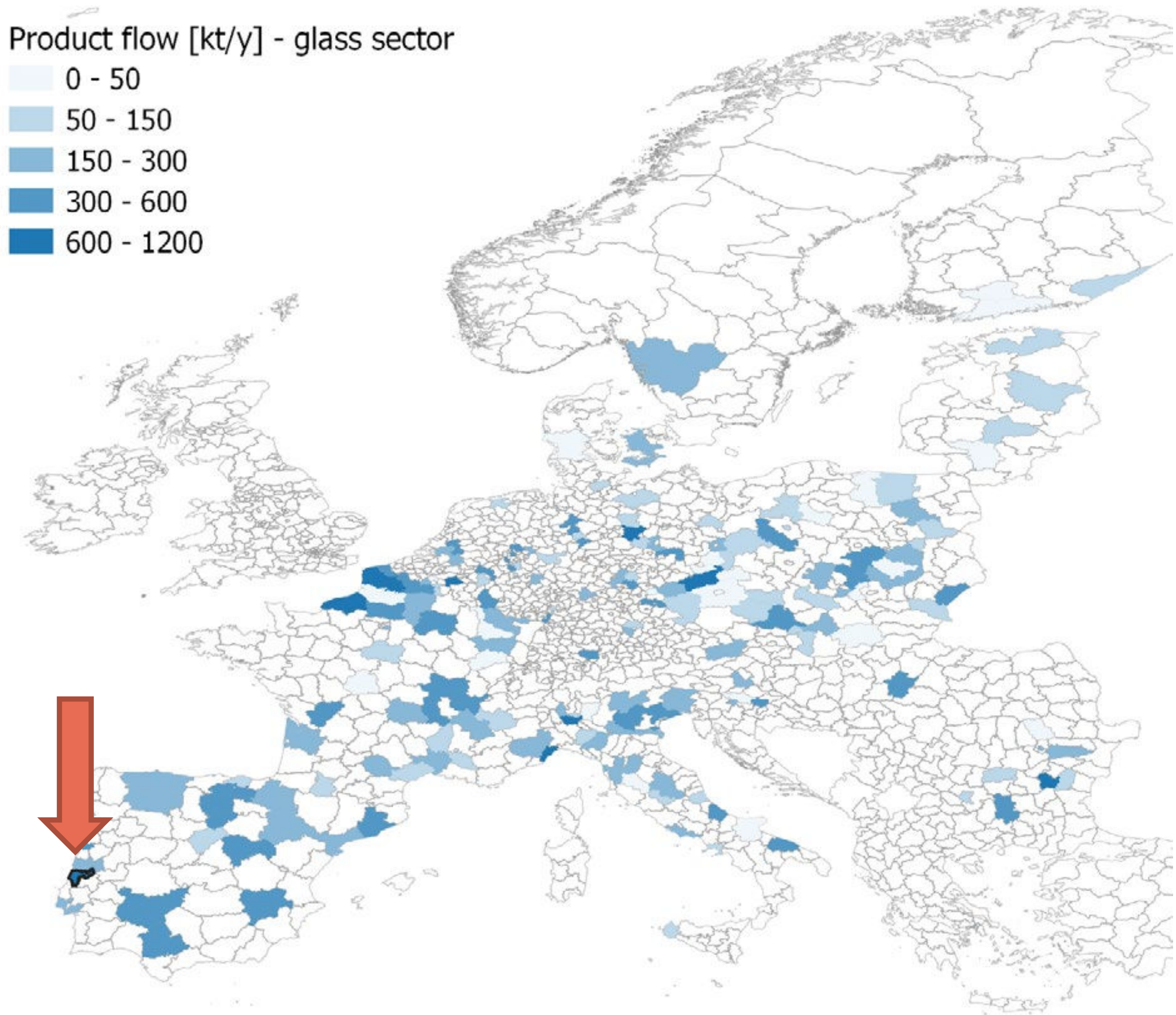

Figure 10 Glass sector capacity production across Europe, with region PT16F in Portugal with the highest production capacity (from AIDRES database).

Similarly, to cement, the glass sector has a wider spread across regions. The average number of AIDRES sectors in a NUTS3 with glass production is 1.5. Around 47% of the regions has only glass production (no symbiosis), and only 5% of glass-producing regions has the potential to establish IS with three or four other sectors. Glass production shares regions mainly with cement (Figure 9) and chemical (Figure 15).

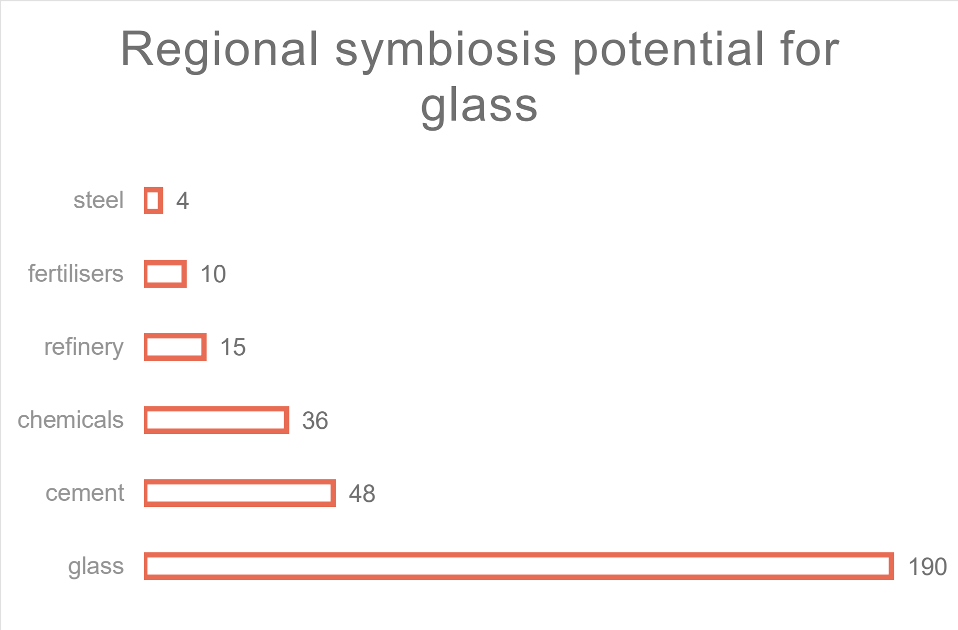

Figure 11 Number of NUTS3 regions with glass production added with other AIDRES sectors

4.5. Fertiliser

The fertiliser sector often has a consumer role in symbiosis, with an inclination towards the valorisation of waste and by-products from other industrial sectors. The sector has reported synergies with refining, metal production and paper industries [4].

The fertiliser sector, as a supplier, valorises by-products, water and energy for symbiosis, having reported synergies with chemicals, food & beverage and the aluminium sector [4]. A total of 27 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 18). The most relevant future synergies are related to H_2 and CO_2 infrastructure. The concentration of carbon dioxide in fertiliser production enables efficient capture technologies. Moreover, the traditional use of hydrogen transitioning to green hydrogen from electrolysis leads to potential symbiosis based on hydrogen or oxygen supply at scale.

The valorisation of gaseous emissions in the sectors has currently high relevance due to the level of CO_2 emissions (1.5-2 t CO_2/ t NH3 or twice the level of cement) with close to 100% purity [10]. Currently, such emissions are used in urea production which is often an integrated production process, or sold to third parties to compensate for emissions allowance often paid. The emissions come from the methane reformer step to produce H_2. There is currently no economic competition with other technologies, e.g., Electrolysis) due to the energy prices and carbon policy, however both are expected to change in the coming decades.

Fertilisers as consumers in symbiosis schemes tend to valorise waste, by-products and water, having reported synergies mostly with refining, non-ferrous metal production, and food & beverage sectors [4]. The latter two are none-AIDRES sectors. A total of 16 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 19). The most relevant streams for the future are H_2, O_2 and electricity. The production of ammonia is also promising for energy grid balancing when electrised hydrogen is part of the power system, especially if there is a high share of renewable energy. However, large volumes of hydrogen production in the European Union could have an impact on the availability of low-cost electricity for direct electrification. Additionally, the use of biomass feedstock from other sectors is expected to be especially beneficial in reaching the carbon neutrality goals of the sector [11], [12].

The fertiliser sector has a presence in 38 NUTS3 regions (Figure 13). The average production per region is 1.7 Mt/y (including ammonia, nitric acid and derivates). There is a maximum fertiliser production of 7.1 Mt/y in region NL341 (Zeelandic Flanders, the Netherlands), the port of Terneuzen, with also a production of chemical (3.3 Mt/y).

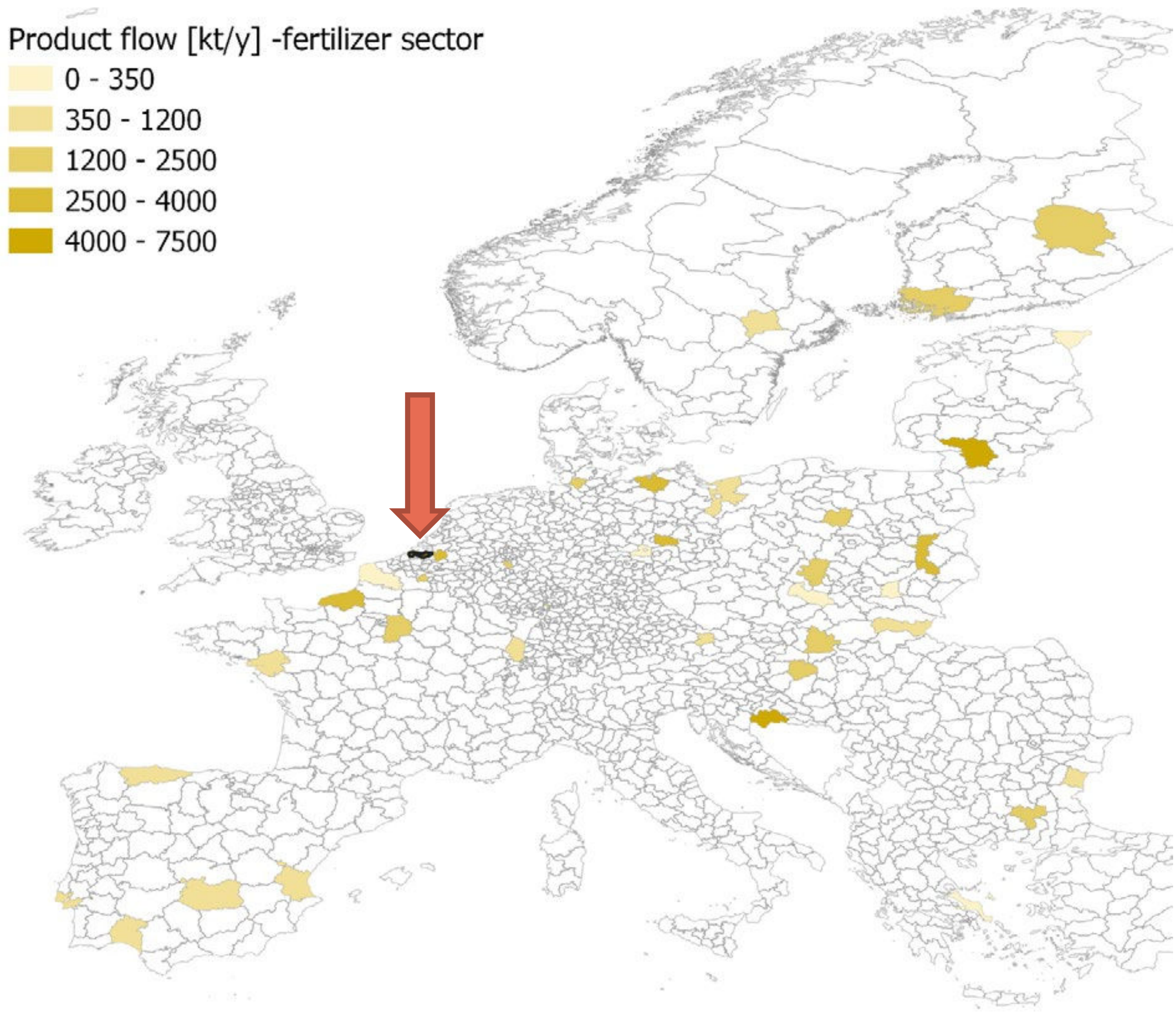

Figure 12 Fertiliser sector capacity production across Europe, with region NL341 in the Netherlands with the highest production capacity (from AIDRES database).

The fertiliser sector has potential partners for symbiosis in most regions. The average number of AIDRES sectors in a NUTS3 with fertiliser production is 2.4. Around 25% of the regions with fertiliser production has no symbiosis options (due to the lack of other AIDRES sectors in the same region). Around 20% of fertiliser producing regions has the potential to establish IS with maximum or four other sectors, mainly with chemical (Figure 15) and cement (Figure 9).

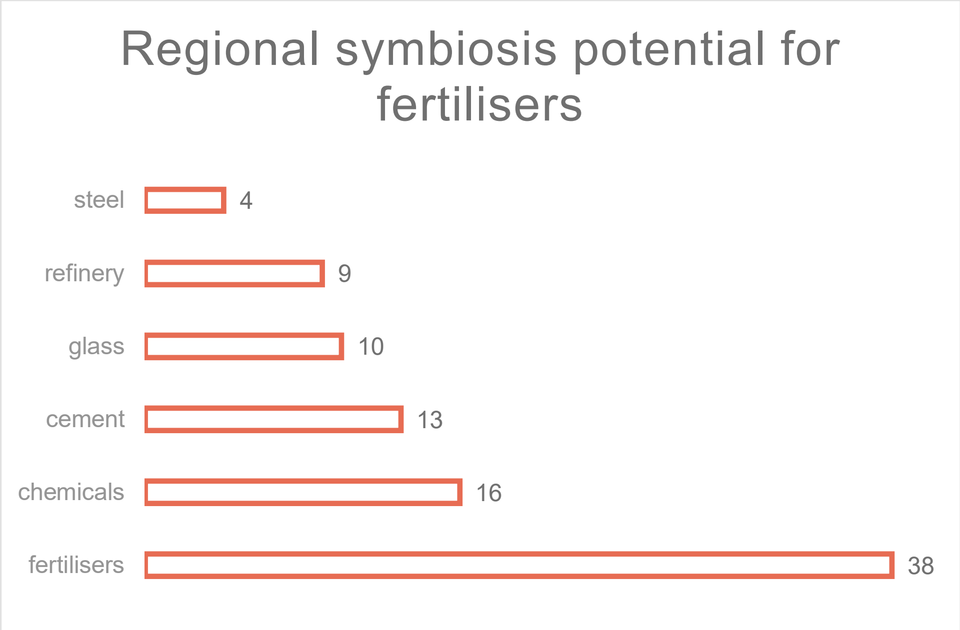

Figure 13 Number of NUTS3 regions with fertiliser production added with other AIDRES sectors

4.6. Chemical

The chemical sector is both a consumer and supplier to symbiosis, with an inclination towards valorisation of energy, waste, and by-products with other industrial sectors. The chemical sector is well integrated, in chemical clusters and with the refining industry in Europe, and has frequently reported synergies with steel and cement industries [4].

The chemical sector, as a consumer, valorises energy, waste and by-products for symbiosis, having reported most synergies with energy supply, steel and other metal industries [4]. A total of 12 synergies are selected to assess integration in the AIDRES modelling task (Appendix Table 16). The most relevant future synergies are related to renewable electricity, hydrogen, and CO_2, including (chemical) recycling of waste streams as intermediate products such as from syngas out of emissions from the steel sector to methanol and plastics. Additionally, symbiosis with the agricultural sector is expected to increase, developing a higher share of bio-feedstock for chemical synthesis [9].

Alternative synthesis pathways using CO_2 are targeted to produce polymers, solvents, fuel additives, and precursors (methanol, organic acids, carbamates, alcohols, aldehydes) for many other sectors e.g.: from detergents to cosmetics. However, most of the pathways are at lab-scale and demonstration level, pending maturation to reach commercial viability [10]. Compared with other sectors, chemical include some processes with a very high level of purity of CO_2 in their emissions, bringing opportunities for internal valorisation.

The chemical sector, as a supplier, valorises energy and by-products for symbiosis, having reported synergies with energy supply, cement and other non-ferrous metal sectors [4]. A total of 9 synergies was selected to assess integration in the AIDRES modelling task (Appendix Table 17), all related to energy as heat and the calorific value of output streams.

The chemical industry has a presence in 118 NUTS3 regions (Figure 15). The average production per region is 860 kt/y. There is a maximum chemicals production of 17 Mt/y in region BE211 (‘Arr. Antwerpen’, Belgium), the Port of Antwerp-Bruges, with also refineries (38.9 Mt/y) and fertilisers (3.4 Mt/y) present in the port industrial infrastructure.

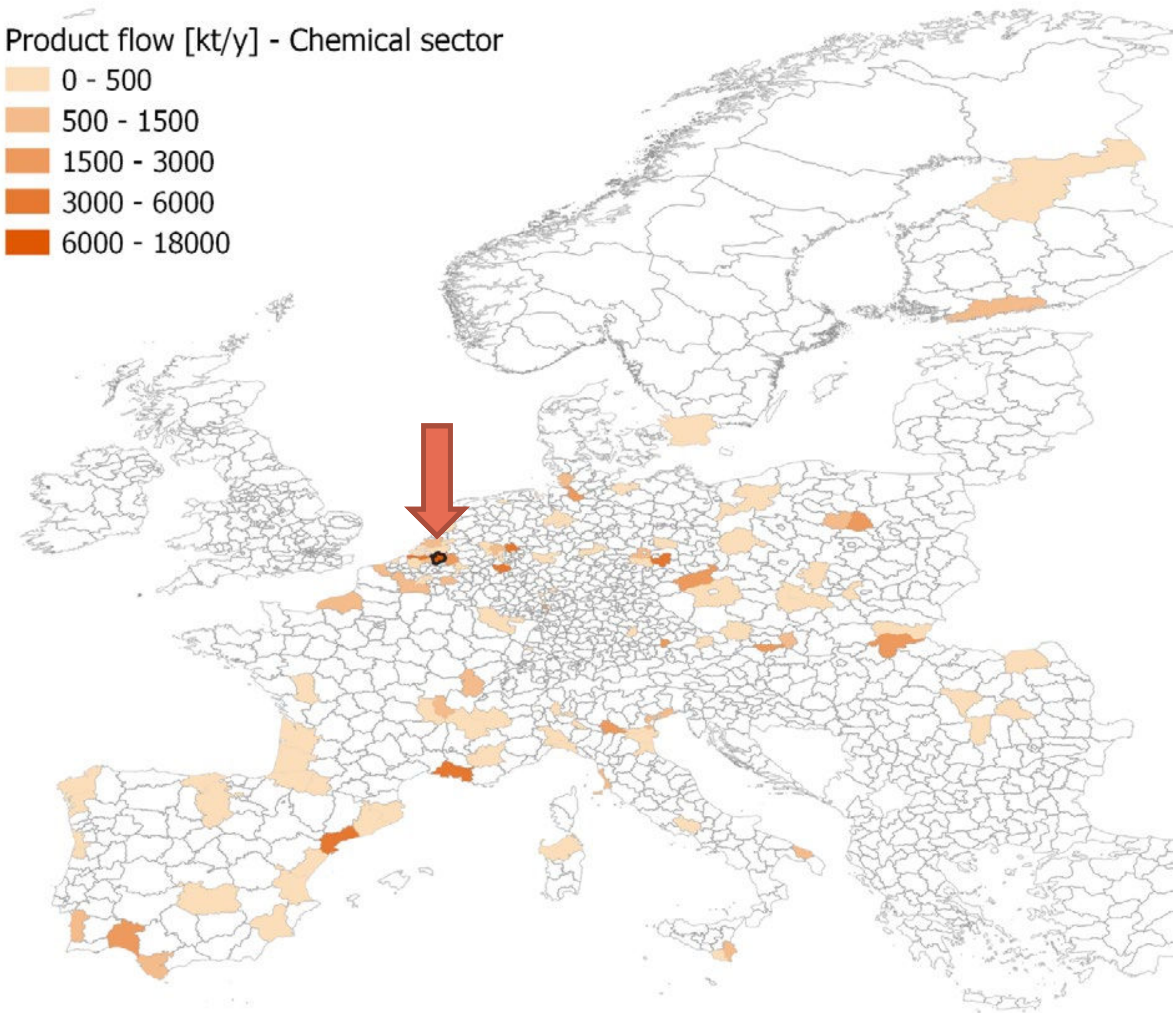

Figure 14 Chemical sector capacity production across Europe, with region BE211 in Belgium with the highest production capacity (from AIDRES database).

The chemical sector has potential partners in symbiosis in most regions. The average number of AIDRES sectors in a NUTS3 with chemicals production is around two. Nearly 35% of the regions with chemicals production has no symbiosis options (due to the lack of other AIDRES sectors in the same region), and about 10% of chemicals producing regions has the potential to establish IS in clusters with over two or four other sectors (being four the maximum). Chemical sites share regions mainly with glass (36 regions) and refining (32 regions) sectors (Figure 15).

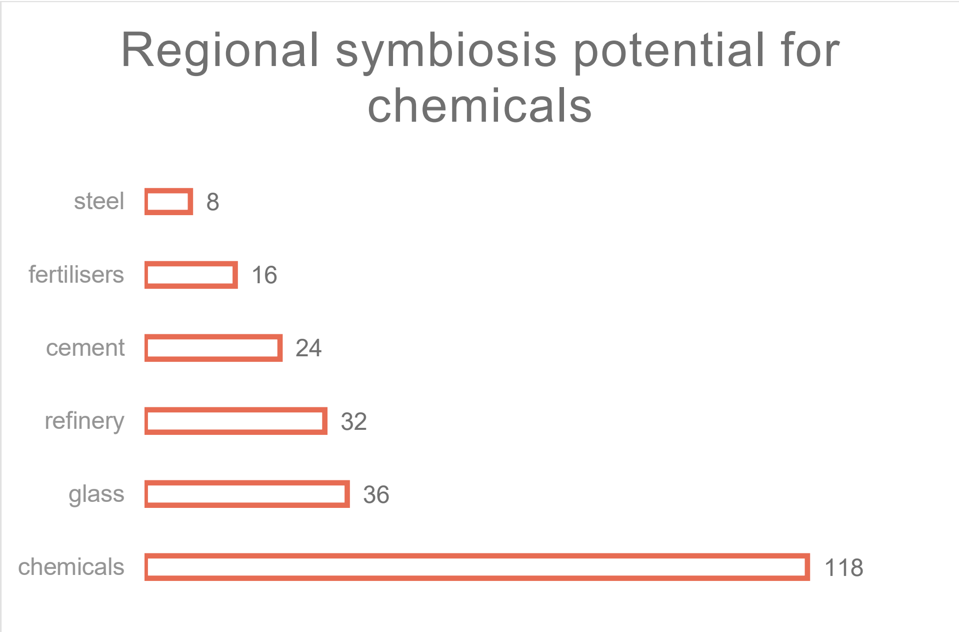

Figure 15 Number of NUTS3 regions with chemical production added to other sectors' production

5. Industrial symbiosis for clusters

This section focuses on the industrial symbiosis options at the cluster level and the application of the method to identify clusters and regions with high potential for IS.

5.1. IS cases common to all sectors

Industrial symbiosis in clusters often drives cluster level innovation, resource efficiency, and emissions reduction. A combination of solutions such as systemic efficiency, electrification, hydrogen and CCUS has the potential to reduce industrial GHG emissions footprint by up to 40% by 2030 [13]. Most potential for industrial clusters lies in systematic solutions by adopting leading synergy practices such as cogeneration, increased recycling, energy recovery and process integration. Also, direct electrification and the use of renewable heat for low-to-medium temperature processes via commercially available technologies promise up to 15% reduction in industrial clusters. CCU-S and H_2 will be increasingly crucial beyond 2030 as their infrastructure develops [13].

The effectiveness of net-zero solutions at the level of clusters depends on local cluster characteristics [13]:

- Industry composition
- Geography
- Existing infrastructure
- Energy cost and policy

Net zero solutions for clusters mainly refer to [13]:

- Systematic efficiency and circularity, up to 15% emission reduction potential

- Direct electrification and renewable heat, up to 15% emission reduction potential
- Hydrogen, up to 10% emission reduction potential
- CCUS, up to 3% emission reduction potential in 2030, higher impact expected in 2050

We have selected two generic cases towards carbon neutrality common to all sectors for additional analysis and dissemination. One related to renewable energy and another related to carbon capture infrastructure. The case of renewable energy implementation is analysed in this section in the context of hydrogen production systems powered by renewable energy. The second case on carbon infrastructure includes insights into recent regional projects. The one-pagers for each case can be found in the appendixes of this report.

5.1.1. Renewable energy implementation

The use of renewable energy is key in all sectors. Symbiosis projects around the utilisation of renewable energies in the AIDRES sector were analysed.

More specific cases are related to using renewable energy to power electrolysers for hydrogen production. Hydrogen as an energy carrier promises multiple applications in processes where electricity cannot be used. Electrolysis infrastructure can be at onsite and cluster levels but also at national or regional (EU) levels, leading to multiple options for infrastructure planning. A key factor in the hydrogen economy is oxygen production as a by-product, stimulating the oxyfuels process and CCU-S cases because it affects both CAPEX and OPEX of carbon capture infrastructure [8].

One of the main drivers behind the potential of renewable energy demand is the electrification of industries. More specifically for onsite and shared electricity production, storage, and distribution infrastructure at a cluster level. Also, virtual power plants and Power Purchase Agreements bring additional options triggering flexibility in an industrial cluster, incentives for retrofitting and implementing hybrid technologies [13].

There are key challenges for the case that need to be addressed [13]:

- Competitive price of electricity against other carriers
- Capital investment needs
- Technical complexity
- ROI conflicts with current assets

However, reports highlight carbon pricing, reducing electricity taxation, cross-sector collaboration, and technology-supporting schemes as enablers [13].

5.1.2. Carbon Capture and Utilisation/Storage

Capturing and storage or utilisation of carbon is the second generic case included for symbiosis, as most sector associations acknowledge the need for storage of CO_2 to meet their climate targets. Currently, there is a political debate about carbon utilisation as a reduction strategy due to the complex traceability of emissions and the required long-term sequestration. Such pathways are critical when process emissions cannot be avoided in improved production routes (such as cement, glass, or ammonia production). Current barriers to implementation are *i.e.,* costs associated with capturing depending on the purity of the CO_2 stream, CO_2 transport infrastructure and geological factors associated with carbon storage. Therefore, the focus of the case is the infrastructure for capturing, purifying and other logistical aspects.The Port of Rotterdam offers an excellent example of potential clustering for CCS (Figure 16). The Porthos project aims to enable the transport of CO_2 from industry in the port and store it in empty gas fields in the North Sea [13]. A shared pipeline will run through heavy-industry refineries and hydrogen producers, transporting CO_2 to a compressor station. The compressed gas will be sent to an offshore platform to be pumped to empty gas fields 3km beneath the North Sea seabed. The project is expected to store 2.5 Mt of CO_2 per year, equivalent to 10% of the total emissions produced by the industrial sector in Rotterdam. The project has an expected investment of around half a billion euros, having the first storage by the end of 2024.

Figure 16 Porthos project map - CCS from the Port of Rotterdam

A more specific case of carbon utilisation is the production of methanol from CO_2 and H_2 as an integrated hub with electrolysis [8]. Such a case has multiple reinforcing synergies. Hydrogen can be used as feedstock for fuel production (Figure 17). Also, during the production of hydrogen, oxygen is released as a by-product that can be used to lower the dilution of CO_2 streams in cement or steel manufacturing, reducing the cost of carbon capture infrastructure.

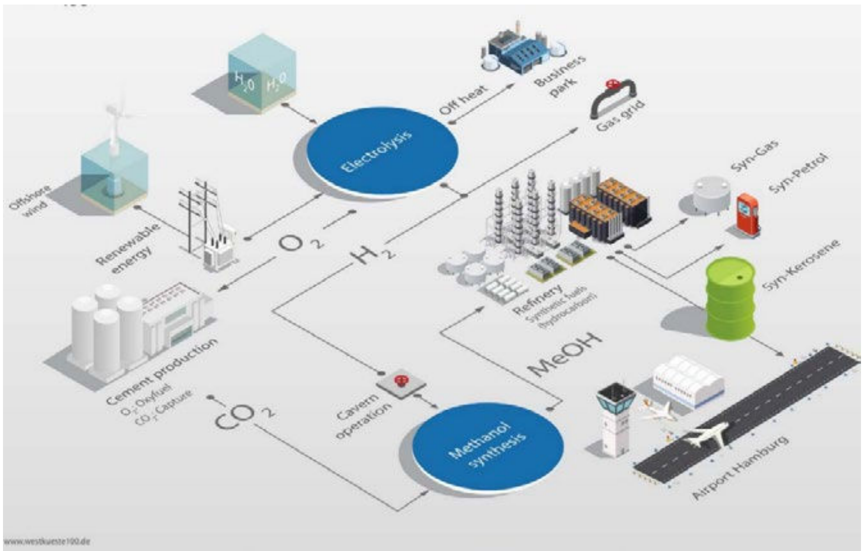

Figure 17 Green hydrogen hub (Holcim report 2021)

The AIDRES sectors have installations across 416 NUTS3 regions in Europe. The region with the highest output is BE211 (Port of Antwerp-Bruges in Belgium), with 59 Mt/y producing mainly refinery products and chemicals, laying the ground for further exploration of symbiosis.

5.1.3. Modes of industrial symbiosis in clusters

Two types of synergies were defined according to academic literature:

- Mutualisation symbiosis with focus on infrastructure
- Exchange symbiosis with focus on energy and material flows

Mutualisation of infrastructure per region (scaling function)

Mutualisation is common to all sectors as it covers processes present in the production routes of most products considered:

- CO_2 capture units
- Electrolysers (H_2, O_2)-> market vs internal production

The key output of the synergy is CAPEX reduction due to economies of scale, as the joint infrastructure has a higher processing capacity (Figure 18).

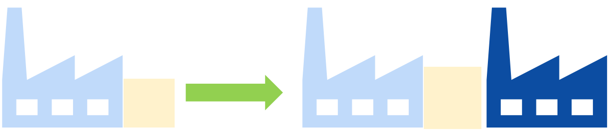

Figure 18 Industrial symbiosis by a mutualisation of (new) infrastructure

Exchange of resources per region (input-output substitution)

Resource exchange is a type of symbiosis that uses selected by-products for exchange in current and future production routes for the several industrial sectors (Figure 19). The case applies to the use of alternative fuels and materials, substituting raw materials.

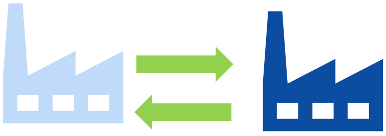

Figure 19 Industrial symbiosis by exchange of by-products across sectors

5.2. Clustering and selection methods

This section explains the method of selecting and ranking clusters to explore their potential for industrial symbiosis using the AIDRES database. In the first step, geographical clustering is based on the distance between sites, sector diversity conditions and NUTS3 boundaries. In a second step, the clusters are indexed according to their potential to IS, and then analysed to verify such potential beyond the index.

Step 1: Cluster database

Clustering analysis is done to identify the clusters present within a NUTS3 region (average equivalent radio of 39 km) based on a maximal distance of 15 km for at least two sites (DBSCAN in ArcGIS) which is especially suitable for industrial symbiosis [14], [15]. This method sets constraints on how to cluster, leading to the identification of clusters of multiple geometries. Resulting clusters coincide with recent studies related to the location of large carbon emitters [16].

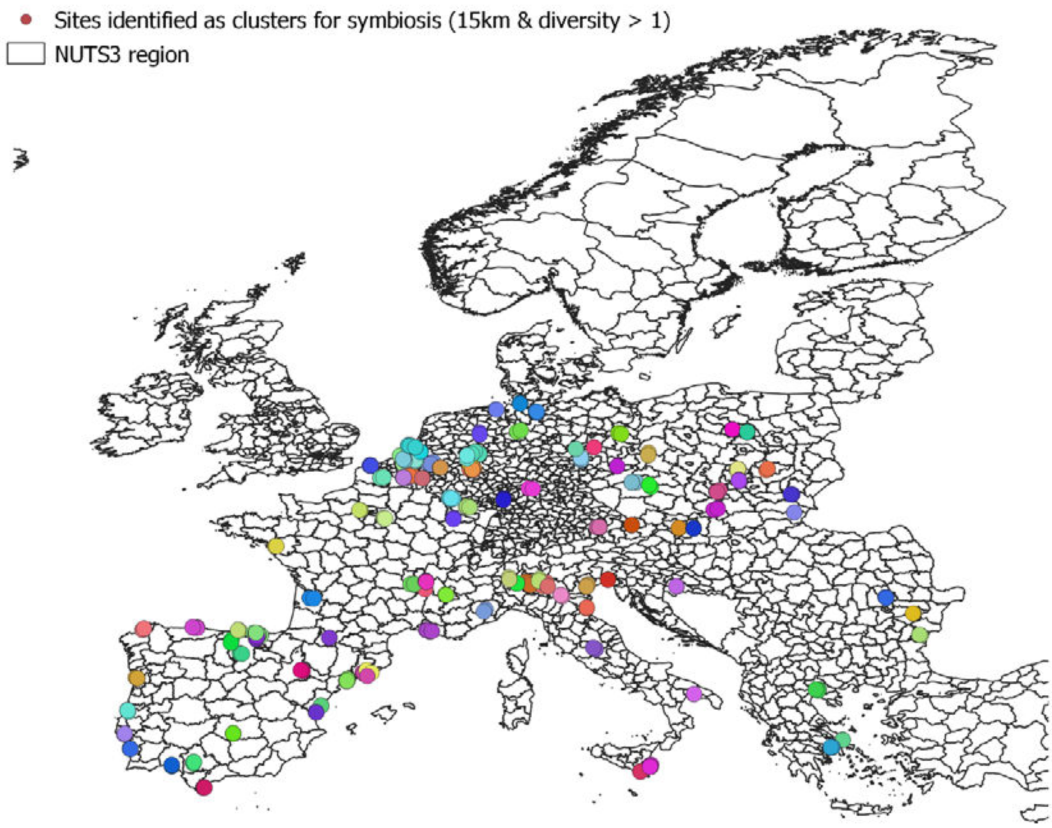

Figure 20 Clusters within NUTS3 regions, ensuring each clustered site with a 15 km distance to at least another site.

Step 2: Ranking of clusters and analysis (UGent based on doctoral research)

The resulting clusters are ranked considering their regional production capacity and the diversity of sectors integrated into an adapted index for industrial symbiosis (Figure 20) related to existing literature [17], [18].

- The production capacity is considered a solid reference for ranking, given the goal of the AIDRES project to transition the current industrial ecosystem (with fixed production capacities) towards low carbon and net zero economies.
- Economies of scale and scope drive symbiosis [19]. Economies of scale increase the symbiosis potential due to the volume of resources available, meaning that the larger the production site, the higher the possibilities to develop economies of scale in symbiosis. Economies of scope increase the symbiosis potential based on the diversity of industries in a region, opening a range of options for valorisation of waste and by-products. Based on economies of scale, the potential for symbiosis is relatively higher in regions with higher production. On the other hand, economies of scope can develop in regions producing a diverse output (multiple sectors) [20].

Equation 1 IS index for clusters

$$\boldsymbol{IS\ index\ for\ cluster\ i} = \sum_{sector\ j}^{n_i} \frac{\boldsymbol{Cluster\ production_j}}{\boldsymbol{Max\ production_j}}$$

$$Cluster\ production_j = Production\ (kt) of\ sector\ j\ in\ cluster\ i$$

$$Max\ production_j = Highest\ production\ (kt)\ of\ sector\ j\ accros\ all\ clusters$$

$$n_i = number\ of\ sectors\ in\ cluster\ i$$

Highlights of the initial selection of clusters (full ranking available in Appendix B)

- Distance threshold.
  - Minimum two AIDRES sectors sites with a maximum distance of 15 km -> scale change to clusters instead of NUTS3.
- High production volume
  - From the six sites with the highest production capacity/rate per sector, expect for the largest cement site, due to the lack of appropriate sites for clustering in the region.
- Systematic NUTS3 assessment.
  - Clusters allocated to single NUTS3 regions.
  - All regions assessed to identify clusters.
- Balance of sector diversity.
  - The best balance of sector diversity with production capacity.
    - Ranking to focus on best-balanced clusters.
    - According to the IS index applied to all clusters.

Remarks:

- Geographically defined clusters are split when NUTS3 boundaries are present. It implies not only that clusters are smaller than geographically expected, but it might also affect its diversity (less sectors present in the cluster). However, only six regions have more than one cluster, and all of them are outside the scope of our selected clusters (highest IS index). This means that in the scope of AIDRES, the regional and industrial cluster analyses are equivalent.
- The used clustering approach only considers the maximum distance between two individual sites, leaving the distance between any two points of the same cluster open. This leads to clusters with sites that are over 15km apart, if the shape of the cluster is longitudinal (e.g., harbour of Rotterdam). This should not be an issue since linear clusters are also considered geographical hubs, if the maximum distance between any site within this type of cluster is in the range of 8-31 km.
- When applying the index to a cluster database with a maximum distance of 33 km between two sites, the ranking excludes clusters in Italy, Germany, Spain, and Slovakia. However, it includes two clusters in Poland (PL524, PL722), one in Portugal (PT170) and one in the Czech Republic (CZ042), primarily because of involving more cement sites. It is, however, recommended to keep the 15 km as clustering parameter because the maximum resulting distance between the two most separated sites in a cluster can reach over 30 km (Table 1). Such distance might be unfeasible for some shared infrastructure cases. However, for other cases such as by-product exchange in cement and steel sectors, an economical resource exchange distance could reach over 30 km.

- The average area of the NUTS 3 regions varies between countries, with an average size close to the equivalent area of a 15 km radius for Belgium, Netherlands, and Germany. Whereas in e.g.: Sweden and Finland larger average areas for NUTS3 regions are applicable.
- Critical sectors are left out for clustering and symbiosis purposes (energy production, urban centres, etc.). However, the same method can be used to further expand the scope of symbiosis..

In order to have a better representation of the EU, an additional four clusters were added to the top 15 of the lists:

Table 1 AIDRES selected industrial region menu for IS use cases of the AIDRES database

Rank	ID	NUSTS 3	Country	Description	Cement	Chemical	Fertilisers	Glass	Refineries	Steel	Max d (km)
1	c34	BE211	Belgium	Arr. Antwerpen, Belgium		16,165	1,062		42,416		15.4
2	c226	BE323	Belgium	Arrondissement of Mons	1,374	134	2,100	202			15
3	c38	NL341	Netherlands	Zeeuwsch-Vlaanderen, the Netherlands		3,295	7,100				8
4	c48	ES120	Spain	Asturias	944		715	240		4,911	17.1
5	c177	ITC47	Italy	Brescia	1,451					4,745	30.5
6	c4	FRL04	France	Port regions of Bouches-du-Rhône	273	2,177			26,842	4,861	21.3
7	c194	DE409	Germany	Märkisch-Oderland	1,894			134			9.7
8	c133	ES213	Spain	Vizcaya/Bizkaia	1,262			75	11,000	2,402	30.6
9	c94	NL33C	Netherlands	Groot-Rijnmond, Netherlands		1,340			56,200		24.8
10	c205	ES511	Spain	Barcelona	1,564	134		149		1,319	24.7
11	c28	LU000	Luxemburg	Luxemburg	952			439		2,327	13.9
12	c219	PT16F	Portugal	Região de Leiria, Portugal	20			1,155			8.7
13	c220	DEA12	Germany	Duisburg, Kreisfreie Stadt, Germany		43				12,849	14.2
14	c174	SK022	Slovakia	Trenčín Region	1,300			291			16.7
15	c62	DEA23	Germany	Cologne at the Rin river		4,321	1,647	311	9,250		27.9
19	**c202**	**PL224**	**Poland**	**Częstochowski, Śląskie, Poland**	**493**			**591**		**800**	**11.5**
20	**c114**	**EL642**	**Greece**	**Euboea, Central Greece, Greece**	**1,529**		**165**				**1.7**
30	**c129**	**BG331**	**Bulgaria**	**Varna, Bulgaria**	**1,092**		**405**				**6.1**
72	**c55**	**RO312**	**Rumania**	**Călărași Rumania**				**193**		**281**	**2.2**

It can be noticed that there are no Nordic clusters included. This is due to multiple factors:

- Scope of EII sectors in AIDRES (limited to 6 sectors)
- Size of EII industries in Nordic countries (AIDRES focus on mostly large installations)
- Cross-sectoral diversity (different AIDRES sectors must be present in the same cluster)

The cluster list represents recommended options to quantify the industrial symbiosis potential, i.e., the IS use case of the AIDRES database (section 4 in this report). Additional sectors and parameters in the clustering algorithm can be added or changed to develop new IS scenarios [21].

6. AIDRES database for IS impact (use cases)

Using the AIDRES database (WP1), we analyse regions with a high potential for IS in terms of energy and emissions for the AIDRES reference routes and the AIDRES EU mix routes 2050 for all sectors, including the quantification of critical resources for symbiosis (captured CO_2 for mutualisation of infrastructure). Building on such analysis, we expand the symbiosis options by making use of the IS database and the EPOS IS generic cases, together with a qualitative analysis of the potential impact at a cluster level (Figure 21 IS use case based on the AIDRES database).

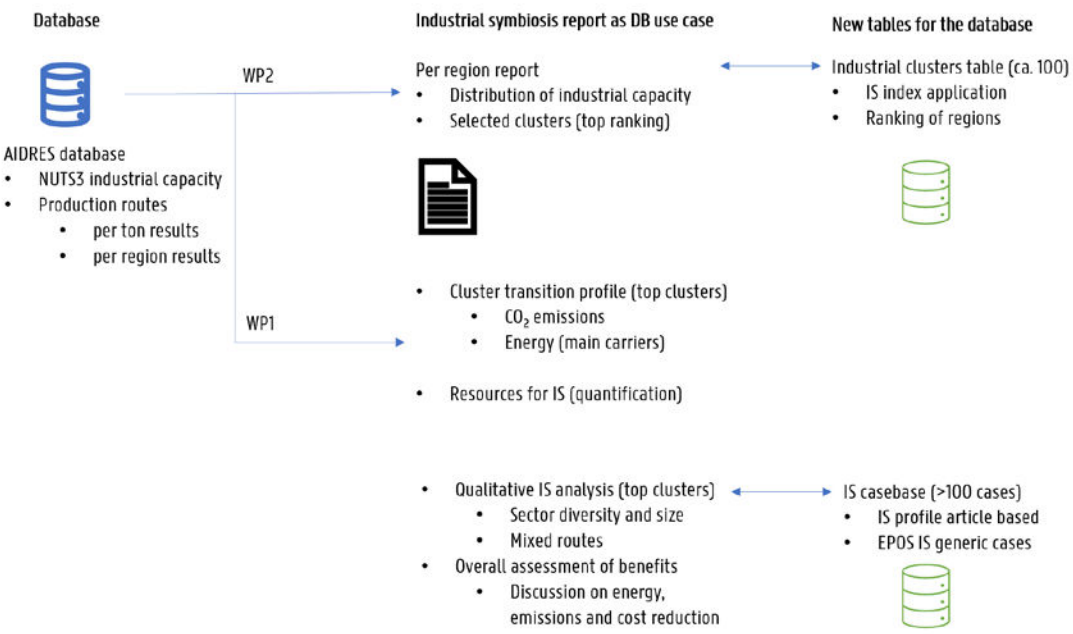

Figure 21 IS use case based on the AIDRES database

Industrial symbiosis in clusters is considered to cover at least one of the following benefit categories:

- Lower energy carriers need (energy per year)
- Lower raw materials need (tonnes per year)
  - e.g., Steel slag in cement, captured CO_2 for eFuels production
- Lower CO_2 emissions (tonnes per year)
- Lower TOTEX (OPEX+ annualised CAPEX)

Reducing resources or emissions in symbiosis is the product of process integration across industrial sectors. The baseline for such reduction refers to the sites without integration aggregating resources and emissions individually, which can be compared with the resource or emissions profile of the same sites in symbiosis.

Lower energy and material carriers refer to reusing alternative materials from other sectors. In the case of energy, it is an equivalence in energy units or an indicator based on the lower heating value of the carrier. In the case of materials, it is an equivalence in mass units or an indicator based on a specific chemical property of the stream.

Finally, the reduction of CO_2 emissions can be broken down into scope 1 (direct onsite emissions), scope 2 (indirect emissions related to energy) and scope 3 (other indirect emissions) symbiosis, depending on the scope of reduction. Scope 1 symbiosis may refer to carbon capture when emissions are prevented from being emitted at the site; this can be a way to mitigate when, e.g., emissions are phased out of scope 1 to scope 2 or 3. It can be a way to eliminate by e.g., reducing or eliminating emission sources or long-term storage of carbon emissions. Scope 2 symbiosis refers to energy exchanges that reduce energy-related emissions outside the production site (utilities), which is especially relevant in the case of heat integration networks. Scope 3 symbiosis refers to reducing emissions in the supply chain, upstream raw materials and downstream (end-consumption and disposal). This is of critical relevance for cases of material and by-product exchange, where emissions related to the extraction and processing of raw material are avoided.

In scope 1 symbiosis, refining and chemical sectors typically include production routes with CO_2 inputs (AIDRES scope) and is highlighted for these routes. In scope 2 symbiosis, excess heat availability is considered for heat integration and electricity production in the clusters, leading to lower electricity demand and scope 2 emissions. In terms of scope 3 emissions, the assumption of avoided emission due to the substitution of raw material is outside the scope of the AIDRES project.

In order to give an overview of the IS impact, a qualitative overview was performed (Table 2). The impact refers to the comparison between the cluster with AIDRES EU mix routes 2050 and the same cluster adding symbiosis options. The expected impact can be reduction, increase, or neutral. As a result, a reduction is the utilisation of fewer resources or enabling fewer emissions. An increase refers to the possibility of increasing resource consumption due to symbiosis. A neutral impact refers to the possibility of enabling a symbiosis without apparent impact on a specific indicator. The initial hypothesis is that the indicators may have a reduction due to the symbiosis opportunities in the cluster.

Table 2 expected qualitative impact template for clusters

Indicator	Expected IS impact	Reasoning
TOTEX		
Energy		
Raw materials		
CO_2 emissions		

6.1. Use cases for selected clusters

This section illustrates use cases for mutualisation and exchange symbiosis for five selected clusters in Europe.

Each cluster case includes:

- Cluster description (location, sector diversity and size).
- Cluster transition (comparison of energy demand and emissions indicators between refence 2018 and AIDRES EU mix routes 2050).
- Qualitative analysis of symbiosis and expected impact on the cluster.

The cluster analyses start with a selected region based on the criteria for symbiosis, showing potential for symbiosis (clustering parameters and IS index). As a reality check, the region is illustrated on a map, including an indication of the production capacities of different sectors and the location of cities nearby. The AIDRES database is used to generate such maps.

Next, the clusters are characterised by their energy demand and carbon emissions profiles based on the AIDRES database. Filters in the database allow the focus on baseline information of the sector in terms of time (2018) and production routes. Such information is the baseline to analyse the transition in the cluster.

Figure 22 Five-step method to obtain analyse of the impact of clusters based on the AIDRES database

Filters also allow focus on the 2050 time horizon in 4 scenarios, variation of energy prices, emissions on energy carriers and future production routes for each product in the sectors. The AIDRES database contains from 1 to 12 different routes for a single product depending on the sector. There is also the option to choose AIDRES EU mix routes 2050 containing multiple routes' energy and material profiles to achieve a reduction target in direct emissions. In order to deal with the uncertainty of the transition to 2050, the AIDRES EU mix routes are used in the cluster cases together with scenario 5. Energy and direct emission variations do not depend on the selected scenario, the scenario is only relevant for total emissions. The database user can tailor a cluster case for specific routes instead of AIDRES EU mix routes to explore more specific transitions across different scenarios, that is different energy carrier prices.

Table 3 Selection of routes for the cluster use cases of the AIDRES database

Sector	Product	Selected route in clusters
Cement	Portland Cement II, LC3	AIDRES EU Mix routes 2050
Chemical	Olefins, Polyethylene, PolyEthylAcetate	AIDRES EU Mix routes 2050
Fertiliser	Ammonia, Urea, Nitric-Acid	AIDRES EU Mix routes 2050
Glass	Flat, Container, Fibre glass	AIDRES EU Mix routes 2050
Refinery	Light Liquid Fuel	AIDRES EU Mix routes 2050
Steel	Primary, Secondary Steel	AIDRES EU Mix routes 2050

The purpose of the selected routes is to illustrate the use of the AIDRES database and are not intended to be recommended pathways for the cluster. The AIDRES databases contain multiple routes for each sector in each cluster. Further exploration of the AIDRES databases and their production routes is encouraged to explore other routes for the sectors in any given cluster, obtaining multiple energy profiles for the same cluster.

Based on the sectors present in the cluster and selected routes, the IS case base is filtered to propose critical symbiosis cases. The material or energy flows shared by multiple processing units and sector blueprints (shared layers) are the key focus of symbiosis. The symbiosis options correspond to R1, R2, R3 or R4 circular strategies depending on the synergy case specified between the involved sectors (see Appendix A). The IS use cases for industrial symbiosis utilise the AIDRES database, including the IS case bases and EPOS IS generic cases for selected clusters.

Next, based on the cluster transition needed (changes in energy carriers), additional symbiosis cases are suggested based on the collection of IS generic cases expanded from the EPOS project (APPENDIX C). Finally, a qualitative assessment of the impact of symbiosis on the cluster is presented.

The NUTS3 regions were selected from Table 1 considering a geographical balance, i.e., excluding multiple NUTS3 regions from the same country and trying to cover north, south, central, western, and eastern Europe.

6.1.1. Belgium/Antwerp (id c34/NUTS3 BE211)

This cluster is located in the Port of Antwerp-Bruges, in the Flemish region of Belgium, where chemical, fertiliser and refinery sectors are present. Compared across all EU27 NUTS3 regional production capacities, the BE211 region hosts the largest production of chemicals and a large capacity for oil refining.

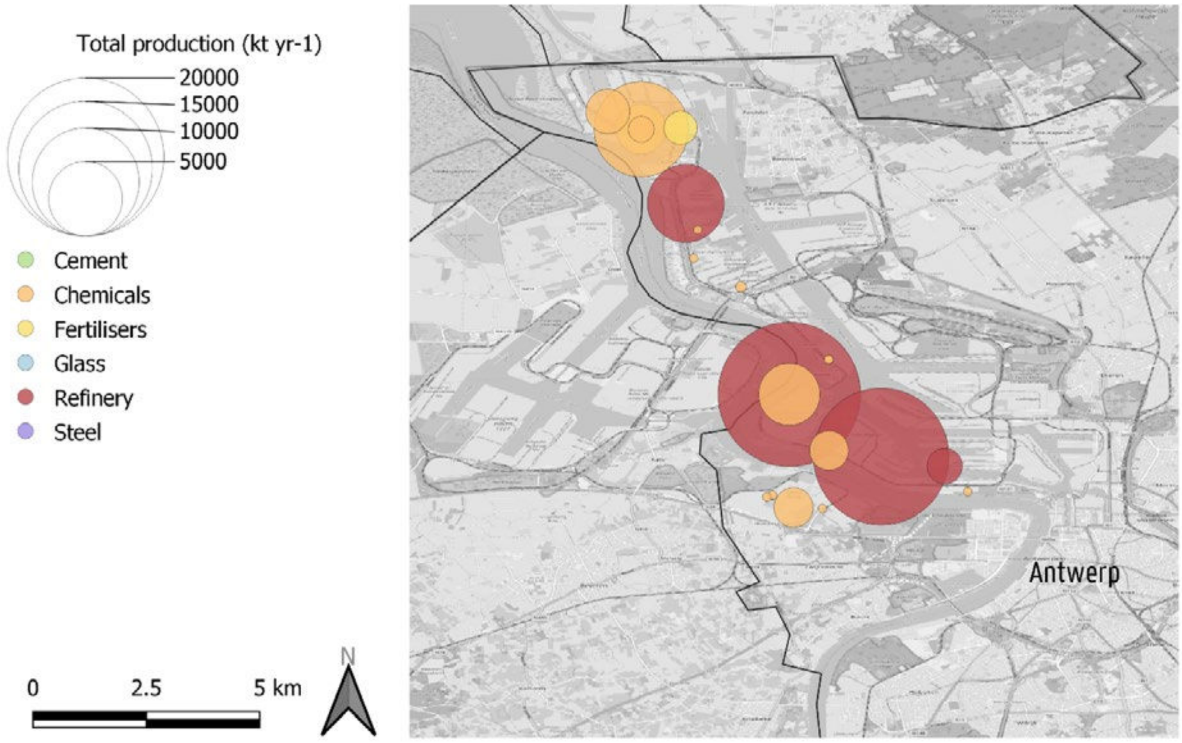

Figure 23 BE211 cluster map shows size and location of the sectors, with refinery and chemical as the major producers.

The AIDRES database provides insights into the region by applying following filter for the reference production route in the AIDRES database.

NUTS3	BE211
is_ref_route	1
scenario_id	0
route_name	(All)

According to the AIDRES database, the refining sector is the largest driver for energy demand carriers in the BE211 cluster. Most energy demand is supplied as crude oil (77%), followed by naphtha (16%) and natural gas (6%). Consequently, the estimated total emissions in the cluster are driven by the refinery sector, but the direct emissions in the cluster are driven by the production of chemicals due to the emission intensity of the process. The AIDRES database provides additional insights on the region by applying following filter for the AIDRES EU Mix 2050 production route in the AIDRES database.

NUTS3	BE211
is_ref_route	0
scenario_id	5
route_name	EU-mix-2050

The EU Mix 2050 for the refining sector implies a reduction of one-third of the production of liquid fuels, leading to a direct reduction in the energy demand and emissions in the BE211 cluster. Comparing the results for the BE211 cluster between the AIDRES reference scenario and the AIDRES EU Mix 2050 scenario, a decrease in energy consumption by 2050 is projected. The implementation of biomass as the leading energy carrier in the cluster will lead to a dramatic reduction in oil consumption, and an increase of twelve times in electricity consumption (Figure 24 B211 cluster energy demand with an overall reduction due to the mixed route 2050 and more even distribution of the demand across energy carriers, minimising the use of fossil fuels (based on AIDRES database).).

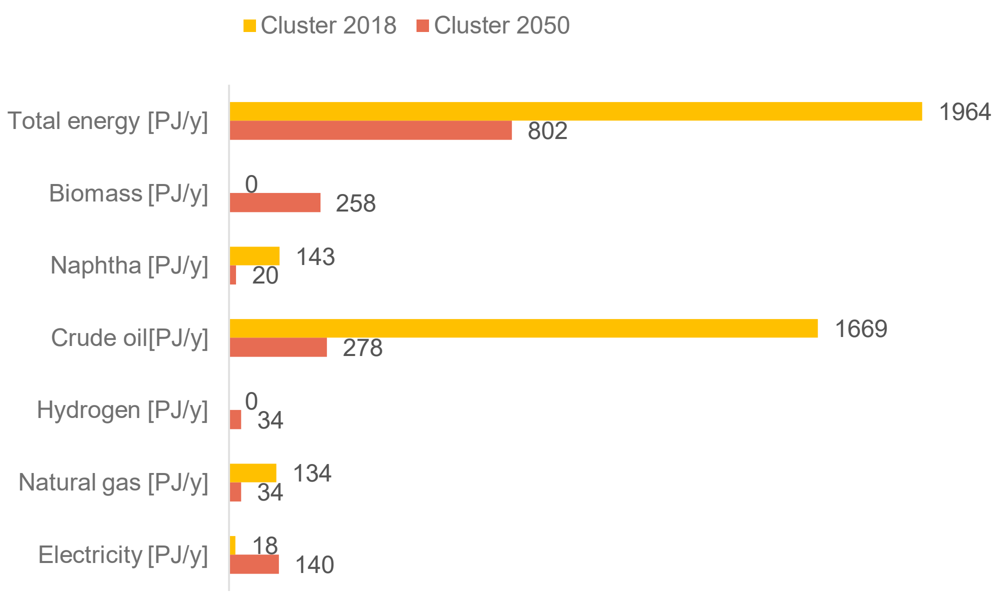

Figure 24 B211 cluster energy demand with an overall reduction due to the mixed route 2050 and more even distribution of the demand across energy carriers, minimising the use of fossil fuels (based on AIDRES database).

The cluster reduces direct emissions by 92%, total emissions reduced 79%, and a carbon capture of 3.4 Mt of CO2/y, mostly in the chemical sector (Figure 25).

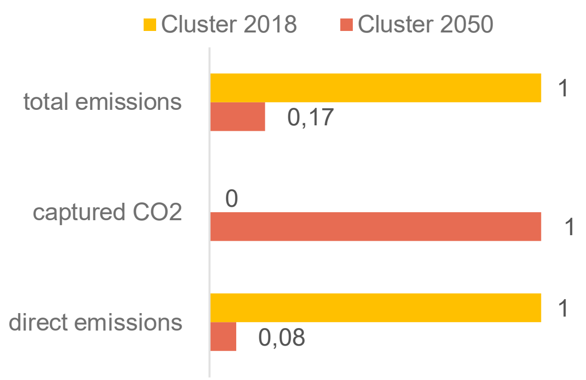

Figure 25 BE211 cluster direct emissions meet the reduction targets with the AIDRES EU mix routes in each sector relative to the reference routes in 2018 based on AIDRES database.

Making use of the IS case-base (Appendix A),the refining sector can provide synergies related to heat and biomass logistics. Considering the size of the refinery operations in the BE211cluster, there is potential to provide heat to other industries or the urban district and the generation of electricity using heat and biomass residues. As a consumer, the refinery sector can use CO_2 as raw material to manufacture e-fuels (available in the AIDRES database). Similarly, the chemical sector can substitute of naphtha with CO_2 from other processes.

Mutualisation of CO_2 logistics infrastructure between the chemical and fertiliser sectors is also an option for the cluster, as in both sectors the selected routes require carbon capture to reach CO_2 reduction targets. Another potential synergy for the cluster is the mutualisation of hydrogen infrastructure, which is relevant for all the sectors present in the cluster. It can go from joint logistics such as purchase, transport, and storage and on-site production (electrolyser).

The EPOS IS generic cases matrix expanded in the scope of the AIDRES project suggests additional options for IS in the cluster, adding options for electric power based on demand-based management options and joint purchase of renewable energy to cope with the electrification required in the cluster (Table 4).

Table 4 EPOS IS generic cases relevant of relevance for the BE211

EPOS IS insights
Shift from coal to electricity-opportunities for flexibility and demand response strategies in the clusters
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf
Opportunities for joint purchase of wind power or infrastructure development
epos_case05.pdf (aspire2050.eu)
High level of water available to develop joint water infrastructure (water networks and joint treatment)
epos_case09.pdf (aspire2050.eu)
epos_case15.pdf (aspire2050.eu)
High level of heat available for the district
epos_case03.pdf (aspire2050.eu)
CO2 upgrade hubs
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case21.pdf
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case16.pdf

Overall, the highest impact for symbiosis in the cluster depends on the evolution of the refining and chemical sectors, mainly related to feedstock needs, excess heat, and demand response options for electric power management. Thanks to the presence of fertilisers, the industrial cluster may also support hydrogen and biomass networks. The impact of symbiosis for the cluster may lead to decreasing TOTEX, energy demand, and raw materials (Table 5) and requires specific information on the production sites for further assessment.

Table 5 Summary of expected qualitative impact in the BE211 cluster

Indicator	Expected IS impact	Reasoning

Energy	Reduction	Synergies for heat waste use and electricity production, assuming no increase in production capacities.
Raw materials	Neutral	Synergies to facilitate the logistic of renewable feedstock (biomass).
CO_2 emissions	Neutral	Synergies related to CO_2 infrastructure facilitate the operations but do not further impact the direct emissions levels. (see section 5.1.2.)
TOTEX	Reduction	The synergies related to biomass, CO_2 and H_2 may reduce costs due to economies of scale and scope.

6.1.2. France/Fos-sur-Mer (id c34/NUTS3 FRL04)

The FRL04 cluster is located in Fos-sur-Mer, about 30 km away from the city of Marseille, in the Port regions of Bouches-du-Rhône of France, with production of cement, chemicals, refinery and steel. Compared across EU27 production capacities, the FRL04 cluster contains large production capacities of chemicals and steel added with a large refining capacity.

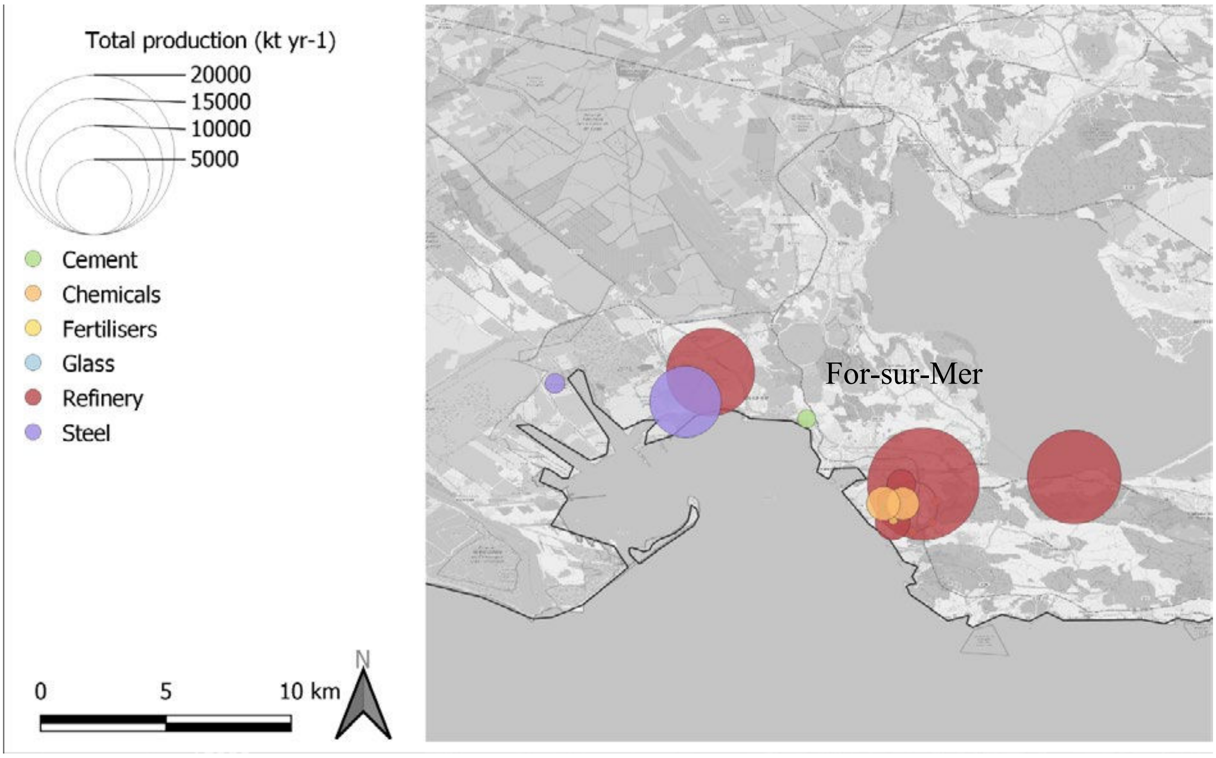

Figure 26 FRL04 cluster map shows size and location of the sectors, with refinery, chemicals and steel as the major producers.

The AIDRES database provides insights into the region by applying following filter for the reference production route in the AIDRES database.

NUTS3	FRL04
is_ref_route	1
scenario_id	0
route_name	(All)

According to the AIDRES database, the refineries drives the demand for energy carriers in the FRL04 cluster. Most energy demand is supplied as crude oil (76%), followed by naphtha (13%) and natural gas (3%). In terms of direct and total emissions in the cluster, the production of steel drives the largest share of emissions. The AIDRES database provides additional insights on the region by applying following filter for the AIDRES EU Mix 2050 production route in the AIDRES database.

NUTS3	FRL04
is_ref_route	0
scenario_id	5
route_name	EU-mix-2050

The AIDRES EU 2050 for the refining sector implies a reduction of one-third of the production of liquid fuels, leading to a direct reduction in the energy demand and emissions in the FRL04 cluster.

Comparing the results for the FRL04 cluster between the AIDRES reference scenario and the AIDRES EU Mix 2050 scenario, there will be a decrease in energy consumption by 2050. The implementation of biomass as one of the leading energy carrier in the cluster will lead to a dramatic reduction in oil consumption, and an increase of about fifteen times in electricity consumption (Figure 27).

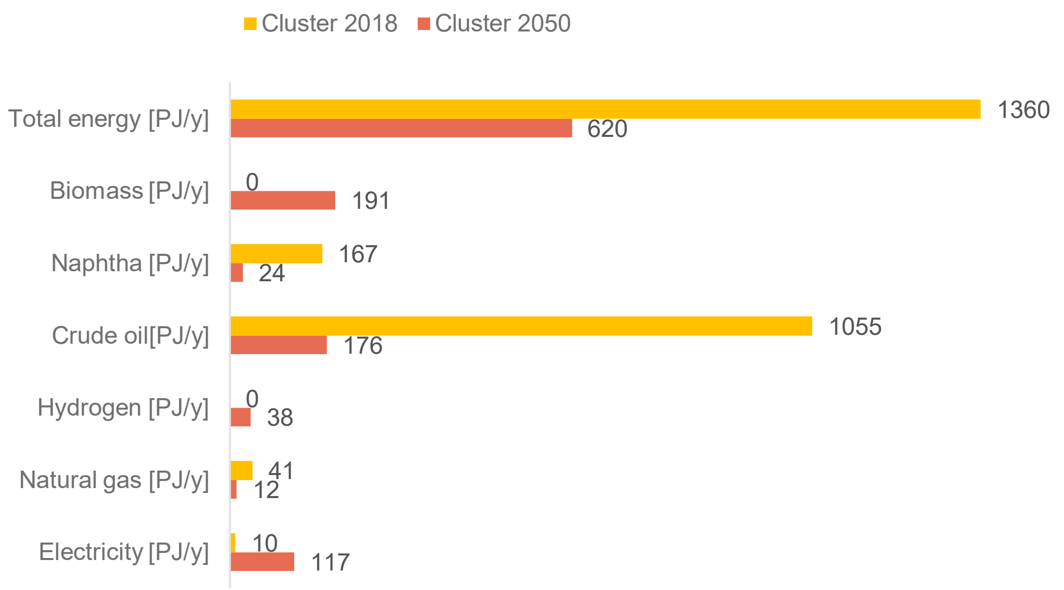

Figure 27 FRL04 cluster energy demand with an overall reduction due to the mixed route 2050 and more even distribution of the demand across energy carriers, minimising the use of fossil fuels (based on AIDRES database).

The cluster reduces direct emissions by 88%, capturing 3.2 Mt of CO_2/y mostly in the steel and chemical sector (Figure 28).

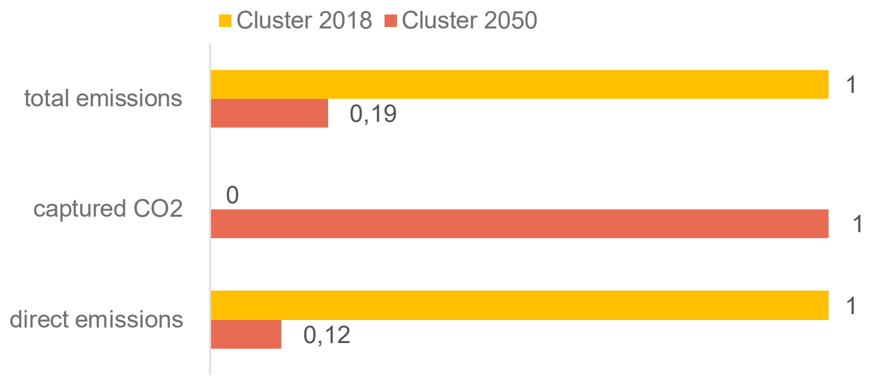

Figure 28 FRL04 cluster direct emissions meet reduction targets with the AIDRES EU mix routes in each sector relative to the reference routes in 2018 based on AIDRES database.

Making use of the IS case-base (Appendix A), the refining sector can provide synergies related to heat and electricity to other sectors. Considering the size of the refinery sites in the FRL04 cluster, there is potential to provide heat to other industries or the urban district and the generation of electricity using heat and biomass residues. As a consumer, the refinery sector can use CO_2 as raw material to manufacture e-fuels (available in the AIDRES database). Similarly, the chemical sector can substitute of naphtha for CO_2 from other processes.

As a supplier, the steel sector can provide heat and slag production to the cement sector. However, due to differences in size between the sectors, there would be much more slag available than needed in the cement sector. Additionally, adjustments in the formulation of cement may be needed as the steel-making processes considered for 2050 are based mostly on the direct reduction route for steel.

Mutualisation of CO_2 logistics infrastructure between the chemical and fertiliser sectors is also an option for the FRL04 cluster, as in both sectors the selected routes require carbon capture to reach CO_2 reduction targets. Another potential synergy for the cluster is the mutualisation of hydrogen infrastructure, which is relevant for all the sectors present in the cluster. It can go from joint logistics such as purchase, transport and storage and on-site production (electrolyser).

The use of biomass in the refining sector combined with the carbon management capabilities in the cluster may lead to pilot projects on negative emissions, combining biomass-powered processes with carbon capture and sequestration capabilities, e.g., in the cement sector.

The EPOS IS generic cases matrix expanded in the scope of the AIDRES project suggests additional options for IS in the cluster, adding options for electric power based on demand-based management options and joint purchase of renewable energy to cope with the electrification required in the cluster (Table 6).

Table 6 EPOS IS generic cases relevant of relevance for the FRL04 cluster

EPOS IS insights
Shift from coal to electricity-opportunities for flexibility and demand response strategies in the clusters
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf
Opportunities for joint purchase of wind power or infrastructure development

epos_case05.pdf (aspire2050.eu)
High level of water available to develop joint water infrastructure (water networks and joint treatment)
epos_case09.pdf (aspire2050.eu)
epos_case15.pdf (aspire2050.eu)
High level of heat available for the district
epos_case03.pdf (aspire2050.eu)
CO_2 upgrade hubs
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case21.pdf
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case16.pdf

Overall, the highest impact for symbiosis in the FRL04 cluster depends on the evolution of the refining, chemical and steel sectors, mainly related to feedstock needs, excess heat, and demand response options for electric power management. Additionally, there is a high potential to support hydrogen and CO_2 networks in the cluster. The impact of symbiosis for the cluster may lead to decreasing TOTEX, energy demand, and raw materials (Table 7), and requires specific information on the production sites for further assessment.

Table 7 Summary of expected qualitative impact in the FRL04 cluster

Indicator	Expected IS impact	Reasoning
Energy	Reduction	Synergies for heat waste use and electricity production, assuming no increase in production capacities.
Raw materials	Reduction	Synergies with slag, substituting other primary materials requiring extraction. Synergies of water networks may reduce the demand for water.
CO_2 emissions	Neutral	Synergies related to CO_2 infrastructure facilitate the operations but do not further impact the direct emissions levels
TOTEX	Reduction	The synergies related to CO_2 and H_2 may reduce costs due to economies of scale and scope.

6.1.3. Spain/Asturias (id c48/NUTS3 ES120)

The ES120 cluster is located in the north of Spain in Aviles, close to Gijon and Oviedo (Figure 29), with the presence of cement, fertiliser, glass and steel sectors. Compared across EU27 NUTS3 regional production capacities, the region contains a large steel site (20% larger than the EU average), a near EU average cement and glass production capacity and a relatively small production capacity of fertilisers.

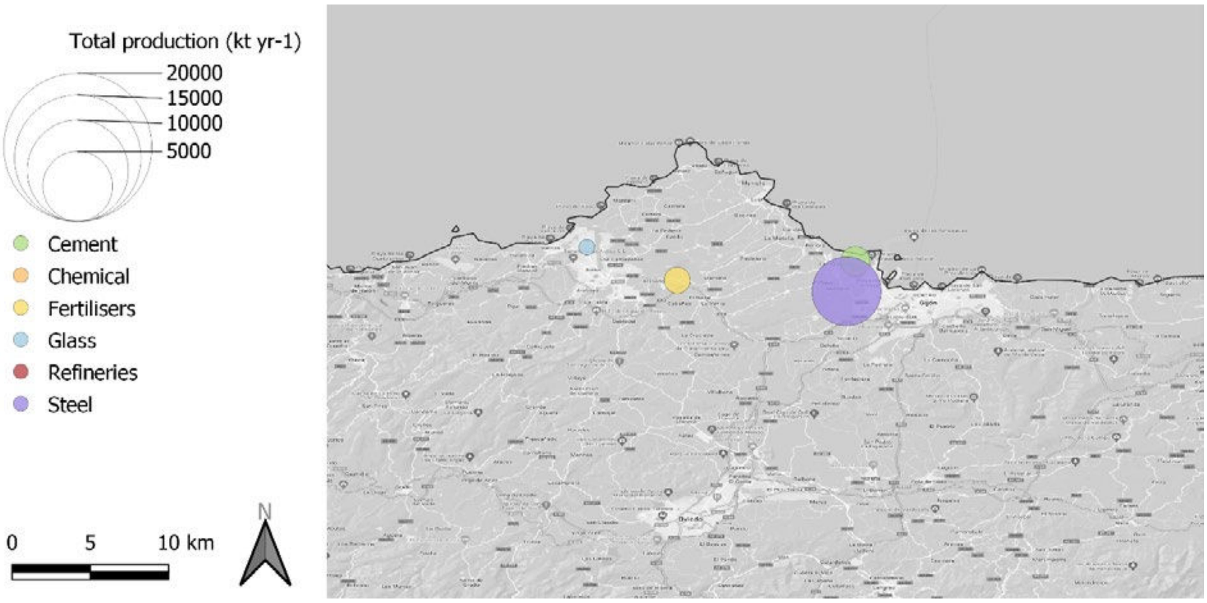

Figure 29 ES120 cluster map shows the size and location of the sectors, with steel as a major producer.

The AIDRES database provides insights into the region by applying following filter for the reference production route in the AIDRES database.

NUTS3	ES120
is_ref_route	1
scenario_id	0
route_name	(All)

According to the AIDRES database, steel production drives the energy demand in the ES120 cluster. Most energy demand is supplied as coal (84%), and minor contributions of natural gas and electricity. Consequently, the direct emissions in the cluster are driven by the steel sector (92%). The AIDRES database provides additional insights on the region based on the AIDRES EU mix routes 2050 by applying the following filter:

NUTS3	ES120
is_ref_route	0
scenario_id	5
route_name	EU-mix-2050

According to the AIDRES database, large reduction in direct carbon emissions depends heavily on the transition of the steel sector in the ES120 cluster, changing the energy mix towards hydrogen. Hydrogen becomes the main energy carrier in the cluster driven by the direct reduction route for steel making. Comparing the results for the cluster between the AIDRES reference scenario and the AIDRES EU Mix 2050 scenario, there is a decrease in energy consumption in the cluster. This is possible due to the switch from coal to hydrogen as the main energy carrier with higher energy efficiency use and also due to a higher level of electrification (increasing the precision in the use of energy) (Figure 30).

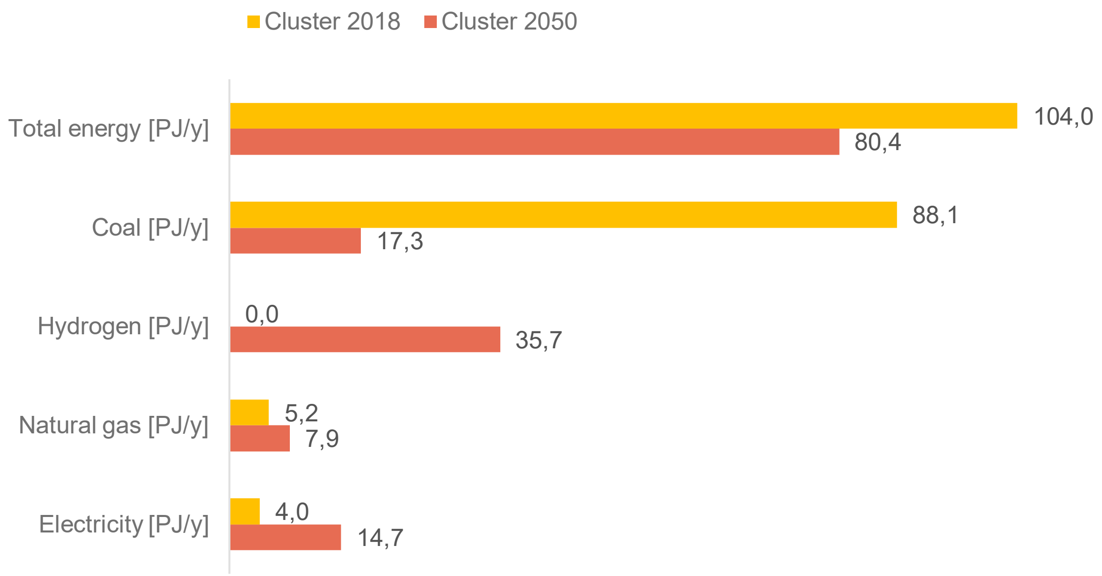

Figure 30 ES120 cluster energy demand with an overall reduction due to the mixed route 2050 and more even distribution of the demand across energy carriers (based on AIDRES database).

In terms of emissions, total emissions were reduced by 86%, direct emissions 87%, and the capture of 1.4 Mt of CO_2/y was mostly in the steel sector (Figure 31).

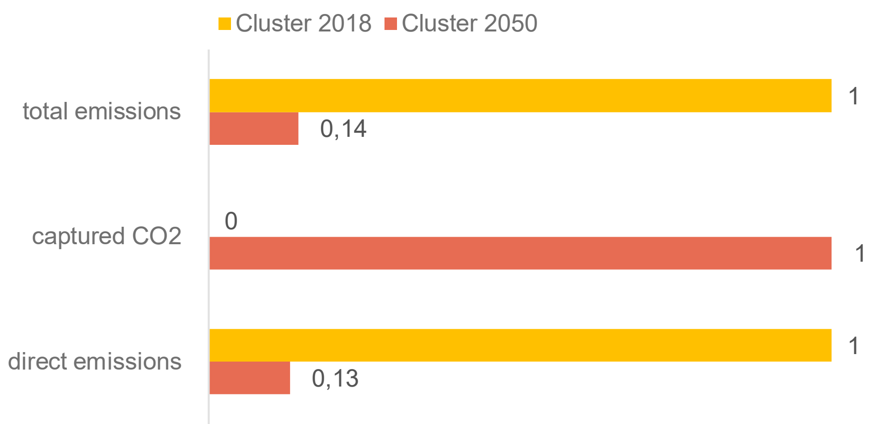

Figure 31 ES120 cluster direct emissions meet the reduction targets with the AIDRES EU mix routes in each sector relative to the reference routes in 2018 based on AIDRES database.

Making use of the IS case-base (Appendix A), the steel sector can provide synergies related to heat and slag production. Considering the size of the steel production sites in the ES120 cluster, there is potential to provide heat to other industries or the urban district and the generation of electricity using heat to other industries or the urban district and the utilisation of slag in the cement sector. On the other hand, the steel sector requires to capture and transport CO_2 generated in the processes and overcapacity in the processing of carbon capture in the steel sector can enable the service of carbon capture for the other sectors, though in a much lower scale.

For the cement sector as a supplier, synergies related to heat and carbon capture with the steel sector are suggested, leading to the recovery of energy, and potentially reducing energy demand and costs. The cement sector as a consumer in symbiosis is expected to reduce traditional synergies such as the use of alternative fuel and modification on the steel slag use, as the quality of slag is expected to change in the new production routes for steel (mainly via the direct reduced iron route or DRI.

The glass and fertiliser sectors are both suppliers and consumers of hydrogen, opening the possibility for joint electrolysers infrastructure. There may also be a business case to involve the steel industry, but additional details of the specific routes selected for the clusters are required.

The EPOS IS generic cases matrix expanded in the scope of the AIDRES project suggests additional options for IS in the cluster, adding options for electric power based on demand based management options and joint purchase of renewable energy to cope with the electrification required in the cluster (Table 8).

Table 8 EPOS IS generic cases relevant of relevance for the ES120 cluster

EPOS IS insights
Shift from coal to electricity-opportunities for flexibility and demand response strategies in the clusters
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf
Opportunities for joint purchase of wind power or infrastructure development
epos_case05.pdf (aspire2050.eu)
High level of carbon capture leading to opportunities
epos_case21.pdf (aspire2050.eu)
epos_case16.pdf (aspire2050.eu)
High level of water available to develop joint water infrastructure (water networks and joint treatment)
epos_case09.pdf (aspire2050.eu)
epos_case15.pdf (aspire2050.eu)
High level of heat available for the district
epos_case03.pdf (aspire2050.eu)

Overall, the highest impact for symbiosis in the ES120 cluster depends on the steel sector, mainly related to overcapacity in carbon capture and logistic infrastructure, excess heat, and demand response options for electric power management. Thanks to the presence of glass and steel sectors, the industrial cluster may also support recycling services for the urban centres nearby. The impact of symbiosis for the cluster may lead to decreasing TOTEX, energy demand, and raw materials ((Table 9), requiring specific information on the production sites for further assessment.

Table 9 Summary of expected qualitative impact in the ES120 cluster

Indicator	Expected IS impact	Reasoning
Energy	Reduction, mostly for cement, glass, and fertiliser sectors	Synergies with energy production.
Raw materials	Reduction, mostly for cement	Synergies with slag, substituting other primary materials requiring extraction.

CO_2 emissions	Neutral	Synergies identified do not lead to additional reductions of emissions in the overall scope of the AIDRES project, but reduce barriers to the implementation of effective climate-neutral strategies in a joint approach. (see section 5.1.2.)
TOTEX	Reduction, mostly for cement, glass, and fertiliser sectors	Synergy with potential over-capacity in the steel sector infrastructure and logistic capacity of the port location.

6.1.4. Poland /Częstochowski cluster (id c202/NUTS3 PL224)

The PL224 cluster is located in the central part of Poland between the cities of Lodz and Katowice (Figure 32), with the presence of cement, glass, and steel sectors. Compared across EU27 NUTS3 regional production capacities, the PL224 region contains a large glass production, average secondary steel production and relatively small cement production.

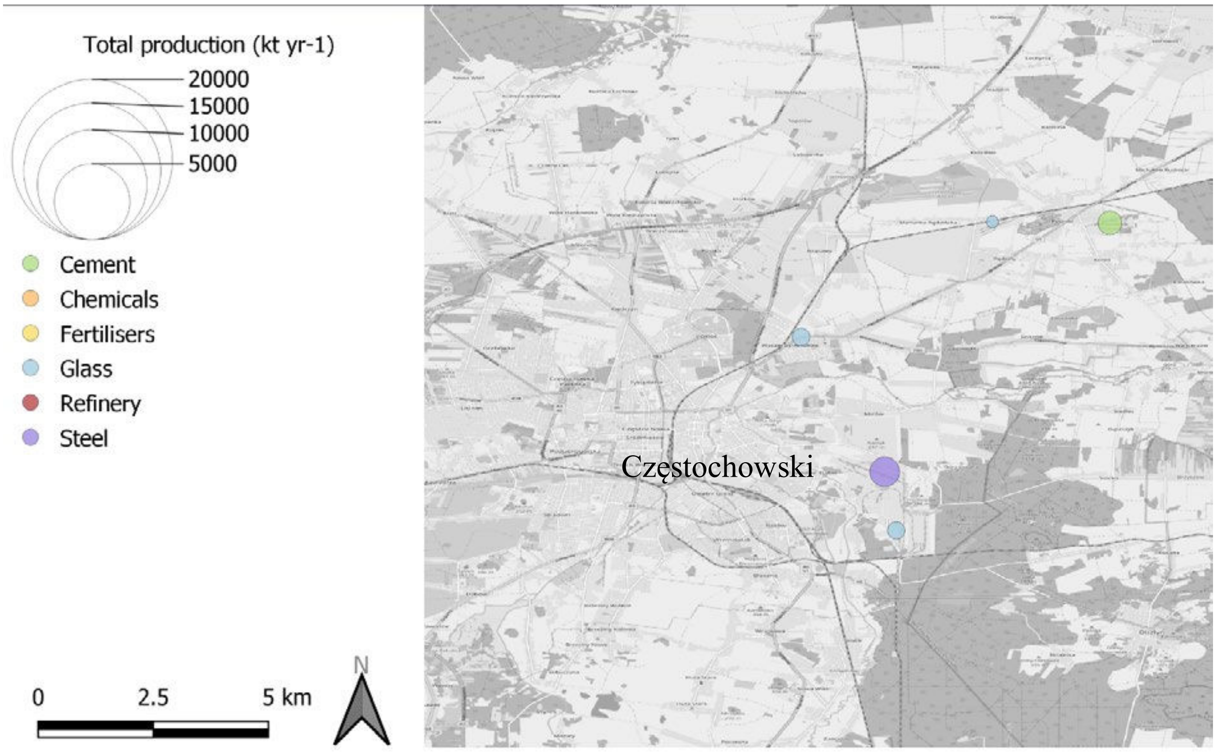

Figure 32 PL224 map shows the size and location of the sectors, with steel and glass as the major producers.

The AIDRES database provides insights into the region by applying following filter for the reference production route in the AIDRES database.

NUTS3	PL224
is_ref_route	1
scenario_id	0
route_name	(All)

According to the AIDRES database, glass production drives the energy demand in the PL224 cluster. Most energy demand is supplied by natural gas (48%) and electricity (30%) due to the secondary production of steel and a minor contribution of coal. However, the direct emissions in the cluster are driven by cement production due to process emissions. The AIDRES database provides insights on the region for AIDRES EU mix route 2050 applying the following filter:

NUTS3	PL224
is_ref_route	0
scenario_id	5
route_name	EU-mix-2050

According to the AIDRES database, the transition to targeted reduction in direct carbon emissions in the cluster depends on the transition of the cement and glass sector, changing the energy mix towards electricity and hydrogen. Electricity becomes the main energy carrier in the cluster, driven by electrification in the glass sector. Comparing the results for the cluster between the AIDRES reference scenario and the AIDRES EU Mix 2050 scenario, there is an increase in energy consumption in the cluster (driven by carbon capture in the cement sector), the implementation of hydrogen, a dramatic reduction in natural gas consumption, and a significant increase in electricity consumption, becoming the main energy carrier in the cluster (Figure 33).

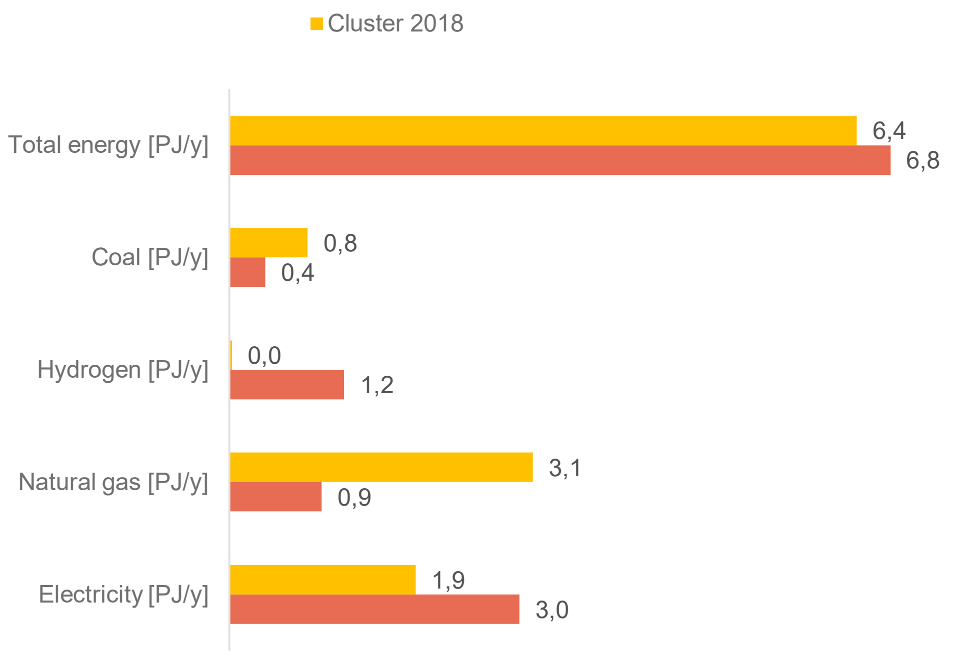

Figure 33 PL224 cluster energy demand with an overall reduction due to the mixed route 2050 and more even distribution of the demand across energy carries based on AIDRES database.

In terms of emissions, the cluster reaches **direct** reduction below 85% (secondary steel sites remain flat as an electrified process), total emissions reduced by 88% and capture of 276 kt of CO_2/y, mainly in the cement sector (Figure 34).

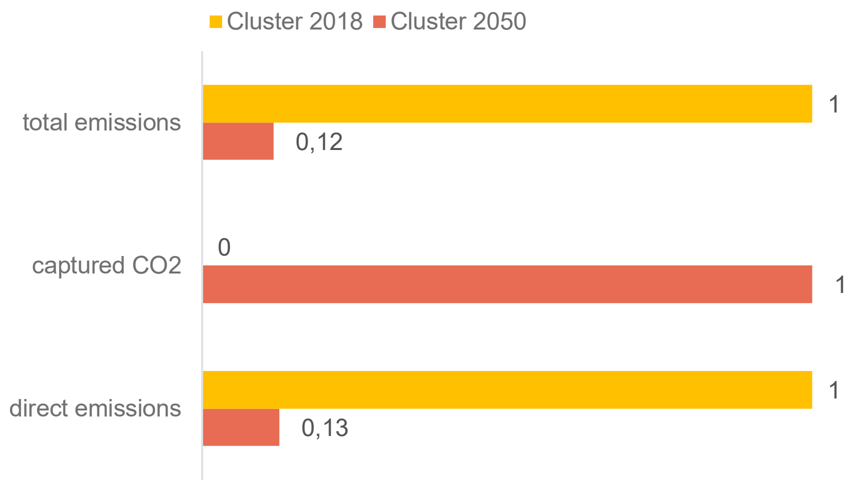

Figure 34 PL224 cluster direct emissions meet the reduction below 85% with the AIDRES EU mix routes in each sector relative to the reference routes in 2018 based on AIDRES database.

Making use of the IS case-base (Appendix A) for the cement sector as a supplier, synergies related to heat and CO_2 are the most prominent ones. This can lead to the recovery of energy, potentially reducing the energy demand and the cost, especially in collaboration with the glass sector in the PL224 cluster. The cement sector as a consumer in symbiosis is expected to reduce traditional synergies such as the use of alternative fuel and modification on the steel slag use, as the quality of slag is expected to change in the new production routes for primary steel. According to the quantitative information on industrial symbiosis, overcapacity in the processing of carbon capture in the cement sector can enable the service of carbon capture for the other industrial sectors at a lower scale in the PL224 cluster.

Synergies between glass and secondary steel are related to the electrification of processes and the potential for the joint generation and purchase of electricity. Using excess heat from glass and cement to produce electricity seems to be an option for symbiosis.

The EPOS IS generic cases matrix expanded in the scope of the AIDRES project suggests additional options for IS in the cluster, adding options for electric power based on demand-based management options and joint purchase of renewable energy to cope with the electrification required in the cluster (Table 10).

Table 10 EPOS IS generic cases relevant of relevance for the PL224 cluster

IS insights
Shift from coal to electricity-opportunities for flexibility and demand response strategies in the clusters
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf
High level of carbon capture leading to opportunities
epos_case21.pdf (aspire2050.eu)
epos_case16.pdf (aspire2050.eu)
High level of water available to develop joint water infrastructure (water networks and joint treatment)
epos_case09.pdf (aspire2050.eu)
epos_case15.pdf (aspire2050.eu)

Overall, the highest impact for symbiosis in the PL224 cluster depends on the cement and glass sector, mainly related to overcapacity in carbon capture and logistic infrastructure, excess heat, and demand response options for electric power management. Thanks to the presence of glass and secondary steel, the industrial **cluster supports recycling services for the urban centres nearby**. The impact of symbiosis for the cluster may lead to decreasing TOTEX and energy demand (Table 11), requiring specific information on the production sites for further assessment.

Table 11 Summary of expected qualitative impact in the PL224 cluster

Indicator	Expected IS impact	Reasoning
Energy	Reduction	Synergies for electricity production based on excess heat.
Raw materials	Reduction	Synergies with recycling networks of glass and steel may increase recycling rates reducing the primary raw material consumption.
CO_2 emissions	Neutral	The synergies identified do not lead to additional reductions of emissions in the scope of the AIDRES project
TOTEX	Reduction	The synergies are related to the mutualisation of logistic infrastructure for recycling inputs and CO_2.

6.1.5. Bulgaria/Varna (id c129/NUTS3 BG331)

The BG331 cluster is located in the east of Bulgaria, close to Varna (Figure 35), with the presence of cement and fertiliser sectors. Compared across NUTS3 regional production capacities, the region contains an average cement site and a small fertiliser site.

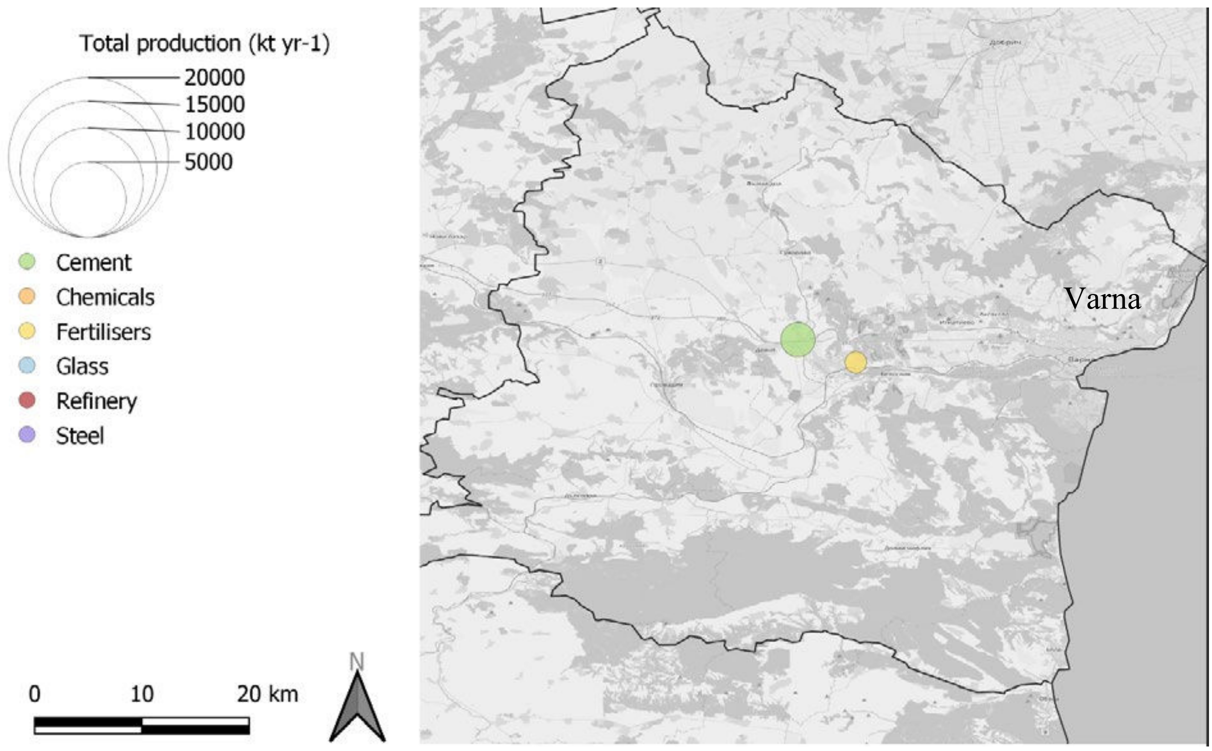

Figure 35 BG331 cluster map shows the size and location of the sectors, with cement as the major producer.

The AIDRES database provides insights into the region by applying following filter for the reference production route in the AIDRES database.

NUTS3	BG331
is_ref_route	1
scenario_id	0
route_name	(All)

According to the AIDRES database, fertiliser production drives the energy demand in the cluster. Most energy demand is supplied by natural gas (70%) and minor contributions of coal and electricity. Consequently, the direct emissions in the cluster are balanced between fertilisers and cement production, both having process emissions. The AIDRES database provides additional insights on the region based on the AIDRES EU mix routes 2050 by applying the following filter:

NUTS3	BG331
is_ref_route	0
scenario_id	5
route_name	EU-mix-2050

According to the AIDRES database, the transition towards the reduction targets in direct carbon emissions depend on the transition of the fertiliser and cement sectors, changing the energy mix towards electrification of fertiliser production. Hydrogen becomes the main energy carrier in the cluster used for fertilisers production (all from the market, no electrolysis used in the industries). Comparing the results for the cluster between the AIDRES reference scenario and the AIDRES EU Mix 2050 scenario, there is an increase in energy consumption in the BG331 cluster (mainly in the cement sector due to carbon capture), the implementation of hydrogen as the main energy carrier in the cluster, a dramatic reduction in natural gas consumption, and an increase in electricity consumption (Figure 36).

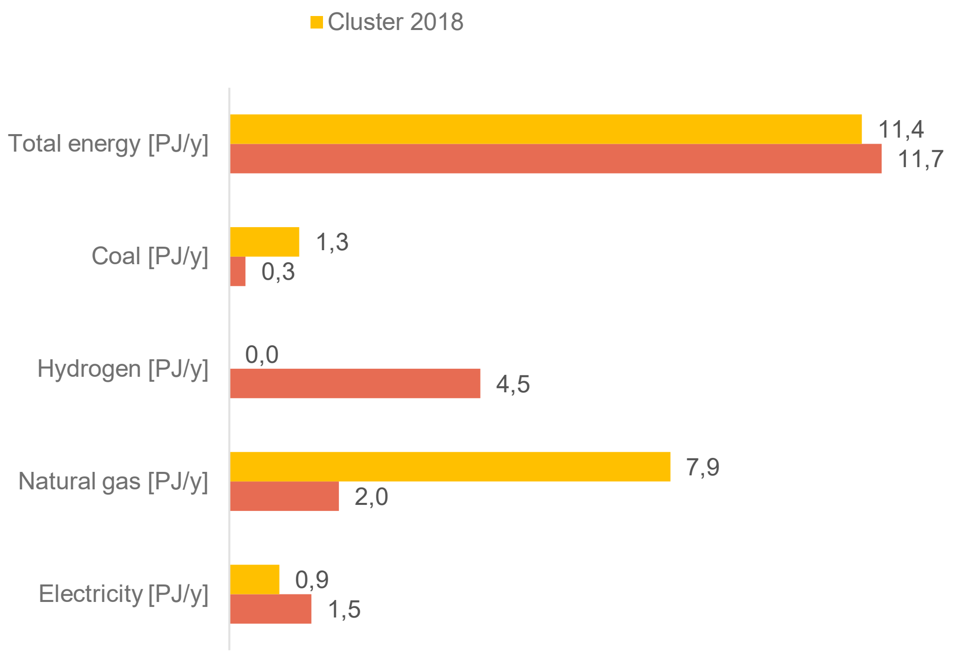

Figure 36 BG331 cluster energy demand with an overall increase due to the mixed route 2050 and more even distribution of the demand across energy carriers (based on AIDRES database).

In terms of emissions, the cluster meets the direct emissions reduction of 95%. Total emissions were reduced by 94%, with a capture of 647 kt of CO2/y in the cement sector (Figure 31).

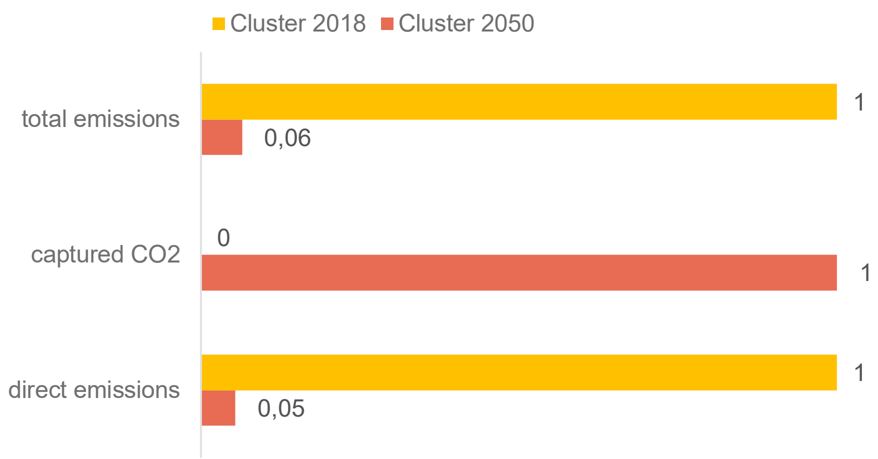

Figure 37 BG331 cluster direct emissions meet the reduction targets with the AIDRES EU mix routes in each sector relative to the reference routes in 2018 (from AIDRES database).

Making use of the IS case base (Appendix A) for the cement sector as a supplier synergies related to heat and carbon capture with the fertiliser sector are suggested, leading to the recovery of energy, potentially reducing the energy demand and costs. As a consumer, the sector requires alternative fuel gases that may be provided by fertiliser production (biomass use). Cement and fertiliser production routes require to capture and transport their CO_2. Thus, the mutualisation of infrastructure related to CO_2 may be an enabler towards carbon neutrality. The EPOS IS generic cases matrix expanded in the scope of the AIDRES project suggests additional options for IS in the cluster, adding options for electric power based on demand-based management options and joint purchase of renewable energy to cope with the electrification required in the cluster (Table 12).

Table 12 EPOS IS generic cases relevant of relevance for the BG331 cluster

EPOS IS insights
Shift from coal to electricity-opportunities for flexibility and demand response strategies in the clusters
https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf
Opportunities for joint purchase of wind and solar power or infrastructure development
epos_case05.pdf (aspire2050.eu)
epos_case07.pdf (aspire2050.eu)
epos_case18.pdf (aspire2050.eu)
High level of carbon capture leading to opportunities
epos_case21.pdf (aspire2050.eu)
epos_case16.pdf (aspire2050.eu)
High level of water available to develop joint water infrastructure (water networks and joint treatment)
epos_case09.pdf (aspire2050.eu)
epos_case15.pdf (aspire2050.eu)
High level of heat available for the district
epos_case03.pdf (aspire2050.eu)

Overall, the highest impact for **symbiosis in the BG331 cluster depends on both the cement and fertiliser sectors**, mainly related to the use of bio-based fuels and the mutualisation of infrastructure for CO_2. Depending on the production routes, the cluster may become a biomass or biomass waste hub for the region. The impact of symbiosis for the cluster may lead to decreasing TOTEX, energy demand, and raw materials (Table 13), requiring specific information on the production sites for further assessment.

Table 13 Summary of expected qualitative impact in the BG331 cluster

Indicator	Expected IS impact	Reasoning
Energy	Reduction	Synergies with energy production based on heat.
Raw materials	Reduction	Synergies related to the potential use of biomass and water reuse.
CO_2 emissions	Neutral	Synergies identified do not lead to additional reductions of emissions in the scope of the AIDRES project but reduce barriers to implementing effective climate-neutral strategies in a joint approach.
TOTEX	Reduction	Synergies related to hydrogen and carbon emissions logistics taking advantage of economies of scale and scope.

7. Concluding remarks and recommendations

The cluster cases showed that the AIDRES database is helpful in the identification and study of the energy transition at the level of industrial clusters. In such a context, industrial symbiosis cases can support the energy transition towards carbon neutrality goals of the different regions.

Due to the high demand for energy and resources, AIDRES industries tend to be located in regions with easy access to large amounts of resources. Regions with the highest potential for symbiosis are often important regional harbours because they can share a common strategy to develop industrial symbiosis. Best practices on logistic strategies for the exchange of waste and by-products are an example of such a strategy, making use of the common advantages and opportunities.

Refining and fertiliser sectors share at least one other AIDRES sector in more than 70% of the regions. Contrastingly, primary steel production and cement exist less frequently in the vicinity of other industries in a NUTS3 regions, with more than 50% having no other AIDRES sector in the same region. However, in reality there might be other, non-AIDRES industrial sectors present. The definition of the NUTS3 regions, instead of a geographical boundary, might also lead to specific cement sites being closer located to other industries. Including additional sectors would improve the potential for symbiosis, especially the power sector, non-ferrous metals, pulp and paper and urban districts.

A recommendation to improve the clustering approach would be a hybrid option combining NUTS3 with geographical clustering, outside the NUTS3 boundary. It is recommended to identify hubs for industrial symbiosis in two stages. In the first stage, geographical cluster analysis is applied to a validated database where the AIDRES database can be used as a benchmark. Economic and geospatial parameters for clustering such as distances, number of sectors, etc. are readily available in the AIDRES database. In the second stage, the clusters are framed into the NUTS3 regions in order to facilitate coordination strategies at multiple administrative levels, allowing multi-NUTS3 level clusters.

Building on the concept of hubs for circularity conceptualised in the P4Planet partnership, the UGENT-ECM team built a geographical clustering algorithm to identify industrial hubs with high potential for circularity, including urban centres. [21]. Results suggest that adding cities enables the identification of more suitable hubs for circularity. It is recommended to explore further the relationship of industrial hubs with cities hubs to enhance circularity through industrial symbiosis. The AIDRES project provides a robust database for further investigating such relations.

Local parameters beyond the AIDRES project are necessary to define the potential of symbiosis in defined clusters [16]. The geographical distribution of renewable energy resources or biomass availability, may influence the location and re-location of industries and clusters. Balancing potential carbon leakage effects with the Carbon Border Adjustment Mechanism[22] and the hypothetical Renewables Pull Effect [23] are factors to consider when dealing with infrastructure for symbiosis in Europe. Also, variations in policy maturity across countries and experience with mitigation instruments need to be considered. Finally, a balanced implementation of mature technology options with short-term orientation (mostly profit) and less mature longer-term technological options is crucial to avoid lock-in effects in clusters [9], i.e., industries need to prepare for a management of change and enhanced innovation in a sustainability-supporting ecosystem.

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9. Appendix

Appendix A, Industrial Symbiosis cases table (IS profile per sector)

A resource category was developed to identify the different synergies across sectors, grouping streams from different sectors into two main subgroups (Figure 38). The first category was called ‘energy’, grouping synergy cases such as heating & cooling, fuel substitution (for heat generation), and electricity, where its generation takes place as part of the synergy. The non-energy synergies correspond to CCU-S and material substitution. If the resource is a CO_2 stream that can be captured for further utilisation or sequestration, it corresponds to the former. If the resource is not a CO_2 stream, it is classified as the latter, meaning that it replaces an input product of another sector.

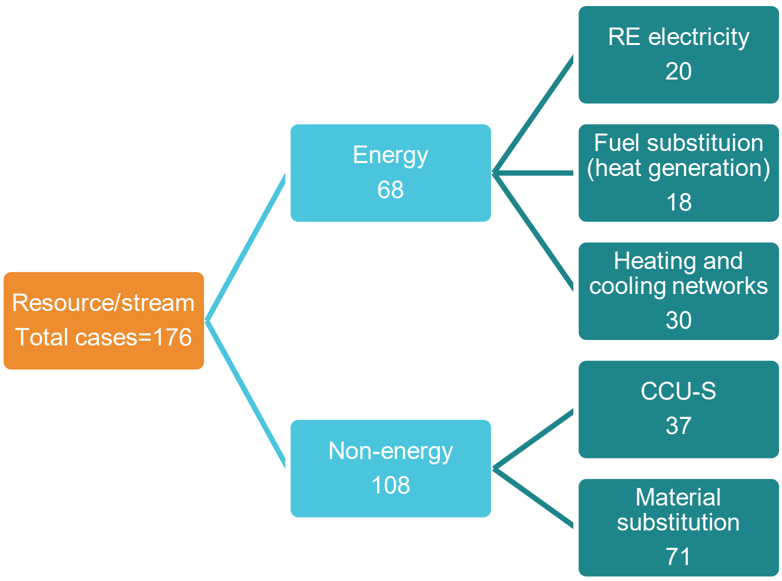

Figure 38 IS case categories enable insights on the type of synergies to consider per sector considered in the IS case-base

In the context of the circular economy, the synergies are classified from R1 to R4. The cases are R2 by default, reusing the stream with minimal processing in other sectors. The corresponding classification is recycling if the synergy requires a high level of processing i.e.: carbon capture. In the case that synergies indicate a relationship with the selected carbon-neutral technologies aligned to the R1 strategies, the case is classified as R1. Finally, in the case of waste to power i.e.: cement sector for fuel substitution, then the corresponding classification is R4 (energy recovery).

Table 14 Cement as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
6	chemical	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
7	fertiliser	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
8	glass	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
9	refinery	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
10	steel	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
31	all	cement	Renewable electricity	R1	RE	Electricity	Electricity	NA
41	refinery	cement	Fuel/Mineral substitution	R2	NA	coke	Coal_Q1	NA
42	steel	cement	Mineral substitution	R2	NA	BF_Slag_Granulated	BF_Slag_Granulated	NA
43	steel	cement	Mineral substitution	R2	NA	BF_Slag	Bessemer_Slag	NA
44	steel	cement	Mineral substitution	R2	NA	BOF_Slag	Bessemer_Slag	NA
45	steel	cement	Mineral substitution	R2	NA	CC_Slag	Bessemer_Slag	NA
46	steel	cement	Mineral substitution	R2	NA	LM_Sludge	Sludge_cement	NA
47	steel	cement	Mineral substitution	R2	NA	RM_Liq_Sludge	Sludge_cement	NA
48	steel	cement	Mineral substitution	R2	NA	BF_Sludge	Sludge_cement	NA
49	steel	cement	Mineral substitution	R2	NA	BOF_Sludge	Sludge_cement	NA
50	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	dee_waste	PLF	NA
51	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	light_hydrocarbons_waste	PLF	NA
52	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	medium_hydrocarbons_waste	PLF	NA
53	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	heavy_hydrocarbons_waste	PLF	NA
87	steel	cement	Material substitution	R2	MOE	Oxygen	Oxygen	NA
89	steel	cement	Material substitution	R2	Alk_Electrolysis	Oxygen	Oxygen	NA
99	all	cement	Material substitution	R1	electrolysis	Oxygen	Oxygen	NA
179	steel	Cement	Fuel/Mineral substitution	R2	NA	COG	hydrogen	Alternative fuels
180	all	Cement	Material substitution	R1	electrolysis	hydrogen	hydrogen	Alternative fuels
182	fertiliser	Cement	Fuel/Mineral substitution	R2	AmmoniaUREa	h2	hydrogen	alternative fuels
187	all	Cement	RE electricity	R1	Renewable	Electricity	Electricity	alternative fuels
194	fertiliser	cement	Material substitution	R2	P2A	O2	Oxygen	NA
211	all	cement	Fuel/Mineral substitution	R1	NA	Natural_gas	Natural_gas	Alternative fuels

Table 15 Cement as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
1	cement	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
2	cement	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
3	cement	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
4	cement	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA

5	cement	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
104	cement	all	CCU-S	R3	NA	rawmill_wstco2_OUT	EAF_Fumes	MEA
105	cement	all	CCU-S	R3	NA	kilnpc_gases_OUT	EAF_Fumes	MEA
107	cement	all	CCU-S	R3	NA	kiln_co2_OUT	EAF_Fumes	MEA
108	cement	all	CCU-S	R3	NA	kilngcu_gases_OUT	EAF_Fumes	MEA
111	cement	all	CCU-S	R3	NA	rawmill_wstco2_OUT	Tail_Gas	VPSA
112	cement	all	CCU-S	R3	NA	kilnpc_gases_OUT	Tail_Gas	VPSA
114	cement	all	CCU-S	R3	NA	kiln_co2_OUT	Tail_Gas	VPSA
115	cement	all	CCU-S	R3	NA	kilngcu_gases_OUT	Tail_Gas	VPSA
118	cement	CCM	CCU-S	R3	NA	rawmill_wstco2_OUT	Fluegas	Mineral-PCC
119	cement	CCM	CCU-S	R3	NA	kilnpc_gases_OUT	Fluegas	Mineral-PCC
121	cement	CCM	CCU-S	R3	NA	kiln_co2_OUT	Fluegas	Mineral-PCC
122	cement	CCM	CCU-S	R3	NA	kilngcu_gases_OUT	Fluegas	Mineral-PCC

Table 16 Chemical as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
1	cement	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
11	steel	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
19	refinery	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
25	fertiliser	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
29	glass	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
32	all	chemical	RE electricity	R1	Renewable	Electricity	Electricity	NA
167	steel	chemical	Material substitution	R2	Primary	COG	hydrogen	Methanol-to-olefins
168	all	chemical	Material substitution	R1	Electrolysis	hydrogen	hydrogen	Methanol-to-olefins
184	all	chemical	RE electricity	R1	Renewable	Electricity	Electricity	M2O
188	Steel	chemical	Material substitution	R2	HISARNA	Captured_CO2	CO2	M2O
189	Steel	chemical	Material substitution	R2	MEA	Captured_CO2	CO2	M2O
190	Steel	chemical	Material substitution	R2	VPSA	Captured_CO2	CO2	M2O

Table 17 Chemical as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
6	chemical	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
15	chemical	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
22	chemical	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
27	chemical	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
30	chemical	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
50	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	dee_waste	PLF	NA
51	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	light_hydrocarbons_ waste	PLF	NA
52	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	medium_hydrocarbo ns_waste	PLF	NA
53	chemical	cement	Fuel/Mineral substitution	R4	Synthesis	heavy_hydrocarbon s_waste	PLF	NA

Table 18 Fertiliser as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
7	fertiliser	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
16	fertiliser	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
23	fertiliser	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
25	fertiliser	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
26	fertiliser	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
152	fertiliser	refinery	Fuel/Mineral substitution	R2	AmmoniaUR ea	h2	hydrogen	NA
153	fertiliser	Steel	Material substitution	R2	AmmoniaUR ea	h2	hydrogen	Shaft_furnace(H2)
154	fertiliser	Steel	Material substitution	R2	AmmoniaUR ea	h2	hydrogen	Shaft_furnace (NG_H2)
156	fertiliser	glass	Material substitution	R2	AmmoniaUR ea	h2	Hydrogen	Float
157	fertiliser	all	CCU-S	R3	AmmoniaUR ea	co2em	Fluegas	mineral-PCC
158	fertiliser	Steel	CC	R3	AmmoniaUR ea	co2em	EAF_Fumes	MEA
159	fertiliser	Steel	CC	R3	AmmoniaUR ea	co2em	Tail_Gas	VPSA
166	fertiliser	glass	Material substitution	R2	AmmoniaUR ea	h2	hydrogen	Fuel-switching
174	fertiliser	Fertiliser	Material substitution	R2	AmmoniaUR ea	h2	hydrogen	biomas to amonia
178	fertiliser	refinery	Material substitution	R2	AmmoniaUR ea	h2	hydrogen	FT fuels
182	fertiliser	Cement	Fuel/Mineral substitution	R2	AmmoniaUR ea	h2	hydrogen	alternative fuels
194	fertiliser	cement	Material substitution	R2	P2A	O2	Oxygen	NA
195	fertiliser	refinery	Material substitution	R2	P2A	O2	Oxygen	NA
198	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	DRI_EAF
199	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	EAF_scrap
200	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	HISARNA
201	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace(H2)
202	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace (NG_H2)
203	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace (NG)
204	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	TGRBF
205	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	VPSA
206	fertiliser	glass	Material substitution	R2	P2A	O2	Oxygen	Float

Table 19 Fertiliser as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
2	cement	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
12	steel	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
20	refinery	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
27	chemical	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
28	glass	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
33	all	fertiliser	RE electricity	R1	Renewable	Electricity	Electricity	NA
15 0	all	fertiliser	Material substitution	R1	electrolysis	hydrogen	h2	AmmoniaURea

151	steel	fertiliser	Material substitution	R2	NA	COG	h2	AmmoniaURea
160	all	fertiliser	Material substitution	R1	electrolysis	Oxygen	O2	Nitric_acid
161	steel	fertiliser	Material substitution	R2	MOE	Oxygen	O2	Nitric_acid
162	steel	fertiliser	Material substitution	R2	Alk_Electrolysis	Oxygen	O2	Nitric_acid
171	steel	Fertiliser	Material substitution	R2	NA	COG	hydrogen	Biomas to amonia
172	all	Fertiliser	Material substitution	R1	electrolysis	hydrogen	hydrogen	Biomass to ammonia
174	fertiliser	Fertiliser	Material substitution	R2	AmmoniaURea	h2	hydrogen	biomas to amonia
185	all	fertiliser	RE electricity	R1	Renewable	Electricity	Electricity	P2A
191	biomass_input	fertiliser	Material substitution	R1	Waste_biomass	biomass	biomass	B2A

Table 20 Glass as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
8	glass	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
17	glass	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
24	glass	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
28	glass	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
29	glass	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA

Table 21 Glass as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
3	cement	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
13	steel	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
21	refinery	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
26	fertiliser	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
30	chemical	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
34	all	glass	RE electricity	R1	Renewable	Electricity	Electricity	NA
143	steel	glass	Material substitution	R2	MOE	Oxygen	Oxygen	Float
144	steel	glass	Material substitution	R2	Alk_Electrolysis	Oxygen	Oxygen	Float
145	all	glass	Material substitution	R1	electrolysis	Oxygen	Oxygen	Float
146	all	glass	Material substitution	R1	electrolysis	hydrogen	hydrogen	Float
147	steel	glass	Mineral substitution	R2	NA	BF_Slag_Granulated	Slag	Float
148	steel	glass	Mineral substitution	R2	NA	BF_Slag	Slag	Float
149	steel	glass	Mineral substitution	R2	NA	BOF_Slag	Slag	Float
156	fertiliser	glass	Material substitution	R2	AmmoniaURea	h2	Hydrogen	Float
163	steel	glass	Material substitution	R2	NA	COG	hydrogen	Fuel-switching
164	all	glass	Material substitution	R1	electrolysis	hydrogen	hydrogen	Fuel-switching
166	fertiliser	glass	Material substitution	R2	AmmoniaURea	h2	hydrogen	Fuel-switching

183	all	glass	RE electricity	R1	Renewable	Electricity	Electricity	EM
206	fertiliser	glass	Material substitution	R2	P2A	O2	Oxygen	Float

Table 22 Refinery as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
4	cement	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
14	steel	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
22	chemical	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
23	fertiliser	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
24	glass	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
35	all	refinery	RE electricity	R1	Renewable	Electricity	Electricity	NA
39	steel	refinery	Fuel/Mineral substitution	R2	NA	COG	hydrogen	NA
88	steel	refinery	Material substitution	R2	MOE	Oxygen	Oxygen	NA
90	steel	refinery	Material substitution	R2	Alk_Electrolysis	Oxygen	Oxygen	NA
100	all	refinery	Material substitution	R1	electrolysis	Oxygen	Oxygen	NA
103	all	refinery	Material substitution	R1	electrolysis	hydrogen	hydrogen	NA
152	fertiliser	refinery	Fuel/Mineral substitution	R2	AmmoniaURea	h2	hydrogen	NA
175	steel	refinery	Material substitution	R2	NA	COG	hydrogen	FT fuels
176	all	refinery	Material substitution	R1	electrolysis	hydrogen	hydrogen	FT fuels
178	fertiliser	refinery	Material substitution	R2	AmmoniaURea	h2	hydrogen	FT fuels
186	all	refinery	RE electricity	R1	Renewable	Electricity	Electricity	FT fuels
192	Biomass_input	refinery	Fuel/Mineral substitution	R1	Waste_biomass	biomass	biomass	FT fuels
195	fertiliser	refinery	Material substitution	R2	P2A	O2	Oxygen	NA
207	Steel	refinery	Material substitution	R2	HISARNA	Captured_CO2	CO2	FT fuels
208	Steel	refinery	Material substitution	R2	MEA	Captured_CO2	CO2	FT fuels
209	Steel	refinery	Material substitution	R2	VPSA	Captured_CO2	CO2	FT fuels

Table 23 Refinery as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
9	refinery	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
18	refinery	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
19	refinery	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
20	refinery	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
21	refinery	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
40	refinery	Steel	Fuel/Mineral substitution	R2	NA	coke	Coke	NA
41	refinery	cement	Fuel/Mineral substitution	R2	NA	coke	Coal_Q1	NA

55	refinery	CCM	CCU-S	R3	NA	hydrocarbon Gas	Fluegas	Mineral-PCC
56	refinery	CCM	CCU-S	R3	NA	contaminate dGas	Fluegas	Mineral-PCC
57	refinery	CCM	CCU-S	R3	NA	offGas	Fluegas	Mineral-PCC
58	refinery	CCM	CCU-S	R3	NA	acidGas	Fluegas	Mineral-PCC
59	refinery	CCM	CCU-S	R3	NA	fuelGas	Fluegas	Mineral-PCC
63	refinery	all	CCU-S	R3	NA	hydrocarbon Gas	EAF_Fumes	MEA
64	refinery	all	CCU-S	R3	NA	contaminate dGas	EAF_Fumes	MEA
65	refinery	all	CCU-S	R3	NA	offGas	EAF_Fumes	MEA
66	refinery	all	CCU-S	R3	NA	acidGas	EAF_Fumes	MEA
67	refinery	all	CCU-S	R3	NA	fuelGas	EAF_Fumes	MEA
68	refinery	all	CCU-S	R3	NA	hydrocarbon Gas	Tail_Gas	VPSA
69	refinery	all	CCU-S	R3	NA	contaminate dGas	Tail_Gas	VPSA
70	refinery	all	CCU-S	R3	NA	offGas	Tail_Gas	VPSA
71	refinery	all	CCU-S	R3	NA	acidGas	Tail_Gas	VPSA
72	refinery	all	CCU-S	R3	NA	fuelGas	Tail_Gas	VPSA
82	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coal_steel	DRI_EAF
83	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coal_steel	EAF_scrap
84	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Pulverized_Co al	HISARNA
85	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coke_BF	TGRBF
86	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Pulverized_Co al	TGRBF

Table 24 Steel as a supplier in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
10	steel	cement	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
11	steel	chemical	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
12	steel	fertiliser	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
13	steel	glass	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
14	steel	refinery	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
39	steel	refinery	Fuel/Mineral substitution	R2	NA	COG	hydrogen	NA
42	steel	cement	Mineral substitution	R2	NA	BF_Slag_Gran ulated	BF_Slag_Gran ulated	NA
43	steel	cement	Mineral substitution	R2	NA	BF_Slag	Bessemer_Sla g	NA
44	steel	cement	Mineral substitution	R2	NA	BOF_Slag	Bessemer_Sla g	NA
45	steel	cement	Mineral substitution	R2	NA	CC_Slag	Bessemer_Sla g	NA
46	steel	cement	Mineral substitution	R2	NA	LM_Sludge	Sludge_ceme nt	NA
47	steel	cement	Mineral substitution	R2	NA	RM_Liq_Sludg e	Sludge_ceme nt	NA
48	steel	cement	Mineral substitution	R2	NA	BF_Sludge	Sludge_ceme nt	NA
49	steel	cement	Mineral substitution	R2	NA	BOF_Sludge	Sludge_ceme nt	NA
54	steel	CCM	CCU-S	R3	NA	Fumes	Fluegas	NA
60	Steel	CCM	CCU-S	R3	HISARNA	Captured_CO 2	Fluegas	NA
61	Steel	CCM	CCU-S	R3	MEA	Captured_CO 2	Fluegas	NA

62	Steel	CCM	CCU-S	R3	VPSA	Captured_CO 2	Fluegas	NA
87	steel	cement	Material substitution	R2	MOE	Oxygen	Oxygen	NA
88	steel	refinery	Material substitution	R2	MOE	Oxygen	Oxygen	NA
89	steel	cement	Material substitution	R2	Alk_Electrol ysis	Oxygen	Oxygen	NA
90	steel	refinery	Material substitution	R2	Alk_Electrol ysis	Oxygen	Oxygen	NA
131	Steel	CCM	CCU-S	R3	Shaft_furnac e(H2)	SF_H2_Fume s	Fluegas	mineral-PCC
132	Steel	CCM	CCU-S	R3	Shaft_furnac e (NG_H2)	SF_NG_H2_F umes	Fluegas	mineral-PCC
133	Steel	CCM	CCU-S	R3	Shaft_furnac e (NG)	SF_NG_Fume s	Fluegas	mineral-PCC
143	steel	glass	Material substitution	R2	MOE	Oxygen	Oxygen	Float
144	steel	glass	Material substitution	R2	Alk_Electrol ysis	Oxygen	Oxygen	Float
147	steel	glass	Mineral substitution	R2	NA	BF_Slag_Gran ulated	Slag	Float
148	steel	glass	Mineral substitution	R2	NA	BF_Slag	Slag	Float
149	steel	glass	Mineral substitution	R2	NA	BOF_Slag	Slag	Float
151	steel	fertiliser	Material substitution	R2	NA	COG	h2	Ammonia URea
161	steel	fertiliser	Material substitution	R2	MOE	Oxygen	O2	Nitric_acid
162	steel	fertiliser	Material substitution	R2	Alk_Electrol ysis	Oxygen	O2	Nitric_acid
163	steel	glass	Material substitution	R2	NA	COG	hydrogen	Fuel-switching
167	steel	chemical	Material substitution	R2	Primary	COG	hydrogen	Methanol-to-olefins
171	steel	Fertiliser	Material substitution	R2	NA	COG	hydrogen	Biomas to amonia
175	steel	refinery	Material substitution	R2	NA	COG	hydrogen	FT fuels
179	steel	Cement	Fuel/Mineral substitution	R2	NA	COG	hydrogen	Alternative fuels
188	Steel	chemical	Material substitution	R2	HISARNA	Captured_CO 2	CO2	M2O
189	Steel	chemical	Material substitution	R2	MEA	Captured_CO 2	CO2	M2O
190	Steel	chemical	Material substitution	R2	VPSA	Captured_CO 2	CO2	M2O
207	Steel	refinery	Material substitution	R2	HISARNA	Captured_CO 2	CO2	FT fuels
208	Steel	refinery	Material substitution	R2	MEA	Captured_CO 2	CO2	FT fuels
209	Steel	refinery	Material substitution	R2	VPSA	Captured_CO 2	CO2	FT fuels

Table 25 Steel as a consumer in symbiosis

ID	Sector_1	Sector_2	Case	CE	BP1_name	layer_name_1	layer_name_2	BP2_name
5	cement	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
15	chemical	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
16	fertiliser	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
17	glass	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
18	refinery	steel	Heat_network	R2	NA	Heatcascade	Heatcascade	NA
36	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	NA
40	refinery	Steel	Fuel/Mineral substitution	R2	NA	coke	Coke	NA
73	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	DRI_EAF

74	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	EAF_scrap
75	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	HISARNA
76	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	MEA
77	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	MOE
78	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	Shaft_furnace (NG_H2)
79	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	Shaft_furnace (NG)
80	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	TGRBF
81	all	steel	RE electricity	R1	Renewable	Electricity	Electricity	VPSA
82	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coal_steel	DRI_EAF
83	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coal_steel	EAF_scrap
84	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Pulverized_Coal	HISARNA
85	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Coke_BF	TGRBF
86	refinery	steel	Fuel/Mineral substitution	R2	NA	coke	Pulverized_Coal	TGRBF
91	all	Steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	DRI_EAF
92	all	steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	EAF_scrap
93	all	steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	HISARNA
94	all	steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	Shaft_furnace(H2)
95	all	Steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	Shaft_furnace (NG_H2)
96	all	Steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	Shaft_furnace (NG)
97	all	Steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	TGRBF
98	all	Steel	Material substitution	R1	electrolysis	Oxygen	Oxygen	VPSA
101	all	Steel	Material substitution	R1	electrolysis	hydrogen	hydrogen	Shaft_furnace(H2)
102	all	Steel	Material substitution	R1	electrolysis	hydrogen	hydrogen	Shaft_furnace (NG_H2)
141	input_plastic	steel	Material substitution	R2	NA	Plastic_mix	Plastic_mix	Plastic_pretreat
153	fertiliser	Steel	Material substitution	R2	AmmoniaURea	h2	hydrogen	Shaft_furnace(H2)
154	fertiliser	Steel	Material substitution	R2	AmmoniaURea	h2	hydrogen	Shaft_furnace (NG_H2)
158	fertiliser	Steel	CC	R3	AmmoniaURea	co2em	EAF_Fumes	MEA
159	fertiliser	Steel	CC	R3	AmmoniaURea	co2em	Tail_Gas	VPSA
198	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	DRI_EAF
199	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	EAF_scrap
200	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	HISARNA
201	fertiliser	steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace(H2)
202	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace (NG_H2)
203	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	Shaft_furnace (NG)
204	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	TGRBF
205	fertiliser	Steel	Material substitution	R2	P2A	O2	Oxygen	VPSA

Appendix B IS cluster ranking table (100 clusters/regions)

Table 26 Ranked AIDRES clusters with production capacity per sector (t/y) and the IS index

Rank	Cluster	NUSTS 3	Cement	Chemical	Fertiliser	Glass	Refinery (oil processing capacity)	Steel	IS index
1	c34	BE211		16,165.0	1,062.0		42,416.0		1.9
2	c226	BE323	1,374.0	134.0	2,100.0	202.0			1.2
3	c38	NL341		3,295.0	7,100.0				1.2
4	c48	ES120	944.0		715.0	240.0		4,911	1.2
5	c177	ITC47	1,451.0					4,745	1.1
6	c4	FRL04	273.0	2,177.0			26,842.0	4,861	1.1
7	c194	DE409	1,894.0			134.0			1.1
8	c133	ES213	1,262.0			75.0	11,000.0	2,402	1.1
9	c94	NL33C		1,340.0			56,200.0		1.1
10	c205	ES511	1,564.0	134.0		149.0		1,319	1.1
11	c28	LU000	952.0			439.0		2,327	1.1
12	c219	PT16F	20.0			1,155.0			1.0
13	c220	DEA12		43.0				12,849	1.0
14	c174	SK022	1,300.0			291.0			0.9
15	c62	DEA23		4,321.0	1,647.0	311.0	9,250.0		0.9
16	c139	ES618	985.0			394.0		715.0	0.9
17	c180	ITG19	715.0	874.0			25,900.0		0.9
18	c56	ITC41	1,587.0	134.0					0.8
19	c202	PL224	493.0			591.0		800.0	0.8
20	c114	EL642	1,529.0		165.0				0.8
21	c237	PL721	1,484.0			20.0			0.8
22	c238	ITC16	1,136.0			220.0			0.8
23	c150	DEA36		5,711.0		464.0			0.8
24	c6	ITC46	1,253.0			21.0		622.0	0.7
25	c37	BE352		1,130.0		757.0			0.7
26	c168	EL522	1,195.0				3,300.0	255.0	0.7
27	c102	DE26A	938.0			202.0			0.7
28	c228	FRE11	249.0	989.0				5,995.0	0.7
29	c176	ES523	996.0		940.0				0.7
30	c129	BG331	1,092.0		405.0				0.6
31	c167	DEE0C	1,053.0			73.0			0.6
32	c76	PL22B				370.0		3,547.0	0.6
33	c209	ES511	556.0			281.0			0.5
34	c25	AT312		43.0	935.0			4,896.0	0.5
35	c47	PL923		2,670.0			18,700.0		0.5
36	c19	ES211				538.0		280.0	0.5
37	c153	EL306	416.0				12,300.0	510.0	0.5
38	c166	DEB34		2,960.0	1,420.0	98.0			0.5
39	c157	ITF43					6,000.0	4,520.0	0.5
40	c106	BE234		100.0				5,300.0	0.4
41	c18	FRK25		134.0		471.0			0.4

42	c127	CZ080		134.0	350.0	93.0		2,925.0	0.4
43	c225	DEE0E		43.0	2,516.0				0.4
44	c67	FRG01			1,000.0		11,000.0		0.3
45	c155	ES514		1,820.0			12,428.0		0.3
46	c26	ES412		134.0		353.0			0.3
47	c95	FR102			1,564.0		5,100.0		0.3
48	c41	ES612		734.0			12,000.0	660.0	0.3
49	c98	ES615		1,600.0	857.0		5,000.0		0.3
50	c29	DEA11		311.0		323.0			0.3
51	c152	BE213		2,429.0		169.0			0.3
52	c96	ES130	542.0					132.0	0.3
53	c13	FRF31	476.0					554.0	0.3
54	c64	DEA27		2,463.0			7,940.0		0.3
55	c236	ITC46	530.0					133.0	0.3
56	c112	ES422		134.0	985.0		7,810.0		0.3
57	c135	DEE0B		815.0	170.0		11,400.0		0.3
58	c31	DE927		43.0		315.0			0.3
59	c97	ITH42				246.0		684.0	0.3
60	c21	DE600					10,100.0	1,047.0	0.3
61	c116	ITG18	471.0	165.0					0.3
62	c45	FRI12		134.0		275.0			0.2
63	c39	PL619		534.0	1,500.0				0.2
64	c144	ITH35		624.0		228.0			0.2
65	c69	DE945		43.0			13,000.0		0.2
66	c128	FRF33		181.0		248.0			0.2
67	c57	PT181		181.0			11,842.0		0.2
68	c191	FR103	322.0					484.0	0.2
69	c16	AT127		90.0			11,216.0		0.2
70	c171	ES243				210.0		275.0	0.2
71	c33	ITC41				164.0		693.0	0.2
72	c55	RO312				193.0		281.0	0.2
73	c158	NL411		47.0		200.0			0.2
74	c101	ITI22				83.0		1,289.0	0.2
75	c198	ITC4B		134.0		182.0			0.2
76	c70	FRK24		181.0		175.0			0.2
77	c215	SK010		695.0			6,482.0		0.2
78	c222	NL342		134.0			8,300.0		0.2
79	c72	DE214		1,029.0			5,064.0		0.2
80	c17	PT170			400.0			1,100.0	0.1
81	c193	FRK26		449.0			6,258.0		0.1
82	c138	FRE12			180.0	120.0			0.1
83	c75	PL821				145.0	200.0		0.1
84	c90	DE949					4,600.0	533.0	0.1
85	c20	ES522		134.0			5,200.0		0.1
86	c12	BE224		43.0				949.0	0.1
87	c159	FRJ26		134.0		78.0			0.1
88	c204	CZ020		224.0			3,300.0		0.1
89	c196	BE32C		425.0		50.0			0.1
90	c58	RO316				22.0	2,800.0		0.1
91	c123	SK042		43.0	405.0				0.1

92	c173	PL432	43.0	61.0			0.1
93	c131	PT11A	134.0			600.0	0.1
94	c105	HR028			2,200.0	89.0	0.0
95	c103	DED2F		40.0		77.0	0.0
96	c86	ES130	134.0			412.0	0.0
97	c197	ES111	134.0			385.0	0.0
98	c104	DEF05	268.0		800.0		0.0
99	c52	ITH57	274.0		500.0		0.0
100	c189	CZ020		21.0	100.0		0.0

Appendix C EPOS IS generic cases matrix (adapted for the AIDRES rectors)

Table 27 IS generic cases expanded from the EPOS project

#	Generic case	Clustering topic	CE	Cement	Chemical	Fertiliser	Glass	Refinery	Steel
1	Waste fuel valorisation	Replace fuels	Recover	x	x	x	x	x	x
2	CO2 mineralisation	Carbon dioxide	Recycle	x	x	x	x	x	x
3	District heating	Heating and cooling	Recover	x	x	x	x	x	x
4	Energy optimisation	Heating and cooling	Recover	x	x	x	x	x	x
5	Wind power	Electricity	Reduce	x	x	x	x	x	
6	Coke valorisation	By-product	Reuse	x	x		x	x	x
7	Solar electric power	Electricity	Reduce	x	x	x	x	x	x
8	Industrial heat networks	Heating and cooling	Recover		x	x	x	x	x
9	Industrial water networks	By-product	Reuse	x	x	x	x	x	x
10	Co-product valorisation (minerals)	By-product	Reuse	x			x	x	x
11	Co-product valorisation (cement)	By-product	Reuse	x	x				x
12	Demand Side Response	Electricity	Reduce	x	x	x	x	x	x
13	CO valorisation from steel	By-product	Reuse		x				x
14	Industrial CO2 capture and utilisation	Carbon dioxide	Reuse	x	x	x	x		x
15	Wastewater treatment	Electricity	Reduce		x	x	x	x	x
16	Industrial CO2 capture and storage	Carbon dioxide	Recycle	x	x	x	x	x	x
17	Waste plastic valorisation in Steel	By-product	Reuse	x	x				x
18	Solar heating power	Heating and cooling	Reduce	x	x			x	
19	Steel slag valorisation	By-product	Reuse	x	x		x	x	x
20	Waste plastic valorisation in cement	By-product	Reuse	x	x				x

21	Hub for CO2 upgrading	Shared services	Reduce	x	x	x	x	x	x
22	Mineral cluster with joint logistics	Shared services	Reduce	x			x		x
23	Biomass cluster with joint logistics	Shared services	Reduce		x	x		x	x
24	Glass recycling	Mechanical recycling	Recycle				x		
25	Steel recycling	Mechanical recycling	Recycle						x
26	Waste plastics valorisation in Chemicals	Recycling	Recycle		x				

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