Industry cluster typology as driver for energy demand-supply scenarios in Europe

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Abstract:

In 2024, the European Commission mandated Mario Draghi to prepare a report on European competitiveness. A key finding of the report is that high energy costs undermine the competitiveness of EU energy-intensive industries, whilst uncertainties regarding the long-term energy landscape have contributed to a significant decline in industrial investment. One approach to address this challenge is by joining forces via industry clustering, which can help reduce costs by sharing infrastructure and coordinating investments at regional, national, or transnational level. Yet no EU-wide mapping of cross-sectoral energy symbiosis framed by industry and policy transition pathways has yet been conducted.

This gap is addressed by introducing an industry cluster typology, embedded in the RES2Go tool, to correlate local renewable energy supply with high-resolution spatial data on current and future industrial energy demand across Europe. The cluster structure is characterised by two complementary intrinsic dimensions: the Industrial Symbiosis index, a scale-oriented indicator for clustering projects, and the Sectoral Diversity index, a scope-oriented indicator capturing sectoral compositional balance. The tool draws on the AIDRES database, which provides site-level data for process industry sectors, whilst JRC databases capture renewable energy potential for onshore wind and solar. The modelling starts with the 2018 reference pathway and adds an electrification scenario, compared with the climate law-aligned pathways published by DG CLIMA (2025), to identify bottlenecks associated with strong electrification paths and suggest how to reduce supply congestion.

The tool results in an EU-wide mapping of cluster opportunities for energy-intensive industries. The most scale-intensive clusters are concentrated in the industrial triangle spanning Belgium, Luxembourg, and North-Rhine Westphalia. They shift from annual electricity matching or small deficit into deep deficit when electrifying. For mid to low-range scope-oriented clusters, renewable ambition can meaningfully reverse the supply balance. Two main policy drivers emerge from the study: large, hard-to-abate clusters characterised by limited local renewable energy potential where industrial symbiosis can play a central role, and smaller, more specialised hubs with stronger renewable matching potential and higher electrification opportunities. This cluster typology provides a strong basis for further analysis of infrastructure integration for energy sourcing, including electricity grids and power plants, to support a competitive process industry transition.

Keywords:

Industrial clusters; Energy; Typology; Sustainability; Energy modelling.

1. Introduction

The competitiveness of European energy-intensive industries (EIIs) has become a key concern due to surging energy prices and rising supply security challenges in Europe [1]. The Draghi report [2] and the Clean Industrial Deal [3] highlight the growing tension between the industrial transition required to achieve net-zero objectives by 2050 and the economic implications of energy costs, resulting market instability and slower pace of infrastructure investment.

Against this backdrop, industrial clustering has gained recognition as a promising structural response to simultaneously advance competitiveness and emission reduction. Industry and policy-oriented organisations, including the European Round Table for Industry and the World Economic Forum [4], emphasise the role of spatial concentration in enabling shared infrastructure, coordinated investment, and industrial symbiosis. The IPCC similarly endorses clustering initiatives within its dedicated chapter on industry [5]. This convergence of positions, across both climate and economic rationales, frames clusters as a vehicle to reduce transition costs, broaden access to renewable energy supply, and support collective pathways towards electrification and deep emission reduction.

Nevertheless, the benefits of clustering are inherently context specific and contingent upon the availability of renewable energy across both current and future time horizons. A systematic assessment of local renewable energy potential in conjunction with industrial demand therefore requires a framework for informed decision-making by public and private stakeholders alike

1.1. Industrial clustering for decision making: state of the art

Despite growing attention to industrial clusters as a policy instrument, the existing literature offers limited quantitative and spatially-explicit assessments at the European scale. Some tools and databases aim to address parts of this challenge, but an integrated approach is still missing. The AIDRES database [6] provides a structured inventory of industrial energy demand across European regions, whilst Hotmaps [7] has advanced spatially resolved heat demand mapping at the EU level. A systematic review by Dhondt *et al.* [8] underscores the importance of linking industrial areas, energy demand, and transition pathways through a clustering approach, yet notes that existing contributions tend to remain confined to specific sectors or national contexts. A notable illustration is the cluster taxonomy developed for Northern Italy [9] which offers a rigorous analysis of energy consumption and carbon dioxide emissions but is grounded in current industrial processes and does not incorporate future scenario assumptions. Neither does it take into account the EU scope. Collectively, these contributions expose a persistent gap: the absence of data-driven frameworks capable of systematically comparing industrial clusters across Europe, under divergent industrial pathway assumptions.

This study addresses these gaps by developing an EU-wide, spatially-explicit industrial cluster typology that integrates industrial energy demand, process emissions, and renewable energy supply potential. Employing the RES2Go framework [10], the analysis combines data from the AIDRES database with renewable energy scenarios to identify and characterise industrial clusters across Europe for a reference year and a 2050 electrification pathway. The resulting typology is applied to assess structural bottlenecks and support opportunities for targeting meaningful policy decisions, whether public or private, that most effectively support the transition of the European industry as well as energy system investments.

2. Data and Methodology

This study employs the preliminary RES2Go framework (v1) to construct an EU-wide industrial cluster typology integrating energy demand, process emissions, and renewable energy supply potential. RES2Go was developed by the Ghent University ECM research group, as part of the PIECE project in collaboration with DG ENER and the Joint Research Centre [11], and is designed to support evidence-based decision-making on industrial cluster transitioning by enabling the systematic comparison of demand and supply configurations across European regions. The framework applied here includes the EU Climate Law trajectory, which mandates a 90% net greenhouse gas emission reduction by 2040 and full climate neutrality by 2050 [12].

The analytical workflow proceeds in three stages. Firstly, cluster boundaries are delineated using the algorithm described in Section 2.2, identifying significant concentrations of energy-intensive industry drawn from the AIDRES site-level database. Secondly, industrial energy demand profiles are constructed for each cluster under two pathway assumptions: a reference configuration corresponding to 2018 process conditions, and a 2050 electrification pathway reflecting high electrification uptake. The electrification pathway is benchmarked against a set of law-aligned KPI corridors, which serve as reference bounds for assessing the plausibility and ambition of the projected demand trajectory. Thirdly, typology indices are applied to characterise each cluster according to its and production capacity (scale) and sectoral composition (scope). The potential for renewable energy supply is then attributed to each cluster using the ENSPRESO and EMHIRES datasets assuming a renewable policy deployment scenario, which enables the assessment of local supply in response to the industrial electrification demand. Together, these three stages form the basis of a typology to classify clusters, not only by industry type but also by production profile and energy demand across transition scenarios. The suggested typology can be used as a practical instrument to inform policy decisions regarding industrial renewable energy deployment and net-zero transition planning.

2.1. RES2Go v1

RES2Go is a web-based analytical tool, designed to support the configuration and assessment of industrial clusters under varying energy scenarios [10]. The tool is structured around three main modules: industrial energy demand, renewable energy supply, and cluster assessment. It integrates several underlying databases to produce spatially-explicit, scenario-dependent outputs at cluster level. Figure 1 presents the overall architecture of the framework. The present study employs RES2Go v1 as the primary analytical platform to define cluster parameters, configure industrial pathway assumptions, and evaluate renewable energy supply potential across EU member states. The industrial energy demand layer derives from the AIDRES project database, which constitutes the methodological backbone of the tool's demand-side representation. The AIDRES project, commissioned by EU DG Energy in 2020, was designed to map transition pathways towards climate neutrality for six key process industries: steel, chemicals, refineries, fertilisers, glass, and cement and to quantify their respective demands for renewable energy carriers and feedstock under alternative production routes. To do so, individual industrial processes were modelled using the OSMOSE simulation framework [13], which delivers per-tonne estimates of energy demand by carrier, raw material inputs, direct process emissions, and associated investment and operational costs. The process models are referred to as blueprints, a concept originally introduced by the EU Horizon 2020 EPOS project as a methodological device to overcome confidentiality constraints and enable the sharing of commercially sensitive process data in support of industrial symbiosis assessments [14]. By abstracting site-level data into generalised process representations, blueprints allow for energy and material flow profiles to be shared and scaled without disclosing proprietary operational details.

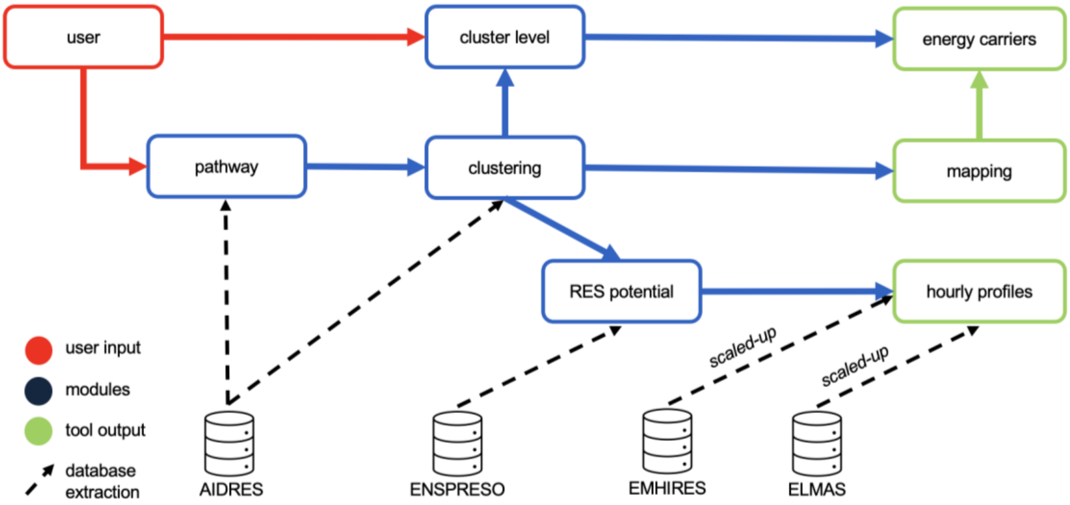


Figure. 1. *Relationship flow chart of RES2Go v1 tool*

In AIDRES, the blueprint output was subsequently scaled to a georeferenced database of EU production sites and their respective capacities, generating spatially-explicit energy and feedstock demand estimates at NUTS3 level. The reference year for the AIDRES database was 2018, with forward projection constructed for 2050. To reflect the uncertainty inherent in anticipating which production routes individual sectors will adopt over this horizon, the AIDRES project introduced so-called EU mix route scenarios. Under this approach, total sectoral production capacity for each process was represented as a weighted combination of multiple technology routes, with weights determined in consultation with industry representatives and sector federations. For primary steel production, for instance, the 2050 electrification pathway projected a dominant share for hydrogen-based direct reduced iron paired with an electric arc furnace [15]. Analogous mixed-route constructions were developed for the remaining five sectors. It should be noted, however, that this approach has a recognised limitation at site level: individual industrial facilities typically follow a single production route rather than operating a portfolio of technologies simultaneously. The mixed-route scenarios therefore cannot be considered directly representative of site-level investment decisions, though they retain analytical value for characterising aggregated sectoral demand trajectories at NUTS3 and cluster level, whereas AIDRES was focused on site level.

In RES2Go, the renewable energy supply layer integrates two complementary JRC datasets: the ENSPRESO database [16] and the EMHIRES dataset [17]. ENSPRESO provides spatially resolved estimates of technical renewable energy potential across EU member states, while EMHIRES complements this by providing historical annual weather data to analyse temporal matching potential, both at NUTS2 level. This spatial resolution of the supply layer is an important consideration: it means that supply estimates reflect a broader regional footprint than the cluster itself, which should be borne in mind when interpreting whether a cluster demand creates either a significant or a marginal draw on its surrounding regional resource base.

RES2Go v1 introduces a set of key performance indicators (KPIs) that operationalise the comparison between demand and supply at cluster level. Three KPIs are selected to match the analytical scope of RES2Go: carbon intensity (scope 1 emissions per tonne of product), specific total energy demand (MWh/t), and electricity share (percentage of total energy demand in TWh).

The *Pathway module* in RES2Go v1 enables the definition and projection of industrial energy pathways at the site level. Furthering the AIDRES database, this module provides input data on energy, feedstock, and emissions per tonne of product for six energy-intensive sectors: steel, chemicals, refineries, fertilisers, glass, and cement. Users can develop pathways by selecting pre-defined scenarios, creating new pathways from scratch, or uploading existing ones. The module calculates weighted averages when multiple production routes exist for a product, allowing for flexible representation of different technologies and energy carriers. These pathways are then projected onto industrial sites, producing site-level estimates of energy and feedstock consumption, and CO_2 emissions, which form the basis for subsequent clustering and analysis.

The *Clustering module* leverages site-level energy and production data to identify spatial groupings of industrial activity, *in casu* clusters, that can be relevant for energy optimisation and industrial symbiosis. RES2Go v1 implements multiple clustering algorithms, including KMeans, weighted KMeans, capped KMeans, and DBSCAN (Density-Based Spatial Clustering of Applications with Noise), which allow users to account for both spatial proximity and the significance of energy consumption or emissions. Each clustering algorithm has its relevance as described in Mendez Alva *et al.* [18] and elaborated below.

The *Time Series module* integrates temporal dimension into the analysis by aligning industrial load profiles with local renewable energy generation. Industrial demand is represented using hourly profiles derived from the ELMAS database, scaled to match the annual energy volumes estimated in the pathway module. Renewable generation is obtained from ENSPRESO and EMHIRES databases at the NUTS2 level, allowing users to select scenarios and years that reflect different weather or renewable conditions. However, this time dimension is not considered within this study, focusing on annual energy only.

2.2. Cluster description

The description of industrial clusters and subsequent classification into typologies requires two methodological choices: the spatial algorithm used to delineate clusters from dispersed production site data, and the approach adopted to characterise cluster types, whether based on intrinsic structural properties or scenario-dependent supply and demand configurations.

For cluster delineation, DBSCAN is employed as the sole algorithm, given that this study focuses specifically on dense industrial concentrations and their potential to be supplied by locally generated renewable energy. Mendez Alva *et al*. [18] compared three geo-based clustering algorithms applied to European process industry location data, evaluated the respective capacity to identify potential hub locations for urban-industrial symbiosis, and identified DBSCAN as particularly well suited to detecting spatially coherent industrial agglomerations irrespective of their shape, without requiring the number of clusters to be pre-specified.

The area enclosed within cluster boundaries could therefore reasonably be expected to host sufficient renewable energy generation capacity to be assessed against local industrial demand. This parameterisation reflects a deliberate analytical choice: clusters are defined not as tightly bounded facility groups but as spatially coherent industrial zones whose territory could support the primary supply of local renewable energy. Using the thresholds set by Mendez Alva *et al*. [18], the inter-site distance is kept at 25 kilometres and the minimum number of sites is set to five, yielding a total of 34 clusters, as illustrated in Figure 5.

3. Scenario definition

The scenario framework employed in this study is constructed along two independent dimensions: industrial energy demand pathways derived from the AIDRES database, and renewable energy supply assumptions drawn from the ENSPRESO dataset, developed by the European Joint Research Centre as an EU-28-wide open resource for energy system modelling [16]. This dataset provides technical potential estimates for wind and solar from 2010 to 2050 at NUTS2 level, derived from coherent GIS-based land-restriction scenarios that incorporate assumptions on land use, protected areas, agricultural practices, and broader socio-economic conditions. For wind, resource evaluation accounts for setback distances and high-resolution geo-spatial wind speed data; for solar, potentials are derived from irradiation data and available area.

Three supply levels are introduced reflecting progressively less restrictive assumptions regarding land availability, technology deployment constraints, and policy acceptance. Within RES2Go, renewable energy supply potential is attributed to each cluster by applying a surface-area ratio between the cluster footprint and the encompassing NUTS2 region, assuming a uniform spatial distribution of renewable resources across that region. This approach allows for cluster-level supply estimates to be derived directly from NUTS2 totals.

Two industrial pathways are defined from the AIDRES database. The reference pathway reflected 2018 production conditions across the six sectors in scope and serves as the baseline for benchmarking the forward-looking configuration. It captured the pre-transition industrial landscape, characterised by fossil fuel dominance, minimal electrification, and limited carbon capture integration. The electrification pathway selects per product the highest electro-intensive routes available in the AIDRES database, departing from AIDRES 2050 pathway, supplemented by carbon capture and storage when electrification alone is insufficient to achieve deep emission reductions as described by Dhondt and Van Eetvelde [15]. In all configurations, production volumes are capped at the maximum recorded capacity to facilitate bottleneck identification, unlike in the AIDRES project where the production was set to decrease until 2050.

Figure 2 presents the energy carrier breakdown per tonne of product across both configurations for all six sectors. Several structural contrasts are immediately apparent. Cement shifts from coal dominance in the reference pathway to electricity and biomass under electrification, with CCS-integrated routes enabling negative net emissions in the most ambitious configurations. Chemicals exhibit the highest absolute electro-intensity under electrification, with certain olefin routes exceeding 10 MWh/t. Fertilisers show the most intense transition: near-total natural gas dependency in the reference gives way to electrolytic hydrogen under electrification, achieving near-complete emission elimination in ammonia production. Glass follows a comparatively moderate trajectory, with electricity replacing natural gas at approximately 1.5–1.7 MWh/t under electrification. Refineries remain among the most carbon-intensive in the reference pathway and rely on combined electricity, biomass, and CCS to achieve meaningful reductions under the 2050 pathway. Steel illustrates the shift from coal-intensive BF-BOF routes towards hydrogen DRI-EAF configurations, whilst secondary scrap EAF routes remain the least carbon-intensive across all scenarios due to their electricity-only profile. Primary steel and steam crackers (olefins) remain below this threshold, reflecting the decision to exclude molten oxide electrolysis and to maintain a high biomass share in the cracker route. This is available as preset pathway on the RES2Go webtool.

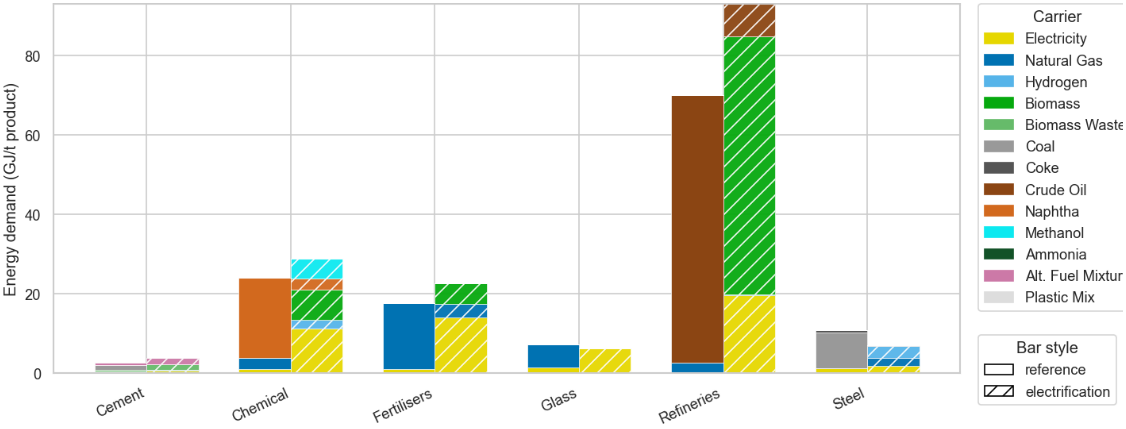


Figure. 2. *Specific energy carrier breakdown per sector for reference (left) and electrification pathway (right)*

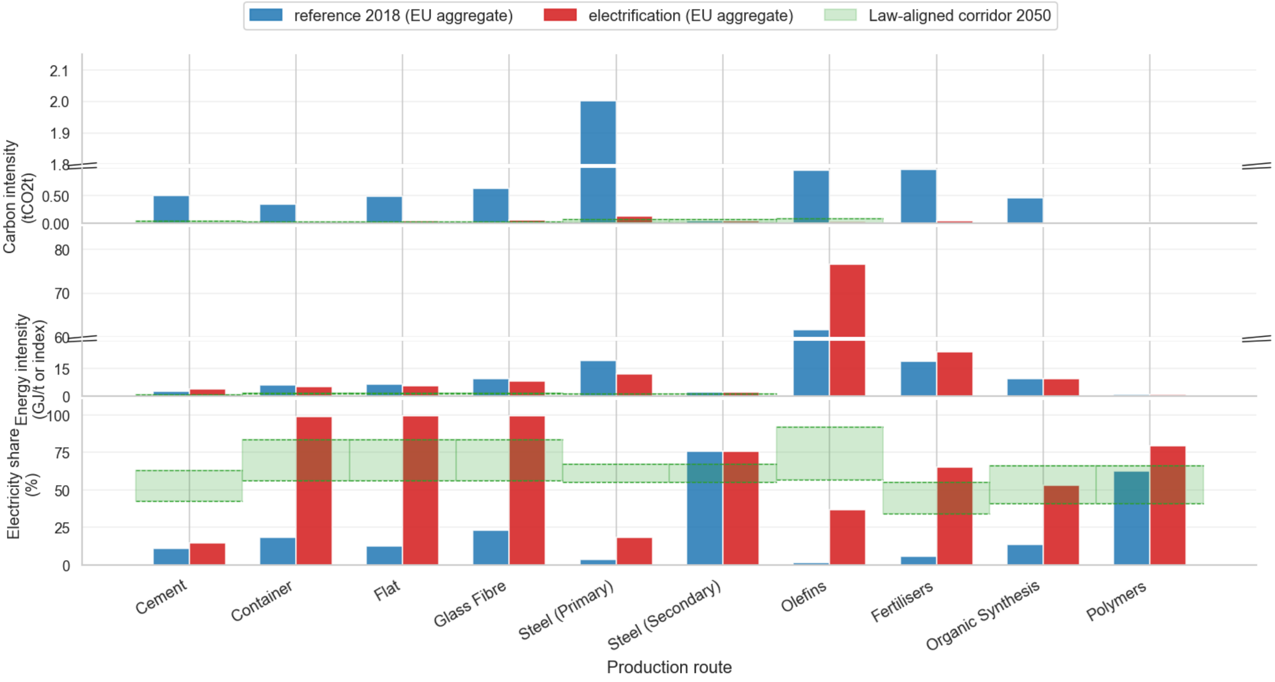


Figure. 3. *Reference (blue) and electrification (red) pathway compared to climate law-aligned KPI corridor (green).*

Across all production routes, the electrification scenario drives carbon intensity toward zero, meeting or exceeding the DG CLIMA law-aligned corridor minimum for glass, secondary steel, and chemicals, which is a deliberately extreme assumption, as discussed previously. Energy intensity declines across most routes under electrification. The electricity share rises substantially across all routes, with most reaching or surpassing the upper bound of the law-aligned corridor by 2050, as shown in figure 3. Cement and primary steel production do not meet the corridor due to a smaller representation of production routes, available from AIDRES, compared to the ones used by DG CLIMA.

It should be noted that scenario configuration does not alter the intrinsic cluster typology, which is determined solely by sectoral composition, geographic distribution, and the spatial clustering of industrial sites.

4. Results

This paper presents results that are structured along both typological dimensions introduced in section 2.2. The intrinsic typology, presented in section 4.1, characterises the current industrial landscape in terms of sectoral composition, geographic distribution, and symbiosis potential, independently of any scenario assumption. The scenario-based typology, presented in section 4.2, evaluates how the relationship between industrial energy demand and local renewable energy supply potential evolves under the pathway configurations defined in section 3. Together, both dimensions provide a layered reading of the European industrial cluster landscape: the first anchored in observed structure, the second oriented towards transition dynamics both aiming to guide policy decisions.

4.1. Intrinsic Cluster Typology

The structural characterisation of industrial clusters is established prior to any energy supply assessment. It uses three intrinsic dimensions derived exclusively from site-level production data: cluster size (number of registered sites), the Industrial Symbiosis index (IS; scale-oriented), and a Sectoral Diversity index (SD; scope-oriented).

The IS index for cluster c is defined in [19] as:

$$\mathrm{IS}_c = \sum_j \frac{\mathrm{Cluster\_production}_{j,c}}{\mathrm{Max\_production}_j}$$

where j iterates over the sectors present in cluster c, $\mathrm{Cluster\_production}_{j,c}$ denotes the total production (kt) of sector j within cluster c, and $\mathrm{Max\_production}_j$ denotes the highest production of sector j recorded across all EU clusters. This formulation measu the relative weight of a cluster per sector present in the cluster, such that a cluster commanding dominant production volumes across multiple sectors receives a proportionally elevated score. The index is therefore scale-oriented, as it is primarily sensitive to production volumes.

The (SD) index, based on the Shannon diversity index [20], is widely applied in ecology to measure species diversity within a biome relative to individual abundance. Here, it is adapted to quantify sectoral diversity within a cluster, defined as:

$$\mathrm{SD}_c = -\sum_i \frac{n_i}{N} \ln\left(\frac{n_i}{N}\right)$$

where n is the number of distinct industrial sectors i represented within cluster c and N is the total number of sites. This index treats all sites as equivalent units irrespective of their production volume, which is why it is scope-oriented. These two indices are therefore complementary, together constituting an intrinsic typology that captures both the scale and scope dimensions of industrial clusters.

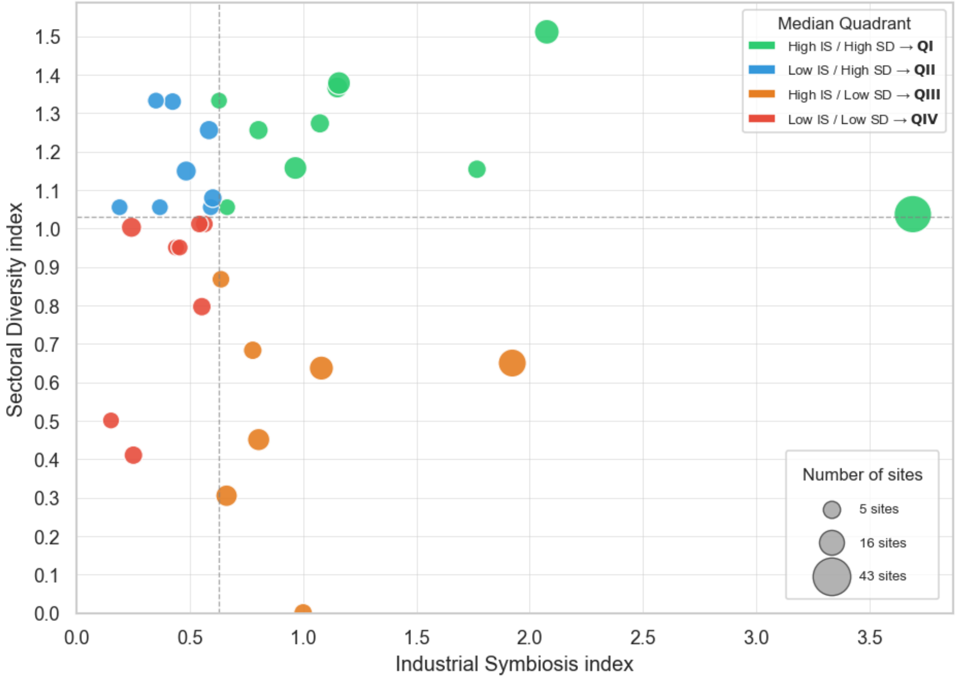


Figure. 4. *Industrial cluster intrinsic typology using 3 KPIs (Industrial Symbiosis (IS), Sectoral Diversity (SD) and number of sites). Using IS and SD indices as orthogonal axes and setting median values as thresholds (IS = 0.63 and SD = 1.06), clusters distribute across four structural quadrants.*

The IS and SD indices are represented as orthogonal axes, distributing clusters across four structural quadrants with thresholds set at median values for both indices. This quadrant approach is conceptually analogous to the Industry–Infrastructure Quadrant introduced in [21]. Each quadrant position corresponds to a distinct form of industrial symbiosis: cross-sectoral exchange is associated with a high SD index, whilst intra-sectoral exchange characterises a low SD index, indicating the potential for economies of scope. The IS index reflects economies of scale, thus referring to the nature and impact of a collaborative action without hierarchy in clustering value between the quadrants. Both low and high IS indices conditions offer viable pathways for symbiotic collaboration, albeit of differing character.

Quadrant I: High IS, High SD: Structurally optimal (green in figure 5)

The industrial triangle, spanning Belgium, Luxembourg, and North-Rhine Westphalia, represents favourable structural conditions for cross-sectoral industrial symbiosis. Where both indices are high, clusters combine a near-balanced multi-sectoral composition with production volumes approaching EU maxima, constituting the structural prerequisites for diversified, high-throughput symbiotic networks. Therefore, for those clusters, the economic advantages associated with industrial symbiosis at scale create such endogenic incentives for self-organisation that collaborative arrangements may already be well established. The Ruhr area, the largest cluster in the dataset (43 sites), illustrates this: commanding dominant production across multiple sectors simultaneously, it presents the broadest scope for cross-industry material and energy flows, including slag valorisation, shared utility networks, and integrated thermal management, already largely developed.

Quadrant II: Low IS, High SD: Diverse but scale-marginal (blue in figure 5)

Clusters in this quadrant have a multi-sectoral composition without the production volumes necessary to compete with the large - mostly western EU - industrial clusters. Here, most business parks and local industry zones are situated. The Ostrava region in the eastern Czech Republic is representative for QII: it has a near-balanced sectoral distribution of chemical, fertiliser, glass, and steel companies, yet the combined output remains modest. These clusters may benefit substantially from local industrial symbiosis policies, yet remain less targeted for major energy investments due to their overall lower economic performance compared to clusters with a higher IS index.

Quadrant III: High IS, Low SD: Specialised but productive (orange in figure 5)

Clusters with an elevated IS index reflect production volumes approaching EU sectoral maxima in the dominant sectors, whilst a low SD value indicates a close to mono-sectoral composition of the sites present. The symbiosis potential is therefore primarily intra-sectoral (e.g. waste heat exchange, joint energy supply, by-product valorisation, material recycling) rather than cross-sector energy and material flows. The two major European port clusters, Rotterdam and Antwerp, fall within this quadrant; they are predominantly driven by a number of large chemical industry sites. This is opposed to QI which combines sites with higher sectoral diversity, resulting a higher SD index, whilst maintaining high production levels.

Quadrant IV: Low IS, Low SD: Homogeneous and small (red in figure 5)

All clusters in this quadrant are small (n = 4-5 sites), mono-sectoral (one or two sectors), and produce below EU sectoral maxima. These clusters have both lower structural variety and smaller throughput volume necessary for large-scale industrial symbiosis. However, their structural homogeneity means that renewable energy infrastructure solutions developed for one site are readily transferable across sites within this cluster, reducing both assessment complexity and deployment costs.

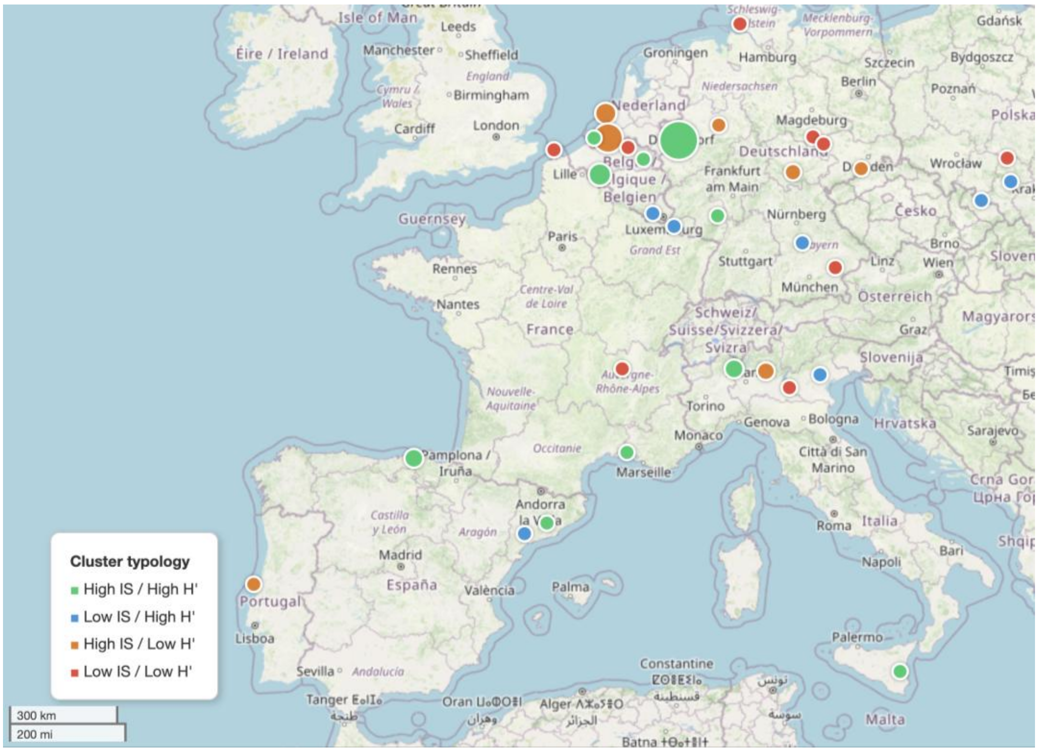


Figure. 5. *Map of industrial cluster in Europe using DBSCAN (min sites = 5 and min distance = 25 km). Each colour corresponds to a type of cluster using the IS-SD quadrant. The circle size is proportional to number of sites (from 5 to 43).*

4.2 Scenario-based typology

The transition from the 2018 reference pathway to the electrification pathway produces a structurally distinct industrial energy landscape across EU clusters. To analyse this shift and support the scenario-based typology, two KPIs are employed — one for PV and one for wind onshore electricity generations.
The Potential Self-Sufficiency Ratio (PSSR) is a widely used metric for comparing energy demand against available supply. However, given the large variation in electricity demand across clusters, a direct PSSR comparison risks obscuring meaningful trends. To address this, the decimal logarithm of the PSSR is applied defined as follows:

$$\log\left(\mathrm{PSSR}_{PV/Onshore}\right) = \log\left(\frac{\mathrm{PV\_potential\_supply/onshore\_wind\_potential\_supply}}{\mathrm{electricity\_demand}}\right)$$

When log(PSSR) is negative, local annual supply cannot match the annual energy demand from the industrial cluster, if positive the industrial cluster is self-sufficient from an annual energy point of view.

The KPIs are applied across two scenarios, each combining the electrification industrial pathway with either the medium or high renewable energy source (RES) potential as defined by ENSPRESO. Both scenarios are compared against a baseline combining the reference industrial pathway with low RES potential. This baseline configuration represents the most conservative condition, against which a moderate or substantial increase in RES deployment can be assessed for sufficiency. The purpose of this comparison is to identify the extent to which policy ambition in RES implementation (medium vs high) determines cluster-level potential self-sufficiency outcomes under electrification.

4.2.1. Reference scenario

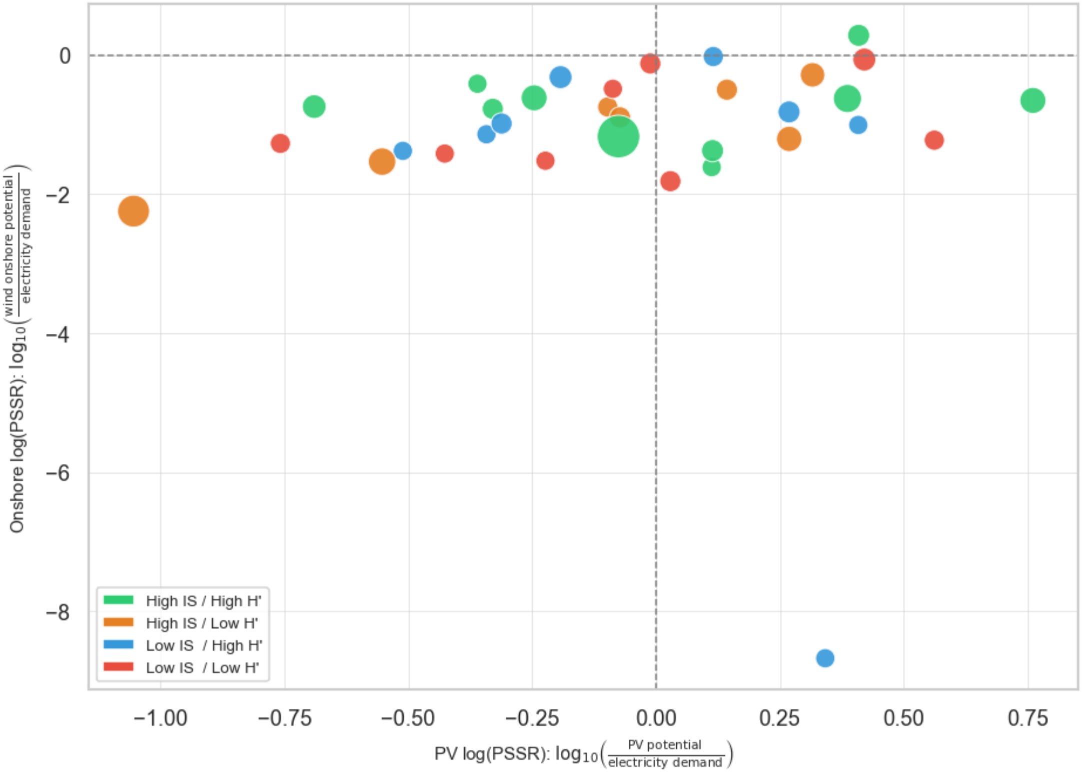


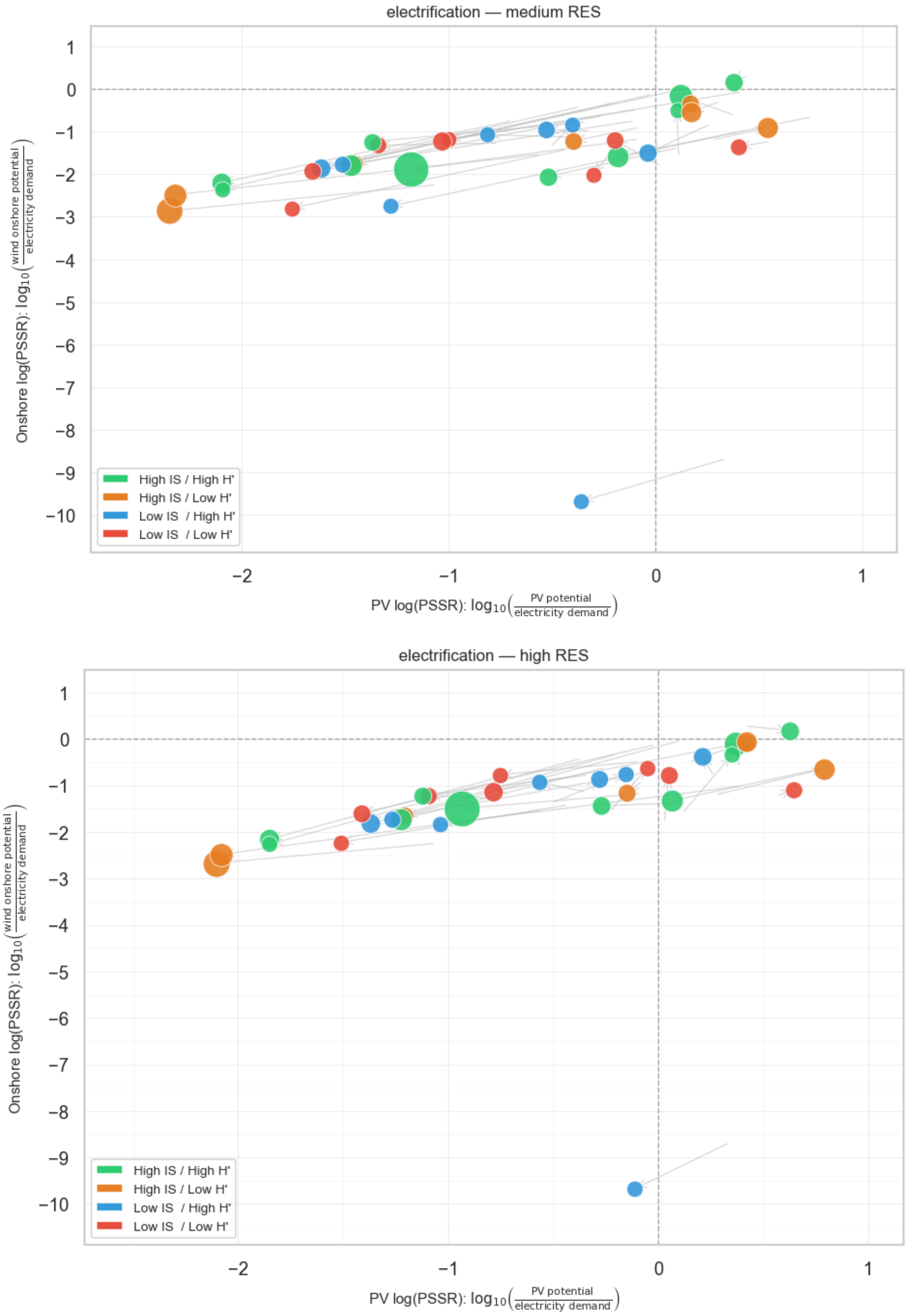
Figure. 6. *Baseline industrial cluster typology using onshore and PV log(PSSR), combined with the cluster typology. The circle size is proportional to number of sites (from 5 to 43).*

Solar PV matching annual electricity demand is the dominant pattern, with most clusters recording positive values, indicating that annual solar generation potential exceeds local electricity demand. This reflects the combined effect of adequate irradiance, large cluster areas, and modest electricity demand in many cases. Favourable positions are, therefore, observed in all clusters. However, clusters with high electricity demand or severely constrained land record negative or near-zero values, with Antwerp (BE) the most marked case, combining solar deficit with the lowest onshore wind residual in the dataset, consistent with its profile as a dense, high-demand industrial port complex.

Wind onshore shows a more consistently negative RES index, indicating that wind generation potential falls short of electricity demand across the majority of clusters. Given broadly comparable wind resource conditions across European sites, this pattern is likely attributable to land availability constraints. Venice Area (IT) illustrates this most starkly, recording a strongly positive solar surplus alongside an extreme wind deficit due to lack of wind potential, which forecloses large-scale onshore wind deployment. The Bilbao area (ES) displays a partial exception: despite belonging to Quadrant I, it achieves a positive position on both axes, suggesting that sufficient renewable energy resources offset annual electricity demand. The Ruhr area (DE) is positioned close to the origin with a marginally negative wind and PV PSSR, occupying a position indicative of an industrial cluster with a self-sufficiency ratio that remains sensitive to future electrification levels.

Overall, solar PV potential self-sufficiency exhibits substantial variation across clusters, with log(PSSR) values distributed broadly on both sides of zero. Onshore wind potential self-sufficiency is more uniform, remaining negative across the majority of EU clusters and concentrated in the range between zero and minus two. No systematic relationship between cluster typology and renewable self-sufficiency potential emerges from the data. This suggests that, irrespective of the industry profile, all clusters retain the capacity to approach annual energy self-sufficiency by combining solar and wind resources.

4.2.2. Electrification scenarios



(a)

(b)

Figure. 7. *Industrial cluster typology for low (a) and high (b) RES electrification scenarios using onshore and PV log(PSSR), combined with the cluster typology. The circle size is proportional to number of sites (from 5 to 43).*

Under both electrification scenarios, the most substantial shift relative to the reference is observed among high IS clusters (in blue and green on figure 7). The marked leftward and downward displacement of these clusters indicates that rising electricity demand, driven by the electrification of high-consuming industrial sectors such as primary steel, chemicals, and fertilisers, outpaces any concurrent expansion of renewable generation potential, with Rotterdam as key example of this strong shift. This deficit is consistent across both the low and high RES scenarios, confirming that demand growth is the dominant driver rather than supply constraint alone.

Some clusters exhibit a more favourable supply position under a high RES scenario compared to the mid RES scenario. This underscores the material impact of renewable capacity deployment at the cluster scale: when the self-sufficiency potential is close to the origin under an electrification pathway, incremental renewable capacity expansion is sufficient to restore or maintain supply adequacy. The convergence of similarly positioned specialised clusters, characterised by low sectoral electrification such as cement and primary steel production, also has implications for energy system planning such as the Bilbao area (ES). Shared renewable resource profiles and comparable demand structures create conditions conducive to coordinated infrastructure investment and mutual energy balancing. However, the reduced scale of demand variation within and across these clusters may simultaneously diminish the load-smoothing effect that underpins flexible grid operation, potentially reducing the benefits of demand-side flexibility mechanisms between industry

5. Conclusion

This study develops a universal industrial cluster typology using two indices, the IS index and the SD index, combined with PV/onshore potential self-sufficiency indicators assessed across baseline and electrification scenarios. Scale-intensive clusters face the most severe constraints for renewable supply under electrification pathway, whilst structurally homogeneous clusters retain broad potential self-sufficiency under high electrification, providing a structured evidence frame for different policy decision strategies across the European industrial landscape.

5.1. Key findings

This study presents an industry cluster typology integrating industrial energy demand, sectoral composition, and renewable energy supply potential under reference and electrification pathways. The central finding is structural: large, multi-sectoral, high-throughput agglomerations, such as concentrated in the industrial triangle spanning Belgium, Luxembourg, and North-Rhine Westphalia, are precisely the clusters facing the deepest renewable energy supply deficits in the electrification pathway. The transition from fossil fuel-based to electro-intensive production routes drives demand growth that consistently outpaces any expansion in local renewable generation potential, for both RES scenario assumptions. Conversely, more homogeneous clusters show higher renewable matching potential and sensitivity to RES deployment ambition, identifying them as priority locations for early electrification investments. Together, these findings suggest that no single policy instrument is sufficient: large hard-to-abate clusters require coordinated infrastructure solutions, grid reinforcement, cross-border energy sourcing, and intra-cluster symbiosis, whilst smaller hubs offer more accessible routes towards self-sufficiency by renewables. The RES2Go typology provides a replicable, spatially-explicit basis for targeting such interventions across the European process industry landscape.

5.2. Limitation and discussion

Whilst comprehensive for the six energy-intensive sectors in scope, the AIDRES database may underrepresent European industrial landscape, particularly smaller manufacturing facilities that are more adequately captured by E-PRTR. Additional blueprints would be required to extend pathway coverage to these sites for future scenario assessment, as well as to update the reference baseline pathway, which has evolved since 2018. At site level, the mixed-route scenario construction does not reflect the single-technology commitment typical of individual facility investment decisions, which limits the direct applicability of cluster-level findings to site-level planning. Renewable energy supply potentials are attributed at cluster level under an assumption of uniform spatial distribution across the region. This assumption is unlikely to hold in practice, particularly for densely urbanised clusters where land availability for renewable deployment is structurally constrained. The recently released ENSPRESO 2 dataset (January 2026) provides higher spatial (1x1km) granularity for wind potential only but was not available at the time of this analysis; its integration would be suitable for refining future iterations of this work. Comparison with alternative renewable energy potential assessments would further strengthen the robustness of the supply-side characterisation. Time resolution is the missing element for analysing electricity supply and demand matching. This could be addressed in future research by exploring the time profile module in RES2Go v1.

5.3. Future research

Some analytical extensions would materially strengthen the framework presented in this paper. Updating the reference baseline to incorporate post-2022 production data and revised capacity estimates would improve the representativeness of the intrinsic typology and its relevance to current policy deliberations. Expanding the sectoral scope to include additional industry sectors and even non-ETS sectors, guided by emerging blueprints beyond the six AIDRES sectors, would broaden the typology coverage and improve the alignment with the full set of net-zero KPIs published by DG CLIMA [12]. Also, an equivalent potential self-sufficiency analysis could be conducted for biomass, given the availability of corresponding estimates within the ENSPRESO dataset.

References

[1] European Commission. Proposal for a Regulation of the European Parliament and of the Council establishing a framework of measures for the acceleration of industrial capacity in strategic sectors and amending Regulations (EU) 2018/1724, (EU) 2024/1735 and (EU) 2024/3110. Brussels; 2026 Mar 04.

[2] Draghi M. The future of European competitiveness. Luxembourg: Publications Office; 2025. doi:10.2872/1823372.

[3] European Commission. The Clean Industrial Deal: A joint roadmap for competitiveness and the low-carbon transition. 2025 Feb 26.

[4] World Economic Forum. Unleashing the Full Potential of Industrial Clusters: Infrastructure Solutions for Clean Energies. 2025 Jan.

[5] Fischedick M. *et al.* Industry. In: Edenhofer O., Pichs-Madruga R., Sokona Y., Farahani E., Kadner S., Seyboth K., et al., editors. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press; 2014.

[6] Girardin L. *et al.* AIDRES: A Database for the Low-Carbon Transition of the Heavy Industry in Europe. In: Proceedings of the 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023); 2023; Las Palmas de Gran Canaria, Spain. ECOS 2023:2637–48. doi:10.52202/069564-0237.

[7] Hotmaps Project. The open source mapping and planning tool for heating and cooling – Available at: https://www.hotmaps-project.eu/ [accessed 24.7.2025].

[8] Dhondt N., Vandevelde L., Van Eetvelde G. A European review of the potential role of industrial clusters in the energy system when leveraging energy synergies. Energy Reports 2025;14:3298–309. doi:10.1016/j.egyr.2025.10.019.

[9] Sechi S., Giarola S., Leone P. Taxonomy for Industrial Cluster Low-Carbon Transition: An Analysis for the Italian Hard-to-Abate Industry. Energies 2022;15(22):8586. doi:10.3390/en15228586.

[10] Duvillard T., Dhondt N., Van Eetvelde G. RES2Go: Matching energy demand and supply in industry hubs in Europe. Zenodo; 2025 Nov 07. doi:10.5281/zenodo.17549998.

[11] Duvillard T., Dhondt N., Van Eetvelde G. UGent ECM RES2Go Tool. European Commission, Joint Research Centre (JRC) [Dataset]; 2025 Oct 06. Available at: http://data.europa.eu/89h/d8835f35-6d14-40d5-a55e-eaaf973aef58 [accessed (Information uncertain — requires further research?)].

[12] CLIMACT, Directorate-General for Climate Action (European Commission), ICF. European climate law-aligned transition pathways: guidance document and all 25 sectoral fiches. Luxembourg: Publications Office of the European Union; 2025. Available at: https://data.europa.eu/doi/10.2834/5592048 [accessed 27.11.2025].

[13] Yoo M-J. *et al.*. OsmoseLua – An Integrated Approach to Energy Systems Integration with LCIA and GIS. In: Gernaey K.V., Huusom J.K., Gani R., editors. Computer Aided Chemical Engineering, vol. 37. 12th International Symposium on Process Systems Engineering and 25th European Symposium on Computer Aided Process Engineering. Amsterdam: Elsevier; 2015. p. 587–92. doi:10.1016/B978-0-444-63578-5.50093-1.

[14] Cervo H., Ferrasse J-H., Descales B., Van Eetvelde G. Blueprint: A methodology facilitating data exchanges to enhance the detection of industrial symbiosis opportunities – application to a refinery. Chem Eng Sci 2020;211:115254. doi:10.1016/j.ces.2019.115254.

[15] Dhondt N., Van Eetvelde G. Cluster-level transition pathways for climate neutrality: exploring industrial symbiosis through game theory. In: Proceedings of ECOS Paris 2025; 2025; Paris, France. p. 7615.

[16] Ruiz P. *et al.* ENSPRESO – an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energy Strategy Reviews 2019;26:100379. doi:10.1016/j.esr.2019.100379.

[17] Gonzalez A.I., Zucker A., Careri F., Monforti-Ferrario F., Huld T., Badger J. European Meteorological derived High Resolution RES generation time series for present and future scenarios. JRC Publications Repository. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC105937 [accessed 17.7.2025].

[18] Mendez Alva F., De Boever R., Van Eetvelde G. Hubs for Circularity: Geo-Based Industrial Clustering towards Urban Symbiosis in Europe. Sustainability 2021;13(24):13906. doi:10.3390/su132413906.

[19] Mendez Alva F. *et al* AIDRES – Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes: methodology on industrial symbiosis. Luxembourg: Publications Office; 2023. doi: 10.2833/148445 [accessed 17.3.2025].

[20] Ortiz-Burgos S. Shannon-Weaver Diversity Index. In: Kennish M.J., editor. Encyclopedia of Estuaries. Dordrecht: Springer; 2016. p. 572–3. doi:10.1007/978-94-017-8801-4_233.

[21] Dhondt N., Mendez Alva F., Van Eetvelde G. Introducing Industrial Clusters in Multi-Node Energy System Modelling by the Application of the Industry-Infrastructure Quadrant. Sustainability 2024;16(6):2585. doi:10.3390/su16062585.