

Advanced Energy System Integration through Industry Clustering

Nienke Dhondt

Doctoral dissertation submitted to obtain the academic degree of
Doctor of Electromechanical Engineering

Supervisors

Prof. Greet Van Eetvelde, PhD - Prof. Lieven Vandeveldel, PhD
Department of Electromechanical, Systems and Metal Engineering
Faculty of Engineering and Architecture, Ghent University

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Supervisors

Prof. Greet Van Eetvelde, PhD, Ghent University

Prof. Lieven Vandevelde, PhD, Ghent University

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SUMMARY

Europe is at crossroads; its industry is under high pressure to become climate neutral while facing huge challenges to stay competitive. A key pillar of the net-zero policy is the transition to a clean energy system in order to supply industry with secure, affordable and sustainable energy, with targets set for renewable energy consumption, energy efficiency, emission reduction and green hydrogen production. However, the economic downturn and high energy prices since 2020 threaten the much-needed investments in clean technologies and process modifications, with energy-intensive industries deferring investment decisions. This leaves the energy system trapped in a waiting game. Necessary but capital-intensive network developments to prepare for the future —yet uncertain— industry needs, might not be pursued without guaranteed demand. Conversely, if networks are not adequate at times when industry needs them, investments in cleaner processes can no longer be pursued.

Leveraging industrial clusters provides a way forward. Sectors like steel, chemicals, refineries, etc. tend to co-locate to operate an extensive web of material and energy flows and even services, hence exploiting synergies that benefit all parties. Advantages of industrial symbiosis include *i.a.* the local optimisation of energy and resources, improved efficiencies, risk spreading and cost reduction due to economies of scale and scope. There still lies plenty of untapped potential for synergies to advance the energy transition in industrial clusters, from a local to a pan-European level. In the end, such collaborations are advantageous not only to the industrial stakeholders, but to the energy system as a whole, as they enhance energy and resource efficiency.

As a response to the Antwerp Declaration in 2024 —invigorated in 2025 and 2026— and the entailing Antwerp Dialogues, Europe is adjusting its climate and industrial strategy, currently still tabled as designed in pre-crisis times, towards policy that supports industry's transition and does not further undermine its competitiveness. Policymakers increasingly acknowledge the potential of industrial clusters. An illustrative example can be found in the Draghi report dated September 2024, which refers to industrial clusters as a way to enhance industrial competitiveness without compromising climate neutrality targets [1].

With the potential of industrial clusters and energy synergies widely recognised, it is still unknown how and if this potential will ever be reached, nor how scalable and replicable the benefits will be. The central objective of this PhD is to explore the role of industrial clusters in the energy system, in support of the energy transition

towards climate neutrality. The research scope encompasses the most energy- and resource-intensive industry sectors, eventually covering a significant share of total industrial energy demand and emissions. These sectors are also the largest drivers behind the energy system transformation required to remain aligned with EU ambitions. The research on industrial clusters in this work is performed at two levels: first from the point of view of clusters at the overarching energy system, and second at the cluster-level energy system to identify industrial symbiosis opportunities.

In short, the main research questions of this dissertation can be expressed as follows:

1. What role can industrial clusters play in the energy system and how will cluster dynamics transform over the coming decades?
2. How can industrial symbiosis advance energy system integration to support industry clustering and optimise business and system value?

The first research question is purpose-driven and aims to illustrate how clustering can be a way forward, partly circumventing the challenging industry and energy context. Chapter 1 presents a background on the two core concepts of this work: industrial clusters and industrial symbiosis and reflects on important past research. Chapter 2 provides the theoretical background, presenting the state of the art in research on the topic. It also encompasses a review of cluster-based policies in other regions to benchmark the European cluster approach to other continents. Chapter 3 converts the findings into a modelling framework, the Industry-Infrastructure Quadrant, that introduces industrial clusters in energy system modelling to advance industry representation in terms of spatial and technical granularity. To understand the importance of cluster dynamics in the energy system, it is necessary to model its impact. The methodology leverages existing IS tools and resources, such as industry blueprints to extract detailed information on industrial processes and cluster algorithms to define industrial clusters. Chapter 4 eventually integrates the framework in the well-known, open-source energy system model PyPSA-Eur to validate the added value of clustering in energy system models. This work limits the scope to three industry-dense countries: Belgium, the Netherlands and Germany and introduces a next step to perform a EU-wide cluster transition study. Cluster-based energy system models are proven to be useful for strategic energy planning. Governments and network operators rely on such models to take well-informed decisions about infrastructure investments based on future demand projections. To align them with clusters creates more transparency in harmonising high-level EU ambition with local intra-cluster and inter-cluster needs.

The second research question is means-driven, uncovering the industrial symbiosis potential that could catapult industrial clusters forward in their transition and optimise the energy system bottom up. Chapter 2 provides an overview of such

synergies in line with Draghi's recommendation. The work departs from the industrial symbiosis case-base from Mendez Alva [2] and enriches it with synergies involving emerging mid- and high-TRL technologies. To complete the work, chapter 5 tackles one specific industrial symbiosis case, renewables sharing. The work runs through the first three stages of the industrial symbiosis life cycle, touching upon legal, economic, spatial, technical and social disciplines and increasing awareness for technical and non-technical barriers and enablers of the synergy. Afterwards, a mixed-integer linear programming optimisation model validates the incentives to collaborate. To conclude, cooperative game theory principles such as the Equal Sharing Point, Shapley value and Nucleolus are applied to verify whether the synergy is a win-win for all stakeholders, monitoring the fair distribution of costs and benefits and the stability of the coalition.

The results of this dissertation underpin Draghi's recommendation. They illustrate how industry clustering can advance Europe's path to climate neutrality while sustaining industry's competitiveness. The work improved the understanding of the prominence of industrial clusters in sustainable energy systems and paved the way for more cluster-based initiatives and research.

Keywords: industrial cluster, energy system, industrial symbiosis, energy-intensive industry

SAMENVATTING (DUTCH SUMMARY)

Europa staat op een kantelpunt; de industrie staat onder grote druk om klimaatneutraal te worden, terwijl ze tegelijkertijd voor grote uitdagingen staat om concurrentieel te blijven. Een belangrijke pijler van het Europese klimaatbeleid is de transitie naar schone energie om betaalbare en duurzame energie voor de industrie te waarborgen. Om dit beleid kracht bij te zetten, werden doelstellingen bepaald, onder meer voor het gebruik van hernieuwbare energie, energie-efficiëntie, emissiereductie en de productie van groene waterstof. De sputterende economie en de hoge energieprijzen sinds 2020 belemmeren echter de broodnodige investeringen in duurzame technologieën en processen. Energie-intensieve industrieën stellen hun investeringsbeslissingen uit waardoor de energiesector een afwachtende houding aanneemt. Noodzakelijke maar kapitaalintensieve netwerkontwikkelingen, anticiperend op een toekomstige – maar nog steeds onzekere – industrievraag, worden te vaak niet doorgezet zonder vraagzekerheid. Omgekeerd, wanneer netwerken niet toereikend zijn op het moment dat de industrie er beroep wil op doen, kunnen investeringen in duurzame processen niet plaatsvinden.

Precies hier kunnen industriële clusters (IC) een uitweg bieden. Energie-intensieve sectoren zoals staal, chemie, raffinaderijen, enz., vestigen zich typisch in elkaars nabijheid om gezamenlijk een intensief netwerk van materiaal- en energiestromen te beheren, en zelfs diensten te delen. Dergelijke clustering faciliteert de onderlinge samenwerking en stimuleert synergieën waarvan de collectieve meerwaarde de individuele baten overstijgt. In vakjargon wordt dit industriële symbiose (IS) genoemd. Voordelen zijn onder meer de optimalisatie van lokale energie- en materialenstromen, hogere efficiëntie, risicospreiding en kostenbesparingen dankzij schaalvoordelen. Industriële clusters hebben nog veel onbenut potentieel tot samenwerking en bieden dus een open kans om de energietransitie te bevorderen, van lokaal tot pan-Europees niveau. Uiteindelijk zijn dergelijke samenwerkingsverbanden niet alleen voordelig voor de industrie, maar ook voor het globale energiesysteem, aangezien ze de lokale energie- en grondstoffenefficiëntie verbeteren.

Als reactie op de Antwerp Declaration van februari 2024 – die in 2025 en 2026 opnieuw plaatsvond – en de daaruit volgende Antwerp Dialogues, paste Europa zijn klimaat- en industriestrategie aan. Het beleid dient de industrie- en energietransitie te ondersteunen, doch terzelfdertijd het concurrentievermogen van de Europese industrie niet verder te ondermijnen. Beleidsmakers erkennen hiertoe in toenemende mate het potentieel van ICs. Een illustratief voorbeeld wordt gevonden

in het Draghi-rapport van september 2024, waarin clusters worden aangehaald als een middel om het industriële concurrentievermogen te versterken zonder afbreuk te doen aan de klimaatneutraliteitsdoelstellingen [1].

Hoewel de meerwaarde van industriële clusters en industriële symbiose algemeen wordt erkend, is het nog onduidelijk of en hoe dit potentieel ooit zal worden benut, en in hoeverre de voordelen schaalbaar en reproduceerbaar zullen zijn. De centrale doelstelling van dit doctoraatsonderzoek is dan ook het verkennen van de rol van industriële clusters in het energiesysteem, ter ondersteuning van de transitie naar klimaatneutraliteit. Hierbij ligt de focus op energie-intensieve industrieën, om zo een aanzienlijk deel van de totale energievraag en uitstoot te vertegenwoordigen. Deze sectoren zijn ook de drijvende krachten achter de transformatie van het energiesysteem die noodzakelijk zijn om in lijn te blijven met EU ambities.

Het onderzoek naar industriële clusters in dit werk speelt zich af op twee niveaus: ten eerste vanuit het perspectief van industriële clusters in het overkoepelende energiesysteem, en ten tweede binnen het clusterniveau om IS-opportunities te identificeren. De belangrijkste onderzoeksvragen in dit proefschrift kunnen als volgt worden geformuleerd:

1. Welke rol kunnen industriële clusters spelen in het energiesysteem en hoe zal hun dynamiek de komende decennia veranderen?
2. Hoe kan industriële symbiose een doorgedreven integratie van clusters in het energiesysteem bevorderen en systeemwaarde optimaliseren?

De eerste onderzoeksvraag is doelgericht en illustreert hoe clustervorming een weg vooruit biedt door de uitdagende context van de industrie- en de energiesector gedeeltelijk te omzeilen. Hoofdstuk 1 gaat in op de twee kernbegrippen van dit werk: industriële clusters en industriële symbiose, en biedt een overzicht van belangrijke voorgaande studies. Hoofdstuk 2 beschrijft de theoretische achtergrond van dit werk en biedt de stand van zaken in onderzoek naar dit onderwerp. Het omvat ook een overzicht van de beleidsvorming inzake ICs om zo de Europese aanpak te vergelijken met die van andere continenten. Hoofdstuk 3 vertaalt de bevindingen naar een modelleringskader, het Industrie-Infrastructuurkwadrant, dat ICs als concept introduceert in energiesysteemmodellen. Dit verbetert de representatie van de industrie in dergelijke modellen, zowel op ruimtelijk als technisch vlak.

Om het belang van clusters in het energiesysteem te begrijpen, wordt de impact ervan gemodelleerd. De voorgestelde methodologie maakt gebruik van bestaande IS-tools en -bronnen, zoals de industriële blueprints met gedetailleerde informatie over bedrijfsprocessen en verschillende clusteralgoritmen om ICs te definiëren. Hoofdstuk 4 past de methodologie vervolgens toe in het courante, open-source

energiesysteemmodel PyPSA-Eur om de toegevoegde waarde van clusters in energiesysteemmodellen te bevestigen. Voorliggend werk focust op drie EU-landen met een hoge industriële aanwezigheid: België, Nederland en Duitsland. Een volgende stap is het uitvoeren van een Europese studie naar clustertransities. Energiesysteemmodellering gebaseerd op clusternoden blijkt van strategisch nut voor de regionale energieplanning. Overheden en netbeheerders kunnen dergelijke modellen gebruiken om weloverwogen beslissingen inzake infrastructuur-investeringen te nemen en deze te evalueren op basis van toekomstige vragen van clusters. Door deze afstemming ontstaat er meer transparantie bij de poging tot harmoniseren van de ambitieuze EU doelstellingen met de lokale behoeften binnen en tussen clusters.

De tweede onderzoeksvraag is middelengericht en heeft tot doel het potentieel van industriële symbiose bloot te leggen. Het werk wil aantonen hoe synergieën een duidelijke impuls kunnen geven aan industriële clusters in transitie en zo het energiesysteem vanuit de basisvraag kunnen optimaliseren. Hoofdstuk 2 biedt een overzicht van dergelijke synergieën, in overeenstemming met de aanbevelingen van Draghi. Dit onderzoek vertrekt van de lijst met synergieën opgesteld door Mendez Alva [2] en vult deze aan met nieuwe opties, b.v. als gevolg van opkomende technologieën die een gemiddeld-tot-hoge TRL-status bereikt hebben. Hoofdstuk 5 behandelt een typische casus van industriële symbiose: het delen van hernieuwbare energie. De studie doorloopt de eerste drie fasen van de levenscyclus van IS, waarbij juridische, economische, ruimtelijke, technische en sociale disciplines aan bod komen om het bewustzijn te vergroten voor technische en niet-technische hindernissen en stimulansen. Vervolgens valideert een optimalisatiemodel de samenwerking. Principes uit de coöperatieve speltheorie, zoals het Equal Sharing Point, de Shapley-waarden en de Nucleolus, worden toegepast om na te gaan of de synergie een win-winsituatie oplevert voor alle partners, met aandacht voor een eerlijke verdeling van kosten en baten, en de stabiliteit van de coalitie.

De conclusies van dit proefschrift onderschrijven de aanbevelingen van Draghi. Ze laten zien hoe industriële clusters kunnen bijdragen om Europa dichterbij klimaatneutraliteit te brengen, terwijl ook het concurrentievermogen van de industrie kan behouden blijven. Dit onderzoek versterkt het inzicht in de rol van industriële clusters binnen een duurzaam energiesysteem en opent de weg naar meer initiatieven en onderzoek ter zake.

Kernwoorden: industriële cluster, energiesysteem, industriële symbiose, energie-intensieve industrie

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ABBREVIATIONS

AC-DC	Alternating Current – Direct Current
AEL	Alkaline Electrolysis
AIDRES	Advancing Industrial Decarbonisation by assessing the future use of Renewable EnergieS in industrial processes
BE-ETF	Belgian Energy Transition Fund
BF-BOF	Blast Furnace - Basic Oxygen Furnace
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Usage and Storage
CEFIC	European Chemical Industry Council (in French Conseil Européen des Fédérations de l'Industrie Chimique)
CES	Community Energy System
CHP	Combined Heat and Power
CID	Clean Industrial Deal
CRF	Capital Recovery Factor
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DEN	Distributed Energy Network
DRI	Direct Reduced Iron
DSO	Distribution System Operator
DSR	Demand-side Response
EAF	Electric Arc Furnace
EC	European Commission
ECM	Energy and Cluster Management research group

ECSP	European Chemical Sites and Parks Platform
EED	Energy Efficiency Directive
EIIs	Energy Intensive Industries
EIP	Eco-Industrial Park
ENTSO-E&G	European Network of Transmission System Operators for Electricity and Gas
EPOS	Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis
E-PRTR	European Pollutant Release and Transfer Register
ESM	Energy System Model
ESP	Equal Sharing Point
ETS	European Trading System
EU	European Union
GIS	Geographic Information System
GT	Game Theory
H2020	Horizon 2020
H4C	Hubs for Circularity
HAC	Hierarchical Agglomerative Clustering
HVAC	Heating, ventilation, and air conditioning
HVDC	High-Voltage Direct Current
IAA	Industrial Accelerator Act
IC	Industrial Cluster
IDEES	Integrated Database of the European Energy System
IEA	International Energy Agency
IED	Industrial Emissions Directive
IIQ	Industry-Infrastructure Quadrant
IRENA	International Renewable Energy Agency
IS	Industrial Symbiosis

JRC	Joint Research Centre
LCOE	Levelised Cost of Energy
LESTS	Legal Economic Spatial Technical Social
MEA	Monoethanolamine
MILP	Mixed-Integer Linear Programming
MOE	Molten Oxide Electrolysis
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NIMBY	Not In My BackYard
NSP	North Sea Port
NUTS	Nomenclature of territorial units for statistics
OPEX	Operating Expenditures
ORC	Organic Rankine Cycle
P2P	Peer-to-peer
P2X	Power-to-X
P4Planet	Processes4Planet partnership
PE	Polyethylene
PEA	Poly-Ethyl-Acetate
PIECE	Potential for Industrial Energy Clustering in Europe
PPA	Power Purchase Agreement
PPP	People, Planet, Profit
PV	Photo Voltaic
RE	Renewable Energy
REC	Renewable Energy Community
RED	Renewable Energy Directive
RISERS	Roadmap for Industrial Symbiosis standardisation for Efficient Resource Sharing
SES	Shared Energy Storage

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SME	Small and Medium-sized Enterprises
SMR	Steam Methane Reforming
SPIRE	Public-Private Partnership in the European process industries sectors of ceramics, cement, non-ferrous metals, chemicals, minerals, refining, steel, water and engineering
TIC	Total Installed Cost
TRILATE	TRILateral research for optimal Investments in Adequate cross-border infrastructure
TRL	Technology Readiness Level
TSA	Total Site Analysis
TSO	Transmission System Operator
VNR	Vlaamse Nutsregulator
VPP	Virtual Power Plant
VRES	Variable Renewable Energy Sources
WEF	World Economic Forum

CHAPTER 1 INTRODUCTION

The introduction chapter illustrates the relevance of and motivation behind the research done. Firstly, it describes the current industrial landscape in Europe and important policy measures from the recent past. Secondly, it presents a comprehensive background on the two core concepts of this work: Industrial Clusters (ICs) and Industrial Symbiosis (IS). To complete, the objectives, scope and contributions of this work are outlined.

1.1 INDUSTRIAL POLICY LANDSCAPE

Europe is at crossroads. Its industry is under high pressure to become climate neutral while facing huge challenges to stay competitive. Especially since the Green Deal of 2019 [3], the climate neutrality ambition has dictated EU's industrial strategy. The formal statement to cut down the continent's emissions to net-zero by 2050 was translated into legally binding targets; 55% emissions reduction by 2030 when comparing to 1990 (referred to as Fit-for-55), and climate neutrality by 2050. In 2025, the EU Commission (EC) added an additional, intermediate target of 90% emissions reduction by 2040, again comparing to 1990 [4]. These overarching targets triggered reformations in other policy packages and instruments. First of all, there is the Emissions Trading System (ETS). Under the principle "the polluter pays", ETS comprises a carbon market of emission allowances. Within the scope of ETS are power and heat generation, industrial processes and aviation. Maritime transport is included since 2024 and from 2027 onwards also road transport and buildings enter ETS 2. The cap on allowed emissions lowers continuously, which aims to incentivise investments in renewable energy, improve efficiency of installations and clean technologies in a cost-effective manner. As a consequence of the Green Deal, ETS ambition was sharpened in 2023 to remain aligned with the Fit-for-55 target. To prevent carbon leakage, where firms shift production abroad to avoid carbon costs, undermining emission reductions, ETS allocates free allowances to Energy-Intensive Industries (EIIs). As part of the Fit-for-55 package, such free allowances are planned to be phased-out by 2034 to further stimulate investments in mitigation technologies. [5] To compensate, the Carbon Border Adjustment Mechanism (CBAM) has been developed and is installed from 2026 onwards. In an attempt to level the playing field with other regions that do not impose carbon taxes, CBAM puts a price on the emissions of certain imported goods produced outside the EU. The scope of

products includes cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. [6] Reforms in line with the Green Deal and the ETS revision also triggered adaptations in other policy packages, like the Renewable Energy Directives (RED) and Energy Efficiency Directives (EED). Comparing RED II (2018) with RED III (2023), the target share of renewables by 2030 increased from 32% to 40% in 2021, and through the REPowerEU plan to 42.5%. Additionally, sector-specific goals were determined. For industry, a mandatory target was set on hydrogen, of which 42% should categorise under renewable fuels of non-biological origin, and industry must increase the use of Renewable Energy (RE) per year by 1.6%. [7] Similarly for the EED, the initial energy efficiency improvement target of 32.5% by 2030 (2018) was sharpened to 39% (primary) and 36% (final energy consumption) [8]. Within the EC, discussions are ongoing to tune down some of the targets listed above to lower the stress on EU industry.

For the industry sector to meet the targets listed above, an overhaul towards clean technologies is deemed necessary, at first supported by the Green Deal Industrial Plan and the Net-Zero Industry Act [9,10] but early 2026 invigorated by the Industrial Accelerator Act (IAA) [11]. Multiple mitigation techniques are being developed and rolled out in parallel. The main pathway building blocks are increased material and energy efficiency and circularity, feedstock switch, fuel switch, new processes (e.g., electrification), carbon capture and storage (CCS), and, as a last resort, offsetting emissions [12]. According to a recent report from McKinsey, energy-intensive industry sectors like steel, cement, chemicals and fertilisers are only at the start of the transition, with insufficient maturity of the required clean processes and many interdependencies in the transition steps such as to expand renewables capacity [13]. Technology unreadiness is just one of barriers industry nowadays faces in Europe. In February 2024, the EU industry assembled for the first time under the Antwerp Declaration to raise awareness of the need for an industrial policy that supports industry's transition and does not further undermine its competitiveness [14]. The list of hurdles included *i.a.* the incoherent and complex regulatory framework, the administrative burden of over reporting, the lack of public funding to de-risk investments, high energy prices, permitting difficulties for necessary infrastructure and overestimated demand for net-zero products. Through the Antwerp Dialogues, discussions were invigorated between policy makers, sector federations and companies [15]. Their consensus on specific aspects of the original declaration, such as climate, energy and electrification, aimed to support future decision making. Remarks concerning the lack of European competitiveness led to the publication of the highly anticipated Draghi report in September 2024, which paints a comprehensive picture of the challenges faced by EU industry and formulates policy recommendations for the next EC [16].

Draghi's message resonated with the newly established EC in December 2024: commitments were formulated in the strategic agenda for the period 2024-2029 and the mission letters to the new commissioners-designates stipulated to work on an improved industrial policy and Clean Industrial Deal [17,18]. In January 2025, the EC renewed these commitments by transforming the Draghi report into a roadmap: the Competitiveness Compass [19]. On February 26 2025, the EC released the Clean Industrial Deal (CID): A joint roadmap for competitiveness and decarbonisation. It addressed the competitiveness concerns raised by struggling energy-intensive industries that reconvened in Antwerp again that year for the second edition of the Antwerp Declaration. The recently established EC aims to harmonise industrial policy with the climate neutrality targets, which were reconfirmed in the CID. [20] One of the elements of the CID is the Affordable Energy Action Plan, which aims to lower energy bills in tandem with promoting the energy transition in an Energy Union [21]. To lower the administrative burden, the EC launched the Omnibus package with simplifications in sustainable finance, CBAM registrations, and the corporate sustainability reporting directive [22]. Later, also sector-specific action plans emerged for the automotive [23], steel and metals [24], and the chemicals industry [25,26].

More than one year after the Draghi report and the launch of various plans and acts in response to industry's call to action, the challenging context in EU remains worrisome, if not even more acute. Market conditions have degraded, trade tariffs have gone up, and tangible results from the updated industrial and energy strategies are limited or welcomed as too little too late [27]. In February 2026, representatives of EU EIs gathered once more in Antwerp for a call to action, followed by the dedicated EU Council summit held in Alden Biesen the day after.

The economic downturn and high energy prices since 2020 threaten the much-needed investments in clean technologies and process modifications, with energy-intensive industries deferring investment decisions. Recent conflicts in the Middle East introduced another energy crisis, resulting in strongly increasing fossil fuel prices in Europe. The industrial context cannot be uncoupled from the energy context and a hesitating industry sector leaves energy system developments trapped in a waiting game. A crucial prerequisite for successfully completing the energy transition cost-efficiently and timely is a guaranteed and secure supply of affordable and renewable energy and resources for process industries [28]. Beyond investments in R&D&I for new, clean technologies, the supporting infrastructure and supply chains must be adjusted and enhanced. The one cannot go without the other, and the selection of a mitigation pathway strongly relates to the availability, accessibility, and affordability of clean energy sources. This implies the presence of infrastructure for electricity and molecules (hydrogen, CO₂, etc.) [29]. According to a

report on challenges and opportunities for EIs in the energy transition, a lack of infrastructure is recognised as a critical hurdle by the EU Committee on Industry, Research, and Energy, and its progress will strongly influence the future of energy-intensive process industries in Europe [30]. Electrification will increase the pressure on currently existing electrical grids and, to implement hydrogen and CCS technologies, in most cases new infrastructure will still have to be built. Typically, decisions on the future layout and operation of these backbone grids are out of the scope of industry but in the hands of grid operators. Where to expand infrastructure with new or stronger segments? How to provide for future energy needs, not only from industry? Which road will each of the EI sectors take in the range of mitigation options, and how will it locally affect the supply chains for energy and feedstock? Grid operators are confronted with many questions and challenged with the exercise to balance decisions with investment costs and risks of stranded assets. Necessary but capital-intensive network developments to prepare for the future—yet uncertain—industry needs, might not be pursued without guaranteed demand. Conversely, if networks are not adequate at times when industry needs them, investments in cleaner processes can no longer be pursued. On top of this, time is of the essence as the permitting, construction, and development of grid (as well as industry) adjustments take time. The first efforts should focus on readying the supply backbones to answer future industry and societal needs.

Despite the numerous challenges, it is important to balance the pros and cons, and notice the silver lining in this transition. Draghi often refers to the current transition as an opportunity for Europe to become a frontrunner in clean technologies and production [16]. From his longlist of measures, today hardly 10% has been fully implemented [31]. One of the recommendations focuses on regional green industrial clusters around energy-intensive companies, which is fully embedded in the work of this thesis [1]. According to Draghi, clustering can boost the uptake of local renewable energy and improve the business case of necessary infrastructure developments. In addition to competitiveness, leveraging industrial clusters also provides a solution to the chicken-and-egg situation between industry and energy system developments by jointly optimising both ends on a cluster level.

1.2 INDUSTRIAL CLUSTERS

Usually, ICs accommodate an above-average number of enterprises in an area, resulting in an increased density of local economic activity, thus significantly contributing to employment in the region. ICs typically operate an extensive web of energy and material flows, provided by efficient and effective infrastructure tailored to the local needs. The composition of an IC can vary, both in sector representation

as in size, ranging from small and medium-sized to large enterprises, including the most energy-intensive process industries. Also geography strongly influences the cluster characteristics, determining for example whether or not a cluster is waterborne, port-anchored, well-connected via pipelines and/or has access to renewable energy sources [32].

Such cluster approach is not new. In fact, industry clustering is of all times. Chemparks are a typical example, like ChemCologne which restructured accordingly already in the mid-90s [33]. A total of 63 chemical parks can be found across Europe, mainly concentrated in the North-West (see Figure 1) [34]. In addition to chemical parks, the European Commission defined fourteen industrial ecosystems as part of its industrial strategy in 2020, each encompassing a different value chain to potentially centre a cluster around [35]. A number of organisations depart from this cluster concept, with the common ambition to increase the total of IC initiatives through the replication of success stories. The World Economic Forum (WEF) collects knowledge on cluster cooperation for economic growth, employment and energy transition worldwide, and formulates strategies and insights in their annual reports [36]. They are currently active in 40 clusters, in twenty countries spread over five continents [37]. The key European public-private organisation that highlights IC benefits is A.SPIRE [38]. One of their initiatives, Hubs For Circularity (H4C), successfully searched for a method to identify and screen existing ICs in Europe [39]. The H4C consortium established a community of practice for skill sharing and knowledge transfer [40]. Completing the shortlist, the European Cluster Collaboration Platform also offers tools and centralises information and data since 2015 [41].

The reasoning behind the cluster focus is found in the numerous benefits that result from closer cooperation in an industry hub. According to the WEF, opportunities resulting from the co-location of companies include scaling effects, risk spreading, infrastructure sharing, resource and energy optimisation through supply and demand aggregation and increased efficiency through circularity [37]. Such benefits of scale and scope are typical examples of industrial symbiosis, the collaboration of individual organisations to achieve a win-win situation [42].



Figure 1 Map of all EU Chemparks (orange circles indicate multiple Chemparks), source ECSPP [34].

1.3 INDUSTRIAL SYMBIOSIS

Derived from the Greek words *syn*, *bios* and *ergon*, which can be translated to together, life and work, the terms *symbiosis* and *synergy* refer to the joining of forces [42]. Inspiring examples can be found in the field of biology, where the behaviour of organisms with respect to each other is subject to the conceptualisation of *symbiosis*. Contradictory to a successful synergy in industry that is supposed to lead to a win-win situation for all parties, not all symbiotic interactions in biology result in mutual benefits. Martin *et al.* define six possible relationships by combining all possible individual outcomes: stakeholders can receive an advantage, a disadvantage, or remain neutral from the interaction [43]. Mutualism occurs when all stakeholders experience a benefit from the synergy, and Weng *et al.* further specify between symmetric and asymmetric mutualisation, or in other words, the equal or non-equal distribution of advantages and disadvantages [44].

The term *industrial symbiosis* officially comes into play “when industries cooperate to gain benefits that exceed what can be achieved individually” [42]. Whether they are part of the same sector or cross-sectoral, companies can decide to collaborate in terms of materials and energy streams and services, driven by a wish, need or duty [2,39,42]. Advantages of IS include the local optimisation of energy and resources,

improved efficiencies, risk spreading and cost reduction due to economies of scale and scope. Research on IS often refers to ICs as excellent environments for initiating such synergies between stakeholders due to their proximity [2,45]. The shared academic history between IC and IS dates back to the principles of industrial ecology introduced in the 90s, but since a few years the topics have increased in popularity again through the circular economy movement and resource efficiency efforts [42]. Therefore, literature often refers to ICs as eco-industrial parks, with Kalundborg in Denmark as a textbook example [46]. Of course, being located in an IC is no necessary prerequisite to engage in a synergy, as for example the exchange of materials and waste can cover large distances, exceeding the cluster outlines.

Given the growing interest from policy and decision makers in the potential of IS and ICs, tools and resources that facilitate such initiatives are much desired. Maqbool *et al.* describe the development cycle of IS as a sequence of five stages: IS identification, assessment, barrier removal, implementation and follow-up (see Figure 2) [47].

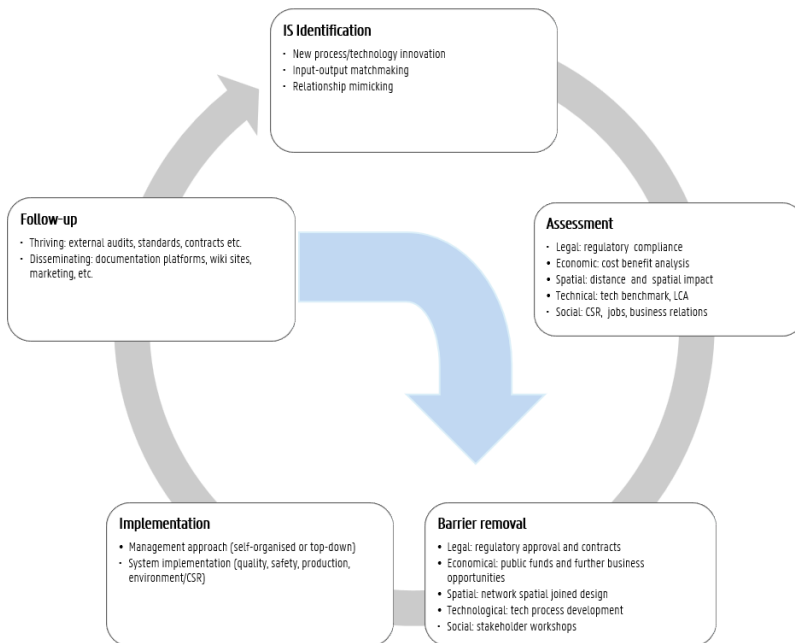


Figure 2 Five stages of the IS life cycle, source [2], adapted from [47].

The first step is symbiosis identification, which can be approached in three ways: through process innovation creating new input-output flows, existing sink-source matchmaking between sectors, or the replication of known IS success stories [2]. Once an IS opportunity is spotted, an assessment of barriers and enablers, both technical and non-technical, tailored to the cluster's context is performed. Any

identified hurdles can be addressed, removed or compensated before actual IS implementation in step 4. Management schemes organising the synergy can be separated in three categories: self-organised, third-party support or top-down. Once implemented, a continuous improvement cycle needs to be installed to monitor the proper functioning of the synergy, flagging new or emerging barriers threatening the collaboration. [47]

Recent work in the field of IS has resulted in tools and resources to support practitioners throughout the entire life cycle. To facilitate the IS identification step, industrial blueprints and IS case-bases can be consulted (see Sections 1.3.1 and 1.3.2). To gather a holistic view on the potential barriers and enablers to IS implementation in a cluster, a LESTS survey can be applied (Section 1.3.3).

1.3.1 INDUSTRY BLUEPRINTS

The matchmaking procedure between input and output flows (material and energy) to see where exchanges are possible, heavily relies on detailed information of industrial processes. Sharing such data however is not straightforward, as it often comprises commercially sensitive information, especially in very competitive processing industry sectors like chemicals and steel. Data sharing conflicts between companies hinder the implementation of IS already at its very first step of the life cycle, as the potential to collaborate might never be uncovered. The EPOS project, short for “Enhanced energy and resource efficiency and performance in process industry Operations via onsite and cross-sectorial Symbiosis”, aimed to make industry more (cost-)efficient, competitive and sustainable by facilitating cross-sectoral IS. Within the scope were five key sectors in EU industry: cement, chemicals, minerals, steel and engineering. By creating virtual profiles of typical production processes, from now on referred to as industrial blueprints, the data sharing issues are circumvented and useful information can be transferred across sectors. [48]

Cervo describes in detail how a blueprint is created. The goal is to collect a set of relevant, sufficiently but not overly detailed information to represent a given process. Figure 3 summarises the scope of a blueprint, with data on a process unit available in four categories: thermal and electrical energy flows, material inputs and outputs and main services. Data consistency and reliability are verified through the closing of key energy and mass balances using a Pareto approach, thus only including the major flows in the system. Blueprints serve for multiple stakeholders to come to a common understanding of what a process requires and delivers. Their goal is not to perfectly describe a process, but rather to give an approximate representation. After all, perfectly corresponding to the real-life process(es) on which a blueprint was based no longer circumvents data sharing conflicts. In the end,

all blueprints undergo an aggregation and anonymisation step by mixing public and real-site data. When applying a blueprint, the user can easily define the production output using a scaling factor. [49]

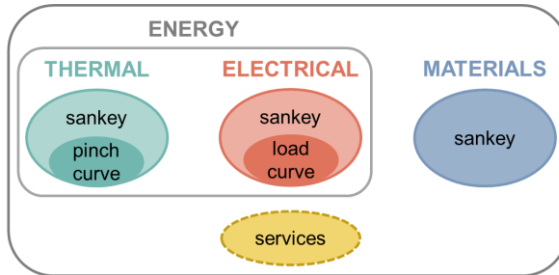


Figure 3 Schematic overview of a blueprint, source [49].

To identify IS opportunities in and between blueprints, visualisations on the thermal energy (Sankey and pinch curves), electrical energy (Sankey and load curves), and material flows (Sankey diagram) and services (pie chart) aid users in the matchmaking procedure. Afterwards, users can go one step further and combine multiple blueprints into a larger superstructure, building towards a virtual cluster profile.

EPOS created blueprints for the refinery, chemicals (synthesis and polymerisation), steel, cement and minerals sectors [48]. As a follow-up project, AIDRES (Advancing industrial decarbonisation by assessing the future use of renewable energies in industrial processes) applied the blueprint concept to find pathways towards climate neutrality for six process industries and their respective demand for renewable energy and feedstock. The scope is extended to include more processes and added the sectors glass and fertilisers. For each process within scope a reference production route was selected, and alternative routes were explored in accordance with typical mitigation strategies, e.g. electrification, hydrogen, carbon capture (CC), biomass etc. Each route was modelled with OSMOSE, a tool developed by the IPESSE research group at EPFL to model and design complex integrated energy conversion systems for process integration and optimisation [50]. The tool delivers information on a per-ton-of-product basis of a process' energy demand per carrier, raw material input, emissions and investment and operational costs [51]. In addition to the blueprint models, a geographic database of EU production sites and their capacities was constructed [52]. The per-ton output of the blueprints was then scaled to this database to generate future energy and feedstock demand estimates on a NUTS3-level. Most recently, the TRILATE project also picked up the blueprint concept to validate the infrastructure needs of ICs in the trilateral region Belgium – the Netherlands – North Rhine-Westphalia to provide industry with secure, affordable and sustainable energy [53,54].

1.3.2 IS CASE-BASES

According to the IS life cycle, synergies can be initiated through the replication of success stories. To centralise all knowledge on existing IS cases, Mendez Alva developed a case-base of recent works and created sector profiles for steel, chemicals, and cement [2,55]. Such an IS case-base gives a useful overview of all collaboration options between two or more processing industries. At the core sits the MAESTRI database with 242 IS cases, for each case describing the input and output sector and the resource exchanged [56]. A second public database completing Mendez Alva's repository is SCALER, which reports on 100 synergy schemes including a techno-economic and environmental assessment [57]. The blueprint matchmaking procedure in the EPOS project generated 21 generic IS cases with a high replication potential in ICs, including the mutualisation of PV and wind power installations, local energy optimisation, exchange of waste heat and demand side response [48]. The case-base was applied in AIDRES as part of the methodology to assess the IS potential of EIs in EU ICs [58], and is currently subject to a standardisation of IS practices in the EU RISERS (2025) project [59].

After removing duplicates and filtering on EIs, Mendez Alva's case-base consists of over 100 IS cases, of which 68 energy-related [2]. Three distinct categories are made with respect to energy synergies: renewable electricity, fuel substitution (for heat generation) and heating and cooling networks. In addition, Mendez Alva also identifies two general IS cases applicable to any IC, no matter its composition or size [58]. The first one is shared renewable energy generation capacity (photovoltaics or wind turbines) and the second one is infrastructure related to carbon capture for storage or usage. The latter can also be argued for hydrogen infrastructure.

1.3.3 LESTS SURVEY

It is one thing to identify a potential synergy, but to implement it in a cluster is another matter. Even if an exchange of waste or resources or mutualisation of infrastructure is technically feasible, non-technical barriers still need to be overcome for IC initiatives and synergies to succeed. Observations from existing and reported examples illustrate that the benefits of IS are often held back due to the lack of a legal framework, accountability, transparency and trust between stakeholders, unclear economic benefits, spatial constraints as a result of regional planning, or missing support or acceptance from local communities [42]. Van Eetvelde *et al.* developed the LESTS survey roughly 25 years ago, which includes Legal, Economic, Spatial, Technical and Social indicators to assess the viability of a synergy in a multidisciplinary manner. By means of a pentagon, the stability and effectiveness of IS are visually represented on all five dimensions, as can be seen in

Figure 4. As a practical basis for IS initiatives in eco-industrial parks, the LESTS methodology was published as a book series [60–62].

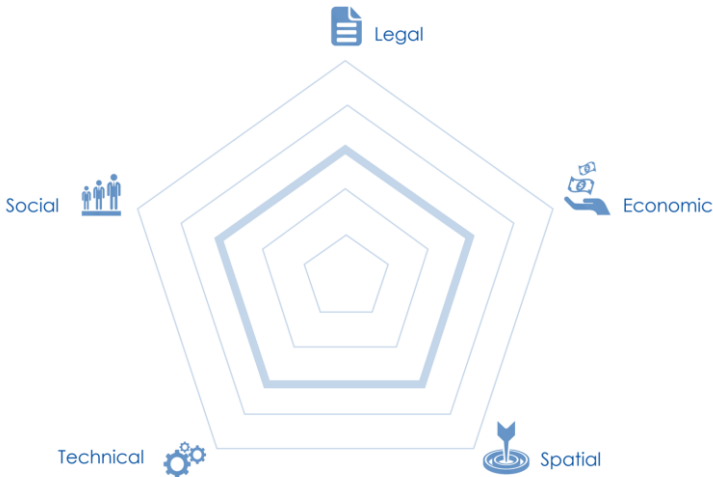


Figure 4 LESTS pentagon, source [2].

During the EPOS project, LESTS was applied 1) to map the IS potential in ICs, 2) to systematically screen the synergy on all five dimensions towards implementation and 3) in a later stage to improve the organisation of cross-sectoral IS initiatives [2]. The latter refers to the IS life cycle and more precisely the iterative feedback loop that occurs beyond early stage IS, positioning LESTS as a management support tool for its entire lifetime.

Following the example of the LESTS survey, other strategic analysis frameworks like PESTL (Political, Economic, Social, Technological, Legal) were developed to evaluate the multidisciplinary nature of IS [63].

1.4 THESIS OBJECTIVES, SCOPE AND OUTLINE

1.4.1 OBJECTIVES AND RESEARCH QUESTIONS

The central objective of the present work is to explore the potential of industry clustering and industrial symbiosis in advancing the energy transition towards climate neutrality while enhancing industrial competitiveness. The research scope encompasses the most energy- and resource-intensive industry sectors in line with the EC's definition of EII, eventually covering a significant share of industrial energy demand and emissions [28]. In 2023, industry represented 24.6% of EU's final energy consumption, mainly from (petro-)chemicals (21.5%), non-metallic minerals (14.5%),

paper & pulp (14.3%), food & drinks (12.9%) and iron & steel (10.6%) [64]. Roughly two thirds of the final energy demand that year was supplied as electricity and natural gas. These sectors are also the largest drivers behind the energy system developments required to remain aligned with EU ambitions.

The research on ICs and IS in this work is performed on two levels: one looking from the point of view of clusters to the larger energy system, and the second looking at the energy system within the cluster to leverage energy synergies. Organising the research questions in this way nicely reflects the intermediate position ICs take in the larger energy system. Clustering offers a way to harmonise high-level energy strategies with local needs and opportunities. The research questions of the thesis are:

- What role can industrial clusters play in the energy system and how will cluster dynamics transform over the coming decades?
- How can industrial symbiosis advance energy system integration to support industry clustering and optimise business and system value?

The first research question is purpose-driven and illustrates how clustering can be a way forward, circumventing the challenging industry and energy context described in Section 1.1. Chapter 2 provides the theoretical background, presenting the state of the art in research on the topic. It describes the mutual dependency between the energy system and industry's transition, addresses the main challenges like grid congestion, and illustrates how clustering and effective collaboration within can result in system-wide benefits. Chapter 3 converts the theory into a modelling framework that introduces ICs in energy system modelling (ESM). After all, to understand the importance of cluster dynamics in the energy system is to illustrate its impact through modelling. Chapter 4 eventually integrates the framework in a well-known ESM, PyPSA-Eur, to validate the added value of clustering in energy system models.

The second research question is means-driven and uncovers the potential of industrial symbiosis to catapult industrial clusters forward in their transition and optimise the energy system bottom up. In the comprehensive overview of synergies that could bring system-wide benefits, as presented in Chapter 2, a reflection is already included on the barriers and enablers to the collaboration. To complete the work, Chapter 5 tackles one specific IS case: shared renewables. The work runs through the IS life cycle and touches upon all five LESTS disciplines, increasing awareness for barriers and enablers to the synergy, before modelling to validate the incentives to collaborate.

1.4.2 RESEARCH OUTLINE AND OVERVIEW OF WORK DONE

The challenges industry faces while transitioning towards climate neutrality are a driving force for researchers to help find suitable pathways and viable technology solutions. Whereas past research used to study industrial sectors separately, the current trend is to leverage the geospatial proximity of companies and optimise the transition on a cluster-level in symbiosis. Aware of the untapped potential of ICs and IS, this work addresses some of the research gaps and strengthens the link with the energy system.

The cluster concept is leveraged to improve industry representation in energy system modelling for strategic energy planning, harmonising high-level EU ambition with local developments. This thesis introduces a novel framework that not only tackles the spatial dimension by aligning the energy network nodes with ICs (peer-reviewed article [65]), but also the technical dimension by creating flexible and detailed industry cluster transition pathways based on blueprints (conference article [66]). To verify the added value of the framework, it is implemented in PyPSA-Eur, a widely-used, sector-coupled model (conference article [67]). Hence, the thesis contributes to the open-source ESM research community.

A thorough literature review on the state of the art in research on energy synergies is performed in line with Draghi's recommendation to focus efforts on ICs (peer-reviewed article [68]). The overview of energy-related IS cases includes, in addition to the ones already reported by Mendez Alva, synergies involving emerging mid- and high-TRL (Technology Readiness Level) technologies. In the period between the publications of MAESTRI (2017) - EPOS (2019) - SCALER (2019) and now, certain clean technologies that were left out of the scope then have reached higher TRL levels or even market uptake. A complete overview of all clean energy technologies and their TRL score is annually updated and published by the International Energy Agency (IEA) [69]. Hence, this work already reflects on how these future, clean technologies can be leveraged in symbiosis, identifying new ways to collaborate. More specifically, the implementation of industrial high-temperature heat pumps, energy storage (e.g. through batteries) and electrolyzers or other forms of hydrogen production, including supporting infrastructure, deserve additional attention.

One of the presented IS cases, renewables sharing using photovoltaics (PV) and wind, was already identified by the EPOS and AIDRES projects as a generic case applicable to any cluster. This work deepens our understanding of the drivers and barriers to the synergy using the LESTS framework, MILP optimisation and game theory (GT) principles in an attempt to validate the incentives to collaborate.

Table 1 presents an overview of the work and the research novelty of each chapter. The list of publications related to this thesis can be found in Appendix 1. An overview of all datasets and resources used in the work can be found in Appendix 2.

This work served the TRILATE project (BE-ETF), which analysed the need for energy transport infrastructure to guarantee the supply of affordable and clean energy to industrial clusters in Belgium and, by extension, its neighbouring regions [53]. The project included a dedicated work package on the role of ICs in the energy system and the potential of IS.

Table 1 Overview of the work done and research novelty.

chapter	research focus	author's publications
1 Introduction	<ul style="list-style-type: none"> Describes the current industry and energy landscapes. Presents an overview of recent and important works related to the key concepts of this thesis: IC and IS. 	NA
2 Industrial clusters in the energy system	<ul style="list-style-type: none"> Performs a literature review on energy synergies. Identifies potential of IS and ICs in the energy system. Supports Draghi's recommendation to focus efforts on ICs. 	I, II, III, IV, VIII
3 Role of clusters in energy system modelling	<ul style="list-style-type: none"> Presents a novel framework introducing ICs in ESM using the Industry-Infrastructure Quadrant (IIQ). Develops a methodology for cluster-aligned multi-node selection in ESM. Develops industrial cluster transition pathways using blueprints to improve technical industry representation. Screens relevant and compatible ESMs. 	V, VII
4 Industry transition modelling in PyPSA-Eur	<ul style="list-style-type: none"> Applies the IIQ framework to PyPSA-Eur to improve spatial industry representation. 	VI, VII

	<ul style="list-style-type: none">• Leverages industry cluster transition pathways to improve technical industry representation.• Compares default to updated industrial energy demand assumptions and effects on the energy system.	
5 IS case study – shared renewables	<ul style="list-style-type: none">• Performs a LESTS review of the IS case.• Converts IS theory into MILP modelling.• Applies game theory to investigate stakeholder strategies, cost and benefit distribution and coalition stability.	VI

CHAPTER 2 INDUSTRIAL CLUSTERS IN THE ENERGY SYSTEM

Concerns about the competitiveness of European industry in the context of current EU climate policy led to the publication of the Draghi report in 2024 [1]. One of his recommendations is to install regional green industrial clusters around energy-intensive companies. Industrial clusters hold untapped potential to advance the energy transition and reach climate neutrality. However, it is still unknown how and if this potential will be reached, nor how scalable and replicable the benefits will be. This chapter aims to explore the potential role of industrial clusters in the energy system by exposing the research state of the art in academic literature. The Draghi report identifies three benefit categories, each corresponding to typical industrial symbiosis cases: improved investment cases by shared local low-carbon energy generation, improved investment cases by shared infrastructure, and improved energy flows for increased resource efficiency [16].

The first three sections include the literature review that was performed in line with the above benefit categories to understand the enablers and barriers of potential synergies and their impact on the energy system. Most cluster initiatives in the past focused on carbon capture and hydrogen, overlooking electrification as transition pathway [70,71]. This work discusses energy synergies, with a primary focus on the electric power system and system integration.

The fourth section assesses the scalability by positioning the European industrial clusters in the larger renewable energy landscape. Finally, to illustrate the global interest in ICs and the importance of a level playing field, a brief reflection is made on references to ICs in the policy of non-European regions. The chapter has been published as a review paper with the aim to further advance knowledge on the importance of ICs in the energy system and to stimulate the implementation of energy synergies. The review points to future research, some of which are further explored within this thesis (Chapter 5).

2.1 SHARING LOCAL LOW-CARBON ENERGY GENERATION

Global investments in RE increase year after year, a trend that is expected to continue in the second half of this decade, as can be seen from the latest IEA reports [72]. The capacity growth is mainly allocated to solar PV, followed by on- and offshore wind power. Together, they cover 95% of all expected renewable capacity growth by 2030 [72]. Especially for PV, its adoption is enforced by decreasing module costs (prices are more than halved since 2023), social acceptance, favourable

policies and shorter permit timelines [72]. In times dominated by high energy prices, investing in PV installations offers a way for residential, commercial and industrial consumers to lower their energy bills.

The wind power sector is recovering from recent financial and supply chain difficulties, and the capacity addition rate is expected to pick up again in the period 2024-2030 [72]. However, if Europe wants to deliver on its renewables ambition in time, deployment of on- and offshore wind must accelerate immediately. Hence, initiatives like the revised renewable energy directive [7], wind energy action plan [73] and grid action plan [74] induce changes in permitting procedures, auction programs and grid layouts to create more favourable investment conditions. Other REs like hydropower, ocean energy, bioenergy, geothermal and concentrated solar power represent a small share of the renewables expansion. The remainder of this subsection focuses on the implementation of PV and onshore wind in ICs.

According to a briefing paper of E3G, the share of electricity in the final energy consumption of industry is expected to increase from 33% to 41% by 2030, and the total electrification potential is estimated around 90% of the remaining industrial energy demand [71]. ENTSO-E and ENTSO-G recently published their Ten-Year Network Development Plans based on national trends, which predict 42% of the total industrial energy demand in 2030 to be electricity [75]. Electrification of industry mostly implies fossil fuel substitution in heat supply and other utilities [76]. Compared to residential heating, the wider range of temperature requirements in industry makes electrification of heat less straightforward, but not impossible. The IEA keeps track of the TRLs of various electrification technologies, old and new. Multiple electrical heating technologies already reach market uptake (TRL 9-10), both for low and high temperatures [69,71]. Direct electrification of industrial processes is also in development, for example in steel, cement and chemicals, but these technologies only exist as prototypes with TRLs 5-6 and are not expected to reach market uptake in the near future [69]. Electrifying core processes implies drastic changes in the layout and operation of processing plants that are typically heavily integrated. Hence, electrifying process heat and other auxiliaries offers the most realistic mid-term option for energy decarbonisation and should be prioritised over the core processes. To cover the rise in electricity demand, either additional onsite production, more import from the grid, or a combination of both are needed. A paper by Dossow *et al.* reports European statistics on onsite industrial power generation, which accounted for 9% of all EU electrical power generation, and covered 36% of all industrial power demand in 2017 [77]. The share of local production for industry should ideally increase, or at least remain equal, as it would otherwise significantly add to the grid loading in areas sensitive to congestion. 60% of the onsite generated power for 2017 originated from fossil fuels and only 25% from renewables [77]. While in the years to follow RE installations at industry sites

will have expanded to cover more than 25%, the need for a further uptake of RE in ICs for the energy transition to succeed is confirmed.

In addition to climate neutrality, electrification can offer production benefits in terms of yield, quality, controllability and safety [76]. However, operating costs being higher than fossil-based alternatives due to high electricity prices, on top of the needed capital investments for site integration and technology adaption, hinder this promising transition [71]. Investing in solar and wind power can provide a way for industry to reduce the electricity bill, and on top of this, can increase energy self-sufficiency and sustainability [78,79]. Sorknæs *et al.* expect a growing utilisation of wind power and PV in industrial processes due to electrification [80]. However, investing in and integrating RE is not straightforward. The permitting procedure is long and complex, grid congestion accumulates due to inadequate grid infrastructure, available space is rare and even more limited due to NIMBY effect, delays in development and commissioning or, even worse, project cancellation reduce the reliability of investments in Europe and increase the cost on top of the already high upfront capital needed [72,78,79]. EIs operating in very competitive markets characterised by thin profit margins have reservations about investing in RE if there is even a slight risk of increasing operational costs instead of reducing [79]. Such risk aversion is especially the case for individual, smaller companies with limited access to capital and resources, including a lack of workforce expertise [79,81]. As a result, industry misses out on the opportunity for long-term energy cost savings. The intermittency of renewables poses an additional technical limitation for processes depending on a constant and reliable power supply. The implementation of variable RE requires the adaptation of existing processes, or the addition of storage facilities and increased demand-side flexibility [76,78,79]. Section 2.3 discusses optimal energy flows for increased efficiency and also reflects on flexibility from the perspective of an industrial cluster.

The barriers listed above typically prevent industry from investing in a RE portfolio. However, such challenging circumstances can be mitigated when companies collaborate. Sharing PV or wind power capacity is a form of energy symbiosis already put forward by the EPOS project [2,48,82]. The project's main objective was to enable cross-sectoral IS in five key processing sectors: steel, cement, chemicals, minerals and engineering. Supply and demand matching of energy and materials between these sectors resulted in 21 generic IS cases, including #05 wind power sharing and #07 solar power cogeneration [48]. Participants of the synergy can benefit from increased renewable electricity usage, distributed operational and investment costs, shared workforce expertise, reduced CO₂ emissions and improved site integration in the cluster [46,48,81]. The need for affordable and renewable electricity is common to all process industry sectors, not only those targeted in EPOS. Hence, cases #05

and #07 are applicable to all types of industrial clusters, no matter the size or composition. This is in line with one of the recommendations from the AIDRES project, commissioned by the European Commission to assess the future use of renewable energies in industrial processes and currently under revision, and included a study of the IS potential in energy-intensive ICs [58].

Collaborating within ICs to build a RE portfolio is considered a promising way forward. The next step in this work is to consult academic literature to confirm this statement and to expose what is already known about the presented synergies and its implementation in ICs. In order to collect relevant papers, the keywords search options in Scopus, Google Scholar and Web of Science are used to perform a semi-systemic literature review. The list of keywords varies for each section in the paper, but it in general includes terms such as “industrial cluster”, “industry hub”, “industrial park”, “industrial symbiosis” etc.

Maes *et al.* put forward RE-based strategies for energy autonomy in ICs, illustrated by case studies in Flemish industrial parks [46]. Compared to internal energy optimisation, energy clustering requires more time and expertise, but collective production can also include maintenance, energy monitoring and carbon management services to compensate for the extra effort needed. “For business parks that operate in unity stand more chances for energy autonomy based on local renewable energy sources” the authors conclude [46]. Hentschel *et al.* investigate how renewable energy cooperatives (REC) in the Port of Rotterdam can create added value for local businesses and further promote RE deployment [83]. A well-designed REC offers a strong business case with clear financial and societal targets and is organised through a separate legal entity that functions as matchmaker and communicator between all port stakeholders. As part of their action plan, the authors recommend the port to launch a roof renting scheme for jointly operated PV installations to initially launch the REC, as the implementation is straightforward and its effectiveness will stimulate other initiatives. The paper from Eslamizadeh *et al.* departs from a management perspective and discusses industrial community energy systems (CES) for collective renewable energy generation, as an alternative to individual or centralised generation. Based on their literature review and outcomes of the survey distributed in an Iranian IC, it turns out that proper awareness of potential benefits, corporate reputation and trust between the stakeholders are decisive factors for industry’s willingness to participate in industrial CES [78]. According to the authors, industrial CES are not as prominent in academic literature compared to residential CES, which have already reached market demonstration phase [78]. Butturi *et al.* explore RE symbiosis schemes within eco-industrial parks and with nearby urban areas to promote the efficient use of natural and economic resources. The paper does not perform any modelling itself, but

formulates ideal energy system model design features, such as multi-objective optimisation to reflect the trade-off between costs, emissions, and even social aspects, and sufficient temporal and technology detail, including other energy carriers (e.g. heat) [81]. The authors agree with Eslamizadeh *et al.* on the fact that, despite all academic efforts to demonstrate the benefits of shared RE within ICs, progress and implementation stay behind. An explanation can be found in the potential downsides of collective RE, typically linked to ownership and management dilemmas. For example, fairly distributing the costs and benefits of the synergy can be challenging but is typically achieved by scaling each company's contribution to the RE portfolio according to its size or energy demand. Secondly, a possible exit of one of the stakeholders can jeopardise the profitability of the synergy for all others [78,84]. The work of Lechtenberg *et al.* clearly states that coalitional benefits for all synergy stakeholders are only truly sustainable if these are fairly allocated and stable [85]. The latter ensures the coalition is not likely to break down into separate alliances. Chapter 5 discusses RE sharing in a cluster in more detail, in line with the IS life cycle, and develops a modelling framework with GT to validate the added value and verify the fairness and stability of the collaboration.

As an alternative to local low-carbon energy generation, ICs can source RE from outside the cluster through power purchase agreements (PPAs). It is a type of contract where consumers agree to buy RE for a certain period at a fixed price [86]. PPAs give access to large volumes of electricity, e.g. originating from nearby offshore wind farms which, according to Rattle *et al.*, enhances the electrification of ICs [70]. According to the IEA renewables 2024 report, corporate PPAs give the second largest push in utility-scale RE capacity growth, next to competitive auctions [72]. They are especially interesting for large electricity consumers that want to derisk their energy procurement, given the wholesale price volatility. It is not within the scope of this work to discuss individual consumers that sign PPAs. However, if a cluster agrees to sign a PPA together, it categorises as collective purchase of RE [81]. Very little research exists about collective PPAs by an IC. The most relevant source is by Chen *et al.* and investigates different procurement strategies for a group of buyers through GT [86]. Separate, agent-based and joint negotiation are compared in terms of installed capacity and stakeholders' preference using Nash bargaining-based economic models. It certainly is an interesting topic for future research. For example, multiple experts state that small-to-medium-sized consumers or those that lack experience have difficulty to enter the PPA market because of the complex administration or because they have insufficient negotiation power [86,87]. Chen *et al.* present collective PPAs as a means to lower barriers for smaller consumers [86]. Policy-wise, the planned EU Electricity Market Reform also aims to straighten the path for smaller consumers to take part in PPAs [72]. For a more detailed overview

of the different types of PPAs and respective properties, readers of this work are referred to dedicated literature on the topic.

2.2 SHARING ENERGY INFRASTRUCTURE

As mentioned before in the introduction of this thesis, ICs are characterised by an extensive web of material and energy flows, which is reflected in the scale and complexity of the supporting infrastructure. Multiple pathways towards climate neutrality exist, each of them driving different supply chain developments in the operating framework of an existing IC. In fact, industry transition and infrastructure developments find themselves stuck in a vicious circle: industry can only transition if the supporting infrastructure is in place and vice versa. Illustrative examples of potentially large-scale networks connecting clusters in the future are the build-out of the so-called hydrogen backbone in Europe and the various carbon removal programs connecting CO₂ capture installations with offshore storage sites. Furthermore, the increased integration of renewable energy and the expansion of power infrastructure and energy storage will be crucial to reach the targets. Joining forces in infrastructure developments offers a way out of this waiting game, improving the business case of infrastructure developments for both the system operators as well as industrial clients. This section discusses four main infrastructure categories: power infrastructure, heat grids and conversion technologies, hydrogen infrastructure and CO₂ infrastructure for Carbon Capture, Usage and Storage (CCUS). The discussion of the categories is completed with a view on energy storage technologies. The digital infrastructure to facilitate smart operations within an IC is the fifth and final category.

2.2.1 POWER INFRASTRUCTURE

The first and main direct abatement pathway in this review covers electrification and related developments in the electrical energy system. This section elaborates on power infrastructure linked to ICs. The installation of shared local low-carbon energy generation, more precisely PV and wind turbines, was the topic of the previous section. In addition to the generation capacity, there is also a need for distribution of the electrical power to the industrial consumers. A vast amount of academic literature handles local industrial electricity grids, otherwise referred to as industrial microgrids. Typically, an industrial microgrid is defined as a small grid connecting and managing generation units, industry consumers and storage units, and is either connected to the grid or operates in island mode. It is a comprehensive electricity utility that goes beyond merely distributing power, but has the ability to

actively manage power flows and apply storage strategies [46]. According to De Clercq *et al.* and Ahmed *et al.*, industrial microgrids prove to be useful in the replacement of traditionally fossil-based production units by RE and reduce losses in distribution and transmission grids [88,89]. Plenty of development already went into tools that optimise capacity sizing and system configurations. However, some researchers flag that, so far, too little consideration was given to the social, institutional and organisational aspects of industrial microgrids [78,89]. This is crucial for a successful establishment in ICs.

For a guaranteed and secure supply of qualitative power, industry is connected to the power grid, either individually or through an industrial microgrid. There is an upper limit to the amount of power that can be exchanged with the power grid, namely the power transfer limit, and its cost is scaled with the capacity it can handle [90]. Section 2.1 already mentioned that investments in grid capacity, both micro- and transmission-level, are needed to resolve the grid congestion issues to accommodate new RE connections. The expected raise of electricity in the final energy demand of industry will also induce a need for grid reinforcements, especially in ICs where EIs are concentrated. An example can be found in the Port of Rotterdam where by 2030 an additional 5 GW of electricity from the expansion of offshore wind parks will arrive onshore, yet the existing power transmission infrastructure is considered inadequate to host the incoming RE supply, even after fulfilling the local industrial electrification needs [91]. Necessary high-voltage grid projects face similar challenges as RE, namely long project timelines, difficult permitting procedures with strong opposition and high costs (e.g. Ventilus in Belgium [92]). Another aspect that hinders infrastructure developments is the lack of space. This is especially the case in ICs that are known to be very dense, with very little ground surface left available. Space limitations form a barrier to any type of infrastructure, from PV installations and wind turbines, to grids and storage [71]. Maes *et al.* present microgrids as the strong opportunity to assess the IC as a whole instead of each company individually, aggregating and optimally allocating the available space (both roof and ground) to the desirable mix of generation, storage and distribution technologies [46].

A recent trend in academic literature is the hybridisation of RE projects to include storage facilities to better cope with the intermittency of RE and mismatch with demand. The objective of this work is to investigate the synergy potential of such storage facilities and to see how they can be integrated in a cluster. An overview of other ways for ICs to offer flexibility to the grid is part of section 2.3. Shared energy storage (SES) can offer benefits in terms of reduced costs, additional income by providing grid services, fewer RE curtailment and thus higher utilisation rate and lower emissions, lowered dependency on grid imports and grid expansions, and

improved reliability of the power backup system compared to smaller, individual units [93–97]. Thanks to the split of ownership, control and use of SES resources, the capacity allocation can be frequently renewed to remain optimal and to avoid underutilisation [97]. Chen *et al.* apply the SES model to port clusters [95]. Wind curtailment, total OPEX and energy storage OPEX drop by 9%, 7% and 33% respectively in their shared model. Their findings confirm that while separate energy storage facilities suffer from underutilised capacity, collaboration significantly alleviates such wastage. Neri *et al.* apply mixed-integer linear programming to introduce microgrid-based support for RE and battery storage [98]. Compared to the case without battery SES, RE utilisation increased by 7% and both the total system cost and LCOE decreased by 9%. Within an IC or industrial microgrid, SES presents the opportunity to aggregate a group of smaller, idle energy storage resources and allows them to take part in the electricity market [97]. Li *et al.* however predict difficulties with respect to the ownership and operation of SES, characteristic for IS initiatives but hindering its implementation [99]. This is confirmed by Neri *et al.*, who consider the information-exchange aspect and distrust to be the main issue [98]. The paper from Zhai *et al.* departs from large-scale PV systems on industrial building rooftops and searches for the optimal shared energy storage capacity and energy flow scheduling to achieve full RE deployment and maximal self-consumption [100]. Findings indicate that the introduction of peer-to-peer (P2P) energy trading within the cluster reduces the need for SES, and conflicting interests might even prevent the SES synergy to deliver a win-win situation.

Batteries are quickly catching up as their capacity addition rate surpassed pumped hydropower storage [101]. The main electrochemical storage technologies are, ordered by decreasing TRL level, lithium-ion, redox flow, sodium-ion, metal-air and zinc-manganese oxide [69]. While many recent papers opt for batteries, plenty of other technologies exist with varying orders of magnitude of storage capacity and discharge time [102,103], and the list continuously grows as more innovative technologies reach market uptake [69]. The list of battery technologies above can be completed with mechanical storage options like compressed or liquid air, flywheels or gravity-based storage systems. Electrical power can also be converted into chemicals, e.g. to produce hydrogen using electrolysis and afterwards the conversion into synthetic fuels, e.g. e-methane, ammonia, methanol, or reversion back to electricity using gas turbines or fuel cells. If the energy is to be reconverted back to electricity, it is important to remain aware of the round-trip efficiency since every energy conversion induces losses. Storing electricity as hydrogen, produced using an electrolyser (efficiency 60–80%), and afterwards reconvert it back using a fuel cell (efficiency 40 – 60%) results in a round-trip efficiency of 24 – 48% [102]. The efficiency can be improved by recovering the waste heat from the conversion processes. In comparison, reported round-trip efficiencies for pumped hydro,

compressed air, flywheel and lithium-ion battery are respectively 70-85%, 60-80%, 90-95% and 90-95% [102].

In the context of microgrids, batteries seem to be the most prospective option. However, sector coupling and energy conversion technologies allow power to be stored as heat, hydrogen, or other energy carriers. In terms of thermal storage, sensible heat is stored using molten salts, water and solid materials, but also latent heat leveraging the phase change of materials is an interesting option given the higher storage density [69]. Thermochemical storage technologies that use reversible endo/exothermal reactions are also emerging, but remain for now at low TRL levels (early prototypes) [69]. The paper of Guelpa *et al.* suggests that future electrical, heat, natural gas and hydrogen energy infrastructures should be integrated in one large, multi-energy system for optimal management in the cluster [103]. Decision makers should also follow a multi-energy system approach when selecting a suitable energy storage methodology. For example, one of the outcomes of the work of Berg *et al.* is that thermal energy storage is preferred over battery storage in their reported urban-industrial symbiosis case study [104]. Li *et al.* have designed a collaborative operational model for hydrogen SES capable of reducing the OPEX (-9%), the amount of grid-purchased electricity (-12.7%) and carbon emission costs (-25%) of a cluster [105]. The values between brackets are indicative values resulting from the research paper.

2.2.2 HEAT INFRASTRUCTURE

A large part of EIs' energy consumption is related to the high-temperature heat demand of processes [106]. Figure 5 from Lutsch *et al.* nicely illustrates the relative share of each temperature range in the total heat demand (including process heat, space heat and hot water) for multiple industry sectors [107].

Whereas in the past thermal energy was primarily delivered using fossil fuels, nowadays a shift is ongoing towards cleaner heat supply technologies. Direct electrification of heat comprises heat pumps, electric boilers, electric ovens and furnaces. Hydrogen as a fuel can be seen as indirect electrification of heat. Biomass, biogas and waste remain alternative renewable fuel sources, especially for high-temperature heat demand. Recent studies also investigate the potential of integrating geothermal energy [108], nuclear power (using small modular reactors) [108,109] and solar thermal energy [108,110-112] to meet industry's heat demand in the future. Which supply technology is most suited to replace fossil fuels depends i.e. on the required temperature level and the total heat demand [113]. Recently, the EC has shown much interest in small modular reactors and has set the target to install the first demonstrator plants by 2030 [114].

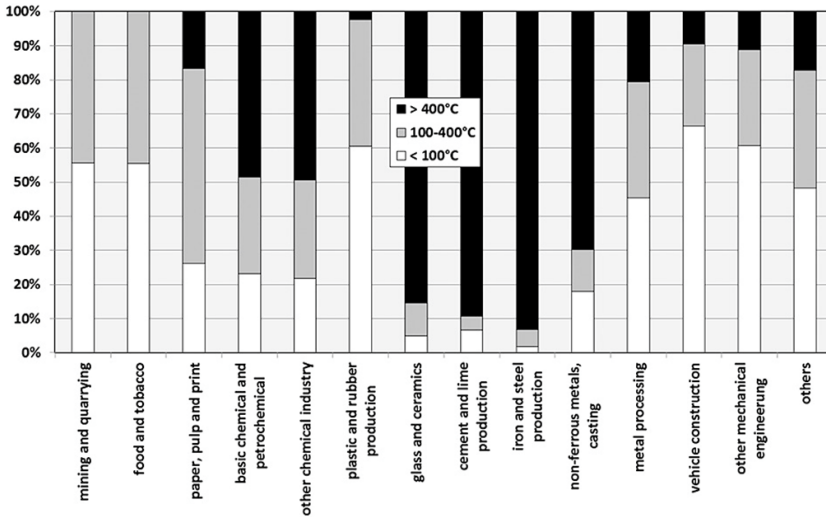


Figure 5 Share of temperature ranges in the total heat demand for various industry sectors. From [107].

ICs have experience with collaborating in terms of thermal energy. The EPOS project presents district heating and industrial heat networks as generic IS cases and acknowledges solar heating as a facilitating RE technology [48]. Industrial heat networks connect multiple demand centres with centralised or decentralised sources and transport hot water or steam. An illustrative example is the Ecluse network in the Port of Antwerp that transports steam from waste-to-energy plants to a handful of chemical plants in the Antwerp cluster [115].

The emerging technologies listed above impact the way future heat grids will be designed and integrated in the clusters and how existing heat grids and combined heat and power (CHP) plants will be modernised. The work of Jiang *et al.* compares multiple industrial park heating designs with electric boilers, solar thermal and high-temperature heat pumps [116]. Poudel *et al.* investigate electricity and district heating from small modular reactors [117]. In addition to the clean technologies, further integrating the recovery of waste heat available in the cluster aligns with the efficiency first principle and is key for heat grid initiatives these days. Emerging clean technologies can recover low-temperature waste heat, hence advance site integration in the cluster and improve energy efficiency. This concept is further explored in section 2.3.1 on optimal energy flows.

2.2.3 HYDROGEN INFRASTRUCTURE

Another transition pathway that gained interest, in addition to electrification, albeit until now failed to deliver, is hydrogen. Preferably the molecule is obtained through

steam methane reformation (SMR), with an efficiency ranging between 60 and 85%, combined with carbon capture or by electrolysis, which, depending on the type of electrolyser, has an efficiency ranging between 62 and 90% [118,119]. The relatively high electricity and natural gas prices in Europe add to the OPEX of hydrogen production. Where possible, direct electrification is cheaper given the higher efficiency of electrification technologies. Industrial feedstock and fuel switching towards hydrogen or hydrogen-derivates also requires large-scale joint investments throughout the entire value chain, again adding to the costs. Hydrogen's physical properties, low volumetric energy density (0.0107 MJ/L at room temperature) despite its good energy-to-weight ratio (120-142 MJ/kg), small molecule size causing leakages, and its chemical properties, hydrogen embrittlement of metal structures, make storage and transmission highly challenging [119]. Efficient transportation requires the hydrogen to be compressed, liquefied or chemically bound into for example ammonia or methanol, and [119].

A European manifesto on hydrogen technologies and systems declares that clusters should be prioritised in early industrial deployment [120]. With the support of the hydrogen valleys initiative that aimed to establish renewable H₂ supply for local demand, EU expected 50 local clusters to be operational or in development by 2030 [121]. However, such unrealistic expectations were adjusted as the EU hydrogen market is also challenged by the uncertain investment climate, regulatory difficulties and inflating costs. This lowers the incentive for hydrogen demand from industries outside the petrochemical sector and puts the buildout of hydrogen transport and other supporting infrastructure on hold [122].

One of the recommendations by the IEA to overcome these hurdles is to form cross-sectoral alliances for skill- and knowledge-sharing and improved coordination of hydrogen production, transport and consumption: an approach well-suited for ICs. Zabik *et al.* compare individual versus collaborative transformation strategies in a steel IC with the opportunity to mutualise hydrogen infrastructure (electrolyser, storage and pipeline), in addition to PV and battery storage [123]. The results indicate no change in technology selection within the individual sites, but the installed capacities alter and the implementation timing of hydrogen technologies advances. In the case with IS, indicative total cost is lower (-7%), mainly due to reduced fuel costs (-17%) and despite the increase in investment (+26%) and CO₂ costs (+9%). To fairly allocate these costs, Zabik *et al.* compare two approaches: proportional to fuel consumption and by applying the Shapley value. The latter is an element from game theory and according to the authors best suited to this IS case. Chapter 5 applies a similar methodology, also leveraging GT principles, to another IS case.

2.2.4 CO₂ INFRASTRUCTURE

Another, end-of-pipe technology that requires significant infrastructure investments is carbon capture for storage or utilisation, or CCUS in short. The most important technologies for carbon capture are physical and chemical absorption, adsorption, cryogenic processing, membrane separation and chemical looping [124]. Especially in process industry sectors that are characterised by direct emissions, CCUS can be of interest if the CO₂ streams are not diluted or dispersed. Second to RE, CCUS is presented by the AIDRES project as a generic IS opportunity relevant to all energy-intensive ICs [58]. Barriers of CCUS implementation include the selection, cost, energy consumption and placement of a capture technology, which may need a purification step depending on the concentration of the stream, and all logistics related to the transport, buffering and final storage of CO₂ which in their turn also add to the costs. According to Leonzio *et al.*, the cost and energy consumption of carbon capture technologies should drop and the capture efficiency should increase for CCS to become more widespread [124]. A study on the energy requirements for CCS applied to a cement plant and a coal power plant reports 0.802 and 1.159 MJ/kg CO₂ respectively [125]. Another source calculated for both a coal and natural gas power plant the energy share that would go to CC infrastructure, corresponding to respectively 20-25% and 15% of the total energy produced [126].

An example of shared CCUS infrastructure can once again be found in the Port of Rotterdam with the Porthos project. A pipeline runs between refineries, hydrogen producers and other energy-intensive industries and collects CO₂ for offshore storage in an empty gas field in the North Sea [127]. Even if local storage is not an option due to the geographical context of an IC, collaboration in terms of capture, treatment and transport infrastructure remains a relevant opportunity, as large scale storage platforms arise elsewhere in Europe, e.g. Northern Lights in Norway in addition to Porthos in the Netherlands [128]. In the Port of Antwerp, the Kairos@C initiative also aims to mutualise CCUS infrastructure, but final investment decisions were recently postponed despite massive funding from Europe [129]. The decision support tool of Wissocq *et al.* explores transition pathways of industrial clusters to distinguish no-regret from non-viable projects [130]. The case study of a French IC, comprising fifteen heterogeneous sites connected by a shared hydrogen and oxygen network, illustrates the importance of future infrastructure mutualisation, primarily CCS, to reach the climate neutrality targets.

2.2.5 DATA SHARING INFRASTRUCTURE

In order to make an industrial microgrid smart and allow for energy system management, digital infrastructure needs to be rolled out in parallel [98]. Energy

system management implies the coordination of an energy strategy in an IC, either centralised or decentralised using local controllers. Butturi *et al.* prefer the latter to cope with the different ownerships of loads, generation units and storage resources [81]. Information and communication technologies, sensors, internet of things, big data and artificial intelligence all have the potential to contribute to an improved and more sustainable energy system. Data sharing infrastructure unlocks cross-sector and cross-actor benefits by resolving grid congestions, reducing RE curtailment and avoiding under-utilised flexibility [131]. P2P energy trading for example allows individual prosumers to conduct energy transactions, but it requires sensors, controls and trading platforms that connect all generators, users and storages to control the multi-direction flow of both energy and information [132]. Virtual power plants (VPPs) coordinate a large number of typically smaller electrical units that, without aggregation, would not meet the requirements to provide grid services or retrieve access to wholesale markets [133]. A VPP can include distributed energy resources, dispatchable or not, energy storage, electric vehicles and other controllable loads, and is virtually managed through software and data sharing infrastructure as if it were one large power plant [133,134]. Europe promotes such digital services that allow for P2P trading, demand and supply aggregation and VPPs, as long as the data sharing infrastructure is secure, reliable and preserve data privacy [135]. From the calls for evidence by the Transmission System Operators (TSOs) for future EU energy security it is clear that strengthening the power system requires coordinated and secure data sharing and guarded digital infrastructure [136].

2.3 OPTIMISING ENERGY FLOWS FOR ADVANCED RESOURCE EFFICIENCY AND FLEXIBILITY

The third category of industrial cluster benefits, according to Draghi, relates to the local optimisation of energy and resources to improve efficiency [1]. The scope in this thesis is extended to include flexibility as well. It is a given that flexibility will be necessary to accommodate more variable RE in the energy system. Hence, the second part of this section elaborates on industrial flexibility and potential synergies.

2.3.1 IMPROVED ENERGY EFFICIENCY

The mission letter addressed to the EU commissioner-designate of energy calls to action in terms of renewable energy, energy storage and demand flexibility deployment [18]. But first and foremost, it reminds policy and decision makers to

hold on to the energy efficiency first principle. This way, stranded assets can be avoided as the future energy supply chains are scaled with respect to what will actually be needed [137]. Increasing energy efficiency lowers the demand for primary resources, leading to cost savings and eventually reduces CO₂ emissions. Pursuing it should not be limited within one facility or site, as more optimisation opportunities present themselves on a cluster-level. According to Butturi *et al.* traditional energy exchanges and energy recovery is one of the four means to implement a collective energy strategy within an IC [81]. One of the EPOS generic IS cases presents cluster integration by recovering waste energy for energy optimisation [48]. In addition, EPOS also identified a second generic IS case specifically targeting waste heat recovery and heat grids. In terms of academic literature, this type of energy efficiency improvement within clusters is the most studied topic. A general conclusion by Hackl *et al.* on energy efficiency investments is that within ICs consisting of several plants with different owners, there is little knowledge about the energy and material flows of others [138]. Only when a complete overview of energy and material streams within a cluster is given and considered for energy recovery and integration, can energy efficiency within the cluster be maximised. This complicates the task as it comprises a large number of thermal process and utility flows. A second hurdle is data sharing. The feedstock and energy inputs and outputs of a process are sensitive commercial information. Through industry blueprints, the EPOS project circumvented this data sharing issue [48]. Thanks to their level of detail, blueprints are perfectly suited for research on material and energy efficiency improvements in ICs. Cervo *et al.* applied the blueprint concept to a refinery to facilitate the data exchange of IS identification [139].

Hackl *et al.* propose the Total Site Analysis (TSA) methodology to spot energy efficiency gains beyond single chemical processes [138,140]. They applied the methodology to a Swedish chemical cluster, which led to a range of heat integration solutions, some straightforward to implement and others very complex due to the strongly interdependent systems. Bungener *et al.* continued the work on TSA for the optimal heat integration within an IC, and focused on the optimal design of an utility system taking into account the various operating modes within a cluster [141]. Such a multi-period TSA tests the resilience of proposed solutions as they will have to deal with heat demand and supply variations. Hackl *et al.* also emphasize that beyond technical feasibility, other factors like aligning long-term cluster development plans, ownership agreements, and data sharing are crucial for the successful collaboration within a cluster [138]. The work of Huang *et al.* gives an overview of waste heat recovery technologies like heat exchangers, heat pipes, boilers, refrigeration and power cycles, heat storage and heat pumps [142]. The latter can be further classified into temperature levels. While low temperature heat pumps are widely implemented by now (TRL 9), high-temperature heat pumps with sink

temperatures between 90 – 160 °C are still in demonstration phase (TRL 7) [69]. Their uptake will create new opportunities to collaborate within a cluster. For example, the work of Vieren *et al.* illustrates the use of high-temperature heat pumps in different industrial heating network configurations to recover waste heat available at low temperatures (<100°C) [143]. The study of the North Sea Port IC reports a large amount of low-temperature waste heat (676 MW) available for upgrading to meet the cluster's high-temperature heat demand (118 MW), which could potentially reduce CO₂ emissions by 70-80% compared to a natural gas boiler. Organic Rankine cycles (ORC) (TRL 9) is another waste heat recovery technology that is capable of converting low- to medium-temperature heat into electricity. Kermani *et al.* investigate the recovery potential of ORCs in industry through the synthesis of a comprehensive superstructure suitable for process integration [144].

Waste heat recovery is not the only focal area for energy efficiency improvements. Equipment upgrades and the electrification of processes and utilities also have a strong potential to lower the primary energy consumption. According to a recent study by McKinsey, in addition to industrial heating and cooling equipment, a large potential remains in the replacement of building HVAC systems and lighting [145]. IS opportunities linked to energy efficiency entail auditing and financing services, and the installation, operation and maintenance of new equipment to replace old appliances.

A third way to improve energy efficiency is by changing the feedstock of a process. The paper industry, for example, saves a significant amount of energy and water when recycling paper waste compared to virgin paper production [146]. The principle also holds for *i.a.* recycled glass [147], aluminium [148] and steel [149]. Such energy savings rely on the proper waste collection and recycling and is rather a synergy between the processing industries and communities, otherwise referred to as urban-industrial symbiosis.

2.3.2 FLEXIBILITY

Flexibility by a storage asset was already part of the previous section that discusses mutualised infrastructure developments, including shared energy storage. SES is not the only means for flexibility within an IC. Demand-side response (DSR) by industry is often presented as a potentially significant contributor to flexibility in the EU power system. Industry may alter its electricity consumption by adjusting production profiles, switching to other energy carriers, altering auxiliary equipment and sources, applying dynamic power purchasing etc., while in some cases providing grid stability services. However, the concept is easily over-simplified, and loses touch with the complexity of an industrial site. A statement often heard in industry is

'electrification first, flexibility second', illustrating the significance of the challenges related to the energy transition in industry.

Expectations for industrial flexibility need to remain within reach. A recent white paper by Cefic, the European Chemical Industry Association, on industrial flexibility in the chemical industry clearly outlines industry's role when it comes down to providing flexibility [150]. Most industrial processes, especially in the chemical sector, run at baseload with an optimal feedstock and energy efficiency [150,151]. Altering the production rate not only affects these efficiencies but also influences emissions and production costs. Technical limitations of dynamic production includes the ramping rates of machines (motors, compressors etc.), the strongly integrated nature of processes exchanging intermediate products and their balanced heat integration. Providing flexibility by oversizing the production capacity or installing hybrid heating would result in additional investment costs. The total capacity of on-site storage of intermediates, especially for chemicals, is legally bound for safety measures [150]. Non-technical limitations include logistics, planning of personnel, business case uncertainties, delivery commitments, limited available space for new installations and so on [150,152].

According to Tennet, the Dutch electrical transmission system operator, companies with a significant electricity consumption operating in a noncontinuous production process that can buffer heat or products, like food and drinks, are best suited for DSR [152]. Ranaboldo *et al.* also believe that the biggest flexibility potential lies in industries with thermal inertia and buffers within the production process [153]. Riese *et al.* and Pierri *et al.* on the other hand consider the continuity and intensity of electricity demand in baseload industry as a positive aspect, as it can serve as an energy sink for RE surplus [154,155]. Zwaenepoel *et al.* performed an assessment of flexible electrical resources in industrial facilities based on load lists and process flow diagrams [156]. The list of equipment is categorised based on function and location in the process to get a better understanding of the potential, e.g. many similar devices with a relative small power can add up to a significant share of the total load. Zwaenepoel *et al.* eventually defined three categories for electrical resources: core processes, utilities and generation (e.g. backup power installations) [156]. The authors propose the utilities category as best suited for flexibility purposes. Baetens *et al.* limit their flexibility assessment of process industry to the utilities category, more precisely electric heating and cooling [157]. It is clear that assumptions on flexibility potential cannot be generalised and each site or process needs a proper assessment. The Cefic paper does agree that on-site (energy) storage and generating capacity in general do have flexibility potential, e.g. where parts of a back-up system have capacity available for grid support. It also avoids some of the challenges linked to DSR mentioned above.

Table 2 Overview of the synergies covered by the literature review per section in line with Draghi's recommendation.

section	synergy
sharing local low-carbon energy generation	<ul style="list-style-type: none"> renewable energy mutualisation: solar and wind power collective power purchase agreements
sharing energy infrastructure	<ul style="list-style-type: none"> microgrids peer-to-peer energy trading shared energy storage battery, heat, molecules heat grids and conversion technologies small modular reactors hydrogen infrastructure mutualisation CO₂ infrastructure mutualisation data sharing infrastructure
optimising energy flows for advanced resource efficiency and flexibility	<ul style="list-style-type: none"> waste (energy) recovery heat, materials (high-temperature) heat pumps organic Rankine cycles coordinated equipment upgrades HVAC, lighting, auditing non-virgin material input demand-side response

The proper context on industrial flexibility should be taken into account when assessing the potential synergies involving DSR in ICs. DSR is part of the EPOS generic IS case-base. It can optimise electricity sourcing in ICs, balance demand, reduce grid loading, enable more RE and lower costs or create additional revenues, and reduce emissions [48,153]. Ranaboldo *et al.* give an overview of the barriers for industry to participate in DSR, including lack of knowledge, data infrastructure, uncertain business cases, regulatory conflicts or market barriers and organisational challenges [153]. To overcome these barriers, the authors present enabling technologies, like energy-aware scheduling, aggregators and digitalisation. Caprara *et al.* investigate how collaboration through flexibility aggregation can be beneficial for an IC in terms of cost reduction (-10%), energy security (-7% imports from grid) and RE penetration [158]. Su *et al.* developed a planning optimisation model that considers the synergy of demand responses and flexibility in an industrial park [159]. Within their model, DSR is made available by electric loads, thermal and cooling loads and storages, and electric vehicle charging stations. This is in line with the proposal of Zwaenepoel *et al.* to focus efforts on utilities rather than core processes. Subramanyam *et al.*

designed a local flexibility market platform tailored for eco-industrial clusters to support industry in their active role in the local flexibility market [160]. Their tool is able to detect optimal flexible hours for down-regulation, which incentivises industry and eventually leads to cost savings. Sadjjadi *et al.* review industrial smart grids that encompass heat pumps based on their operation and design for flexibility [161]. Their findings confirm that there is a flexibility potential in such systems, especially if accompanied with thermal storage, but points out the rather constant and high-temperature heating need from industry that hinders flexible operation compared to fluctuating residential demand.

Table 2 gives an overview of the synergies covered by the literature review in line with Draghi's recommendation to focus efforts on industrial clusters. The review primarily focusses on energy synergies, the power system and system integration.

2.4 SCALABILITY

The previous sections discussed how industrial clusters can leverage synergy opportunities to advance the energy transition and increase EU industry competitiveness in line with Draghi's recommendations. This section briefly reflects on the scalability and replicability of such synergies by positioning European clusters in the renewable energy landscape. Referring to the introduction, industrial clusters are defined by their composition (types of industry sectors present) and geography (area coverage, access to RE sources, port infrastructure, etc.). By combining the outcomes of former research projects, the spread of ICs over Europe and their overlap with regions with abundant RE sources can be illustrated. The aim is to give a notion of the regional importance of industrial clusters in Europe and in the increasingly RE-based energy system.

As a part of the Hubs 4 Circularity project, Mendez Alva *et al.* compared data-based algorithms on their potential to identify ICs [39]. The authors collected data on industrial facilities for nine sectors and 65 economic activities from the E-PRTR database for all 27 EU member states, and for Iceland, Lichtenstein, Norway, Switzerland and the UK. Comparing K-means, Hierarchical Agglomerative Clustering (HAC) and Density-Based Spatial Clustering of Applications with Noise (DBSCAN), the latter performed best due to its ability to tune cluster parameters [39]. The final set of H4C ICs, resulting from DBSCAN with parameter settings epsilon 25 and minPoints 5, serves as a benchmark in this brief analysis. Data on the local RE potential, primarily solar and onshore wind power, are collected from the ENSPRESO database [162]. This EU initiative calculated regional upper limits of RE capacity on a NUTS2 level, taking into account land restrictions, setback distances and geospatial wind

speed and solar irradiation data [163]. It should be noted that offshore wind power is not included in the analysis and clusters with access to such infrastructure can still be directly supplied with offshore wind power. Figure 6 and Figure 7 show the outcomes from both projects. Figure 6 plots the onshore wind power technical potential in gigawatt corresponding to the ENSPRESO reference scenario for 2050. Figure 7 indicates the solar power technical potential, also expressed in gigawatt. The darker an area, the larger the RE potential. Both figures plot the H4C industrial clusters in black. Table 3 summarises all input references and important algorithm settings from the data present in Figure 6 and Figure 7. The capacity for solar and onshore wind power is not uniformly distributed over the European continent. A general trend, noticeable in both figures, is that ICs typically do not overlap with regions with the most abundant RE sources. The largest potential for RE in Europe lies in South-West and East Europe. There is a larger density of ICs in North-West Europe (Belgium, the Netherlands, North Rhine Westphalia) compared to other areas. In Eastern and Northern Europe, there are hardly any ICs. According to Mendez Alva *et al.*, this suggests for additional incentives in those areas to stimulate industrial clustering [39].

The report from the IEA on renewables forecasts a significant increase in renewable capacity in Europe, of which 70% can be allocated to Germany, the UK, Italy, Turkey, France, Spain and the Netherlands [72]. Once again, there is a stronger focus on West-Europe. Hence, also in terms of RE buildout, Eastern EU can benefit from additional incentives. The mismatch between local RE availability and industrial demand presence might be the most clearly illustrated in Germany. Offshore and onshore wind power are primarily present in the North, whilst EIs are located in the South [151]. Energy transmission lines, including their planning and development issues resulting in long lead times, are discussed in Sections 2.1 to 2.3. To mitigate this in the future, Sun *et al.* propose the (partial) transfer of EI industry to RE abundant areas for local consumption [164]. Such renewables pull effect may have its influence on industrial strategies in the future, as investigated by Samadi *et al.* [165]. However, the consequences of industrial relocation go beyond energy cost reduction and have large societal and economic effects.

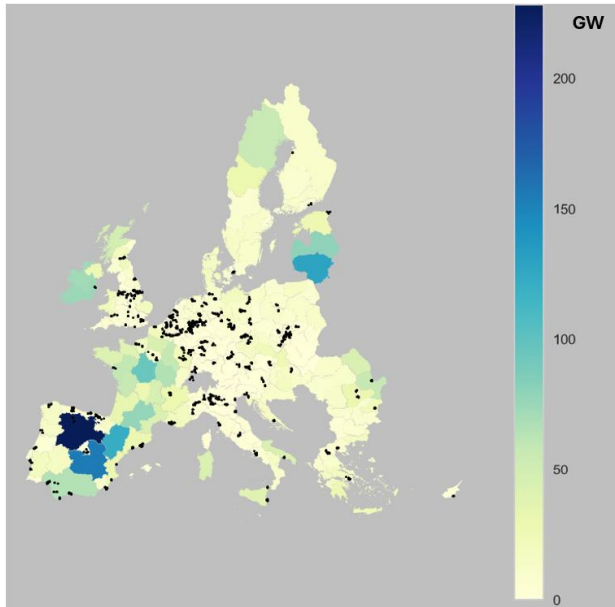


Figure 6 Onshore wind power potential capacity on a NUTS2 level (ENSPRESO), expressed in gigawatt, and H4C industrial clusters in black.

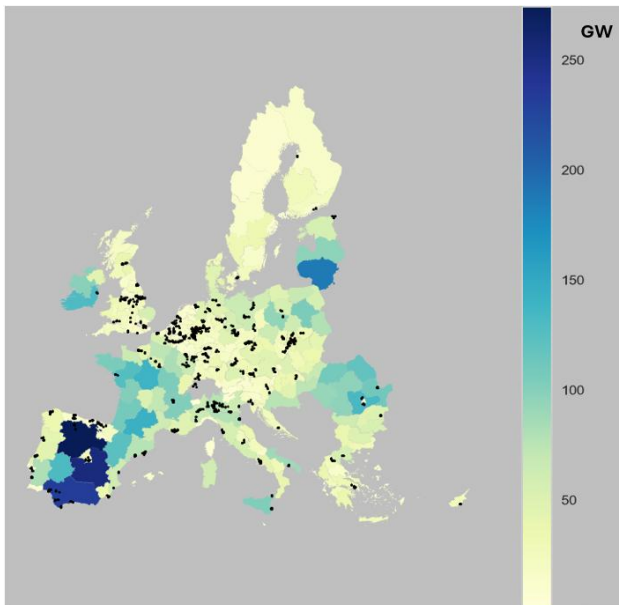


Figure 7 Solar power potential capacity on a NUTS2 level (ENSPRESO), expressed in gigawatt, and H4C industrial clusters in black.

Table 3 Overview of the data presented in Figures 9 and 10, including references.

industrial clusters		
element	description	source
DBSCAN	Density-based spatial clustering of applications with noise	
• parameters	Distance between nodes: epsilon 25 km Lower threshold cluster size: minPoints 5 sites	Mendez Alva <i>et al.</i> [39]
• input data	Latitude and longitude of industrial sites	E-PRTR database [166]
renewable energy landscape		
Solar power	Total solar capacity in GW, medium scenario	ENSPRESO [163]
Onshore wind power	Wind onshore capacity in GW, medium scenario	

Supply and demand matching of RE to EII will become increasingly important in the future and should continue to be explored from a cluster's perspective. So far, the figures above only report on the supply side. The AIDRES project aimed to fill the gap on RE demand projections from energy-intensive sectors [51]. Their efforts resulted in a database of production routes including specific energy demands, suitable for creating climate neutrality pathways and projecting them on EU ICs. Work on a revised version of the AIDRES database is currently ongoing, given both the industrial and energy landscapes have changed drastically since the first publication in 2021. As a main deliverable of the UGent ECM PIECE project, an open-source webtool RES2Go was developed that allows users to create such future industrial energy demand scenarios and assess the potential of energy clustering in Europe [167,168]. To compile ICs from a set of industrial sites, the tool offers two clustering algorithms, K-means and DBSCAN, with user-defined parameter settings. The main argument for including K-means lies in the noise points of DBSCAN: if it is of interest to allocate all industrial sites to a cluster, even if they are somewhat remote, K-means is more suited as a cluster algorithm.

Eventually, both supply and demand come together in strategic energy planning from the point of view of ICs, entering the field of ESM. Chapter 3 explores the use of the DBSCAN cluster algorithm in a methodology to align the nodes from energy

system models with ICs to improve industry's representation. Chapter 3 also reflects on cluster-level transition pathways, resulting future energy demand scenarios and the application of the RES2Go tool in ESM. Both concepts are applied in Chapter 4. The work supports IC-tailored research on RE integration, grid planning, energy system operation, storage needs etc.

2.5 GLOBAL COMPARISON

This section reflects on non-European regions and their policy views on industrial clusters to benchmark the European IC approach with the rest of the world. According to the WEF, several other regions have included ICs as part of their industrial policy strategy, including the United States, China, Japan and India [37]. The IEA keeps track of all energy-related policies globally. From their database, the policies that refer to industrial clusters can be retrieved [169]. Figure 8 clearly shows that the global interest in ICs surged in 2020. In terms of regional distribution, Europe and separate EU countries have the strongest representation, followed by the UK and some Asian countries. This is illustrated by Figure 9. The lack of Chinese IC-related policies in the IEA database is surprising. Especially because plenty of the research papers referred to in this literature review are of Chinese origin. The work of Rattle *et al.* also confirms the significant contribution of Chinese research to academic literature on the topic [70]. A review of national policies on industrial transition by the WEF refers to the Chinese Five-Year Plan and 2035 Strategic Vision Goals [170]. The legislation sets a target of 50 near-zero-carbon zones by 2050 and supports the integration of key technologies and circularity in eco-industrial clusters. While the IEA policy database might not be 100% complete or up to date, these findings do confirm that regions value ICs differently. The topics of these policies also vary strongly, from renewable energy, biobased processing, battery, and hydrogen implementation to CCUS.

Figure 10 shows the Transitioning Industrial Clusters community of the WEF. The map once again confirms the strong focus of EU on ICs compared to other regions. However, the tide is turning and other regions increasingly acknowledge their existing or planned industry hubs. At the time writing this thesis, the three most recently joined members of the community are the Bintulu IC in Malaysia, the Thoothukudi green cluster in India, and the Fos-sur-Mer and Berre cluster in France [36]. The latter is rather surprising as it was also one of the EPOS clusters, together with Dunkirk (France), Visp (Switzerland), Rudniki (Poland) and Hull (UK) [48].

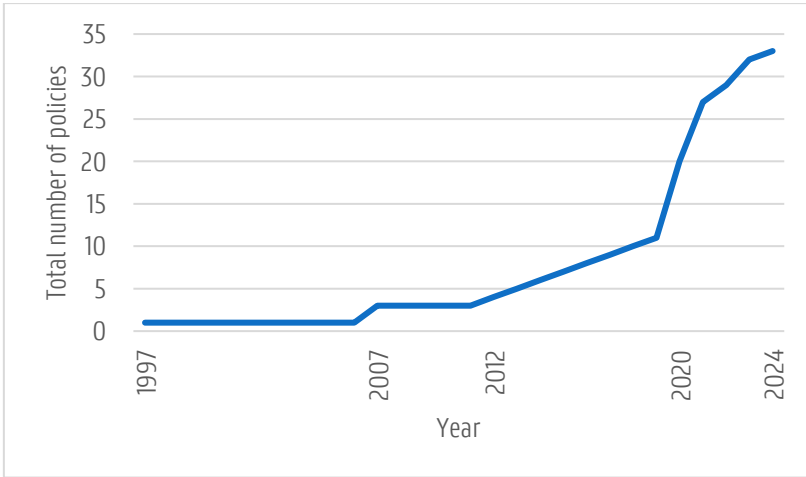


Figure 8 Evolution of the total number of industrial cluster-related policies over the years [169].

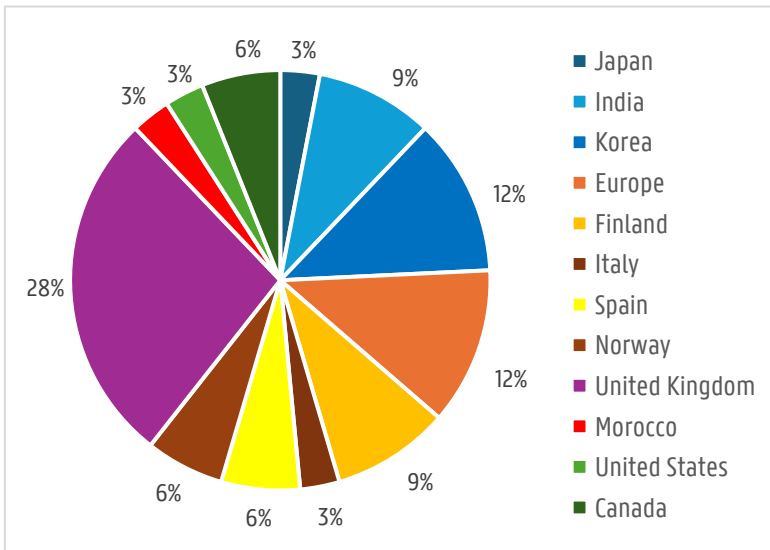


Figure 9 Distribution of the total number of industrial cluster-related policies over the different countries/regions for the year 2024 [169].



Figure 10 Map of the Transitioning Industrial Clusters community (member countries in darker blue) from the WEF (January 2026). [171]

Current discussions on industry competitiveness often refer to the level playing field in global trade with other regions that do not impose a EU-like climate policy [1,15]. Its formal definition is “a situation in which everyone has the same advantages and disadvantages” [172]. Unfortunately, this is not the case in the current EU industry context, i.a. due to the uneven standards on environment and labour, disproportional government subsidies and unfair competition rules when comparing to e.g. China. As a result, EU industries face uneven competitive pressures. An unlevel playing field affects investment decisions. Hence, it shapes the transition of ICs. In a level playing field, there is constructive competition between ICs globally and their cluster-uniqueness can be a decisive factor in their growth. An unlevel playing field hinders organically induced cluster initiatives, as the innovative advantage of an IC in a certain region is overshadowed by cheap resources or lower standards elsewhere.

The recently announced IAA aims to relevel the playing field and make EU industry more resilient [173]. One of its pillars, the industrial acceleration areas, directly favour ICs to drive innovation and IS opportunities. The task for each member state to designate such areas, accompanied with streamlined permitting to fast track developments, will further stimulate IC initiatives.

2.6 CONCLUSIONS

The goal of this chapter is to improve the understanding of the potential role of industrial clusters in the energy system when leveraging their IS potential. In line with Draghi's recommendations, the literature review conducted in this work illustrates the many ways for collaboration in ICs, the benefits, but also the barriers. It exposes the state of the art of energy system research from the point of view of

industrial clusters. Chapter 3 pushes the state of art by transforming existing methods in ESM towards a deeper integration of ICs. Chapter 4 serves as an illustration of the cluster-based methodologies.

From this frontier, multiple promising research leads depart to valorise the potential of ICs in the energy system. A shift towards more simulation-based research and case studies entailing all sorts of ICs might clarify the benefits of shared local renewables, shared energy storage, shared infrastructure and cluster-wide optimisation efforts for increased efficiency, to support their uptake in industrial clusters. Chapter 5 leads by example and targets one specific IS case: RE sharing using PV and wind power. The methodology leverages former tools and resources from IS research into a modelling framework that integrates GT principles.

This thesis is deeply embedded in a European context. However, the policy review of Section 2.5 and the reports by the WEF show there is a global interest in ICs. Hence, case studies should not be limited to European clusters. Also the scope of this chapter, which primarily focuses on the electrical power system, can be broadened in future work to include the complete array of industrial symbiosis cases, energy and non-energy. The scope can be extended even more when nearby cities are included, referring to research on urban-industrial symbiosis. One should also keep track of the technology readiness levels of upcoming clean technologies, as they might offer new ways to collaborate within ICs in the future.

An overview of the contributions of this dissertation to the research field are summarised in Table 34.

CHAPTER 3 ROLE OF CLUSTERS IN ENERGY SYSTEM MODELLING

To reach climate neutrality and circularity targets, industry requires infrastructure guaranteeing available, accessible, affordable, and sustainable supply of clean energy and resources. The layout and operation of the required grids are a key topic in energy system modelling, a research field under constant development to tackle energy transition challenges. Although industry is a core player, its transformation and related policy initiatives are not yet fully reflected, resulting in a research gap. The IC concept, stimulating local cross-sectoral co-operation, circularity, and optimisation, offers untapped potential to improve the spatial and technical representation of industry in ESMs and paves the way for cluster transition research. The objective of this chapter is to investigate the current representation of EIs in ESMs and to contribute to this field by providing a framework that introduces ICs. This approach is still lacking in the current ESM discipline and could improve the support of energy and climate policy. Ultimately, the goal is to maximise system value through the optimal integration of ICs and to provide the basis for co-operation on infrastructure and other assets, de-risking investments, and saving both resources and energy [174].

The first section of this chapter explores the state of the art of industry representation in ESMs, identifying research gaps and pointing to challenges and opportunities for industry clustering. Section 3.2 introduces the IIQ and section 3.3 delivers the complementary methodology for a newly developed framework that looks in parallel at industry and energy infrastructure and facilitates the introduction of clusters in ESMs. Section 3.4 shares the results of the methodology applied to a case study on Belgian industry. Section 3.5 explores cluster-level transition pathways to improve the technical representation of industry in ESMs. Section 3.6 presents an overview of ESMs, their respective approach on industry transition modelling and how these models can benefit from this work.

3.1 BACKGROUND ON ENERGY SYSTEM MODELLING

Providing insights on the future demand and supply of energy commodities and on how to tackle the challenges faced by a variety of actors is the goal of ESM, which is often consulted by policy and decision makers to assess the impact of their plans. Among other applications, ESMs can be used as a support tool for infrastructure development by analysing and comparing different scenarios and identifying what

it takes to maintain the security of supply [175]. The number of models has increased over the past decades, tailoring to the needs of their users and keeping track of the trends challenging current energy systems. Thanks to the large, open-source community feeding ESMs, there is a clear overview of models that are suited to investigate any type of issue related to the energy supply chain [176]. Progressive insight drives developments in ESMs, clearly shown by the wave of models suitable for assessing the integration of renewables and the path towards climate neutrality [177]. Given the importance of energy-intensive industry as a large contributor to both greenhouse gas emissions and energy consumption and its dependence on supporting infrastructure, it is worthwhile to reflect on the representation of EIs in ESMs and if their strategies and investment plans are accounted for in ESM frameworks.

Many reports and policy recommendations point towards the strength of cross-sectoral co-operation within ICs as a leverage for climate and resource neutrality, advancing the energy transition; a trend increasingly picked up by countries in their strategic energy planning [28,29]. The masterplan published by the High-Level Working Group on EIs emphasises the link between optimised infrastructure developments and crossing the borders of industry sectors, regions, and energy commodities, integrating and optimising all segments together [28]. From the list of industry mitigation pathways towards climate and resource neutrality, the WEF expects some to have a larger impact when implemented at the IC level, such as systemic efficiency and circularity, electrification and renewable heat, and hydrogen and CCUS. Acknowledging this is a critical step in reaching the climate targets, ICs put forward an integrated approach for the optimisation of EIs and the supporting infrastructure that is currently still lacking in ESMs.

To study the current representation of EIs in ESMs and how industry clustering can improve this, a literature review is performed to expose the research gap that needs closing. Targeted ESMs in this work include industry as a separate demand sector, split over the different subsectors and covering multiple energy commodities. Summaries of each available model's specific approach, strengths, and weaknesses are the topic of multiple review papers, aiding potential users in their search for ESMs suitable for their research question and exposing research gaps. Often, they provide a categorisation of ESMs based on commonly used modelling characteristics. According to Ringkjøb *et al.*, the main themes are general logic (purpose, approach, methodology), spatiotemporal resolution, and technical and economic features [8].

A second set of ESM review papers provide an overview of the challenges and future work within this modelling discipline. Progressive insight in the energy transition raises new questions and exposes hurdles to be taken along the way. The paper by Prina *et al.* [15] reaches the conclusion that resolution is the main next frontier of

developments in terms of time, space, techno-economic detail, and sector coupling. Crucial for the integration of large amounts of Variable Renewable Energy Sources (VRES), the interlinkages between different energy commodities increase. Hence, Ringkjøb *et al.* mention sector coupling as a research gap within ESMs, together with proper VRES forecasting and uncertainty [8]. Fodstad *et al.* add further to the list and raise attention to behavioural aspects in the energy transition strongly influencing the energy system [177]. Lopion *et al.* warn of an increasing modelling complexity due to high VRES shares, energy storage needs, cross-sectoral technologies, and the internationalisation of energy markets [178]. Next to increased complexity, all four sources also mention the computational burden and its trade-off with improved accuracy. On top of this, one cannot assume the availability of the data required to go to the next level of detail [179,180]. The latter is especially relevant for industry, as confidentiality issues often arise [49]. From this list of challenges and future work, the remainder of this work will discuss improved spatial and technical resolution by representing EIs as part of ICs. This opens up the possibility to include local energy and resource efficiency gains resulting from cross-sectoral co-operation in the context of ESMs. Advancing the technical resolution of the industry sector in ESMs by means of industry blueprints further discussed in Section 3.5.

The discussion on spatial resolution is mostly held in terms of the total number of nodes [181]. Whether or not a model has one or multiple affects energy and material exchanges and allows or hinders taking bottlenecks and transport constraints into account [178]. This is crucial in performing an infrastructure analysis. A trend noticed by Lopion *et al.* shows an increasing number of ESMs allowing flexibility in spatial granularity by altering the number of nodes [178]. In order to go from a single-region to a multiple-region model, you need some sort of division criteria. According to Fodstad *et al.*, splits are often made reflecting public institutions and are categorised as 'energy system independent divisions' [177]. For statistical purposes, EU defined a Nomenclature of Territorial Units for Statistics, also referred to as NUTS regions, at various levels [182]. NUTSO corresponds to countries, NUTS3 to arrondissements and the two levels in between are coherent with the coverage of regional policy (e.g. Flanders in Belgium). This does not reflect typical characteristics or the design of an energy system; an example can be found in the Italian case study framework of Colbertaldo [183]. An opposite approach, 'energy system dependent division', clearly refers to its better ability to represent energy system properties [177]. Examples include splitting with respect to price zones and VRES availability. Ultimately, the element chosen to underpin the division will determine the property represented best.

Most papers in this literature review list the integration of VRES as the main or only an example of the need for increased spatial resolution. This is due to its distributed

and location-dependent nature, influencing production capacity, generation costs, and profiles [179–181]. In their paper on the spatial resolution of VRES in ESMs, Martínez-Gordón *et al.* make use of Geographic Information System (GIS) tools and data clustering, showing promising results [180]. According to the authors, the tools hold potential in other fields as well, like infrastructure layout, supply chain analysis, and demand localisation. ESM and IC research already share common ground on the use of data clustering algorithms. The work by Mendez Alva *et al.* successfully illustrates that its application should not be limited to VRES and compares different clustering algorithms and their ability to retrieve potential H4Cs [39].

The inclusion of industry as a demand sector in ESMs could, similar to VRES but to a lesser extent discussed in the literature, benefit from an improved spatial resolution, especially when results are used to support policy recommendations or infrastructure development. A paper by Frysztacki *et al.* states that regions with high geographic variability in energy demand are equally relevant for increased spatial resolution as heterogeneous regions due to large VRES shares [184]. Also, Fodstad *et al.* suggest dividing regions based on demand [177]. In this thesis, ICs are proposed as a division criterion to go from a single to multiple nodes in ESMs. Each node would then properly represent a cluster in terms of the four WEF characteristics. This format provides new insights into ESMs. The geography and existing infrastructure in ICs influence the pathways towards resource and climate neutrality and, accordingly, steer infrastructure updates and additions to the electron, hydrogen and CO₂ networks. ICs also relate to the energy hub concept in ESMs, serving as coupling points between different commodities as defined by Fodstad and Kriechbaum [177,179] where A.SPIRE sees optimisation opportunities through energy and resource circularity [38].

To conclude the literature review, the focus is shifted to what is already known and written about the application of ICs in ESMs. On this very specific topic, publications are not yet common. Most often, articles either focus on just one IC or a specific technology pathway (e.g., hydrogen). The paper by Sechi *et al.* presents a review of modelling approaches in terms of IC representation and uses a GIS tool that increases the spatial resolution up to the plant level together with a methodology to allocate emissions and total energy consumption to the clusters [185]. The main outcome of the paper is a taxonomy for IC climate neutrality which, according to the authors, is more insightful than classification based on economic activities in the context of energy transition due to its more detailed portrayal of energy supply and demand. In their review of ESMs, Sechi *et al.* come to the conclusion that none apply an IC-based approach as they still stick to sectoral disaggregation [185]. The scope of industrial sectors in Sechi's paper is EIs. However, eventually, the authors decided to leave out refineries and bulk chemicals due to the complexity of the processes

(compared to other sectors) and the lack of required data to execute their presented methodology. According to the results by Mendez Alva *et al.*, these sectors play a significant role both as source and sink of energy and material flows and thus deserve a place in the context of many IC initiatives [55].

An excellent example of IC analysis in terms of a specific technology pathway is presented in the paper by Calvillo *et al.*, in which the authors emphasise that a proper understanding of an IC's composition, geography, and infrastructure is crucial for the development and implementation of a CCS system [186]. The lack of and inconsistency in exact descriptions of ICs is mentioned as a hurdle in their research. Fleiter *et al.* describe a bottom-up simulation model, FORECAST, that is capable of developing future final and useful energy demand profiles and related emissions for industry [187]. The model leverages mitigation options with a high level of technological detail and its scope encompasses EIs and its sub-sectors. While FORECAST provides energy and emission time series for multiple energy carriers and with a high level of detail in terms of sectors, the spatial representation is limited to country or NUTS3 level. Also Burandt *et al.* put effort into the improved technical representation of EIs in the ESM GENeSYS-MOD, primarily by integrating multiple temperature ranges for industrial heat demand [188]. Their spatial resolution is approached in an 'energy system independent' manner as it respects provincial borders. Idem for Wiese *et al.*, who applied a higher level of technical detail for the industry sector in the ESM Balmorel, but considers regional boundaries for the electricity demand allocation [189]. The heat demands, however, are linked with the district heating networks and have a higher level of spatial disaggregation.

In the context of this research, the approach of the AIDRES project to display EIs is most in line with the current objectives. Compared to typical studies on trajectories towards climate neutrality by 2050 that only look at one sector and/or technology pathway at a time, the project's scope includes EU facilities from six crucial EIs (cement, chemicals, fertilisers, glass, refinery, and steel) for which multiple production route options are recognised and converted into blueprints [51]. Results on future energy demand and GHG emission roadmaps from and by these industries are available on a site level and at NUTS3 level. The project picked up the potential of ICs and applied the DBSCAN cluster algorithm, as recommended by Mendez Alva *et al.*, as part of the methodology to estimate the potential of IS to reduce energy and resource consumption and emissions [2]. The energy demand projections on a site level combined with the clustering of the geospatial data allows for the creation of cluster-level transition pathways that can feed into bottom-up ESMs.

From this literature review, it can be concluded that industry representation in ESMs can still improve significantly, both in terms of spatial resolution, composition and technical detail. The IC concept offers an integrated approach and can function as a

bridge between energy systems and industrial sustainability research. It opens up the possibility to further investigate IS opportunities and incorporates cluster transition research into ESMs.

3.2 INDUSTRY-INFRASTRUCTURE QUADRANT FRAMEWORK

Considering the spatial representation of EIs in ESMs in the current literature and applications of ICs so far, this work aims to contribute to the state of the art by providing a classification methodology for regions taking into account the IC characteristics geography, composition, and existing infrastructure. The latter, although seen by the WEF as one of the four key characteristics of ICs and crucial in energy systems, was not yet included in the limited number of papers on the topic. For the remainder of this section, the scope of infrastructure is limited to the backbone grids for both electrons and molecules. Describing both local industry and backbone grid presence can eventually support regional divisions to go to multi-node energy system models useful for IC and ESM research.

The Industry–Infrastructure Quadrant has been developed to simultaneously visualise both local industrial presence, whether or not as part of a cluster, and the availability of energy infrastructure (Figure 11) [65]. This quadrant serves as a visualisation tool to be used in the classification of areas in terms of industry importance and existing backbone grids from which potential nodes of interest for ESM studies can be selected. The horizontal position within the IIQ reflects the local presence of infrastructure elements in an area and runs from high (left) to low (right), adding the lack of infrastructure as a separate case (most right). Similarly, for the vertical industry axis, a top or bottom position in the IIQ reflects a high or low relative importance in terms of industry presence. A clear distinction is once again made for areas lacking industry.

To capture the most meaningful conclusions in the IIQ, areas are categorised by defining the outliers, as shown in Figure 11. The first category consists of regions that do not contain any industrial facilities or nearby infrastructure, which are further referred to as 'out of scope' (A). Secondly, areas without any industrial presence might function as interconnections in the international energy systems. This category is called the 'interconnection corridor' (B). The majority of areas do have industry present, and out of those remaining, three more significant categories are uncovered. These are visualised in the quadrant by means of three axes. The 'industry axis' runs towards the areas with the highest industrial importance (C), grouped together under the term 'cluster potential'. It covers the full scope of infrastructure

presence, high to low, and cluster potential areas that end up to the right in the IIQ indicate candidate areas in need of infrastructure strengthening or expansion.

The second identified axis is the 'remote activity axis', referring to single industries present in an area without any infrastructure nodes (D). The last 'infrastructure axis' corresponds to the areas in which the present infrastructure is more significant than its industry (E). Due to this characteristic, these are called 'infrastructure corridors'. The difference between the 'infrastructure' and 'interconnection corridor' is that regions belonging to the former have industry present, albeit not in a way that it dominates the characterisation of the area, while the latter has no industry present at all. Section 3.4 includes illustrative examples from Belgium for each IIQ category.

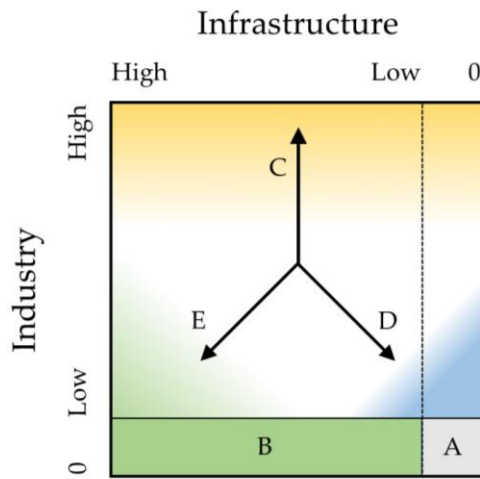


Figure 11 The Industry-Infrastructure Quadrant and its area categories: (A) out of scope; (B) interconnection corridor; (C) cluster potential; (D) remote activities; (E) infrastructure corridor [65].

3.3 MULTI-NODE SELECTION FOR ENERGY SYSTEM MODELLING

In order to make use of this IIQ, data on both industry and infrastructure need to be available and quantified with respect to each other in terms of regional presence. The following sections describe in detail how this can be achieved for both the industry and infrastructure axes, respectively. To support the use of this IIQ concept in future research, the methodology solely relies on open-source data and public data processing tools.

3.3.1 INDUSTRY

The IIQ methodology requires geospatial data on industrial sites to allow analysis in terms of IC potential. As part of the Industrial Emissions Directive (IED) and European Pollutant Release and Transfer Register regulation (E-PRTR), the largest EU industrial complexes are obligated to share data on releases of pollutants and transfers of regulated substances [190]. The resulting datasets cover a wide range of sectors, allocating facilities to an economic activity, and include geospatial data in coordinates. This open-source information is annually updated and can easily be extracted from the database. The scope of economic activities is kept at the definition of EIs according to the High-Level Expert Group [28]. Due to its relevance, the production of food and drinks are added to the selection of activity codes. Infrastructure operators, especially those of electrical grids, keep an eye on this sector due to its large electrification potential [191]. In order to narrow down the selection of industrial facilities and only include the most energy-intensive plants, the IED database is combined with ETS data, which excludes installations below a certain size [192]. As there are no open-source databases on energy intensity at the level of individual industrial assets, the verified ETS emissions of these installations are used as a proxy (data for the year 2021, pre-energy crisis levels). The selection methodology applied here builds on AIDRES, which started from the EU Transaction Log as well, but enlarges the scope of industrial sectors and extends the set of product categories (e.g., in AIDRES, steel finishing sites are excluded) [51,52].

After compiling the industry database from official EU IED and ETS sources, data processing steps include the identification of potential ICs. The paper by Mendez Alva *et al.* on H4Cs compares three different clustering algorithms on the ability to locate potential hubs [39]. DBSCAN was most successful due to its ability to alter the clustering parameters that influence IC density and differentiate clusters from noise points. It was also applied in the AIDRES project [2]. Hence, its use in the field of IC research is continued in this work as well. By means of open-source Python libraries, the algorithm can be applied to the industry database and retrieves clusters of similar density [193].

Users need to define two parameters: the maximum distance between two 'neighbouring' nodes (epsilon) and the minimal number of neighbouring nodes to be considered a cluster (minPoints) [193]. Either an industrial facility is part of a cluster or considered a noise point. The latter can be seen as an indicator for remote industries. Optimal values for epsilon and minPoints are case specific, although minPoints should be equal to or higher than three, and it is not recommended to go above 25 km for epsilon [39]. Hence, a parameter sensitivity analysis complementary to the IIQ goal and purpose is desirable. This methodology suggests

a parameter selection that returns a reasonable number of ICs with a high density of industrial facilities and sufficient coverage of the complete industrial database. The latter can be checked by applying the Pareto principle ('80% of the consequences come from 20% of causes', otherwise known as the 80/20 rule [194]) on the share of ETS emissions allocated to clustered facilities, which should at least reach 80%. The reasoning behind this originates from the typical outcome that a significant share of resources, energy, and emissions can be traced back to only a handful of stakeholders. This limited number of industrial facilities should be covered by the algorithm output.

A high density of clustered facilities implies providing DBSCAN a high minPoints and a low epsilon value. Ultimately, the parameter sensitivity analysis will show the trade-off between density and number of clusters and, together with the Pareto Principle check, it will return a suitable parameter selection for industrial database processing. Visual confirmation of the resulting clusters together with the parameter sensitivity analysis are the two main validation options for the DBSCAN output according to Mendez Alva *et al.* [39].

Once the clusters are defined, the economic activity data linked with the facilities can be used to reflect on cluster industry composition and uncover potential trends for industrial subsectors in the context of the IIQ.

3.3.2 ENERGY INFRASTRUCTURE

This part of the IIQ relies on existing infrastructure, such as backbone grids for the bulk transmission of electricity and natural gas, in the assumption that the energy infrastructure of the future will largely be based on present connections and nodes. Special attention is given to grid interconnections with neighbouring countries and port areas serving as entering points to reflect the international nature of the energy system.

ENTSO-E publishes up-to-date maps of the interconnected electrical power grid in and beyond Europe operating at high-voltage levels of 220 kV and above [195]. These lines are seen as the backbone of the electrical power system and set the scope chosen in this study. It is noted that the focus of this work is on energy-intensive industries, of which the largest consumers have a direct connection to the high-voltage grid. Other industries are connected to lower voltage levels like the medium-voltage grid and below. Connections at lower voltage levels and distribution grids are not included. The offtake and injection of electrical power from the lower grids eventually aggregate at the substations. Possible grid constraints within the clusters are beyond the scope of this work as it primarily targets capacity limitations in the connections between clusters. Three different types of stations are retrieved from

the ENTSO-E maps: regular substations, interconnection stations, of which the lines cross country borders, and AC-DC converter stations. The latter also serve in most cases as interconnections.

In terms of data processing, the exact locations of the substations are used to construct Voronoi diagrams using the SciPy Python module [196]. Each field in the Voronoi diagram corresponds to the nearest substation. The relative size of each of these Voronoi fields and the total number of fields required to cover a certain area are used to reflect the local electrical backbone grid presence. To illustrate the connectivity between the substations, a map of the electrical backbone grid is helpful. This can be derived from the ENTSO-E maps. It shows the current status of the transmission grid and is useful to form statements on future infrastructure expansion needs.

Similar to ENTSO-E, ENTSO-G keeps track of the natural gas transmission system in and beyond Europe [197]. The grid map contains data on cross-border capacities, the locations and sizes of pipelines, liquid natural gas terminals, and large-scale storage and is once again used to set the scope for this study. In terms of data processing, a different approach needs to be made compared to the electrical backbone grid data: instead of focusing on the nodes of the grid, for gas molecules, it is more relevant to look at the most nearby passage of a pipeline. Similar to the electrical backbone grid, a map is useful to illustrate the (missing) grid presence and is derived from the ENTSO-G map.

3.3.3 INDUSTRY–INFRASTRUCTURE QUADRANT APPLICATION

With all required data gathered, processed, and prepared for assessing industry and infrastructure presence, the IIQ can be applied in order to retrieve areas of interest useful for the ESM. Based on the definitions for each of the five typical areas present in the IIQ, the categories cluster potential, interconnection, and infrastructure corridors seem most promising and should be reflected in the ESM node selection. Hence, this part of the methodology discusses a systemic approach to retrieve these areas of interest from the collected industry and infrastructure data and allocate them to a set of ESM nodes.

Making use of the identified axes C and E in Figure 11, the flowchart in Figure 12 presents a decision tree to assess the completeness of the current node selection and the added value of a potential node. A larger set of nodes increases the spatial granularity, thus improving EII and IC representation. However, it also contributes to the computational burden. Hence, unnecessary nodes should be avoided in the final node selection. The grey boxes in the flowchart list the main criteria for node

selection, forcing the user to reflect on both industry and infrastructure presence and coverage.

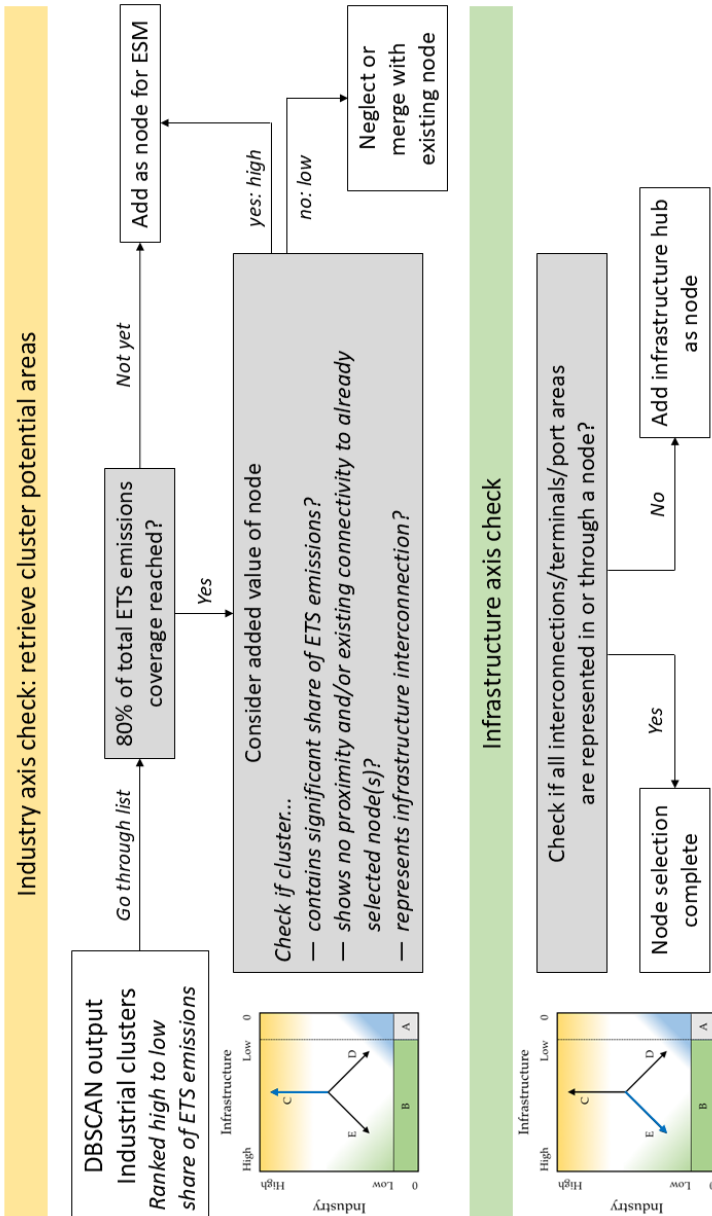


Figure 12 Flowchart describing the node selection methodology for the ESM [65].

The industry axis highlights areas with cluster potential and follows the outcomes of the DBSCAN algorithm after correctly setting the parameters as discussed in

Section 3.3.1. Up until reaching the Pareto limit of 80% coverage of ETS emissions, ICs are automatically added to the node selection. Next, every cluster beyond this limit is checked for significant added value, both in terms of industry and infrastructure importance, and forces the user to evaluate whether creating a new node or a merging opportunity with an existing node is present and desirable. Lastly, the infrastructure axis is considered to evaluate the completeness of the node selection. It returns crucial, yet still unrepresented infrastructure elements, like interconnections, terminals, or port areas. If still missing, these are added to the node selection, purely serving as an infrastructure hub.

The data collection on infrastructure as presented in Section 3.3.2 is especially useful for the evaluation of nodes in the second and third steps in the decision tree. Users can consider the overlap between a cluster and the electrical Voronoi diagram, the proximity of infrastructure passages, and the connectivity through existing infrastructure to other clusters to form a statement on an IC's infrastructure presence.

3.4 IIQ FRAMEWORK APPLIED TO BELGIUM

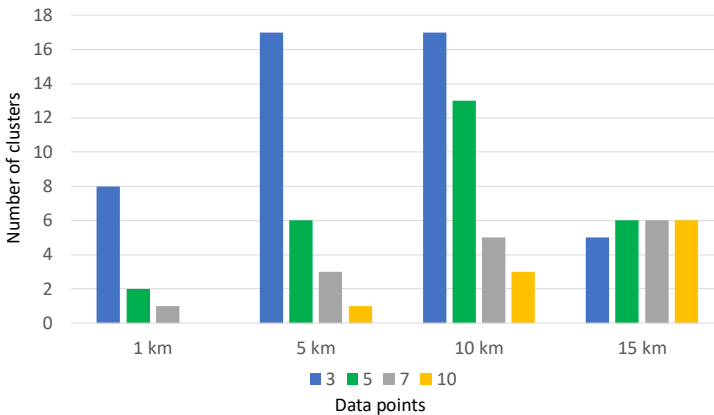
As an example, the IIQ methodology is applied to the full territory of Belgium. Located in the industrial heart of Europe, the Belgian economy is of high importance for export, and its infrastructure provides a gateway to the rest of the continent (e.g., through connections to offshore energy hubs and important centres, like the Port of Antwerp-Bruges, North Sea Port, etc.). The list of Belgian core sectors in terms of total value added includes pharmaceuticals, chemicals, food and drinks, and basic metals and metal products [34].

To construct a cluster map of the Belgian industry, the two-step approach is followed as described in Section 3.3.1, starting from the EU IED and E-PRTR databases with the column 'country code' set equal to BE. Next, the list of facilities is cross-linked with ETS data of Belgium to limit the scope to significant energy-intensive industries. Annual ETS data for the year 2021 are considered for the case study, to reflect the pre-energy crisis level. Duplicates or facilities no longer reporting (e.g., due to shutting down or closure) are removed from the dataset. Finally, applying a filter on the column 'main activity' column sets the scope to EILs (including food and drinks) and returns 186 rows of data. The complete dataset is made available in the supplementary materials of the journal publication related to this work [65].

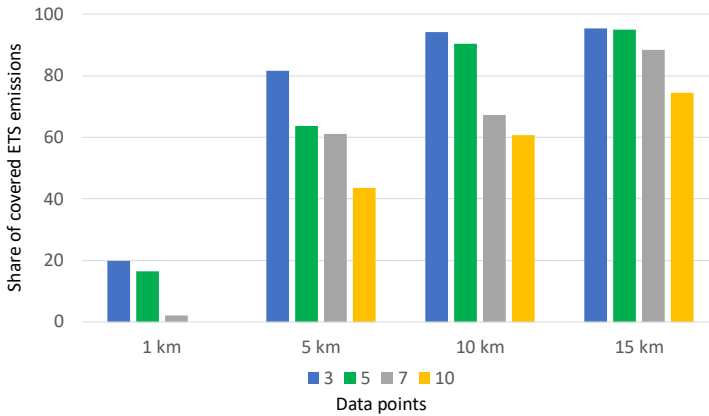
In terms of data processing, the coordinates present in the Belgian industry database are used as a direct input of the DBSCAN cluster algorithm. Two parameters, epsilon and minPoints, need proper defining in order for the algorithm

to return a suitable number of dense clusters that cover at least 80% of total ETS emissions present in the database. The two graphs presented below conclude the parameter sensitivity check. From Figure 13(b), all possible combinations for epsilon and minPoints that reach 80% coverage of ETS emissions can be retrieved. Figure 13(a) can then be used to check the total number of clusters to which this parameter selection corresponds. Epsilon 10 km; minPoints 5 exceeds the Pareto limit, and requires fewer ICs (13) compared to epsilon 10 km; minPoints 3 and epsilon 5 km; minPoints 3 (17). For epsilon 15 km; minPoints 5–7–10 return the same number of clusters (6), but have a decreasing coverage of ETS emissions. Due to the higher resulting density, Epsilon 10 km is preferred over Epsilon 15 km.

A visual check of the clusters, shown in Figure 14, confirms that the desired level of IC density is reached with a parameter selection epsilon 10 km; minPoints 5. This setting is fixed for the remainder of this case study. Out of 186 data rows, 138 facilities are allocated to a cluster, reaching an ETS emissions coverage of 90.4%. Coloured dots correspond to clustered facilities, facilities with the same colour belong to the same cluster. Black dots correspond to noise points (non-clustered industries). The black lines indicate the borders of the arrondissements (NUTS3 regions). The red circle points out a remote industry candidate.



(a)



(b)

Figure 13 (a) Total number of ICs retrieved by the DBSCAN cluster algorithm and (b) respective coverage of ETS emissions by the clustered facilities for epsilon 1-15 km and minPoints 3-10.

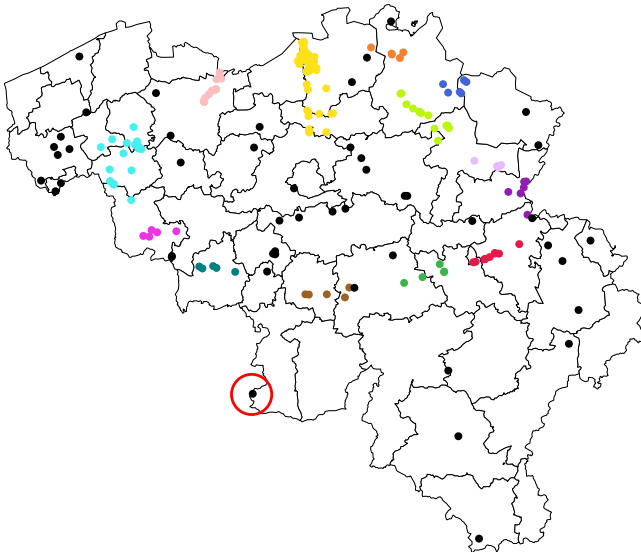


Figure 14 Map of the Belgian industry database after processing by the DBSCAN cluster algorithm (epsilon 10 km; minPoints 5).

For this study, the most recent versions of the ENTSO-E and ENTSO-G maps are used, dating from 2024 and 2026, respectively. Additionally, the maps are cross-checked by the Belgian TSOs for molecules and electricity, Fluxys and Elia, within the context

of the TRILATE project [53,54]. From the ENTSO-E map, the locations and types of electrical substations are derived, and exact coordinates are verified through the use of OpenStreetMap [198]. The SciPy Python module allows for the creation of a Voronoi diagram based on the substation coordinates and divides the Belgian territory according to the most nearby substation. Results are shown in Figure 15(a), in which the fields of the Voronoi diagram are coloured according to the type of substation. Figure 15(b) represents the existing connectivity of the substations.

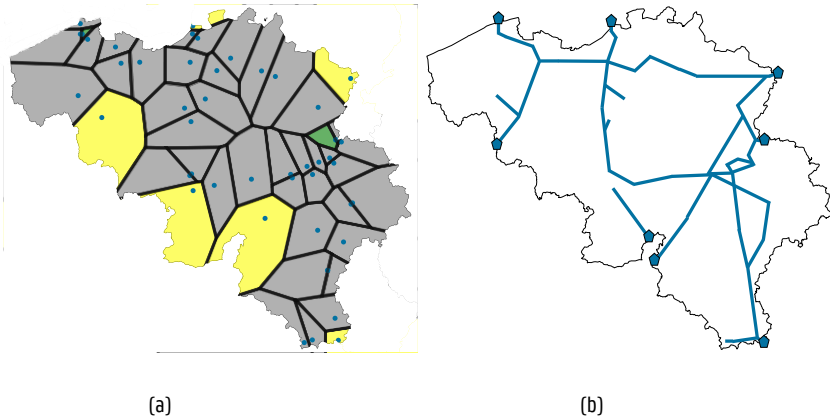


Figure 15 Voronoi diagram of the 220 and 380 kV substations in Belgium. Grey: regular substation; green: AC-DC converter station; yellow: interconnection; (b) map of the electrical backbone grid in Belgium. Each polygon corresponds to an interconnection.

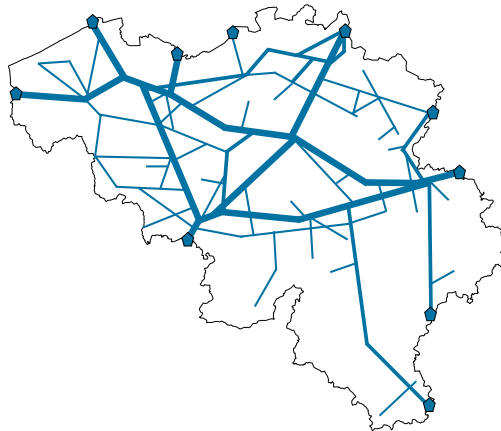


Figure 16 Map of the molecules (natural gas) backbone grid in Belgium. the pipelines correspond to <24" (thin), 24-36" (medium), and >36" (thick) diameters. Each polygon corresponds to an interconnection.

For the molecule backbone grid, the ENTSO-G map forms the basis for a map of the currently existing pipeline transmissions in and through Belgium. Three different

pipeline transmission capacities are distinguished, each corresponding to a different line thickness in Figure 16.

Table 4 contains each IC resulting from the DBSCAN algorithm and its share of ETS emissions and the corresponding node number in the final selection. To ease the discussion, each cluster is given a name that either refers to a nearby city or waterway useful for industry. As the flowchart in Figure 12 proposes, up until the Pareto front, ICs are automatically linked to an ESM node (six in total). Both the electrical and molecule backbone grid maps return in Figure 17, on which the first six nodes are indicated in yellow. The seven remaining ICs are evaluated based on the added value of an extra node. Three clusters, Albert Canal, Namur, and Kortrijk, extend the node selection (light green in Figure 17) due to their emissions share but most importantly because of their position in the energy transmission system. Each of them lies along existing backbone grids connecting to neighbouring countries, visually confirmed in Figure 17. Although Liège has an equal ETS share as Albert Canal, it is merged with the Maastricht node due to its proximity and connectivity through electrical and molecule grids.














The three remaining clusters no longer reach a 1% ETS share and no longer contribute to improving the translation of backbone grids. Hence, these are merged either with the Albert Canal or Maastricht nodes based on proximity.

The last step of the flowchart suggests checking whether all high-importance infrastructure elements are reflected in/through the set of nodes. The maps conclude this is nearly complete. Only one missing infrastructure hub, the port area in Zeebrugge, is manually added to the set of nodes (dark green in Figure 17). With this, all interconnections are covered by at least one of the nodes.

By applying the IIQ framework and its methodology, this case study proposes a set of ten nodes to represent energy-intensive industry through industrial clustering in the energy system models of Belgium. As can be seen in Figure 17, the IC-based nodes nicely correspond to important backbone grid junctions.

Historically speaking, it makes sense that gigawatt energy corridors pass along large demand hubs, like industrial clusters. According to a recent report, industry is responsible for 26.2% of the total final energy consumption in Belgium in 2024 [199]. In terms of energy sources, industry mostly used natural gas, electricity, and, to a lesser extent, crude oil products and solid fossil fuels.

Table 4 Summary of the ICs resulting from the DBSCAN cluster algorithm, corresponding to Figure 17. The ICs are sorted from largest to smallest share of ETS emissions.

colour	cluster name ¹	share of ETS Emissions (%)	add to ESM node selection?	number
	Antwerp	45.7 *		1
	Ghent	15.1 *		2
	Tournai	6.5 *	yes, the Pareto limit has not yet been reached	3
	Mons	5.6 *		4
	Maastricht	4.3 *		5
	Charleroi	2.9 *		6
	Albert Canal	2.7	yes, electron and molecule interconnection	7
	Liège	2.7	good proximity and connectivity to 5	merge with 5
	Namur	1.9	yes, electron and molecule interconnection	8
	Kortrijk	1.1	yes, electron and molecule interconnection	9
	Mol	0.8	no significant added value	merge with 7
	Genk	0.7	no significant added value	merge with 5
	Beerse	0.5	no significant added value	merge with 7

¹ Named after a local city or canal. * Pareto limit reached (80.1%).

The energy transition forces industry to look forward. The mix of energy sources will evolve over the coming decades. Hence, it is useful to also reflect on the planned and required expansion of each grid. This is necessary to enable the energy transition, for example, to bring multi-gigawatt offshore wind power potential inland, distribute hydrogen, and transport captured CO₂ to sinks or storage sites. As already mentioned in Section 3.2, clusters located more towards the right in the IIQ indicate candidate areas in need of infrastructure strengthening or expansion to

make the local energy system future proof and more accommodating to attract new industries. With this in mind, two clusters in Figure 17 immediately pop up as there currently is no electrical backbone grid (≥ 220 kV) present: Tournai and Mons. Hence, connecting both clusters with other nodes is an outcome of this study. This was discussed in the frame of the TRILATE project, in which Elia, the electrical transmission grid operator in Belgium, participated [53]. Elia plans on constructing two new high-voltage power transmission lines. Ventilus would run from the port of Zeebrugge infrastructure hub to the substations present in the Kortrijk cluster area [92]. The second one, Boucle du Hainaut, would connect the Kortrijk cluster to the Charleroi cluster [200]. With this, the underrepresentation of electrical backbone grids in that region would be resolved, and the electrical high-voltage grid would become more redundant (see Figure 18). These findings are anticipated by the IIQ analysis.

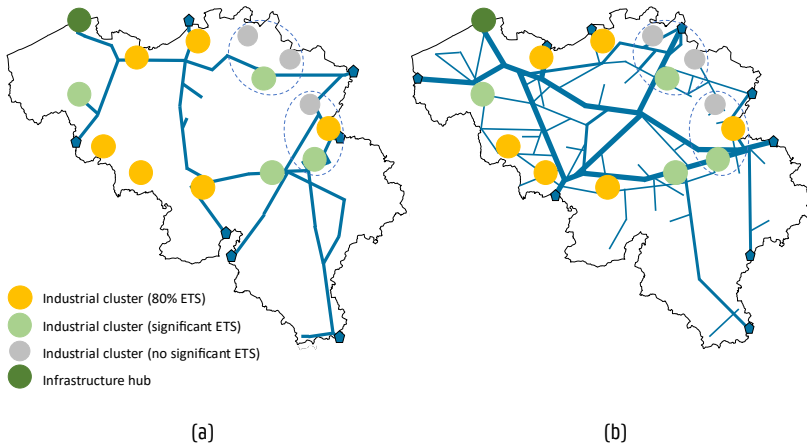


Figure 17 IC-based node selection for the ESM after application of the IIQ framework. Yellow dots correspond to ICs required to reach the Pareto front, light green indicates relevant ICs in terms of infrastructure and/or ETS emissions, and grey dots refer to less significant clusters. Dashed lines group ICs for merging into one larger node. Dark green dots correspond to important infrastructure hubs not yet covered by ICs. (a) Projected results on the electrical backbone grid and (b) on the molecule backbone grid map.

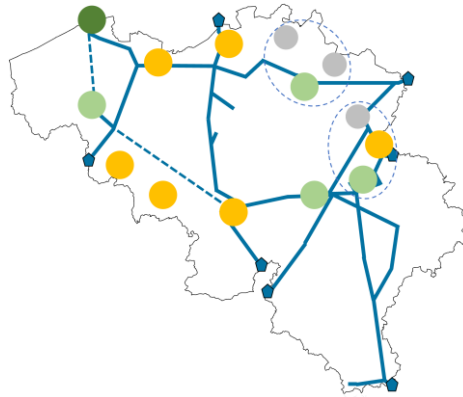


Figure 18 Revision of Figure 20a with the two planned high-voltage power lines indicated by dashed lines.

Finally, Figure 19 returns to the IIQ and gives an example from the case study for each area category. The figure merely serves to illustrate the relative position of the nodes to support the interpretation of the work. Quantifiable indicators on both industry and infrastructure presence can be applied if more precise positions in the IIQ are desired. Based on the data gathered in this work, the share of ETS emissions can be used for the industry axis and the locally installed energy capacity for the infrastructure axis. It is noted, however, that the latter requires detailed information on the backbone grids, which is not always publicly available.

Two clusters, Antwerp and Tournai, illustrate the range of existing infrastructure availability and industry presence in cluster potential areas through their relative position in the IIQ. Antwerp is the second largest European chemical complex, after Ludwigshafen in Germany; and after Houston in the USA, one of the largest petrochemical cluster globally [201]. The significance of its industry and the port activities turn Antwerp into a centre of gravity in the energy system, which is reflected in Figure 17. Also acknowledged as a region with cluster potential, but very different from Antwerp in terms of industry presence and infrastructure availability is the Tournai cluster. Already discussed above and shown in Figure 18, this cluster, composed of cement, ceramics, and food industries, could benefit from electrical grid extensions. The port of Zeebrugge is an excellent example of an infrastructure corridor. Offshore interconnections, both for electrons and molecules, together with offshore wind power arrive at the area from which it departs to fulfil inland demand. Its local industry is insignificant compared to its critical role as an energy hub. Lastly, an example of the remote activity category can be found in a noise point in the Walloon area. Figure 14 highlights a solitary glass factory located near the French border, with no industry or connection to the Belgian backbone grids present in its direct neighbourhood. Its remoteness will most likely have an influence on its energy

transition. The area along the southern part of the border between Belgium and France can be positioned in the interconnection corridor category due to its general lack of industrial facilities, despite numerous electron and molecule grid interconnections.

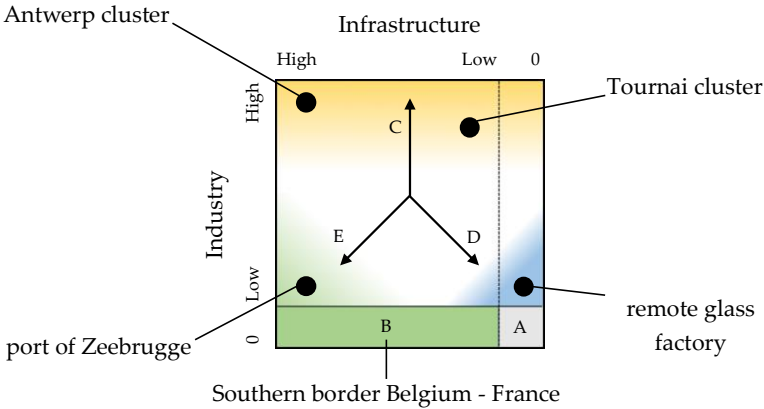


Figure 19 Visualisation of case study results according to the IIQ with a minimum share of 80% covered as cluster potential areas. Area categories: (A) out of scope; (B) interconnection corridor; (C) cluster potential; (D) remote activities; (E) infrastructure corridor.

The way information on energy-intensive industry is collected and processed in Section 3.3.1 allows for the post-processing of the DBSCAN cluster results in terms of industry composition. Agreeing with Sechi *et al*, this extra dimension is of added value in the ESM and provides the opportunity to disaggregate local industrial demand and supply more realistically [185]. The implementation of industry blueprints to improve the energy demand assumptions of EIs is part of Section 3.5. The remainder of this section briefly discusses the clustering tendency of the industrial facilities present in the Belgium and summarises trends on a sector level.

Table 5 contains all industrial sectors, their total number of facilities, and their share of ETS emissions. The last two columns share the post-processing results by dividing the facilities and their respective emissions into either the clustered or non-clustered category according to the DBSCAN output. The table clearly shows that some sectors are more spatially scattered or concentrated than others. In the Belgian case study, all fertiliser and non-ferrous and refinery plants are fully clustered. Steel, chemicals, ceramics and cement, and lime show a strong cluster tendency as well. The remaining sectors are more spread out, which can be seen by the number of noise point (non-clustered) facilities compared to clustered facilities. This is the case for food and drink, glass, and paper and pulp. According to the IIQ,

these noise point facilities are candidates for the remote activity axis. These findings largely confirm the results of Mendez Alva *et al.* [39].

Table 5 The sector composition of the industrial clusters and noise points resulting from the DBSCAN cluster algorithm.

sector	total number of facilities total share ETS emissions	amount clustered	amount non-clustered
cement and lime	12 18.7%	11 17.3%	1 1.3%
ceramics	23 1.7%	15 1.1%	8 0.6%
chemicals	67 31.5%	57 29.8%	10 1.7%
fertilisers	1 2.3%	1 2.3%	0 0%
food and drink	38 4.8%	21 2.2%	17 2.6%
glass	8 2.2%	4 0.6%	4 1.7%
non-ferrous	6 1.4%	6 1.4%	0 0%
paper and pulp	11 2.3%	6 1.2%	5 1.1%
refineries	4 19.4%	4 19.4%	0 0%
steel (incl. processing)	16 15.7%	13 15.1%	3 0.6%
total	186 100%	138 90.4%	48 9.6%

The detailed knowledge of cluster composition can be leveraged for further energy system integration, in particular by addressing the interactions between different energy carriers through industrial activities. Some industrial sectors already function as a service point for various energy carriers, for example, refineries, and future

diversification of energy supply to industry will increase this trend in others as well. The scope of the AIDRES project (cement, chemicals, fertilisers, glass, refinery, steel) gives an impression of targeted sectors that present the largest energy hub opportunities [51]. A high share of clustered facilities is desirable for this selection and is, except for glass, achieved in the case study. Secondly, based on the industry composition of the clusters, certain industrial symbiosis opportunities arise, which support energy and resource efficiency through circularity and optimisation. This work follows the lead from Mendez Alva and paves the way for future cluster transition research in the larger context of the energy system [2].

3.5 CLUSTER TRANSITION PATHWAYS

The previous sections aimed to improve the spatial representation of EII in ESMs by means of ICs, and already paid attention to the sector composition within the clusters and in the noise points. This section targets the technological representation, more precisely, the energy demand assumptions of EII in ESMs. Changes in the energy and feedstock needs of a cluster are the result of the mitigation routes selected by the industries within. ESMs are used by decision makers in a forward-looking approach to provide industry and other sectors with the right supply of clean and affordable energy to meet their demands, and to develop the infrastructure accordingly. A set of industrial energy demand projections, properly corresponding to what is present and ongoing within ICs, is crucial for ESM simulations to be successful in their attempt to ready the energy system and support strategic energy planning.

The works of Fleiter *et al.* and Wiese *et al.* are comparable in terms of ambition to improve industrial energy demand projections. The FORECAST model is able to select from a wide range of highly detailed mitigation routes for various subsectors to render industry climate neutral, and returns transition scenarios for the industry sector [187]. The highest level of spatial resolution in the model corresponds to the districts (NUTS3), after dividing the country-level demand projections over the regions by means of a distribution key based on production capacity and gross value added. The AIDRES project illustrated that such allocation methods can also serve IC transition pathways and further increase the spatial granularity as multiple clusters can be present within the same NUTS3 region [51]. The work of Wiese *et al.* is aware of the interdependencies between industry transition and the operation and design of the energy system and introduces a highly detailed industry model in the established ESM Balmorel [189]. The combination of both models operating at different levels allows to analyse the impact of industrial energy transition on the energy system and vice versa.

In line with Wiese *et al.*, but with ICs as an intermediate level between industrial sites and the larger energy system, this thesis investigates the potential use of the industry blueprints to improve the industrial energy demand projections used in ESMS. This work can be seen as a continuation of the AIDRES project which looked into the pathways of six key process industries, and their respective demands for renewable energy carriers and feedstock. Within the project's original framework, cluster-level transition pathways were introduced to link major trends in energy and feedstock demands with IS opportunities. While in AIDRES only one scenario for 2030 and 2050 were investigated, and IS opportunities were only qualitatively assessed, this work sets up a methodology to leverage the extensive AIDRES database towards multiple scenarios. Each scenario triggers a cluster configuration which inherently drives distinguished infrastructure developments.

For each process within the AIDRES project's scope a reference production route was selected, and alternative routes were explored in accordance with typical mitigation strategies, e.g. electrification, hydrogen, carbon capture, biomass etc. This resulted in a total of 11 production routes for primary steel, 40 for cement, 24 for glass, 28 for fertilisers, 23 for chemicals and 20 for refineries [51]. Each route was modelled with ASPEN and optimised with OSMOSE, which delivers information on a per-ton-of-product basis of a process' energy demand per carrier, raw material input, emissions and investment and operational costs [51]. These models provide virtual profiles for standard industry processes and are referred to as blueprints.

2018 was selected as a reference year and projections for 2030 and 2050 were made as well. To cope with the uncertainty of knowing which pathway(s) a sector would adopt, the AIDRES EU mix route scenarios were constructed. For each process the total production capacity was met by a weighted combination of multiple routes. For example, primary steel production is expected to largely shift from a blast oxygen furnace (100% in 2018) to hydrogen-based direct reduced iron with an electric arc furnace by 2050 ($\approx 60\%$), followed by a blast furnace with CC (18.8%) and natural gas-based direct reduced iron with CC (16.9%) [51]. The same was done for the other five sectors. The share of each production route in the 2030 and 2050 mix routes was decided upon together with industry representatives and sector federations.

Because the instalment of multiple production routes is assumed, the mix route scenarios are no longer representative to scale the output to a NUTS3-level. An industrial site will typically choose only one route to invest in instead of a blend of multiple. This is one limitation of the AIDRES EU mix routes. It is also an important side note to the work of Mendez Alva, which largely departed from the mix route scenarios for the IS opportunities assessment. Nonetheless, he already illustrated the formation of other scenarios by manually selecting production routes for the chemicals and refineries [58]. Another limitation of AIDRES is the restricted scope of

sectors and downstream products that were modelled. Generating cluster-level transition pathways from the AIDRES database hence only paints a part of the picture and neglects many other industry sectors and processes.

In theory, new scenarios in addition to the AIDRES EU mix routes can be simulated from the AIDRES database. A different combination of production routes by altering the weights, or the limitation to one single pathway, can already offer new insights into the future energy and feedstock needs of an IC. The AIDRES consortium promotes such research endeavours by making the database open source. They also offer suggestions for future work, e.g. enriching the database with additional parameters on grid infrastructure (power, hydrogen, natural gas), electricity pricing zones, biomass availability, local policy etc. [51]. This way, the most feasible cluster-level transition pathways can be identified.

In addition to the blueprint models, a geographic database of EU production sites, their activities and capacities was constructed [52]. For an IC of interest, all relevant information can be extracted by filtering on the NUTS3 code or by making use of the coordinates. The per-ton-of-product output from the blueprints are reported as well and can be scaled according to the listed production capacities of a cluster to retrieve the cluster-level demand for energy and feedstock. Results are generated for the following demand categories: electricity, natural gas, hydrogen, coal, cokes, biomass, crude oil and naphtha [52]. Also values for direct CO₂ emissions and the total amount of CO₂ captured are calculated.

3.5.1 ILLUSTRATIVE CASE STUDY

Investigating all possible combinations of production routes, single or weighted, would result in a virtual unlimited number of scenarios. This would not necessarily contribute to a better understanding of the transition of an IC. To illustrate the strongly diverging cluster-level transition pathways, three scenarios are created in line with typical mitigation strategies: an electron route, a hydrogen route and a carbon capture route. This narrows the total number of production routes down to four per sector (reference route included). If multiple production routes are affiliated with a certain strategy, e.g. two options to electrify, the one already used in the AIDRES EU mix route is given priority. The reasoning behind the three storylines is the very diverse infrastructure needs that they would imply for the cluster. Electrification puts additional pressure on the power grids and requires a massive uptake of renewables, and hydrogen and CCS respectively request the buildout of the hydrogen and CO₂ backbone grids.

The above methodology is illustrated for the North Sea Port (NSP) cluster. Originally, the Dutch Zeeland seaports Vlissingen and Terneuzen operated separately from the

Belgian Ghent area. A merger in 2018 formally forged the two parts into one cross-border industrial cluster (Figure 20) [202]. Thanks to its maritime port with connections to inland waterways, pipelines and excellent rail and road infrastructure, the cluster is an access point for global trade to the EU hinterland and beyond. In addition to warehouses and logistic services, there is a strong presence of various processing industries. Four out of six AIDRES sectors are represented in NSP: steel, chemicals, refineries and fertilisers. Non-AIDRES sectors present in the port include paper and pulp, non-ferrous metals, automotive industry and food and drinks.



Figure 20 Map of the North Sea Port area, from [203].

NSP is spread over three NUTS3 areas: *BE234 Ghent* in Belgium, and *NL341 Zeelandic Flanders* and *NL342 Zeelandic other* in the Netherlands. All data related to these arrondissements are extracted from the AIDRES database. Table 6 gives per NUT3 region the companies present, their sector and specific activity (within the scope of AIDRES). Also the production capacity expressed in kilotons per annum is listed in Table 6, together with the reference route that is considered business as usual. The total production capacity remains equal for all processes. This is different compared to AIDRES, where they assumed a decreasing production output from refineries towards 2050. All new cluster scenarios will be benchmarked to the reference route, which mainly relies on fossil resources like crude oil, coal, natural gas and naphtha for energy and feedstock.

Table 6 Reported data on the North Sea Port industrial cluster, extracted from the AIDRES database.

company	NUTS3 code	sector	activity	production capacity [kt/y]	reference route*
ArcelorMittal Gent	BE234	steel	primary production	5300	BF-BOF
Unilin Resins	BE234	chemicals	organic synthesis – PEA	100	(NG) PEA
			ammonia	1900	(NG) NH3
Yara Sluiskil	NL341	fertilisers	nitric acid	1400	(NG) HNO3
			urea	1300	(NG) Urea
			cracker – olefins – ethylene	1810	(LN) O
DOW Benelux	NL341	chemicals	organic synthesis - PEA	1485	(NG) PEA
Zeeland Refinery	NL342	refineries	light liquid fuel	8300	SMR
Eastman Chemical Middelburg	NL342	chemicals	cracker – olefins – all	44	(LN) O
			organic synthesis – PEA	43	(NG) PEA
			polymers – polyethylene	47	(NG) PE

*The names of the production routes listed in Table 5 and 6 correspond to those used in the AIDRES report [51]. **Abbreviations:** AEL – alkaline electrolyser; BF-BOF – blast oxygen furnace; BM – biomass; DEA – diethanolamine carbon capture; DRI – direct reduced iron; EAF – electric arc furnace; FT – Fischer-Tropsch; LN – liquid naphtha; MEA – mono-ethanolamine carbon capture; MeOH – methanol production; MOE – molten oxide electrolyser; MVR – mechanical vapor recompression; NG – natural gas; O – olefins; PE -polyethylene production; PEA – poly-ethyl-acetate production; SMR – steam methane reforming.

Table 7 specifies which alternative production routes are selected to create the new cluster scenarios for the electron route, hydrogen route and CCS route respectively. In the electron scenario, the processes corresponding to the electrification strategy in the AIDRES EU mix routes are selected, except for fertilisers which did not have such a strategy included. To give an indication of the implications of a total electrification of this sector in NSP, the routes which include local green hydrogen production through an alkaline electrolyser are chosen. In theory, the same assumption could be made for the steel sector. This would replace the molten oxide electrolyser with hydrogen DRI, with a local production of green hydrogen. However, because a share of 5.3% of MOE is assumed in the AIDRES EU mix route, this production process is given priority over an on-site electrolyser [51]. As production route for olefins, the electrification of the furnace to provide heat for the naphtha cracker is chosen over the co-electrolysis unit to produce methanol. The hydrogen route does not imply local production. The demand can also be met by import into the cluster through terminals or pipelines. Hence, the routes corresponding to a hydrogen strategy without the on-site AEL are selected.

What is noticeable from the carbon capture and storage route is that it comprises the same processes as the reference route, but with mono-ethanolamine carbon capture and/or diethanolamine carbon capture added to it. The only exception is steel, where the process switches from a blast furnace to natural gas-based DRI with MEA. Another option would be to add MEA to the BF-BOF steel production process.

Beyond the selection of production routes to form scenarios in this work, many other possibilities are left to explore, which was picked up by the PIECE project [167]. Within the framework of this project, the RES2Go tool was developed in collaboration with DG ENER and with feedback from an industry board [168]. It allows users to create future industrial energy demand scenarios from the blueprint outcomes and other relevant sources and to assess the potential of energy clustering in Europe [167,168].

Table 7 Cluster transition scenarios and corresponding production routes for each sector and activity.

Sector	Activity	Electron route*	Hydrogen route*	CCS route*
steel	primary steel	MOE	H2 DRI-EAF	(NG)DRI-EAF-MEA or BF-BOF-MEA
refineries	light liquid fuels	(COEL)MeOH-MEA (COEL)FT-MEA	REF(H2)	SMR-MEA
fertilisers	ammonia	(H2) NH3-AEL	(H2) NH3	(NG) NH3-MVR-MEA-DEA
	nitric acid	(H2) HNO3-AEL	(H2) HNO3	(NG) HNO3-DEA
	urea	(H2) Urea-AEL	(H2) Urea	(NG) Urea-MEA-DEA
chemicals	cracker – olefins – all	(LN+EL) O	(BM+H2-MeOH) O	(LN) O-MEA
	polymers – polyethylene	(Electricity) PE	(H2) PE	(NG)PE-MEA
	organic synthesis – PEA	(EL) PEA	(H2) PEA	(NG) PEA-MEA

3.5.2 RESULTS CASE STUDY

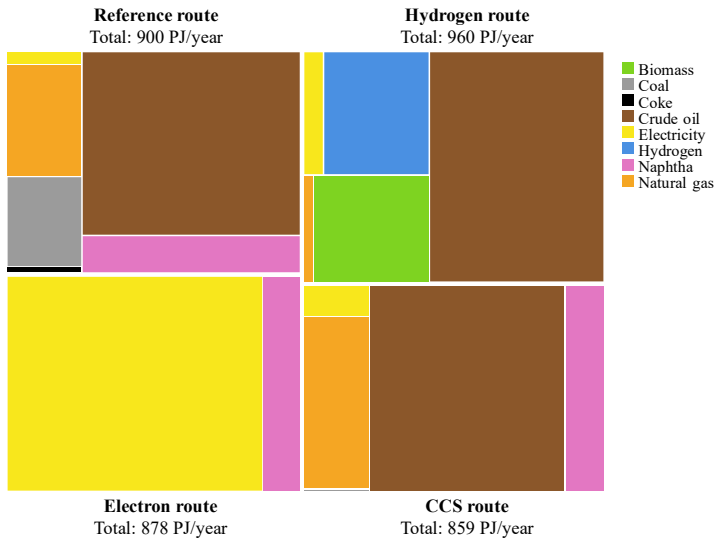


Figure 21 Treemap illustrating the outcomes of the four cluster transition scenarios in terms of energy and feedstock needs, the share of each resource is visualised as relative size.

Figure 21 visualises the energy and feedstock demand per carrier for each of the cluster transition scenarios. All results are expressed in petajoules of energy per annum and the sizes of the squares are an indication of the energy volume. A treemap graph is a visual aid in the comparison of multiple cluster transition scenarios. For example, the smaller sizes of the CCS and electron routes indicate that these routes require less total energy input compared to the reference route. The hydrogen route on the other hand requires an additional 60 petajoules of energy per year, hence the larger square. Tables with the share of each coloured square corresponding to a carrier per scenario and the distribution of the demand of a certain carrier over the production processes are added to the annex (Appendix 3). Such visual support is useful to detect trends, similarities and dissimilarities between the four cluster transition pathways. An interesting question, especially for the work on IS, is to know which sectors are the main drivers behind significant changes in the squares or large contributors to CO₂ emission reductions. For ESM, the shift in demand between energy carriers is of special interest. Hence, the remainder of this section explores the results of all four cluster transition scenarios, both per resource and per production process.

In terms of electricity consumption, a peak in the electron route compared to the other scenarios is no surprise. The increase in electricity demand however is

enormous, going from 2% in the reference route to 87% of the total energy input into the cluster in the electron route. This would no doubt require massive efforts in local electricity infrastructure. The main driver behind this surge in electricity consumption is the refinery sector with a share of 64%. The electricity demand of this sector remains equal in the hydrogen route and roughly doubles in the CCS route, where the total share of electricity is 3% of the energy input into the cluster. Compared to the reference route, the steel sector always significantly increases its electricity consumption. The same trend can be more or less spotted for the production of ammonia and the cracker and, less pronounced, for urea and PEA. Nitric acid production only consumes electricity in the electron route and for PE the consumption remains equal with respect to the hydrogen and CCS routes and increases by 50% in the electron route. Providing the cluster with the right electrical infrastructure, whether by grid alterations or expansions, will be key in all of the investigated cluster transition pathways. Only the scale is still highly uncertain.

The hydrogen demand remains equal in the reference, electron and CCS routes, and is fully allocated to the production of PE. In the hydrogen route, it increases from less than 1% to 19% of the total energy/feedstock input of the cluster, and PE-production is no longer the only sink. All sectors now require hydrogen, with steel as the largest consumer (33%), followed by ammonia (24%) and the cracker (18%). Such a cluster transition scenario depends on the repurposing and further expansion of infrastructure (pipelines and terminals) to transport hydrogen from its production site to the cluster. Within the electron route, hydrogen is assumed to be locally produced through AELs for the fertiliser sector. Hence the electron route would also require local hydrogen infrastructure in the cluster.

Natural gas consumption disappears in the electron route and shrinks to 12% of the reference amount in the hydrogen route where only refineries continue the offtake. It should be noted that in the CCS route the consumption of natural gas increases by 35% compared to the reference route. This can mainly be explained by the process switch in the steel sector towards natural gas-based DRI with MEA. Coal consumption basically disappears, with only a very low demand by steel in the CCS route. This is barely visible in the treemap of Figure 21. Biomass on the other hand appears in the hydrogen route as crucial feedstock for the cracker installation, and accounts for 18% of the total input into the cluster. Important to note is that within the AIDRES EU mix route a biomass option was present for most sectors. The scope of scenarios within this work was limited to electrons, hydrogen and CCS, but widening this with clean energy and in particular biomass-based cluster scenario is acknowledged to be worth exploring in future work.

The significance of the cracker process in NSP is clearly illustrated by Figure 21. The shift towards hydrogen and biomass in the hydrogen route comes at the expense of

the demand for naphtha, which remains equal in the reference, electron and CCS route with respective shares of 12 and 13%. A similar trend can be noticed for crude oil, which remains stable over three routes with a varying share of 58-65%, but disappears in the electron route because of the electrification of the refinery. In the co-electrolysis production route, syngas is produced from carbon monoxide and water and MEA CC separates the CO₂ before it is sent to the methanol synthesis and FT unit to be transformed into light liquid fuel [51]. As previously stated, the cluster-level transition pathways under investigation here are fully aligned with typical mitigation strategies to reflect the most diverse infrastructure needs that would be required by the cluster. Such strong assumptions are not realistic. The above routes would cause huge disturbances in the supply chains of hydrogen, biomass, naphtha and crude oil. Thanks to its user-friendly interface with the AIDRES database, the RES2Go tool can create a wide range of cluster-level transition pathways perfectly suited for scenario studies [167,168].

Table 8 Direct and captured emissions, expressed in kilotons per annum, for each of the four scenarios.

emissions [ktCO ₂ /y]	reference route	electron route	hydrogen route	CCS route
direct	19192,9	315,4	2591,6	873,4
captured	0	2871,8	0	11253,1

Table 8 collects the results in terms of direct CO₂ emissions and captured CO₂ in each of the four cluster scenarios. Especially the captured CO₂ totals are relevant to assess the capacity needed for the CCUS infrastructure. The reference route is selected as baseline with a total amount of direct CO₂ emissions equal to 19192.9 kilotons per year and zero captured. 55% of these direct emissions originate from the BF-BOF steel production process, 17% from the natural gas-based ammonia production and the cracker and refinery each contribute just less than 10%. Compared to this, the hydrogen and CCS routes reduce the direct emissions by 86.5% and 95.4% respectively. In the hydrogen route only the steel and refinery sectors continue to emit. No CO₂ is captured. In the CCS route only nitric acid reaches complete emission reduction (100%). All sectors in the CCS route rely on CC, with in total 11253.1 kilotons captured annually. The largest quantities of captured CO₂ are found in the steel and ammonia production (28% and 27% respectively), followed by the refinery and cracker (another 32% combined). The largest reduction in direct emissions corresponds to the electron route (98.4%), where only the refinery sector is assumed to emit. The electron route also comprises an amount of captured CO₂ emissions

allocated to the refinery, but the total is four times lower than the upper limit set by the CCS route.

The treemap of Figure 21 clearly illustrates that all cluster transition scenarios will require more electricity compared to the reference route. Biomass and hydrogen consumption can surge, at the cost of naphtha demand in the hydrogen route. Natural gas demand can either increase (CCS route), shrink (hydrogen route) or completely vanish (electron route). Cokes will most likely disappear, and coal consumption reduces to the bare minimum. The consumption of crude oil can remain equal to the reference route depending on the scenario, despite the general tendency towards a fossil phase-out. However, while in this study the production capacity of refineries is kept steady, the AIDRES project assumes a decreasing production output towards 2050.

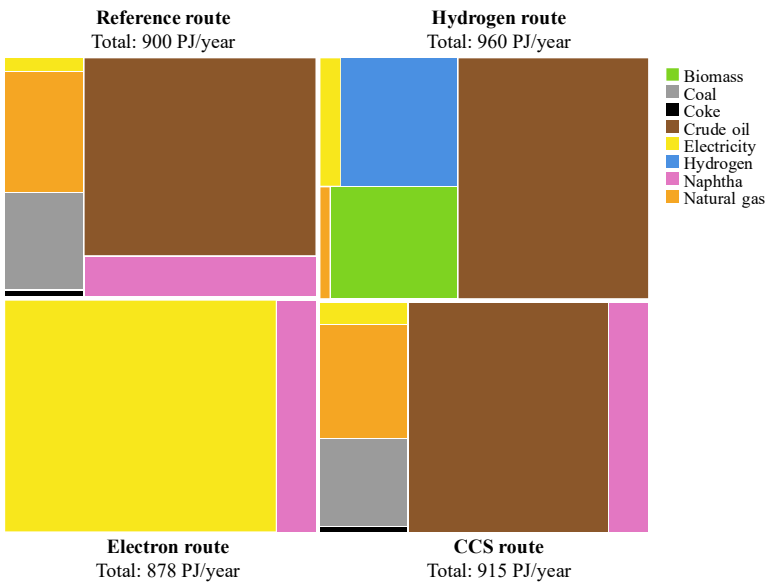


Figure 22 Alternative treemap with a variant for the steel site in the CCS route, illustrating the outcomes of the four cluster transition scenarios in terms of energy and feedstock needs, the share of each resource is visualised as relative size.

Lastly, to compare the mitigation pathways for the steel site in the CCS route, (NG)DRI-EAF-MEA and BF-BOF-MEA, the treemap is replotted in Figure 22. The hydrogen route and electron route stay the same. Changing the production route increases the total energy input to the cluster by 56 PJ/year. The dependency on natural gas decreases and in turn, coal and cokes are continued to be used. The significant shift in energy and feedstock consumption confirms the strong

importance of the steel sector in NSP, thus how one single site can partly dictate the transition direction of a cluster.

A comparative study of cluster transition scenarios gives insights into potential cluster-level resource demands, which in their turn drive infrastructure developments to guarantee adequacy. The electricity infrastructure in NSP will definitely require an upgrade to cope with the additional demand, as the grids in the Dutch part already suffer from congestion (Figure 23) [204]. This places new connection requests from industry and other sectors on a waiting list until grid expansion is completed. TenneT, the Dutch TSO for electricity, expects the bottleneck to be resolved by 2035 [205]. In Vlissingen, a large battery storage facility was announced in December 2025 with a total storage capacity of 1400 MWh and a power rating equal to 350 MW [206]. NSP and the TSOs Fluxys and Gasunie are currently investigating the installation of a network of hydrogen pipelines that will connect both the Dutch and Belgian part of the cluster [202]. Recent communications on the Dutch part confirmed the preferred trajectory consisting of new and retrofitted pipelines as can be seen in Figure 24 [207]. Fluxys on the other hand announced a suspension of the project development as long as the market conditions remain unfavourable [208]. Also CO₂ infrastructure in the cluster is still under investigation, with plans for circular carbon and CCUS in Ghent under the North-C Circular flagship [209]. Yara Sluiskil, the fertilisers producer in NSP, plans to capture CO₂ and, after liquefaction, to transport it to the Northern Lights storage in Norway [210]. In January 2026, NSP announced a collaboration with the UK to install a CCS terminal complemented with a shipping corridor [211]. Lastly, in a study from November 2024, the potential for ammonia transport departing from NSP towards the hinterland is investigated [212]. The study includes three means of transport: pipelines, shipping and rail, and the most cost-optimal option depends on the total amount of ammonia handled. Pipelines are most suited for large quantities, but shipping and rail transport will likely play an important role in creating the market in the near to mid-term.

The cluster transition pathways depend on having the right infrastructure established in time. It is clear that this is highly effort- and cost-intensive. Not only from the industries present in the cluster, but also from the grid operators, who all need to make decisions while facing many uncertainties. This work proposes to look at this challenge from a different angle to see where cluster stakeholders can advance their transition through collaboration. It is a worthwhile exercise as it can focus efforts to generate benefits for multiple parties, or even reinforce a cluster on its whole.

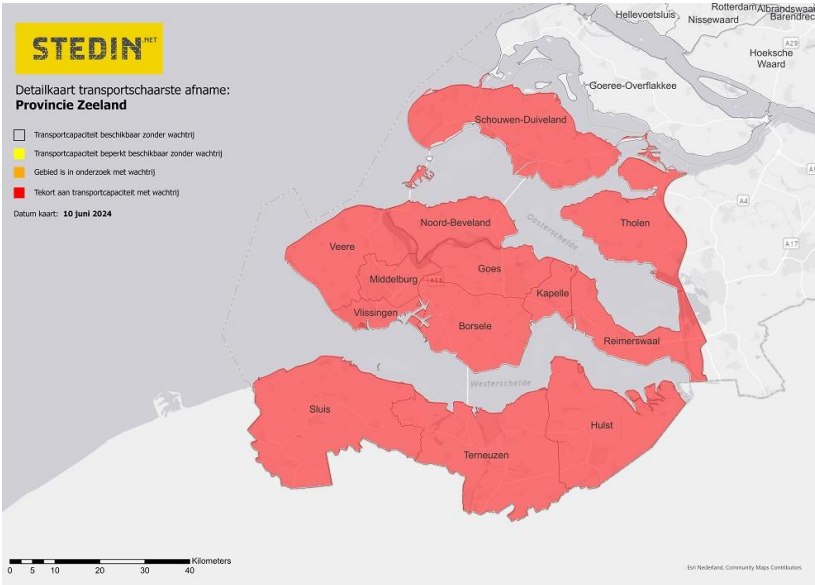


Figure 23 Map of congested areas in the Dutch part of NSP for grid offtake. From [213].

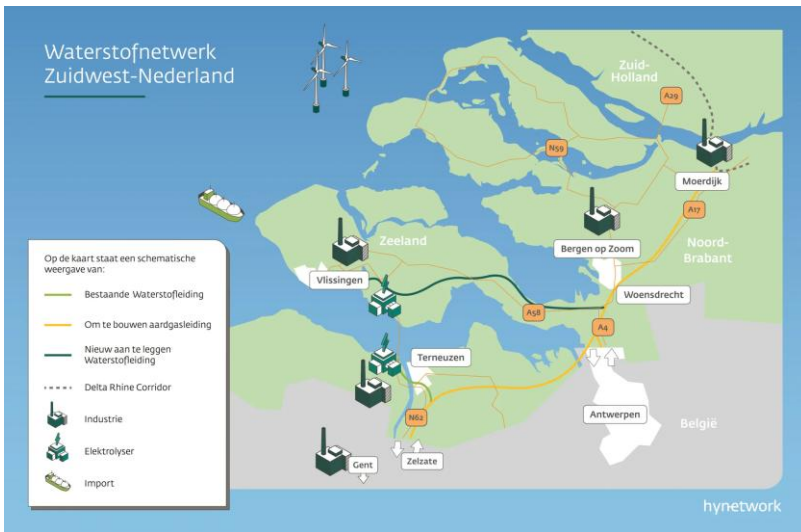


Figure 24 Schematic map of the proposed hydrogen network in the Dutch part of NSP. Yellow lines correspond to retrofitted pipelines, green to existing hydrogen pipelines and dark green to new pipelines. From [207].

3.6 OVERVIEW OF SUITABLE ENERGY SYSTEM MODELS

The openmod initiative collects information on all available open source models and open data in the field of energy system modelling [176]. This section creates an overview of suitable models that could benefit from ICs to enhance their spatial and technical resolution. ESMs of relevance here typically categorise as bottom-up models, since a detailed description of the energy system and especially the industrial sector are needed. The openmod database was searched for all models that include industry as a sector. Models that report 'all' as sector scope are also added to the overview. The resulting list is presented in Table 9. In total, there are 16 models that qualify.

Table 9 Results from the openmod database search.

model	sectors	spatial resolution	industry as explicit subsector	version (date)	developer
Balmorel	user-dependent	regions/countries		V5 (2025)	DTU
OSeMOSYS	all	country		global V1.0 (2024)	KTH Royal Institute of Technology
Energy Transition Model	all	country		continuous	Quintel Intelligence
EnergyScope	all	country/regional		V1.0+ (2023)	EPFL
TIMES	all	local/global		V6+ (continuous)	IEA-ETSAP
DESSTinEE	all	country		V1.0 (2016)	Imperial College London
GENeSYS-MOD	all	country		V3 (2024)	Europa-Universität Flensburg

Energy Policy Simulator	all	one single region		V1.0 (2025)	Energy Innovation LCC
Temoa	all	one single region		V2.0+ (2024)	North Carolina State University
SpineOpt.jl	all	user-dependent	no	V0.9+ (2025)	VTT Finland
Calliope	user-dependent	user-dependent	no	V0.7+ (2025)	University of Oxford
AnyMOD	user-dependent	user-dependent	no	V1.0+ (2023)	TU Hamburg
IRENA FlexTool	all	user-dependent	no	V2+ (2024)	IRENA
NEMO	all	user-dependent	no	V1.0+ (2022)	Enspire
Backbone	all	user-dependent	no	V4+ (2024)	VTT Finland
PyPSA-Eur	user-dependent	user-dependent	yes	V2026.0 2 (2026)	Karlsruhe Institute of Technology, TU Berlin

Secondly, the spatial resolution of the models is checked to see whether or not it is compatible with the node selection procedure described in Section 3.3. From the selection, only seven models allow the user to define the nodes within the system. Lastly, the level of detail of the industry sector representation is investigated. Special attention is paid to the split in subsectors and the inclusion of transition pathways. From the shortlist, PyPSA-Eur resulted as the most suited ES to implement the IIQ framework and integrate the AIDRES database due to its compatible data processing structure, transparency on the modelling framework, extensive documentation and increasing popularity through use-case by researchers, policymakers and TSOs. The other six models do not define industry as explicitly as desired for a straightforward integration of ICs. Chapter 4 continues on this path and

explains how the IC concept can be introduced in the PyPSA-Eur modelling framework.

3.7 CONCLUSIONS

This chapter investigates the opportunity that ICs present to improve the representation of industry in ESMs, in support of strategic energy planning and cluster transition research. The chapter includes a brief literature review on the research state of the art of industry representation in ESM, confirming the need to improve spatial and technical resolution. Contributing to the research field, the IIQ framework developed within this thesis facilitates the introduction of ICs in ESMs by visualising the relationship between industry and infrastructure presence. The complementary node selection procedure solely relies on publicly available data and open-source processing tools. A case study applied to Belgium results in ten nodes to represent the territory, accurately reflecting crucial infrastructure elements, industrial clusters and future needs whilst improving industry representation in terms of space and composition.

To improve the technical details of industry transition pathways used in ESMs with exogenously defined demands, the AIDRES project offers a rich database with untapped potential. From the wide range of production routes for the six EII sectors, various cluster transition pathways can be created to serve as industrial energy demand scenarios. Three cluster transition pathways in line with typical mitigation strategies are already investigated in a case study on NSP to illustrate the strongly diverging infrastructure needs resulting from the shift in aggregated energy and feedstock demands. The RES2Go tool strongly improved the accessibility to the AIDRES database and added modules to cluster the sites and adapt their production capacities. Hence, the tool is leveraged in the methodology presented in Chapter 4 to integrate the IC concept in PyPSA-Eur. According to the brief review of ESMs, PyPSA-Eur has the most complementary model setup to the framework presented in this chapter.

The IIQ framework and methodology have a primary focus EIIs. Even if this tends to disregard other energy actors, such as residential, commercial, and transportation sectors, the focus on the EIIs is not considered as a limitation. The work serves as a benchmark for multi-node ESM applications, with targeted demand sectors going beyond EIIs. On the other hand, the reliance on European data sources, in particular EU ETS, is recognised as a limitation of the work due to its derived or missing information but is justified as it serves as a commonly accepted proxy for energy intensity. It is used in many studies as a workaround for the lack of publicly available,

detailed indicators on energy consumption in Europe and it aims to inspire other regions to duplicate or extrapolate the efforts of IC integration in ESMs.

An overview of the contributions of this dissertation to the research field are summarised in Table 34.

CHAPTER 4 INDUSTRY TRANSITION MODELLING IN PYPSA-EUR

In the previous chapter, it was investigated how industrial clusters can improve the way EILs are represented in energy system models. It offers another approach to the regional disaggregation in multi-node models that is in line with identifying large demand centres, contrary to ‘energy system independent divisions’ that stick to administrative borders. Knowledge from the industry blueprints developed in the EPOS and AIDRES projects have the potential to improve the technical representation of EILs and support assumptions on energy demand projections. From the list of ESMs in Section 3.6, PyPSA-Eur is selected to put the IIQ framework into practice, to validate the methodology for node selection and demand creation, and to illustrate the added value of introducing ICs in ESMs. The main ambition of this work is to contribute to the toolset for strategic energy planning in support of Draghi’s message to focus efforts on ICs in order to accelerate the energy transition and enhance competitiveness. Governments and network operators rely on ESMs to take well-informed decisions about infrastructure investments based on future demand projections. Modelling at a cluster level simultaneously captures the energy system within an IC, useful to detect potential IS opportunities, and the wider system surrounding an IC, seeking regional optimisation. It improves the understanding of the current and future energy infrastructure needs of an IC.

The chapter contains the following sections: Section 4.1 describes the original PyPSA-Eur framework, the default industry scope and energy demand assumptions. In Section 4.2, the IIQ framework is integrated into PyPSA-Eur, explaining how it impacts industrial energy demand assumptions. Section 4.3 includes an illustrative case study on the trilateral region comprising Belgium, the Netherlands and Germany to validate the presented methodology and to illustrate the type of information and insights that cluster-based energy system modelling can capture.

4.1 PYPSA-EUR

PyPSA-Eur is an open-source energy system optimisation model that covers the complete ENTSO-E power system at transmission level in high detail (~5800 buses, ~7300 lines with a voltage level at and above 220 kV and all 36 High-Voltage Direct Current (HVDC) lines) (see Figure 25). It retrieves the most cost-optimal energy system that meets the demand per node for each time instant, minimising investment and marginal costs. The operation of the power system is approached

using linearised power flow equations. Energy infrastructure planning in the model is driven by the following objective function:

$$\begin{aligned} & \min(\text{yearly system costs}) \\ & = \\ & \min \left(\sum_{\text{nodes}} \text{annualised capital costs} + \sum_{\text{nodes,time}} \text{marginal costs} \right) \quad (1) \end{aligned}$$

The model makes use of open databases on existing power plants, local RE availability and respective time series. It allows for sector coupling and models demand and supply from all energy sectors, including industry, residential and transport. Techno-economic assumptions on system components and technologies mainly come from the Danish Energy Agency or other valid public sources. It can be applied to both operational and long-term expansion planning studies and the list of users goes beyond academics to include governments, the EC and several TSOs. [214]

The power network within PyPSA-Eur has a high spatial resolution, and the user can manage the node selection to which the model simplifies, solves and optimises. Hence, the model is compatible with the node selection methodology that aligns with ICs from Section 3.3. As a first step, the base ENTSO-E network is simplified by transforming the grid to its 380 kV equivalent and removing antennas. Transformation to the 380 kV equivalent is done to circumvent data availability issues on the transformers in the network. Antennas in the network correspond to dead ends and are aggregated with their neighbouring bus to reduce the computational load.

Secondly, the network is clustered to reduce it to a given number of zones with one node per zone and aggregated transmission corridors between the nodes. The sum of the generators, storages and loads of the original buses represent the new node. For this, K-means is applied to the original buses of the power network. The length of the lines in between nodes are equal to 1.25 times the crow-flies-distance and the capacities equal to the sum of the original lines [215]. The algorithm is constraint to allocate a share of the nodes to each country in proportion to its overall mean load. Countries with large loads receive a larger number of nodes compared to countries with smaller loads, with the total number of nodes given as an input to the cluster algorithm. This constraint can be altered in the configuration file to user-defined weights on a country level. The simplification ignores grid topology and electrical distances. According to the developers, this is not an issue since the purpose of the model is to optimise the grid capacities with respect to the future demands. The

lower the number of nodes in the simplified network defined by the user, the lower the transmission grid capacity availability factor (e.g. 0.7 x nominal for at least 200 nodes and 0.5 for 37 nodes). This measure is to guarantee N-1 security in the system, meaning the grid will remain operational even after the failure or unexpected outage of a line, transformer, generator, etc. [215]

Alternatively to K-means, the model allows for custom bus maps, clustering with respect to administrative borders at NUTS levels zero to three, or using the HAC cluster algorithm [216,217]. The latter is worthwhile to further investigate as it preserves the network topology while clustering based on regional properties. In PyPSA-Eur, the algorithm builds the clustering on meteorological data [218].

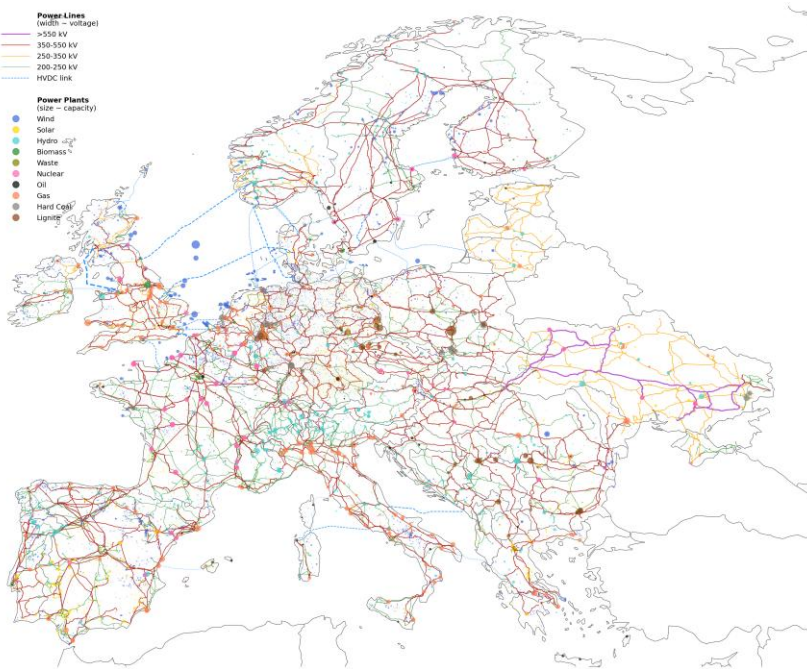


Figure 25 Scope and contents of the power system present in PyPSA-Eur [216].

In addition to the spatial granularity, the second element of novelty in this work is the agility of the industry sector profiles. In the sector-coupled version of PyPSA-Eur, industrial energy demand projections for multiple carriers are exogenously determined and entered into the model. It departs from the Hotmaps industry database, a spatial dataset of all EU energy-intensive sites [219]. The database includes ETS and E-PRTR emissions for the year 2014, which are used to compute each site's production capacity based on emission factors [216]. For every sector, the current energy demand and total material output per country are collected from the JRC-IDEES database (reference year 2023) [220]. Within each country, the total

energy demand per sector is distributed over the model nodes using the production capacities resulting from Hotmaps as distribution key. Towards 2050, the total amount of production output is assumed to remain constant. PyPSA-Eur includes alternative production routes for each sector, mostly implying electrification where possible [221]. The current electricity demand is added on top of the future demand, with the reasoning that it covers loads that remain to be powered with electricity (lighting, compressors, ventilation, pumps, motor drives, etc.) [216]. The same distribution key is used to divide the future industrial energy demand per sector over the model nodes.

For now, the model assumes no industrial relocation will take place. However, according to a recent communication by the team of developers of PyPSA-Eur, work is ongoing to model industry relocation, high-temperature heat sourcing and shipping fuels endogenously [216]. Currently, these parameters are exogenous, thus given as input by the user to the model. The list of endogenous parameters in the current version of PyPSA-Eur includes: the electricity generation fleet, transmission grid reinforcements, energy storage locations and capacities, space and water heating technologies for buildings and low-temperature heat supply for industry, power-to-X technologies and CC. Also the origin of hydrogen, methane and naphtha are determined endogenously by the model [222]. A comprehensive overview of the endogenous and exogenous parameters in PyPSA-Eur is presented in Table 10.

Table 10 Overview of endogenous and exogenous parameters in PyPSA-Eur.

endogenous parameters	exogenous parameters
electricity generation	energy demand
transmission reinforcement	district heating
energy storage	road transport, aviation, shipping
low-temperature heating	industry transition
power-2-X	
CC	

Before the model can converge to an optimal energy system, PyPSA-Eur requires demand values for non-industry sectors. The model derives total loads per country from ENTSO-E and allocates it to the nodes using population density (40% of the total load) and GDP per NUTS3 (60% of the total load) [214]. To avoid double counting in sector-coupled studies, a correction has to be made to the total power demand. As shown in formulas 2 and 3, the share of today's electricity demand allocated to industry is removed from the total load using a correction factor. Afterwards,

industrial load is added separately as 'industry electricity' using the exogenous data inputs and Hotmaps distribution key.

$$f_{\text{correction}} = 1 - \frac{\sum \text{load}_{\text{ind,today}}}{\sum \text{total_load}} \quad (2)$$

$$\text{load}_{\text{non-ind,new}} = f_{\text{correction}} \times \text{total_load} \quad (3)$$

The configuration file in PyPSA-Eur allows the user to tweak assumptions on industry transformation and parameter values. However, this is limited to a handful of sectors: primary and secondary steel, aluminium, high-value chemicals and ammonia/fertilisers. All other values and assumptions are embedded in the coded rules of PyPSA-Eur and are less straightforward to alter. Also the range of production routes is limited, often only including electrification, and lacks transparency in the configuration file. This work aims to improve the level of technical detail of industry transition pathways and increase the flexibility in defining future demand scenarios. Having a good understanding of the way PyPSA-Eur collects industry data and generates future demand projections, the objective is to leverage compatible but more detailed data sources to alter the assumptions, in line with Section 3.5.

The discussion on PyPSA-Eur is concluded with a set of model limitations, of which some are addressed by the methodology presented in this work. Having a good understanding of the model limitations is important to be well-informed when implementing the IIQ framework and analysing the IC-based outcomes.

According to the developers, exogenously defining the transformation pathways of industry is done to avoid penny-switching by the model. The assumptions behind these transformations, however, can benefit from more details resulting from the blueprints and from more flexibility in creating scenarios by use of the RES2Go tool. Also, industry production remains constant and inelastic. The RES2Go tool includes a module to adapt the production capacities on a sector level [168]. Hence, alternative scenarios where industry production in a certain sector drops can easily be included in PyPSA-Eur. Important to note here is that the change in output will reflect on every site in EU corresponding to the sector of interest. Lastly, the demand distribution within a country is assumed to be proportional to population, GDP, and for the sector-coupled version also based on industry distribution keys from Hotmaps. The latter is in need of an update, and ICs can facilitate this.

Other limitations highlighted by the developers relate to the electricity network topology and completeness and are not improved by the IIQ framework. While the grid is based on ENTSO-E information, small distortions and approximations are

present and the connected distribution grids are not part of the model scope. Electricity demand is allocated to a model node using Voronoi cells (similar to the approach in Section 3.3.2) and does not take into account the underlying grid's topology. As a consequence, individual sites might be connected to the wrong substation. Although the node selection in line with ICs cannot guarantee that each site will be correctly linked with the right substation, the IIQ framework confirms the strong correlation between cluster tendency and infrastructure presence. Hence, Voronoi cells driven by ICs will already improve industry representation.

4.2 IIQ APPLICATION

The configuration of the AIDRES database is compatible to the structure of PyPSA-Eur: a list of industry sites including coordinates, production capacities and specific energy demands for production routes which can be scaled to each node's material output. Compared to the default assumptions of PyPSA-Eur, the AIDRES database comprises many more production route options, and allows the user to generate various future industrial demand scenarios by making different combinations of production routes or altering the weights. This section presents the methodology of the extension that replaces the original industrial energy demand assumptions from PyPSA-Eur with data from the AIDRES database. The extension makes use of the RES2Go tool to cluster the industry sites and generate energy demand projections.

Figure 26 illustrates the workflow of the extension. Firstly, the AIDRES industry sites database is used as input to the DBSCAN cluster algorithm. According to Mendez Alva *et al.*, this cluster algorithm is the most effective in identifying ICs based on spatial density [39]. The cluster parameters are chosen in line with Mendez Alva's work, namely 25 km as distance between two sites and 5 nearby sites as lower threshold to count as a cluster. The output of DBSCAN is a set of ICs of interest for ESM. The second step is to align the node selection of the power network in PyPSA-Eur with the resulting set of ICs. As a start, the number of nodes in the model can be set equal to the total number of clusters. If the correspondence is not satisfactory, the number of nodes can be increased. A higher level of spatial granularity improves the level of detail but also affects computational time. Hence, it is desirable to keep the total number of network nodes to a minimum. Alternatively, a custom bus map or changing the weights of the K-means algorithm can be explored.

Once the nodes properly represent the ICs, the PyPSA-Eur model is run with the default assumptions on industrial energy demand. Next, the input file with industrial energy demand per node is altered using the AIDRES industry sites database and the production route scenario of interest to the user created using RES2Go. For each

industrial demand scenario, the PyPSA-Eur model can be re-run to generate updated results. Afterwards, results for the various industry demand assumptions can be compared and analysed to understand the impact of a cluster's transition pathway on the energy system. Outcomes in terms of optimal network compositions, grid reinforcement needs, investments in local generation hubs and storage capacity, etc., can be compared.

Important to note is that with respect to carbon capture, the PyPSA-Eur model will endogenously decide to include the technology in a node, based on the capital costs. The heat and electricity demand of the CC technologies are excluded from the nodal energy balances. For the following comparisons between default and updated energy demand values, CC technologies are left aside from the balance to have the best possible match in terms of energy demand assumptions. However, excluding the energy demand of CC technologies no longer paints a complete picture of IC infrastructure requirements. Leveraging the AIDRES database instead has the potential to rectify this assumption and allows the user to select between production routes with or without CC technologies.

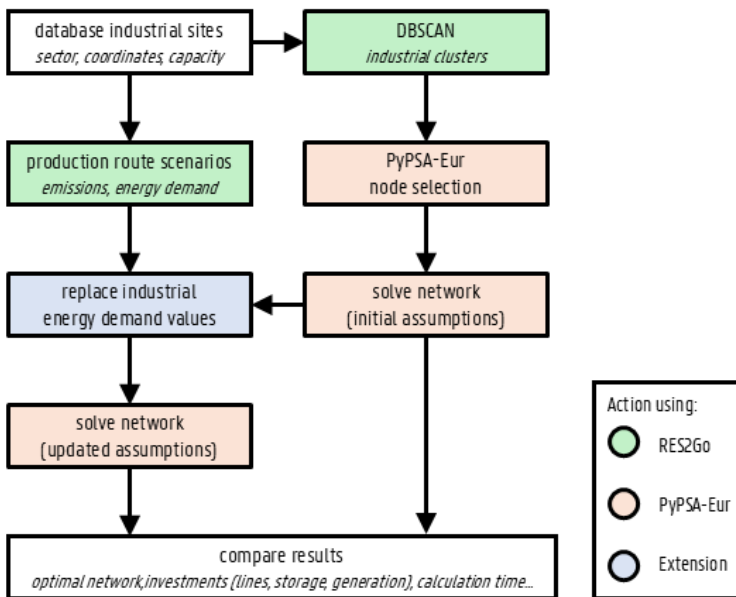


Figure 26 Flowchart of the methodology to create industrial clusters, generate energy demand scenarios using RES2Go (green) and replace the original assumptions in PyPSA-Eur (orange) through the IC extension (blue).

It is noted that the AIDRES database has a limited scope (six sectors) compared to Hotmaps (12 sectors), which affects the coverage of the industrial energy demand in

the model. Nevertheless, the workflow described in Section 4.1 and the formulas described to correct the total power load (2-3) remain valid. Ongoing developments of the RES2Go tool aim to expand the sector scope of industrial production routes and sites beyond the six AIDRES sectors. For now, this work limits the scope of varying industrial demand assumptions to the sectors present in the AIDRES database. Important to note is that the refineries sector is excluded from the methodology, as this sector does not categorise under industry in PyPSA-Eur. The refinery sites are, however, still used to define the clusters.

In addition to the industry sites and production routes database, AIDRES also defines a baseline demand for 2018 using reference production routes, and future demand scenarios for the years 2030 and 2050 [51]. To account for the uncertainty regarding the processes a sector will invest in at a European scale, the scenarios for 2030 and 2050 combine multiple production routes using weights. The selection of production routes and respective weights in the official AIDRES scenarios was decided upon together with industry representatives and sector federations [51]. Given that these assumptions date back from 2018 and considering the significant changes in the European industry context since then, the AIDRES scenarios need to be revised. In this work, however, the AIDRES reference baseline for 2018 is kept to represent the current electricity demand. A reference value is necessary to make the correction in the total load of a node, see formulas 2 and 3. To generate the future industrial energy demand, this work sticks to the AIDRES MIX2050 scenario at first. Later, weights of the production routes are altered to reflect on the impact of cluster transition pathways on the energy system.

The PyPSA-Eur version used in this work is v2026.02.0 [216]. The extension that modifies industrial energy demand assumptions in the model is coded in Python (Appendix 4).

4.3 PROOF OF CONCEPT

To validate the effectiveness of the extension that alters the demand scenarios of specific industry sectors, and the added value of aligning the model nodes with ICs, the methodology is tested on a subset of EU countries with high industry density: Belgium, the Netherlands and Germany. Firstly, various node-selection procedures within PyPSA-Eur are compared to search for a best-fit with the ICs resulting from the DBSCAN cluster algorithm. Next, the extension replaces the default industrial energy demand assumptions of the resulting nodes with values from the AIDRES database, processed by the RES2Go tool.

4.3.1 NODE SELECTION

Applying the DBSCAN cluster algorithm to the AIDRES industry sites in this cross-border region (BE-NL-DE) resulted in fifteen clusters, nicely capturing the dense areas in Belgium (Antwerp, Ghent, Meuse river), the Netherlands (Rotterdam, Terneuzen) and Germany (North-Rhine Westphalen) as can be seen in Figure 27.

The goal is to align the node-selection procedure in the network clustering step of PyPSA-Eur with the set of ICs. Three approaches are explored and afterwards compared in terms of effectiveness. First of all, the traditional K-means cluster algorithm is used without changing the weights of the countries. The total number of nodes is set equal to fifteen, and each country will receive a share of nodes in proportion to its energy demand (mean load). Secondly, the weights of the K-means algorithm are tweaked in the config file of PyPSA-Eur to correspond to the cluster-country division of DBSCAN. Since the North Sea Port (in light blue) is a cross-border cluster, an additional node needs to be defined to enable splitting the cluster in a Belgian and Dutch part. This split is a consequence of PyPSA-Eur respecting administrative boundaries. As a result, Belgium gets five nodes, the Netherlands receives two nodes and Germany nine nodes. A third spatial disaggregation method explored in this work is the custom bus map approach, where the centroid of each cluster is used to define a node. Once again, the NSP cluster is split in a Belgian and Dutch part.

Figure 28 plots the regions of the PyPSA-Eur model when the larger network is simplified to 15 nodes using the default K-means cluster algorithm. Belgium and the Netherlands each receive two nodes, and Germany 11. This can be explained by the larger mean load of Germany compared to both other countries. As a result, the regions do not nicely correspond to the distribution of ICs. In Belgium, the Meuse industrial area is aggregated with the Belgian part of the NSP cluster and the port of Antwerp. All Dutch clusters are aggregated in one region with the second region containing no ICs. Similar trends are noticeable for Germany.

In an attempt to correct the node division over the countries based on the clusters present, the weights of the K-means algorithm are tweaked in the configuration file to correspond to respectively five, two, and nine nodes in Belgium, the Netherlands and Germany. Comparing Figure 29 to Figure 28, the representation of Belgian ICs improved, while the resolution remained comparable for Germany and the Netherlands. Aggregation of clusters to the same node remains an issue in each country.

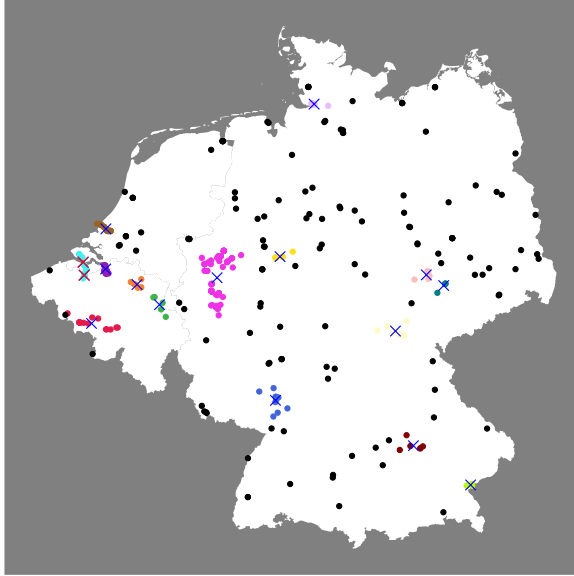


Figure 27 Map of the fifteen ICs in Belgium, the Netherlands and Germany resulting from the DBSCAN cluster algorithm. Each colour corresponds to a cluster while black dots indicate non-clustered sites. The centroid of each cluster is indicated by an X.

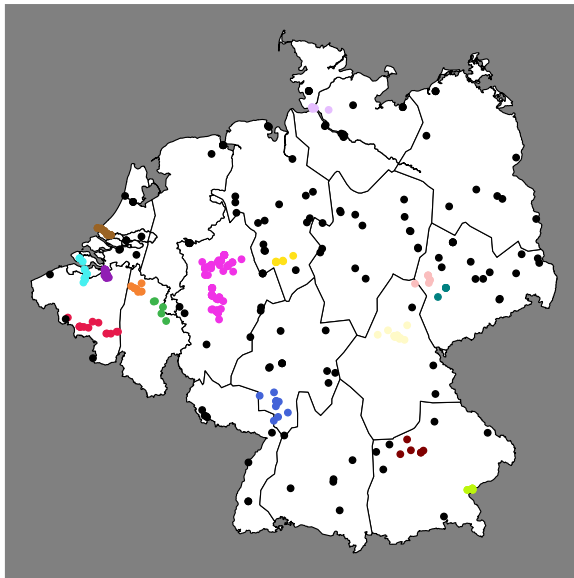


Figure 28 Map of the 15 node regions in PyPSA-Eur from K-means, overlapped with the industrial clusters resulting from the DBSCAN cluster algorithm.

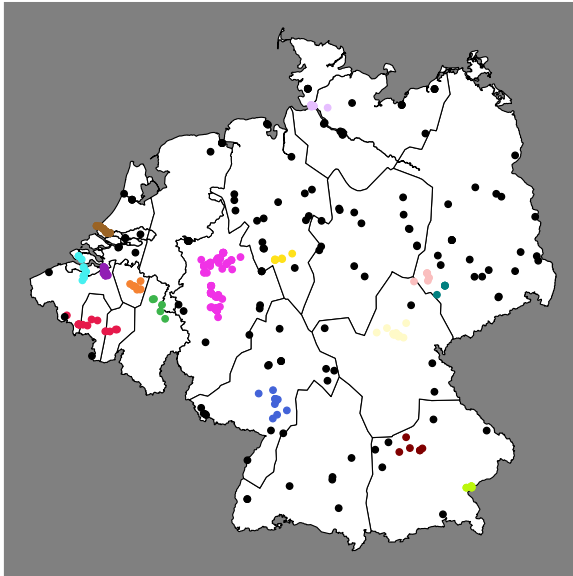


Figure 29 Map of the 16 node regions in PyPSA-Eur from K-means with changed weights, overlapped with the industrial clusters resulting from the DBSCAN cluster algorithm.

The most direct way to force PyPSA-Eur to converge to a set of nodes corresponding to the 15 clusters is to leverage the cluster locations and to create a custom bus map. The centroid is calculated for each IC and indicated by an X in Figure 27. NSP is split in a Dutch and Belgian part, hence there are two centroids corresponding to this cluster. Once the centroids are known, each bus from the simplified network is allocated to the nearest centroid of the country in which that bus is located.

Important to note is that this step uses the simplified network and not the initial network from ENTSO-E. Hence, antennas have already been removed and all lines are converted to their 380 kV equivalent. This is the standard workflow of PyPSA-Eur. As a consequence of the simplification step, the local network in the NSP is strongly reduced. Figure 30 plots the network before and after the simplification step. When applying the cluster centroids as a mapping procedure, the centroid corresponding to the Belgian part of NSP remains empty. All buses are allocated to the Antwerp cluster centroid. Comparing the maps before and after the simplification step confirms this (Figure 30). If France were to be added to the list of countries, the lines coming from the Ghent area would no longer be seen as an antenna due to the interconnection, and the centroid corresponding to the Belgian part of NSP would no longer be empty.

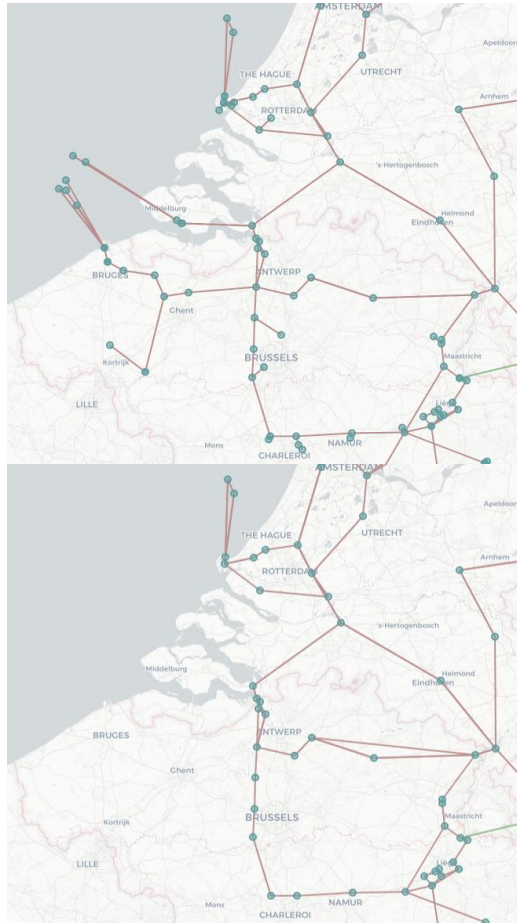


Figure 30 Map before (above) and after (below) the network simplification step of PyPSA-Eur with the following country selection: BE, NL, DE.

To conclude, a custom bus map allows the user to define node preferences but is no guarantee that the simplified model will converge accordingly. For the set of countries and IC centroids used in this study, the custom bus map does not result in a node selection where every IC is represented by a unique node (Figure 31). While there are 16 cluster centroids, there are 15 regions in total.

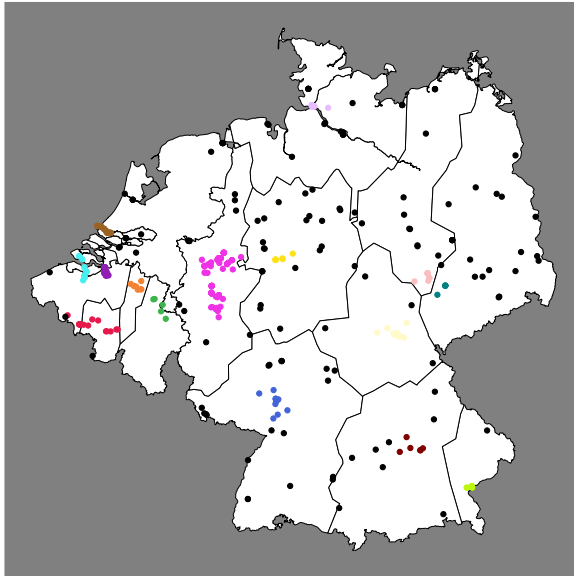


Figure 31 Map of the 15 node regions in PyPSA-Eur using a custom bus map, overlapped with the industrial clusters resulting from the DBSCAN cluster algorithm.

4.3.2 INDUSTRIAL ENERGY DEMAND ASSUMPTIONS

Next, the model converges using both the original and updated industrial energy demand assumptions for 2050. The updated demand assumptions first correspond to the AIDRES MIX2050 scenario [51]. As an intermediate output from the Snakemake workflow of PyPSA-Eur, a table is generated that details industrial demand on a node level for electricity, coal, cokes, solid biomass, methane, hydrogen, low-temperature heat, naphtha, ammonia and methanol. In addition, process emissions are also reported on a node level, together with the current electricity consumption to correct the total load (see formulas 2-3). Table 11 summarises the default industry assumptions and data gathering of PyPSA-Eur that is to be altered by the extension. Important to note is that this dissertation focuses on the energy supply to EILs, hence scope 2 emissions.

The extension replaces the data in this file by data from the RES2Go tool that is projected onto the regions defined in the previous section. The AIDRES database reports on demand for electricity, alternative fuel mixture, biomass (waste), coal, coke, crude oil, hydrogen, methanol, ammonia, naphtha, natural gas and plastic mix and also contains direct CO₂ emissions. Table 11 summarises which data sources from AIDRES are used to replace the original demand values.

The values corresponding to low-temperature heat demand are set equal to zero. Determining how the heat demand of a process should be met is already part of the OSMOSE optimisation that compiles industry blueprints. Hence, low-temperature heat demand is already covered by another energy carrier.

For the sake of completeness, alternative fuels and plastic mix are present in the AIDRES database, but are not part of the PyPSA-Eur scope of energy carriers and feedstocks. In the AIDRES MIX2050 scenario, demand for the former is created by the cement sector and for the latter by the steel sector.

Table 12 lists the current and future industrial electricity demand for each node with the default PyPSA-Eur assumptions, as well as the updated assumptions using the extension and AIDRES database for the sectors cement, chemicals, fertilisers, glass and steel.

Table 11 Default data entries on industrial energy demand in PyPSA-Eur and suggestions to replace by AIDRES data.

PyPSA-Eur data input	data from AIDRES to replace
electricity	electricity (MIX2050)
coal	coal
cokes	cokes
solid biomass	biomass + biomass waste
methane	natural gas
hydrogen	hydrogen
low-temperature heat	0 (part of optimisation OSMOSE)
naphtha	naphtha
ammonia	ammonia
methanol	methanol
current electricity	electricity (reference routes)

Table 12 Industrial electricity demand per node in PyPSA-Eur for the reference year and 2050, left the original assumptions and right the updated values using the AIDRES database.

Node	Electricity demand original assumptions [TWh/year]		Electricity demand MIX2050 assumptions [TWh/year]	
	today	2050	today	2050
BE0	6.96	10.46	1.41	2.30
BE1	8.23	12.75	0.62	0.85
BE2	4.04	7.07	0.76	1.89
BE3	19.03	41.02	6.31	34.89
DE0	4.20	11.18	2.04	3.59
DE1	22.97	46.19	4.72	17.34
DE2	156.80	193.27	7.68	49.10
DE3	1.56	4.01	0.20	0.34
DE4	6.61	23.11	2.41	6.66
DE5	10.00	29.01	2.84	7.97
DE6	12.37	31.53	2.19	6.30
DE7	2.86	7.15	0.93	1.59
DE8	5.90	16.38	1.18	3.04
NL0	31.68	69.23	2.16	11.07
NL1	4.07	16.55	2.50	16.94
total	297.28	518.91	37.96	163.86

Before comparing the network optimisation results of both model versions, the outcomes of changing assumptions need to be well understood. The industrial electricity demand per node changes over the two versions for two main reasons. On the one hand, the sector scope is more limited in AIDRES compared to Hotmaps. On the other hand, the sector-specific pathways towards climate neutrality and resulting energy demands per ton of material output are no longer the same. It is not the aim of this work to compare cluster transition scenarios and values for specific energy demands. Hence, this analysis focuses on the sector-coverage aspect.

Given the focused scope of AIDRES, the updated electricity demand values are expected to be lower compared to the default ones for both the reference year and 2050. This is valid for the reference year. For the year 2050 however, one node slightly increases in loading, indicated in red. The node comprises the Dutch part of NSP. All other nodes report a decrease in demand as expected. To illustrate the relative reduction in load compared to the original values, a colour scale is applied to the regions in Figure 32: white if the load ratio is below 25%, light green if it falls between 25 % and 75 %, and dark green if it is above 75 %, yet smaller than 100%. The Dutch region with an increased load is plotted in red. The average load ratio is 32%.

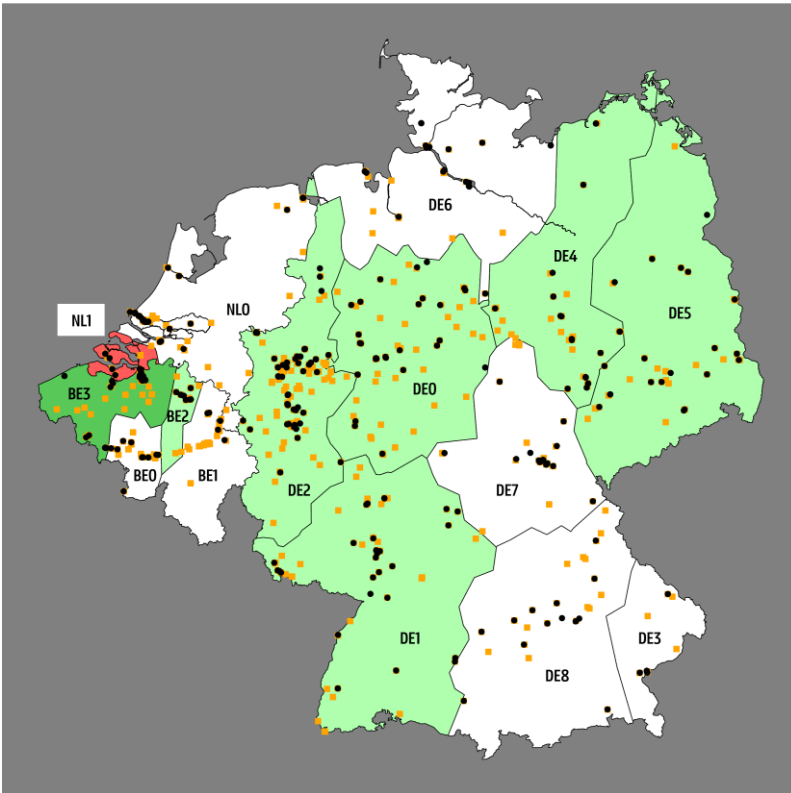


Figure 32 Map of the 15 node regions in PyPSA-Eur, overlapped with the industrial sites of AIDRES (in black) and Hotmaps (in orange). The colour scale of the regions illustrates the ratio between updated electricity demand per node (MIX2050) versus original value: red if >1 , dark green if >0.75 and <1 , light green if >0.25 and <0.75 , and white if <0.25 .

The AIDRES sites are projected in black and the Hotmaps sites in orange to illustrate the site coverage for each region. The figure clearly illustrates how a suitable coverage of sites in both databases does not necessarily result in a good

correspondence of demand projections. Node NL1 has similar projected demands for both model runs, whereas node DE7 drastically decreases, despite a similar site coverage. To resolve this, future work should improve the site and sector coverage of the extension and the underlying RES2Go tool and further enrich the production routes database with validated information on specific energy demands.

To investigate the influence of different sector-specific pathways between the model runs, a second industry cluster transition pathway is introduced to PyPSA-Eur. As mentioned in Section 3.5, the AIDRES MIX routes are not suited to be projected onto a single cluster. The energy demand projections consist of a weighted sum of multiple production routes and require the installation of various production technologies at a site. Another industry transition pathway is created using the RES2Go tool to depart from the AIDRES MIX2050 scenario, from now on referred to as the RES2Go pathway. For each sector, the pathway corresponding the most with the default process in PyPSA-Eur for the year 2050 is selected to facilitate the comparison with the default assumptions. For steel, the model assumes hydrogen-based DRI combined with an EAF for primary production and EAF for secondary production. Glass fully electrifies. The fertilisers sector (incl. ammonia) creates a hydrogen demand; hence the corresponding hydrogen routes are selected. For cement, the model assumes electricity and biomass to be combined with methane for high-temperature heat supply. Hence, the routes corresponding to such energy demand profiles are chosen. The only configuration options in PyPSA-Eur for high-value chemicals refer to the share of recycled materials to replace fossil feedstock. No pathway present in the AIDRES database explicitly refers to substituting a share of primary feedstock by recycled materials. This work focuses on the energy demand of industry and not on circularity mechanisms in the chemical supply chains. Hence, the AIDRES MIX2050 assumptions are maintained for the chemicals sector. The exact configuration of the RES2Go pathway in the tool is included in the annex.

Table 13 repeats the current and future industrial electricity demand for each node with the default PyPSA-Eur assumptions and adds the updated assumptions in line with the RES2Go pathway.

Comparing the RES2Go model run to the default values, the trends are similar to those of the previous table. All but one node decrease in electricity demand due to the change in site and sector coverage. The increase with respect to the default value for 2050 of node NL1 is larger compared to the AIDRES MIX2050 scenario. In fact, most nodes have an increase in electricity demand compared to their equivalent in the MIX2050 run, with an average demand ratio of 33% (1% higher than MIX2050). This is visible in Figure 33, where more regions are coloured light green compared to Figure 32. The electricity demand for 2050 of the nodes BEO and DE7 significantly increase when comparing MIX2050 to the RES2Go run, which can be explained by

the electrification of the glass sector. This example illustrates the strong effect a single sector can have on the cluster-level energy demand assumptions.

Table 13 Industrial electricity demand per node in PyPSA-Eur for the reference year and 2050, left the original assumptions and right the updated values using the RES2Go scenario.

Node	Electricity demand original assumptions [TWh/year]		Electricity demand RES2Go assumptions [TWh/year]	
	today	2050	today	2050
BE0	6.96	10.46	1.41	3.05
BE1	8.23	12.75	0.62	0.89
BE2	4.04	7.07	0.76	2.03
BE3	19.03	41.02	6.31	33.87
DE0	4.20	11.18	2.04	3.72
DE1	22.97	46.19	4.72	16.50
DE2	156.80	193.27	7.68	48.91
DE3	1.56	4.01	0.20	0.41
DE4	6.61	23.11	2.41	6.66
DE5	10.00	29.01	2.84	8.07
DE6	12.37	31.53	2.19	5.51
DE7	2.86	7.15	0.93	2.38
DE8	5.90	16.38	1.18	3.54
NL0	31.68	69.23	2.16	10.82
NL1	4.07	16.55	2.50	17.14
total	297.28	518.91	37.96	163.51

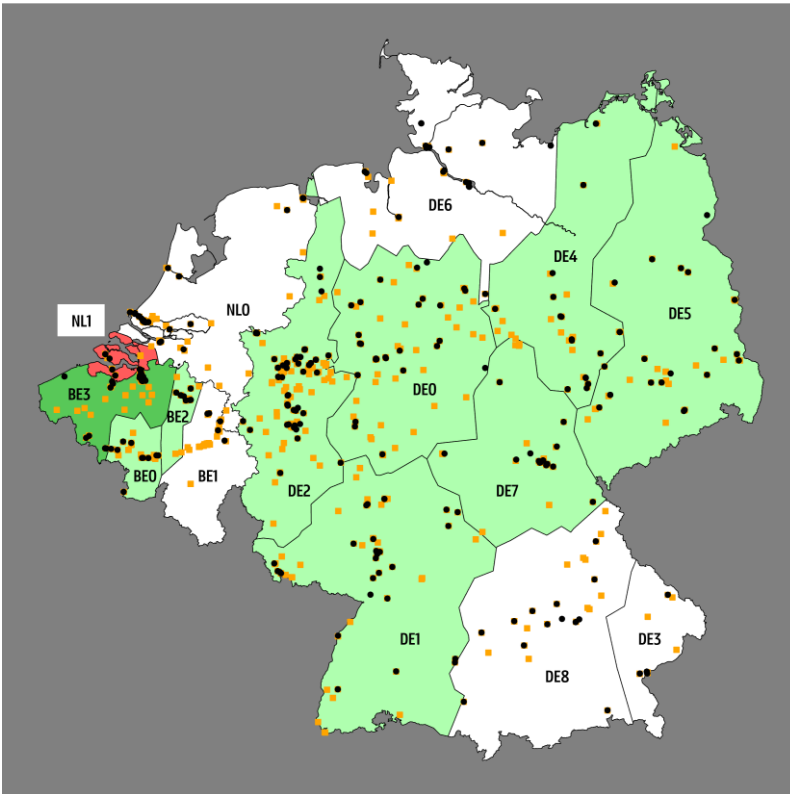


Figure 33 Map of the 15 node regions in PyPSA-Eur, overlapped with the industrial sites of AIDRES (in black) and Hotmaps (in orange). The colour scale of the regions illustrates the ratio between updated electricity demand per node (RES2Go) versus original value.

4.3.3 ENERGY SYSTEM ANALYSIS

With the spatial resolution of the model tailored to ICs and the industrial energy demand assumptions updated in line with the AIDRES database, the influence of industry cluster transition scenarios on the energy system is made directly visible. The sector-coupled energy system is modelled in three separate runs by altering the industry demand scenario, using default, MIX2050 and RES2Go assumptions. All other assumptions, cost data, input values, etc. do not change between runs. Hence, the different results in terms of energy system capacity and technology choices are purely triggered by changes within the ICs. To illustrate a possible application of the extension to PyPSA-Eur, the network optimisation results are compared for all model versions. Changes in industrial energy demand assumptions affect the optimisation of grid reinforcements, as seen in Figure 34 to Figure 36 where line thickness is an indication of the transmission line capacity. The red line corresponds to the DC

connection between Belgium and Germany. Table 14 lists all network lines in need of a capacity expansion. Other non-reported lines do not change. The reported values are expressed in GW and are calculated using formula 4.

$$\text{expansion} = \text{capacity}_{\text{optimised}} - \text{capacity}_{\text{nominal}} \quad (4)$$

As can be seen from Table 14, the targeted lines change when updating the demand values. Depending on the scenario, only line DE2-NLO, line BE3-NL1, or both require an expansion. The substantial capacity expansion of line DE2-NLO in the default scenario drops significantly in the MIX2050 run and disappears completely with the RES2GO assumptions. Instead, the latter two scenarios choose to invest in line BE3-NL1. Of course, the loads in nodes DE2 and NLO are only a fraction of the initial demand values, as can be seen in Table 12 and Table 13.

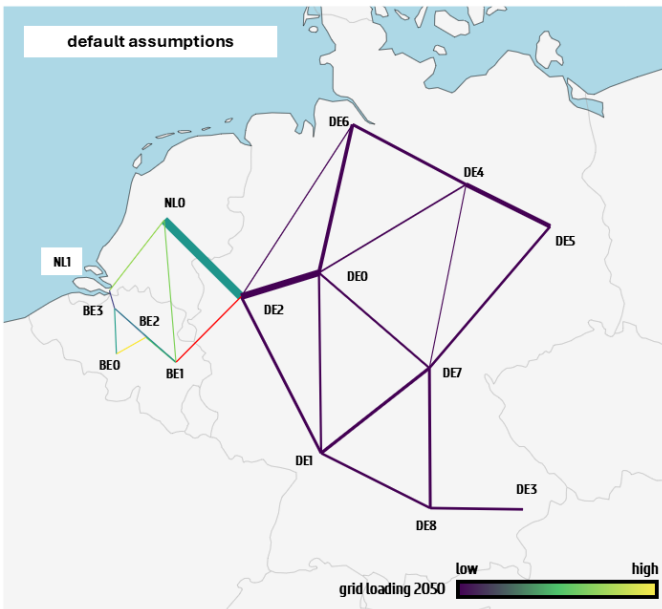


Figure 34 Map of grid loading in 2050 in the 15 node PyPSA-Eur network with original industrial energy demand assumptions. Yellow indicates high and purple low line loading. The line thickness reflects the transmission line capacity. The DC link is in red.

With the updated assumptions, the interconnection capacity between Belgium and the Netherlands expands. A possible driver is the slightly increased node load of NL1, while the load in BE3 remains similar to the default value. This is also visualised in Figure 34 to Figure 36, which illustrate the grid loading in 2050 using a colour scale. Yellow reflects high and purple low line loading. For the largest part in Germany, the grid loading remains equal over the model versions. It can be noticed that the grid loading in the Netherlands and between DE2-NLO decreases. The grid loading in

Belgium alters and moves to the interconnection with the Netherlands, which was not heavily loaded with the default assumptions.

The PyPSA-Eur model already takes into account planned grid extensions, with new or extended lines between nodes DE0 – DE6 and BE1 – BE3 present from 2024 on and between nodes DE4 – DE6 and DE5 – DE7 from 2037 onwards. The DC connection between nodes BE1 and DE2 has a capacity of 1 GW and is not extended.

Table 14 Transmission expansion needs of individual lines for all three model runs. Lines which are not mentioned do not require capacity expansion.

nodes	expansion need default assumptions [GW]	expansion need MIX2050 assumptions [GW]	expansion need RES2Go assumptions [GW]
DE2-NL0	12.65	1.96	0
BE3-NL1	0	2.45	2.45

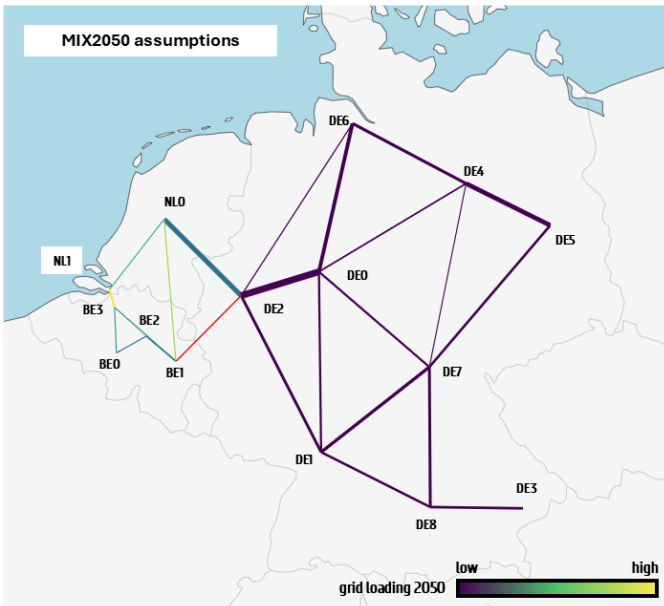


Figure 35 Map of grid loading in 2050 in the 15 node PyPSA-Eur network with MIX2050 industrial energy demand assumptions. Yellow indicates high and purple low line loading. The line thickness reflects the transmission line capacity. The DC link is in red.

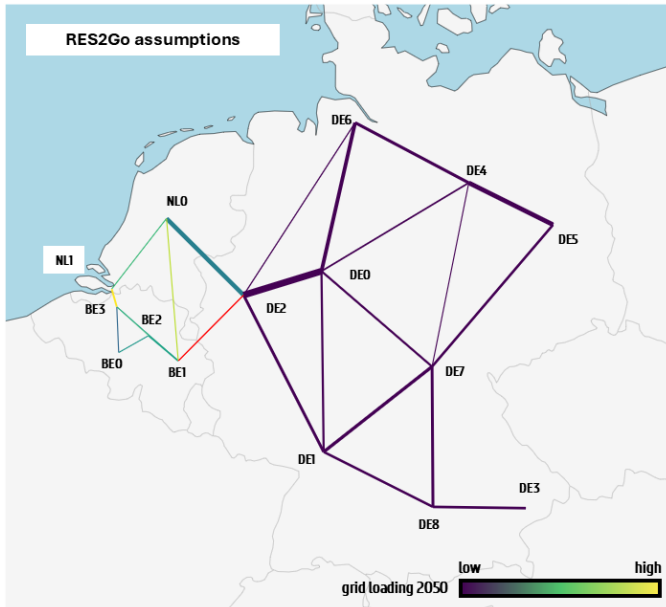


Figure 36 Map of grid loading in 2050 in the 15 node PyPSA-Eur network with RES2Go industrial energy demand assumptions. Yellow indicates high and purple low line loading. The line thickness reflects the transmission line capacity. The DC link is in red.

PyPSA-Eur has two built-in systems to limit transmission expansion. Either it sets a limit on the line volume or on the line cost. Another feature of PyPSA-Eur allows the line expansion to depart from the most cost optimal energy system and limits it to a certain percentage of the existing total volume or cost. The default setting is volume-based and linked to the total energy system cost optimisation.

In addition to electricity, an analysis is made of how the varying industrial demand assumptions are reflected by changes in the hydrogen supply and demand, using the sector-coupled functionalities of PyPSA-Eur. In the default version of PyPSA-Eur, hydrogen is consumed by industry in the production of ammonia and for the DRI process of primary steel production. Hydrogen for high-temperature heat supply is not part of the scope. In the AIDRES-based scenarios (MIX2050 and RES2Go), the consumption of hydrogen is also present in other sectors. Hydrogen supply technologies present in PyPSA-Eur are steam methane reforming (with and without CC) and electrolysis using alkaline electrolyzers. Storage of hydrogen in the model can be done using steel tanks or salt caverns.

Table 15 compares the hydrogen demand of each node for the three model runs. Two important distinctions are noticeable when comparing the default demands with the MIX2050 and RES2Go assumptions. Firstly, it is possible for the hydrogen demand of a node to be negative when using default assumptions. This is a consequence of the

inclusion of the chloralkali process for chlorine production in PyPSA-Eur, which has hydrogen as a by-product.

Table 15 Industrial hydrogen demand per node for the year 2050 in PyPSA-Eur for the original assumptions and the updated values using the MIX2050 and RES2Go scenario.

nodes	hydrogen demand original assumptions [TWh/year]	hydrogen demand MIX2050 assumptions [TWh/year]	hydrogen demand RES2Go assumptions [TWh/year]
BE0	-0.01	0.96	0.37
BE1	-0.04	0.14	0.03
BE2	-0.03	1.30	1.21
BE3	9.55	24.91	36.62
DE0	-0.04	0.69	0.11
DE1	7.72	17.09	25.68
DE2	10.90	34.92	51.91
DE3	-0.02	0.17	0.13
DE4	9.52	17.39	27.34
DE5	0.33	5.16	7.69
DE6	6.75	12.64	20.19
DE7	0.00	0.66	0.02
DE8	-0.04	0.70	0.11
NL0	7.82	14.22	22.43
NL1	11.63	13.95	21.74
total	64.04	144.90	215.57

Changes in the hydrogen demand of the nodes strongly affect the supply side of the model.

Secondly, the demand values resulting from the updated scenarios are remarkably higher. The main driver behind this is the change in the representation of the steel sector. While the total amount of steel output remains the same, the default assumptions in PyPSA-Eur assume only 30% to result from primary steel production.

The remainder of the steel demand is supplied by processing scraps in an EAF. In the updated scenarios, both primary and secondary steel production are assumed to maintain their production output in 2050. Hence, the ratio primary-secondary steel does not change. If the column corresponding to the original assumptions were to be corrected to reflect 100% production output from primary steel plants (by dividing the values by 0.3), the total would come down to 213.47 TWh/year. This approximately matches the RES2Go value.

Table 16 and Table 17 show respectively the total installed electrolysis and steam methane reformer capacity for each node in 2050 for the three model runs. The larger demand for hydrogen as a result of the AIDRES-based scenarios triggers the installation of SMR plants with CC, whereas the model with default industry demand assumptions prefers to install more electrolysis capacity.

Table 16 Installed electrolysis capacity per node for the year 2050 in PyPSA-Eur for the original assumptions and the updated values using the MIX2050 and RES2Go scenario.

nodes	electrolyser capacity original assumptions [GW]	electrolysis capacity MIX2050 assumptions [GW]	electrolyser capacity RES2Go assumptions [GW]
BE0	0	0	0
BE1	0	0.10	0.10
BE2	0	0	0
BE3	1.74	5.68	2.95
DE0	1.99	0.75	0.73
DE1	1.42	0	0
DE2	0	0	0
DE3	0	0.26	0.25
DE4	20.32	0	0
DE5	0.06	0.24	0.21
DE6	1.24	0	0.51
DE7	28.18	0.66	0.57

DE8	0	1.24	1.18
NL0	1.44	2.89	3.61
NL1	2.14	0	0
total	59	12	10

Table 17 Installed SMR capacity per node for the year 2050 in PyPSA-Eur for the original assumptions and the updated values using the MIX2050 and RES2Go scenario.

nodes	SMR capacity original assumptions [GW]	SMR capacity MIX2050 assumptions [GW]	SMR capacity RES2Go assumptions [GW]
BE0	0	4.18	13.33
BE1	0	13.98	14.00
BE2	0	0.22	0.20
BE3	0	9.36	6.21
DE0	0	0	0
DE1	0	9.30	11.36
DE2	0	5.70	8.51
DE3	0	0	0
DE4	0	2.88	4.52
DE5	0	0.69	1.13
DE6	0	2.09	2.92
DE7	0	0	0
DE8	0	0	0
NL0	0	9.51	10.88
NL1	0	9.89	6.41
total	0	67.79	79.48

As a final element of the hydrogen supply chain, storage in salt caverns or steel tanks also differs between the model runs. Total installed capacities range from virtually

zero to 195.2 GWh and 119.5 GWh for respectively the default, MIX2050 and RES2Go assumptions.

4.4 CONCLUSIONS

The transition of energy-intensive industries towards climate neutrality requires substantial effort, not only at site level but also for the energy system that needs to adjust in time to conserve adequacy. To maximise system value, investments at both levels should be aligned and optimised together. Despite the uncertain outlook for industry, energy system planning should continue for any required infrastructure adaptation to be ready in time. Here again, industrial clustering can be a way forward. Not only does it enhance competitiveness, it also improves industry representation in energy system models, both in terms of spatial and technology detail.

This chapter introduces industrial clusters in the open-source PyPSA-Eur framework and describes an extension that updates default assumptions on industrial energy demand with detailed, sector-specific transition pathways. To validate the effectiveness of the extension, the updated model is applied to a subset of EU industry-dense countries: Belgium, the Netherlands and Germany. By comparing results, the impact of a cluster's energy transition on the local energy system is illustrated. This confirms that the extension is useful for strategic energy planning in and across industrial clusters.

The extension departs from a database of detailed, sector-specific production routes to compile the aggregated energy demand of a cluster, increasing flexibility in the scenarios to reflect the current uncertainty industry faces. The model is rerun with both the AIDRES MIX2050 route and a transition pathway created using the RES2Go tool, which aligns closely with the production routes default to PyPSA-Eur. By comparing the extension to the original data sources, a wider range of available production routes is observed and the transparency of the scenarios improves. For example, the heat and electricity demand of CC is not included in the current version of PyPSA-Eur, while RES2Go includes the option for CC in a production route and also integrates the resulting energy demand. Another example of flexibility in defining the industrial demand through the extension is the ability to alter the utilisation rate of each sector to illustrate a drop or increase in production activity. Currently, such a variation of production capacities is still projected on all sites within the same sector in the same way. Future versions of the extension will depart from this to remain aligned with real-world adaptations and policy or market shifts. Similar

developments are ongoing for the technology routes selection, which is also projected on all sites within the same sector.

To improve the spatial representation of industry, the node selection of PyPSA-Eur is aligned with the ICs resulting from the DBSCAN algorithm. Regular K-means, weighted K-means and a custom bus map are compared in terms of regional correspondence with the identified ICs. The latter leverages the cluster centroids to allocate network buses to a cluster region. Future work could investigate the development of a second embedded HAC cluster algorithm for the network that leverages industrial presence instead of RE availability.

Future work using PyPSA-Eur in combination with the extension could start by widening the scope of countries to cover Europe. The work of Mendez Alva *et al.* offers a benchmark to select appropriate ICs for the node selection step [39]. Ongoing work on the RES2Go tool to further expand the scope of industrial sectors and activities will also improve this extension to PyPSA-Eur. Up until then, users need to remain aware of the mismatch in terms of coverage between the Hotmaps and AIDRES databases. Also during the interpretation of energy system optimisation results, users should remain cautious and at all times understand which variables are exogenously or endogenously set by the model. The supply of hydrogen, for example, is an endogenous variable. The validation exercise presented in this work clearly illustrates how this drastically changes between demand scenarios. An important example of an exogenous variable is the primary-secondary steel production ratio that users can define in the config file. Lowering the share of primary steel production, while keeping the total amount of steel produced the same, has significant effects on the hydrogen supply chain. The extension keeps the primary-secondary steel production ratio the same by default.

So far, the time resolution aspect has not yet been investigated. Currently, industrial energy demand is assumed as baseload. Future work could focus on improving the temporal aspects, e.g. industrial load profiles and the complementarity with local RE resources. The model runs in this work use a temporal aggregation of 24 hours. For operational studies, a higher temporal granularity is necessary to reflect intra-day changes in RE generation and to optimally size battery storage assets.

Perhaps the most promising research lead resulting from this work would be a soft-coupling between the RES2Go tool and the PyPSA-Eur energy system model. This can be approached in a unidirectional manner, or bidirectional through manual or automated iterations [223]. According to Burghardt *et al.*, iterative bi-directional soft-linking is more suited than one-directional soft-linking in studies that investigate the interaction between the energy system and industry [224]. For now, all clusters evolve similarly; in other words, the same transition route, for example

for steel, is projected on all steel sites in the industry database. Future work should depart from this assumption and allow for geospatial distinctions in production routes to be made within a sector. Iterating between the tool to define aggregated IC energy demands and the ESM to investigate the consequences of IC transition pathways on the system could facilitate the convergence towards cluster-level transition pathways that are optimal for the larger energy system.

Certainly, the field of ESM is constantly evolving. The development team behind PyPSA-Eur has announced ongoing active development of an endogenous determination of industry relocation by the model [225]. Hence, future versions of the model will have a different approach on industrial demand assumptions. In the meantime, the extension explored in this work anticipates and illustrates the importance of industrial demand assumptions in ESMs.

An overview of the contributions of this dissertation to the research field are summarised in Table 34.

CHAPTER 5 INDUSTRIAL SYMBIOSIS CASE STUDY – SHARED RENEWABLES

With the potential of industrial clusters and energy synergies widely recognised, it is still unknown how and if this potential will ever be reached, nor how scalable and replicable the benefits will be. Chapter 2 presents an overview of energy synergies that advance energy system integration to support industry clustering. This section targets one IS case in particular, in line with the IS life cycle introduced in Section 1.3. Renewable energy sharing, more precisely onshore wind and PV, was already put forward by the EPOS project as a generic IS case with a high replication potential [48]. Also AIDRES presented RE sharing as a key synergy to aid EU ICs in their transition towards climate neutrality [58].

This chapter runs over the first steps of the IS life cycle towards implementation to increase our understanding of the barriers and enablers to RE sharing. It applies the LESTS survey at the highest level, conceptualisation stage, converging to a list of incentives and hurdles to collaborate. In order to debunk some of the barriers and to verify the added value of the synergy, an optimisation model combined with game theory (GT) principles are applied to the case study of a fictitious industry park. Results validate incentives to collaborate, clearly highlighting both the collective and individual benefits.

5.1 IS LIFE CYCLE

Recalling the IS life cycle presented in the introduction of this work (Figure 2), it consists in total of five consecutive steps and an iterative feedback loop to continuously improve the synergy management. The first three steps of the life cycle are IS identification, LESTS assessment and barrier removal. They build towards implementation of the synergy and can to a large extent be generalised, uncoupling it from a specific cluster context. The next three subsections explore these steps if the synergy were to be implemented in a Flemish IC or industry park.

5.1.1 IS IDENTIFICATION

According to Maqbool *et al.*, synergy potential arises through innovation, input-output matchmaking or the replication of success stories [47]. The EPOS and AIDRES projects already emphasised the replication potential of RE sharing [48,51]. In this thesis, the work on cluster transition pathways (Section 3.5) confirms the *wish* for

more clean electricity to facilitate the electrification of processes and utilities. The IIQ of Section 3.2 illustrates the diverging availabilities of energy transmission infrastructure to ICs, indicating the *need* to collaborate for energy supply in areas with weaker grids. Lastly, EU policy measures outlined in Section 1.1, i.e. RED III, imply it is industry's *duty* to accelerate the uptake of RE in the energy system.

Having briefly stated why RE sharing can be identified as a high-potential synergy based on the different drivers from Van Eetvelde *et al.* [42], the next subsection moves to the second phase in the life cycle and completes the LESTS assessment.

5.1.2 LESTS ASSESSMENT

To get a holistic view on the barriers and enablers to RE sharing, the multidisciplinary LESTS survey is applied. Since this work aims to offer a general view on the synergy's feasibility, the assessment is limited to the first level of the survey, corresponding to the conceptualisation stage. The other two levels, going into a more specific context or even a specific case, are not touched upon. However, future work or case study implementations can build from takeaways of the first level [2]. Below, each of the five dimensions are explored in detail by means of a literature review and desktop study. Table 18 summarises key findings.

Legal

A legal basis which provides IS stakeholders with certainty and clarity on task distribution, responsibilities, cost and benefit allocation is essential for any collaboration to succeed [2]. With respect to RE sharing, policy measures related to Renewable Energy Communities (REC) can serve as a benchmark. Through RED II, EU unlocked the participation potential of local citizens, authorities and small companies to form a REC and together produce, consume, store and sell RE [7]. Such a REC should operate as an autonomous legal entity with as main purpose to provide environmental, economic and social benefits to its stakeholders and to not focus solely on financial profit. Because of the latter, policy-wise a distinction has to be made between energy sharing through a REC and what EIs can do. The REC framework specifically targets small and medium-sized companies (SMEs), excluding large-scale industrial producers. No other EU policy framework exists that targets RE sharing in EIs as explicitly as RED II does through RECs. However, a number of EU directives and packages nudge industry towards collaboration in the buildout of RE capacity. The electricity market design directive for example was reformed in 2023 to manage the price shocks resulting from the energy crisis and to increase long-term price stability for consumers and industry [226]. Its two main instruments are corporate PPAs and two-way contracts for difference to guarantee the price both for the energy buyers and producers. In the framework of a PPA,

industries can form consortia and coordinate bids on utility-scale RE installations [227]. The wind power action plan facilitates such coordinated bidding through the RES auctions platform by centralising all information from member states on planned RE auctions to increase the visibility of short-term deployment volumes [228].

Given the richer documentation and similarities in terms of difficulties and encouragements regarding energy sharing, the remainder of the LESTS survey includes findings on RECs, despite their more restricted application scope. Petrovich *et al.* studied the preferences of SMEs to join a REC through a survey on perceived barriers and drivers to participate [229]. Project complexity and unclear obligations ranked second in the final list of important hurdles. Since each member state has some degree of freedom in the implementation of the REC framework into national guidelines, there is no EU-wide consensus on organisational and spatial constraints, including the allowed mechanisms to share electricity, grid tariffs, metering and licensing [229,230]. Such non-uniform legislation hinders the replication of successes if the clusters are not located in the same country or even the same region. Policy should be more streamlined to enhance RE sharing. Secondly, simplifying the permitting procedures of RE installations, particularly for onshore wind, or designating acceleration areas with fewer regulations, were already part of the RED III revision to lower the administrative burden and accelerate deployment [7]. To further promote the corporate PPAs, EU has given each member state the task to assess the relevant legal and administrative frameworks and to revise where needed. Conclusions and action plans are reported in the national energy and climate plans of the member states [231,232].

Economic

The economic added value as a result of a synergy is key to the business case and needs to be fairly distributed among the stakeholders, along with the costs [2]. Resulting from the survey performed by Petrovich *et al.*, energy price stability, lowered costs and need for upfront capital are three top enablers for shared RE [229]. Especially for smaller companies with limited access to capital and energy as a non-core business, the synergy can make a difference by spreading investment costs, confirmed by Butturi *et al.* [233]. EPOS case watches 5 and 7 and also Blassuttigh *et al.* add reduced operating costs to the list of advantages [48,234].

In terms of barriers, SMEs require compensation for the time and effort related to the energy sharing and its governance. This demand can be met by cost-competitive conditions when comparing the REC to other energy providers or by the REC offering additional services like peer-to-peer (P2P) trading and smart energy management [229]. Another element that could enable RE sharing is a reduction in grid tariffs. As

already flagged earlier, the translation of the REC ambition into national regulations differs from country to country. Some countries (e.g. Italy) have more supportive frameworks and financial incentives compared to others (e.g. Germany) that still impose grid fees and taxes [235]. For the case of Flanders (not Belgium as the distribution grids fall under regional jurisdiction), the regulator was tasked with a cost-benefit analysis to see how RECs could lower stress on the grid and avoid grid expansions and costs. Findings helped to determine a suitable compensation for RECs, e.g. through a grid tariff reduction. Unfortunately for the RECs, the exercise did not result in a separate tariff mechanism, at least not for the period 2025-2028 [231]. Still, it can be seen as an enabler to RE sharing and might be revisited by the VNR in the future.

Spatial

One of the biggest gains of local collaboration in a cluster is the optimal space allocation across plots of land compared to a strictly onsite-only planning [2]. The lack of space, both on the ground and on roofs, can be a barrier for a company to install RE [233]. This constraint is lowered when regional planning is approached in a group effort and extends beyond the boundaries of a business park or port area. The Biseps project, for example, aimed to increase the adoption of clean technologies in industry parks [236]. To facilitate, the consortium developed a tool that sizes RE technology capacities based on a cluster's aggregated demand profile and took spatial surroundings into account to see where installations could be put down. In some occasions, local proximity is even a regulatory prerequisite to share RE. The REC transposition into national or regional regulations for example can include a distance limit between the RE projects owned and developed by the REC and its beneficiaries [229]. In addition to RE installations, cluster collaboration also allows for a coordinated approach on other infrastructure elements like grid connections and trajectories within and in between ICs.

The Flemish government prioritises large-scale turbines (>1.5 MW) over small- to medium-sized turbines, as significant efforts are still needed to reach the RE targets. Policymakers look at port areas and business parks to find suitable destinations. Of course, in very densely built ICs, there might be no space left to install wind turbines, or it is not allowed due to a conflict with safety precautions (related to piping, Seveso companies, etc.). The size of a turbine determines the distance rules with respect to residential areas and other critical infrastructure elements. While perhaps not energetically most efficient, also the instalment of smaller and medium-sized turbines contribute to the RE supply, and should be pursued as long as they do not hinder the instalment of large turbines [237].

Technical

The technical feasibility of a synergy is necessary for implementation and its scope goes beyond the sole focus on the clean technologies to include all supporting infrastructure, given space availability, and supply chain elements. Energy system advantages resulting from RE sharing are increased self-sufficiency, increased energy efficiency due to reduced energy transmission losses and reduced emissions [229,238]. The number one concern with respect to RE sharing is the security of supply and technical performance of the installation [229].

Some authors present local RE sharing as a means to avoid grid connection delays as a result of congestion [238]. REC members do not necessarily have to be physically interconnected with the generating capacity and definitely do not need to be behind a single metering point [229]. RECs are allowed to use the public grid, and the management of such infrastructure remains with the DSOs and TSOs, at least in Flanders. EU does not forbid RECs to install and manage infrastructure, but it is the Flemish regulator that decided it is for the best, given the strict conformity rules with respect to safety and operation [231]. A recent development in the energy system is the introduction of flexible connections to the grid [226]. In cases where local grid capacity limitations occur, new or additional connection requests can still be processed with the condition that they no longer reserve a fixed capacity. Flexible connections help solve the long grid connection queues and avoid situations where new installations cannot be coupled with the grid, thus avoiding huge socioeconomic losses [239]. Shared RE and demand-side flexibility can be leveraged by the affected companies to stay below the agreed capacity level. According to Bjarghov *et al.*, many companies have an inherent flexibility potential but lack incentives or expertise to utilise it [239]. The authors see a facilitating role in energy communities. Petrovich *et al.* also highlight flexibility management as an additional service from the REC, either internal to the REC members or as ancillary services or flexibility service providers to the grid, generating additional revenues [229].

Social

Successful IS eventually contributes to a more sustainable society, which is a driver for acceptance and commitment from all stakeholders and the involvement of local communities [2]. According to Petrovich's survey, supporting the local economy is the number three enabler for RE sharing among SMEs [229]. The authors also refer to increased energy awareness and local employment opportunities as facilitators for the social and community acceptance of clean infrastructure, which are crucial to minimise NIMBY (short for "Not In My BackYard") effects that delay or cancel RE or related infrastructure development plans. Recall Ventilus as an illustrative example of the NIMBY effect [92]. Despite its importance to strengthen the local grid

in West-Flanders and beyond and to allow for more (offshore) wind power production from the North Sea in the energy mix, the lack of public support is slowing down the development. Companies might lack internal expertise on RE deployment [229,233]. Hence, through collaborating in a RE portfolio the synergy fills the gap in a human-resource-efficient manner. Still, a significant barrier to RE sharing is the inherent preference for exclusive ownership of installations, fuelled by the idea that one's company would not benefit equally from the synergy than others [229].

The above LESTS analysis is summarised by the table below.

Table 18 LESTS output for the RE sharing case.

	Drivers	Barriers
Legal	Simplified permitting, streamline policy (esp. related to corporate PPAs)	Project complexity, unclear obligations, non-uniform legislation among EU member states
Economic	Energy price stability, lower costs*, reduced upfront capital, special grid tariffs*	“Unfair” benefit/cost allocation*
Spatial	Aligned regional development planning, optimal space allocation*	Conflicts of interest, lack of space*
Technical	Increased self-reliance, self-sufficiency*, efficiency, sustainability, avoid grid congestion*	Concerns about security of supply and technical performance installations
Social	Support local economy, create local employment, training programs, energy awareness of local community	NIMBY, lack of internal expertise, preference for exclusive ownership*, unfair treatment compared to other stakeholders

As illustrated by Van Eetvelde in her book chapter on IS, industry has the potential to generate economical, environmental and societal benefits, underscored by the triple bottom line principle [42]. Such corporate sustainability sits at the core of the People-Planet-Profit (PPP) triangle. In reality, the triangle is typically distorted and economic outcomes dominate the other two dimensions. For a company to pursue a sustainable investment, there needs to be a business case (profit) for the environmental (planet) and societal (people) rewards to take place. Incentives on

all five dimensions convince industry to collaborate, reconfirming the importance of the LESTS survey.

5.1.3 BARRIER REMOVAL

Having a better understanding of the enabling and hindering elements to RE sharing, the next step in the IS life cycle aims to relieve the barriers on all five dimensions. From the LESTS survey summarised in the table above, clarity and transparency are recurring themes, more precisely in the benefit and cost distribution and the overall fairness of the synergy. Take for example the preference to have exclusive rights and full control over the RE portfolio, partly because parties might think their companies would not benefit equally from collaborating as others would.

To validate the added value and to either confirm or debunk some of the concerns, a general modelling framework is developed that simulates RE sharing in an industrial park. The methodology combines a mixed-integer linear programming (MILP) optimisation model, that sizes RE installations and manages the energy flows, with game theory principles to manage the fairness of the synergy. Special attention is given to the incentives to collaborate, and GT helps to understand how individual strategies can affect others' decision making process and eventually determine the collaboration. According to Mendez Alva, IS practitioners need straightforward tools like GT to consider the complex and multidisciplinary trade-offs and to convince industries to collaborate [2]. The findings from the LESTS survey which were translated to the modelling framework are indicated by an asterisk in Table 18.

The next Section explains in more detail MILP optimisation, important GT principles and how the combination of both can be applied to RE sharing, referring to relevant works. Then it describes the modelling framework to simulate RE sharing in ICs that was developed in this thesis. As an illustration, the methodology is applied to the case study of a fictitious industry park.

5.2 METHODOLOGY

5.2.1 BACKGROUND ON MILP MODELLING AND GAME THEORY

A literature review was conducted to collect all relevant studies on RE sharing or similar synergies that apply MILP optimisation and/or GT. This section presents the main findings and recent research trends. Wu *et al.* apply a MILP model to a distributed energy network (DEN) to solve the mismatch between the heat-to-power

ratio of CHP plants and the fluctuating electric and thermal demands of their customers [240]. To leverage the diversified, hence potential complementary, load profiles, interchanges among the customers are allowed by the model. Decision variables are the optimal technology sizing, network layout and DEN operation to minimise to overall annual cost. Also Tay *et al.* and Najafi *et al.* explore the mutualisation of cogeneration assets by various facilities in an EIP, minimising overall cost and environmental impact [241,242].

Lamedica *et al.* deal with the optimal sizing of a wind-PV power plant in an industrial area, taking into consideration the load requirements, the spatial constraints and RE cost parameters [243]. Electricity surpluses are sold to the grid. Novel in this work, the authors chose to optimise the RE portfolio separately for every month of the year to take into account the seasonal effects in both the electricity demand and the RE availability. Afterwards, the model selects the maximum number of wind turbines and PV panels. The work of Moncecchi *et al.* is framed in the Italian transposition of the REC concept into national regulations and incentives [244]. Their model defines the optimal RE sizing based on demand and local availability and investigates the incentivising tariff for energy sharing. Butturi *et al.* study various methods to include RE in the energy network of an EIP [233]. Their MILP optimisation is solved for three different objective functions: the first one minimises the total cost of energy procurement, the second minimises environmental impact and the third considers both. Cosic *et al.* apply MILP optimisation to determine the optimal planning for RECs in terms of operation, PV and SES sizing, with varying grid tariff and feed-in tariff scenarios [245]. The latter can be seen as a market signal to exchange electricity with the grid.

To support RECs in their investment decisions and operation of PV and wind installations, Sousa *et al.* apply MILP to a case study where only one REC member is allowed to invest in RE [246]. The model includes spatial constraints, namely the ground and roof surface available to install PV and wind, and maximises the economic benefit of that specific REC member. Afterwards, the economic benefits from sharing RE is calculated for the REC as a whole and the other REC members individually. In addition to the base case with actual PV and wind power capacity constraints, more scenarios are included that relax the site-specific limitations. This way, the main drivers behind the optimal decisions of RE sizing and sharing are identified. Carvalho *et al.* continue from Sousa's modelling framework and allow multiple members in the REC to invest in RE, each with their own site-specific spatial constraints [230]. Again, the MILP model optimises the installation sizes and energy flows in the REC, including self-consumption, exchange within the REC and electricity bought from or sold back to the grid. The analysis includes two scenarios, one with energy sharing and one without, to assess the economic benefits and evaluate the

enhanced uptake of local RE. Contrary to the objective function of Sousa *et al.*, this work minimises the cost of the entire REC. Sensitivities on RE capital costs and electricity grid tariffs complete the study.

Blasuttigh *et al.* do not perform MILP optimisation. Instead, they developed a selection algorithm for the optimal subset of companies in a cluster to form a REC and size its PV capacity for maximal economic benefit (maximise net present value) without compromising the payback time [234]. The selection procedure is based on the companies' existing PV installations, remaining capacity potential and their electrical load profiles.

Butturi *et al.* conclude that a suitable model to validate the synergy's added value should be a multi-objective optimisation including cost and environmental elements, and contain sufficient temporal and technology detail (incl. the link to other energy carriers) [81]. To cope with the organisational challenges related to RE sharing, e.g. fair benefit and cost spreading, ownership, coalition stability, etc., the model can be complemented with a collaborative layer that leverages GT principles.

Before going into detail about various GT mechanisms of interest to this work, some common terminology is explained that is frequently used in the field.

- A game corresponds to a situation where the decision of an individual player depends on the strategies of others and on how the individual reacts in response.
- Players take rational decisions in the game, usually to select the strategy that benefits their outcome.
- Different strategies played (= actions) lead to different payoffs in the game.
- Payoffs correspond to the outcome of the game, typically the profit or utility received by each player, and depend on the selected strategies of the players.
- Coalitions are formed when all or a subset of players make binding agreements. A game with X players has 2^X possible coalitions, including a complete or grand coalition and an empty coalition.

With respect to the payoffs in GT, a distinction can be made between zero-sum and non-zero-sum games. In zero-sum games, the total payoff size is fixed. In other words, increasing the payoff of one player decreases the payoff of other players so the total amount remains the same. In non-zero-sum games, the total payoff can increase or decrease, depending on the strategies selected by the players in the game. Such games reflect an opportunity to act upon a common interest and to exploit complementarity between stakeholders to reach an improved optimum. Hence, IS in this context can be seen as a non-zero-sum game, encouraging cooperation and coalition formation to reach a win-win situation [2].

There are two main domains in GT, cooperative and non-cooperative games, and the difference between both can be explained by how the collaboration is enforced. Non-

cooperative games focus on the individual strategies and internal agreements are needed in order to work together. Cooperative games on the other hand depart from what a coalition can achieve together and aim to define the type of external enforcement necessary to work together. [2,247] To illustrate a cooperative, non-zero-sum game, Fadzil *et al.* investigate the sharing of carbon permits among plant operators [248]. Instead of confining their operation and investment decisions to the initial carbon permit allocation to each site, which might lead to sub-optimal profits and carbon reduction investments, carbon permits are pooled and redistributed to maximise the total profit. Of course, given some plant operators donate a share of their permits to the benefit of another, the pooled profit also needs to be fairly distributed. Otherwise, conflicts of interest arise and the coalition falls apart. Profit distribution can be based on the marginal contribution of each plant. This way, operators are fairly compensated for pooling their carbon permits and the total profit is larger compared to the situation without collaboration (hence a non-zero-sum game).

It is crucial for cooperative GT to implement mechanisms for an effective and fair allocation of benefits and costs among the partners [240]. If the allocation mechanism is not fair, the cooperation is not stable and will not survive [247]. Plenty of former research resulted in a vast set of mathematical tools that can deal with such complex setups and provide means to fairly distribute payoffs and verify the stability of the coalition. It is of course implied that the payoff is transferable, e.g. profit that can be redistributed, instead of non-transferable, e.g. risk preferences or sustainability improvements.

The Core, for example, guarantees that the coalition will not fall apart because no player has an incentive to leave or to form another one [240]. It is not a single solution and formulates a set of payoff configurations that result in stable coalitions, satisfying both group and individual rationalities [249]. Each individual player must gain from the collaboration, or at least remain unaffected, when comparing to its situation without. The group sum of gains must also be positive and equal the value of the grand coalition. The Core illustrates the range of gains for each individual, with a lower bound equal to zero, satisfying group and individual rationality constraints [249]. It is possible for a Core to be empty, otherwise referred to as the nonconvexity of a game. This occurs when at least one player in the grand coalition has a negative lower bound gain and zero upper bound. In a convex game, the payoff of player i increases as more players join the coalition.

To come to a single payoff allocation solution, various mathematical tools can be applied. The most popular one in literature is the Shapley value [85]. The payoff of each player in the game is based on their marginal contribution to the coalition. In their review of cooperative GT applications in power system expansion planning,

Churkin *et al.* acknowledge the potential, but also the pitfalls and challenges, like scalability issues, nonconvexity of the solution space, the strong dependency on assumptions and incomplete or imperfect information [250]. The Shapley value for example is computationally very intensive and is not suitable for games with a large number of players as it grows factorially. To cope with this, derivatives from the Shapley value were developed (e.g. the Aumann-Shapley extension) [250]. Also the Core is computationally inefficient as its set of constraints grows exponentially with the number of players. In addition to the Shapley value, other allocation methods exist. Another popular option is the Nucleolus. It corresponds to a single point in the core and minimises the inequity of the allocation [247]. Other available allocation methods include Maali's method, the Tau value, the least core, etc. but are less commonly applied in literature [85].

Both the Shapley value and Nucleolus only result in rational solutions for convex games, which is not straightforward in the case of power system studies characterised by topology, technology and capacity constraints [250]. The authors warn that sub-coalition formation, empty or very small Cores, Shapley values not aligning with the Core, and other difficulties could occur in such cooperative game studies. Such effects are an indication of stability issues in the cooperation. In addition, the allocation and its stability strongly depend on the assumptions made and quality of information available in the coalition. In real applications, information in a cooperative game can be used as a competitive advantage [250]. The propensity to disrupt is a metric for the stability of a coalition and the quality of the allocation method in a game, and puts a limit to the ratio of how much other members would lose if a player would refuse to join the coalition compared to how much the player would lose itself [250]. Decreasing the limit shrinks the solution space towards the point where all players have equal propensities to disrupt, corresponding to the Gately point of the game.

Figure 37 illustrates the most important concepts from cooperative GT, based on an example from Churkin *et al.* [250]. The game includes three power system players (A, B and C) who need to negotiate cross-border power lines. The transmission expansion problem was solved using mathematical programming, minimising generation and investment costs within the limits of power balance constraints. The grand coalition {A,B,C} leads to the highest cost savings, and the Shapley value (S) and Nucleolus (N) are calculated to compare fair allocation mechanisms. Additionally, the equal sharing point (E) indicates the resulting profit when splitting savings equally over all players and is centrally positioned in the barycentric coordinate system, representing the cost savings for each player. Each corner of the triangle corresponds to the full allocation of savings to that player. Based on the positions of the Shapley value and the Nucleolus, C is the least important player. The

stability of the coalition is verified by the Core (grey area). All three points S, N and E fall within the Core and are viable allocation mechanisms for this case. The propensity to disrupt is illustrated in the figure for two ratio limits, respectively set equal to one and two. In this case, the Shapley value and the Nucleolus sit near the Gately point (centre of the smallest triangle) and thus both allocation mechanisms are confirmed to be fair and stable.

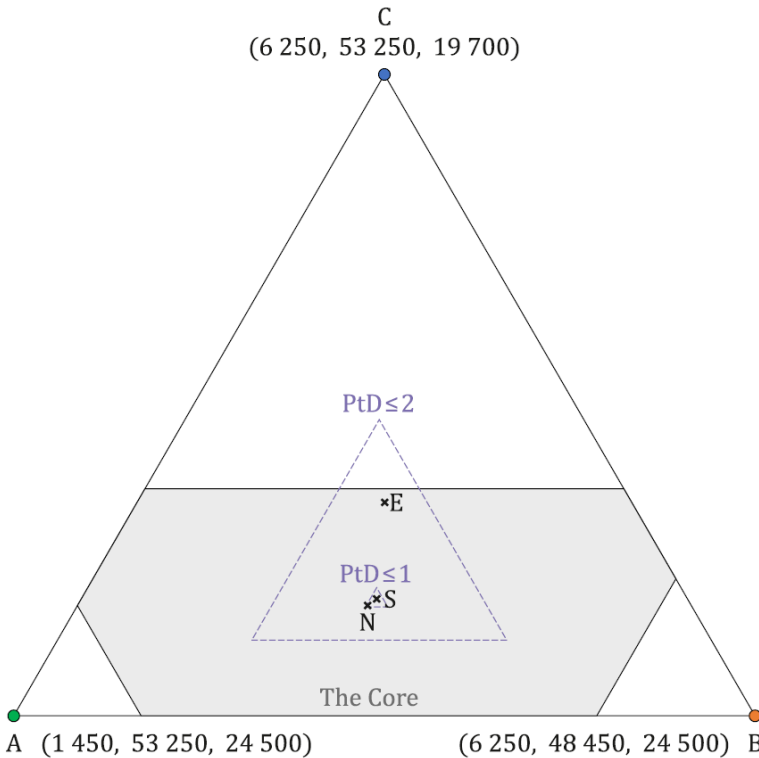


Figure 37 Allocation results and fairness and stability indicators for the illustrative case by Churkin et al. Numerical values represent the cost for the players (A,B,C), S corresponds to the Shapley Value, N the Nucleolus and E the equal sharing point. The Core is indicated in grey and the propensity-to-disrupt regions by the purple triangles. From [250].

Non-cooperative GT consists of independent players who select strategies based on the maximisation of their payoff function, taking into account the effect of other players' strategies, but without any communication or information exchange [244]. The most well-known example of a non-cooperative game is the prisoner's dilemma, in which two prisoners fail to achieve the optimal collective outcome because they cannot communicate, build trust and form an agreement on how to respond [2]. The most important concept in non-cooperative GT is the Nash equilibrium, which can be defined as the selection of strategies among players that leads to their best possible

payoff. In other words, none of the players' payoff can be improved by changing strategies [244]. In a Stackelberg game, the followers determine a best response to the strategy set by the leader. Liu *et al.* apply it to RE sharing in a microgrid with the microgrid operator as a leader setting the internal prices and the prosumers as the followers reacting to the prices set by changing their demand [251]. The remainder of this work focuses on cooperative game theory. However, the application of non-cooperative game theory in the field of energy systems is acknowledged to be a promising research lead and is recommended for future work on this topic.

Some of the works already mentioned above include cooperative GT in their methodology. Wu *et al.* complete their MILP optimisation with the core method to verify that the fair benefit allocation scheme results in a win-win solution [240]. Without compensating the additional operating costs of the consumers that produce more energy than their own needs to feed to the DEN, the partnership is not stable and will be broken. Another work of Wu *et al.* compares four benefit allocation schemes (Shapley, Nucleolus, DP equivalent method and Nash-Harsanyi), each resulting in different fairness and stability scores [247]. According to the authors, Shapley was the fairest allocation method for the case study. Also Moncecchi *et al.* and Najafi *et al.* apply the Shapley value to distribute costs and profits [242,244]. Tay *et al.* apply the Maali cooperative game allocation method based on the stakeholders' contribution portion in the coalition [241]. The work of Blasuttigh *et al.* cannot be considered as compatible with cooperative GT, as their selection algorithm for RECs might exclude sites from joining the coalition to begin with. Take for example Moncecchi's game, where the rules state that participation to the REC has to be open and voluntary [244]. Hence, exclusion is not allowed.

Adding to the list of relevant works, Prete *et al.* investigate microgrid development using the Core and the Shapley value from cooperative GT to arrange the payoff for the three stakeholders: an electric utility, a private investor and residential consumers [249]. According to the authors, the payoff determined through GT can inspire policymakers to draft similar regulations to further enhance collaboration. Long *et al.* incorporated the Shapley value in their P2P trading mechanism and compared it to other energy trading algorithms (bill sharing, mid-market rate and supply demand ratio) to validate its effectiveness [252]. Mitridati *et al.* investigate prosumers' participation as a community in heat and electricity wholesale markets [253]. Similar as Wu *et al.* [247], the work compares multiple allocation schemes (uniform pricing, Vickrey-Clarke-Groves, Shapley and Nucleolus). According to their findings, the Nucleolus allocation method resulted in the best trade-off between stability, incentive compatibility and efficiency for their case study, although no method truly satisfied all desired market properties. The work of Gomes *et al.* uses each member's participation in demand response events to fairly allocate the REC's

RE among its members [254]. Hence, the collaboration is not only fair but also inherently promotes flexibility from its participants. Again, Shapley is used as allocation method.

A final work of interest is that of Bjarghov *et al.* [239]. DSOs and TSOs put forward non-firm grid connections to tackle the long grid connection queues of industrial consumers. New grid connections can be permitted, but the grid operator can lower the capacity delivered or even disconnect the customer if necessary. To continue operating, the new client must be flexible in its demand. Section 2.3.2 already explained that flexibility is not a given for each process. Existing grid customers on the other hand might have an inherent degree of flexibility. Bjarghov *et al.* propose a coordinated approach to future grid connection requests where new clients form a REC with existing clients, optimising their aggregated flexibility potential and the efficient use of grid connection capacities, eventually increasing grid hosting capacity [239]. To validate the concept, the authors have developed an optimisation model incorporating GT principles to fairly trade capacity usage rights within the community and applied it to an illustrative case study.

Having learnt how researchers approached RE sharing in the past, whether or not applying MILP optimisation and/or GT, it is time to compare the findings and research trends with the insights gathered from the LESTS overview. The economic driver behind RE sharing, namely the reduced costs and investment spreading, was the most popular research topic. Additionally, some spatial and policy elements were touched upon by fellow researchers, e.g. onsite capacity limitations and tariff sensitivities. Also, the fairness and to a lesser extent the stability of the collaboration were validated for most of the cases in the literature review.

Other elements from the LESTS overview have not been tackled so far or deserve more attention. Most studies look at the optimal RE portfolio sizing and management to minimise total costs and assume that industrial electricity demand remains the same, not taking into account the electrification trend in industry nowadays. Where possible, electrification is key to the energy transition, and the electricity demand from industry is expected to grow in the coming years. Hence, the RE portfolio sizing from the above studies is no longer optimal if the energy demand of the cluster updates. A second important theme nowadays is grid congestion. Only one study positions the cluster in a congested area with grid connection delays. This work aims to align RE sharing studies with today's industry and energy landscapes and includes grid congestion and industrial electrification as important trends in the model framework because of their influence on the synergy's implementation.

5.2.2 OPTIMISATION MODEL

The flowchart shown in Figure 38 illustrates the modelling framework and scope applied in this work to investigate RE sharing. The methodology consists of two consecutive steps: MILP optimisation to define the optimal RE capacity sizing and operation for each coalition. Afterwards, cooperative GT tools are consulted to fairly distribute the costs and benefits resulting from the synergy among the stakeholders and to validate the stability of the coalition.

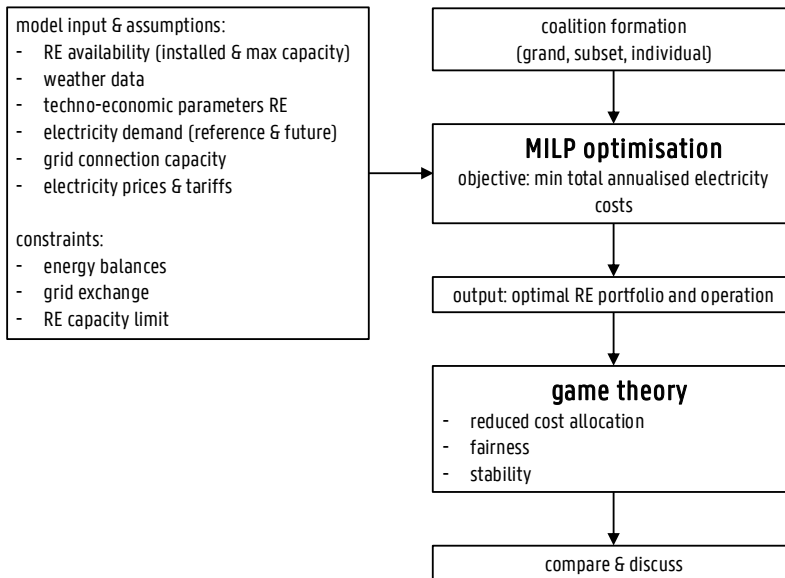


Figure 38 Flowchart of the modelling framework applied to investigate RE sharing.

The optimal RE portfolio and operation for the case study is determined by the MILP optimisation model and depends on various input parameters and assumptions. The flowchart includes the main building blocks of the optimisation step. For each parameter, the data collection and curation and relevant assumptions made are discussed in more detail below.

Electricity demand profile

Two electricity demand profiles are defined for each industry site in the case study. The first one corresponds to the reference demand, or in other words, the demand of the site before implementing its electrification efforts. A second profile defines

its updated electricity demand once the site has (partially) electrified its processes. Both demand profiles are fixed and do not vary as part of the sensitivity analysis.

There are multiple ways in which an electric load profile of a site can be acquired. Ideally, the load profile of a site is measured and shared with external parties. However, as mentioned earlier in Section 1.3.1 sharing such data is not straightforward as it might include commercially sensitive information, or the data are simply not available to begin with. Hence the need for industry blueprints is evident. This work approximates the desired load profiles by scaling generic load profiles from industry sectors with estimated total annual demands.

Within the context of the TRILATE project, the TIMES-BE model outlined various scenarios on how Belgium could reach climate neutrality in a cost-effective manner [54]. The model encompasses a detailed description of the industry sector, including alternative production routes which the model can select during the optimisation of the entire energy system. According to the latest PATHS2050 study, industrial electricity demand will increase by 50-80% by 2050 compared to today's consumption [255]. The regionalisation tool is an extension to TIMES-BE and links the output of the model with an industry database to distribute the energy demand of the industry sector over the Belgian clusters [256]. Current and future annual electricity demand values derived from the regionalisation tool can serve as input for the case study in this work. Alternatively, the RES2Go tool related to the work in Section 3.5 also allows users to generate future energy demand scenarios of sites and ICs and can serve as input to the MILP model [168].

Once the total annual electricity demand per site is known, both reference and future, a sector-specific load profile can be retrieved and rescaled to distribute the total annual demand over 8760 hours. Where a sector-specific load profile is lacking from academic literature, a more generic profile for processing industry can be used instead. Blasuttigh *et al.* rely on normalised sector-specific yearly load profiles that are afterwards scaled to match the site's annual consumption [234]. Each profile corresponds to an activity code from a typical industry sector and includes daily, weekly and seasonal variations [257]. Similarly, the ELMAS database includes a full-year dataset of the electrical load of various industry and tertiary sectors in France [258]. A strong assumption in this work is that the load pattern remains the same before and after electrification. This is not necessarily the case in reality. Because of the limited availability of industrial load profiles in literature, the profile is kept the same. More research on industrial electrification and the creation of generic load profiles should rectify this in the future.

Weather data

The second input category to the MILP model is the availability of local RE generation. The RE technology scope of this work is limited to PV and onshore wind. The Renewables.ninja platform is consulted to generate hourly power output profiles for PV and wind installed at a certain location [259]. The tool departs from raw weather data from satellite observations and global reanalysis models and feeds it to PV and wind power output models [260,261]. Data corresponding to the Gent area are collected from the platform for various weather years. The solar PV installation is assumed to have a capacity of 1 kW, a tilt of 35°, azimuth 180° and a loss fraction equal to 10%. The power output of the PV plants will be scaled with respect to the capacity sizing resulting from the MILP model. Similarly for wind power, the tool allows users to configure the installed capacity (1kW), hub height (80m) and turbine model, and afterwards the power output is scaled with the capacity from the model. The Vestas V112 3.3 MW, a typical market model, was selected for this work and is in line with the technology selection of the BREGILAB study [262].

Existing onsite RE installation and total capacity limit

Each industry site in the case study is characterised by an amount of PV and/or onshore wind that is already installed. It follows the reasoning that these sites have already put effort into installing RE in the past to become more self-reliant and sustainable. At first, the ownership of the to-be-built RE capacity remains exclusive to the respective sites. However, all electricity generated is available for energy sharing. Later in the study, also the ownership of the to-be-built RE capacity is reconsidered to search for the optimal RE portfolio for the cluster members. The case study assumes the sum of the existing RE capacity installed at each site to remain below the peak of its reference demand profile. The same reasoning is applied to set a threshold on the maximum RE capacity that can be installed at each site, but scaled with the updated demand profile. In the work of Carvalho *et al.* the RE capacity size must remain below the grid connection capacity [230]. Similar to Sousa's modelling framework, the case study can also be completed with sensitivities in which the technical capacity limits onsite are altered to study its effect on RE deployment and sharing [246].

Grid connection capacity

Another assumption in this MILP model is the reference grid connection that is available to each of the sites. The currently installed capacity is based on the reference load profile and is scaled to meet the largest peak, neglecting any RE generation capacity installed onsite. Carvalho *et al.* make a similar assumption in their model, rounding up the peak demand of each of the REC members [230]. To

reflect grid congestion issues that prevent industry customers from receiving additional connection capacity, this reference grid connection capacity is kept constant at first. Hence, the electrification of the sites will increase the load profile, but the grid connection capacity will not be adapted accordingly. Later in the study, the grid connection capacity is allowed to increase. The supplying grid to the cluster is assumed to be capable of simultaneously meeting the peak power flows of all sites and at all times. Only the connection to this grid is included in the model.

Techno-economic parameters of RE

The RE technologies are defined by their total installed cost (TIC) and their lifetime. Reported capital expenditure (CAPEX) values in literature range from ~900 to 1100 €/kW for PV and 1300 to 1700 €/kW for wind [230,243,246]. Recently, IRENA published a report on renewable power generation costs in 2024 including TIC values for PV and wind for all regions, including the average costs in EU and Germany. The average TIC for PV in 2024 was 767 \$/kW in EU and 593 \$/kW in Germany. For wind, the average total installed cost was 1640 \$/kW for EU and 1670 \$/kW for Germany [263]. Assuming the German prices to be valid for Belgium as well and converting the currency to € (conversion rate of 25 February), the total installed cost for PV is set equal to 503 €/kW and 1416 €/kW for wind. Comparing to the values reported by Sousa, Carvalho and Lamedica *et al*, the cost of wind power falls within their range and the cost of PV is significantly cheaper. The latter can be explained by the rapidly decreasing costs for PV modules [263].

Using a discount rate (r) of 5% and a lifetime (τ) for PV equal to 25 years and 20 years for wind [230,246], the capital recovery factor (CRF) of each technology can be calculated to reflect the present value of the RE installation in terms of annualised investment costs. CRF can also be seen as the inverse of the present value of a series of equal payments.

$$\text{CRF} = \frac{r(1+r)^\tau}{(1+r)^\tau - 1} \quad (1)$$

Grid tariffs

Three types of tariffs are included in the study. The first is related to the offtake of electricity from the grid by the industry sites. In reality, it comprises a variable grid cost scaled to the total amount of electricity delivered and a capacity tariff based on the peak capacity demand. The latter serves as an incentive to lower peak demands on the grid and spread consumption towards off-peak hours. A recent study commissioned by the Belgian regulator compares electricity prices for large industrial consumers over multiple EU countries [264]. Based on the reported values, the variable tariff in this work is set equal to 11 €/MWh. A second tariff category is related to the cost of the REC facilitator. The SWECO study on RECs in

Flanders assumes a tariff of 5 € per MWh processed by the REC [265]. The third tariff of interest for this work is the grid injection tariff and corresponds to what the coalition receives from sending electricity surpluses to the grid. Again, the SWECO study serves as a benchmark and the price is fixed at 40 €/MWh. Sousa *et al.* apply time of use tariffs on the electricity retrieved from the grid to make a distinction between peak and off-peak hours [246]. Such dynamic grid costs are also under evaluation with the Flemish DSO, but are not yet implemented [265].

Cost of electricity

The total cost of electricity from the grid consists of three elements: the market price (wholesale cost), the network tariffs (already discussed above) and taxes and levies. This study limits itself to the grid and energy components. Similar as in the work of Cosic *et al.*, historical spot market prices are included in the model [245]. Other authors kept the cost of electricity from the grid constant [230]. Hourly EPEX spot market data reflect the variability of electricity prices on the market [266]. To respect the relationship between RE generation and the price determination on the wholesale markets, the weather input data and historical spot market price data always correspond to the same year. Compared to the United States and China, industrial electricity prices in Europe are significantly higher. While wholesale electricity market prices are stabilising since the energy crisis of 2022, the average is still higher compared to pre-crisis levels. In addition, member states leveraged different price interventions at different times, leading to diverging industrial end user prices in Europe that influence investment decisions [267]. An illustrative example can be found in the steel sector, where a substantial difference in electricity prices between France and Belgium (the latter being 1.5 times higher) determines the faith of new electric arc furnaces [268,269].

Objective function

The MILP model optimises towards an objective function that minimises the total annualised electricity cost for all stakeholders *i*. Previously in the work of Deckmyn, the objective function of the optimisation problem included both the minimisation of costs and CO₂ emissions [270]. His microgrid model encompassed thermal generation units, in addition to the utility grid, storages and loads. The emissions resulting from the fuel-burning generators were directly added to the objective function using the quadratic fuel consumption curves. Emissions related to power from the utility grid were included using a linear function with a fixed emission coefficient. Normally, this emission coefficient depends on the instantaneous resource mix, making it a time-dependent variable. In the model presented here, only power from the grid can evoke CO₂ emissions as there are no thermal generators involved in the cluster. For now, minimising CO₂ emissions is left out of

the objective function. Future work could include time-dependent data on grid emission coefficients to expand the objective function.

$$\min \left[\sum_k \left(\text{CRF}_k \cdot \text{TIC}_k \cdot \sum_i P_{i,k,\text{new}} \right) + \sum_t \sum_i \left((T_{\text{grid}} + C_{\text{grid},t}) \cdot E_{\text{grid},i,t} \right) \right. \\ \left. + \sum_t \sum_i T_{\text{shared}} \cdot E_{\text{fromcluster},i,t} + \sum_t \sum_i C_{\text{pen}} \cdot E_{\text{shed},i,t} \right. \\ \left. - \sum_t \left(T_{\text{surplus}} \sum_i E_{\text{sold},i,t} \right) \right] \quad (2)$$

The total annualised electricity cost includes the annualised TIC of the newly installed RE capacities (P), where a distinction is made between PV and wind (k). Secondly, it comprises the cost of purchasing electricity from the grid (E_{grid}) and the related tariff (T_{grid}) at a variable pricing (C_{grid}). Also a tariff (T_{shared}) is put on the electricity shared ($E_{\text{fromcluster}}$) between the coalition members to reflect the cost associated with enabling RE sharing within the cluster, such as metering, transaction and local network-use costs. The objective function includes a penalty (C_{pen}) for any of the load shed (E_{shed}). C_{pen} is a sufficiently large number so the cluster stakeholders will prevent load shedding when possible. Any revenues from selling electricity surpluses (E_{sold}) at the grid-injection tariff (T_{surplus}) are reduced from the total cost. Each simulation run considers a complete year with a temporal resolution of one hour (t).

The model is subject to a number of constraints. The first constraint limits the amount of PV and wind installed at the site to remain below the onsite capacity limit. The amount of additional PV and wind that can still be installed is equal to the difference between the technical capacity limit and the capacity of the existing installation.

$$0 \leq P_{i,k,\text{new}} \leq P_{i,k,\text{cap}} - P_{i,k,\text{existing}} \quad (3)$$

The grid connection capacity also puts constraints on the amount of electricity that can be exchanged with the grid, as consumer and as producer. A binary variable (γ) is added so the site cannot take electricity from and supply electricity to the grid at the same time.

$$E_{\text{grid},i,t} \leq \text{Cap}_{\text{grid},i} \cdot \gamma \quad (4)$$

$$E_{\text{sold},i,t} \leq \text{Cap}_{\text{grid},i} \cdot (1 - \gamma) \quad (5)$$

For each site at every time instant, the electricity received and generated needs to be equal to the amount consumed (D), exchanged or sold. Both load shedding as a form of DSR and RE curtailment (E_{curt}) are included to complete the energy balance. For now, the optimisation model exclusively investigates the synergy RE sharing and does not encompass storage options. The amount of RE available (RE) depends on the weather data and is scaled with the total capacity installed per RE technology.

$$\begin{aligned}
 E_{\text{grid},i,t} + E_{\text{fromcluster},i,t} + \sum_k P_{i,k,\text{new}} \cdot \text{RE}_{t,k} \\
 + \sum_k P_{i,k,\text{existing}} \cdot \text{RE}_{t,k} + E_{\text{shed},i,t} \\
 = E_{\text{tocluster},i,t} + D_{i,t} + E_{\text{sold},i,t} + E_{\text{curt},i,t}
 \end{aligned} \quad (6)$$

Additionally, the RE sharing is also constrained to fulfil the supply and demand balance and the amount of electricity sent to the cluster is capped by the RE production of the site.

$$\sum_i E_{\text{tocluster},i,t} = \sum_i E_{\text{fromcluster},i,t} \quad (7)$$

$$E_{\text{tocluster},i,t} \leq \sum_k P_{i,k} \cdot \text{RE}_{t,k} \quad (8)$$

The non-negativity of some parameters is also given to the MILP model as constraints.

$$E_{\text{grid},i,t}; E_{\text{fromcluster},i,t}; E_{\text{tocluster},i,t}; E_{\text{sold},i,t}; E_{\text{shed},i,t}; E_{\text{curt},i,t}; P_{i,k,\text{new}} \geq 0$$

5.2.3 OVERVIEW CASE STUDY

The fictitious case study includes three industry sites active in three different sectors. The first stakeholder is a food producer that plans to instal low-temperature heat pumps. Based on the powering industry to net zero study performed by Elia, the electricity demand of this sector is expected to increase with ~66% by 2030 [191]. The second site belongs to the paper and pulp industry. Due to a shift towards electric boilers and heat pumps, Elia expects a demand increase of ~40% by 2030. The third site is a glass producer and will only leverage electrical boosting (+15%) in the near future [191]. Knowing the percentage electricity demand increases for each of the sites, a typical plant size and respective electricity consumption for each

sector is derived from the regionalisation tool [256]. This results in annual reference and projected electricity demands for the three sites.

Table 19 summarises the input data on industrial electricity demand for the MILP optimisation. The fourth column lists the source of the selected load profile for each site. It is noted that, where available, a sector-specific load profile is chosen from the work of Seim *et al.* [257]. This is the case for food and paper and pulp. For the glass sector no sector-specific load profile was found. Hence, a surrogate baseload profile corresponding to a continuous operation was created, since the glass furnaces should operate 24/7/365. Figure 39 to Figure 41 illustrate the rescaled load profile according to the reference and future annual electricity demands per site. The load profile of the paper plant clearly includes two foreseen production stops, typically to allow for maintenance on the installations. The peak load in the reference profile is rounded up to size the existing grid connection capacity. For sites A, B and C this corresponds to respectively 11 MW, 14 MW and 4 MW.

Table 19 Data on the industrial sites in the case study.

sector	reference electricity demand [GWh/y]	future electricity demand [GWh/y]	source load profile	grid connection capacity [MW]
A food	54.2	90 (+66%)	WZ10 [257]	11
B paper & pulp	100	140 (+40%)	WZ17 [257]	14
C glass	34.8	40 (+15%)	continuous baseload	4

Table 20 contains all input assumptions on the existing RE installations at each of the sites. The sum of RE capacity remains below the maximum demand load, both for the reference RE and for the total technical potential. Recall that each wind turbine has a total capacity of 3.3MW. This leads to a total installed RE capacity at sites A, B and C of respectively 6.3 MW, 8.3 MW and 3 MW. The total RE capacity limit at each of the sites is 17.9 MW, 19.9 MW and 5 MW respectively. At first, the ownership of the to-be-built RE capacity remains with the sites, e.g. site A will be able to install 5 MW of additional PV and 2 wind turbines. Later in the study, the ownership is contested and the RE potential is redistributed among the sites to optimise the demand and supply matching.

Table 20 Data on the existing RE installations and RE potential of each of the sites in the case study.

	PV installed [MW]	PV capacity limit [MW]	wind installed [# turbines]	wind capacity limit [# turbines]
A	3	8	1	3
B	5	10	1	3
C	3	5	0	0

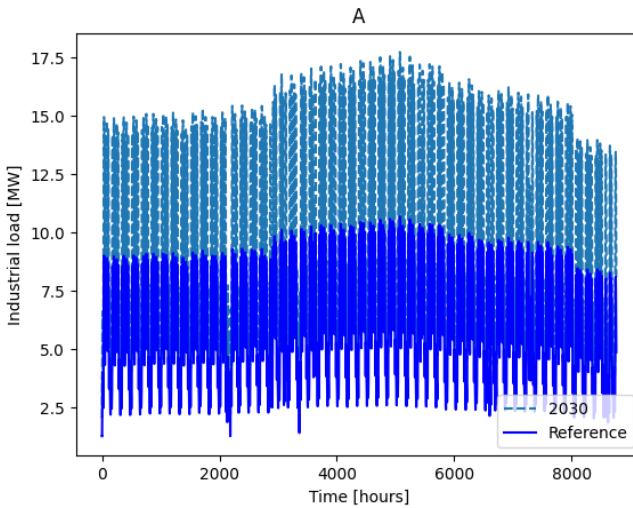


Figure 39 Reference and future electricity load profile for site A active in the food sector.

The model takes into account RE volatility by including RE generation profiles based on historical weather data. Figure 42 and Figure 43 illustrate respectively the wind and PV power output over the whole year. Figure 44 plots the electricity price data derived from the EPEX spot market. Both the electricity price data and RE generation profiles correspond to the year 2024. In all time profiles, the hour 0 corresponds to 1 am, 1st of January and hour 8760 to 11 pm, December 30th. Since 2024 was a leap year, the last day was removed for all time profiles to have the same length. In the RE generation profiles, the seasonality can clearly be seen in the PV power output that surges during the summer period. The largest peaks in the wind power output seem to correspond rather to the winter and spring period. Overlapping the power output profiles of both RE technologies result in a more evenly spread production, highlighting the compatibility of both technologies in a RE portfolio. Negative electricity pricing occurs during the summer period, whereas large peaks occur during fall/winter. On the 12th of December at 5 pm, the electricity price reaches its

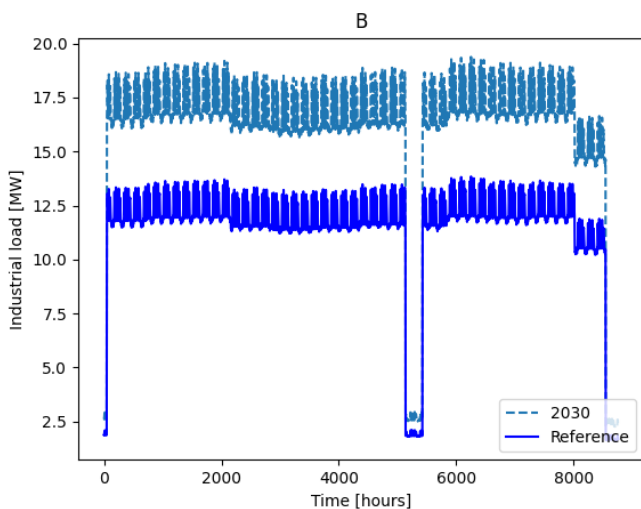


Figure 40 Reference and future electricity load profile for site B active in the paper sector.

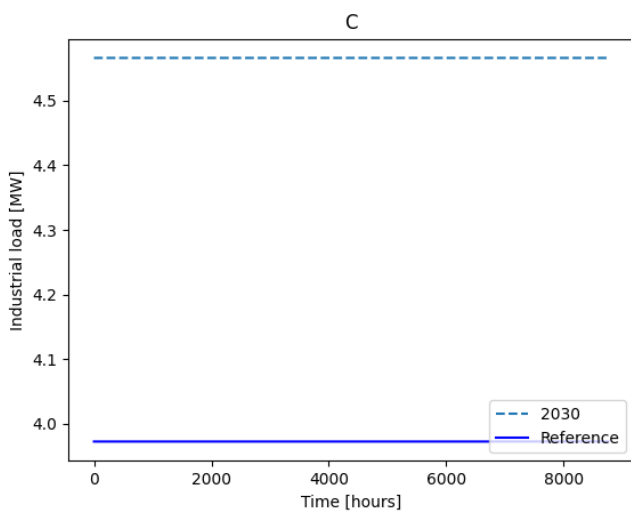


Figure 41 Reference and future electricity load profile for site C active in the glass sector.

largest peak, corresponding to 565.46 €/MWh. PV output at that time instant is zero and the capacity factor of wind is equal to 6.5%.

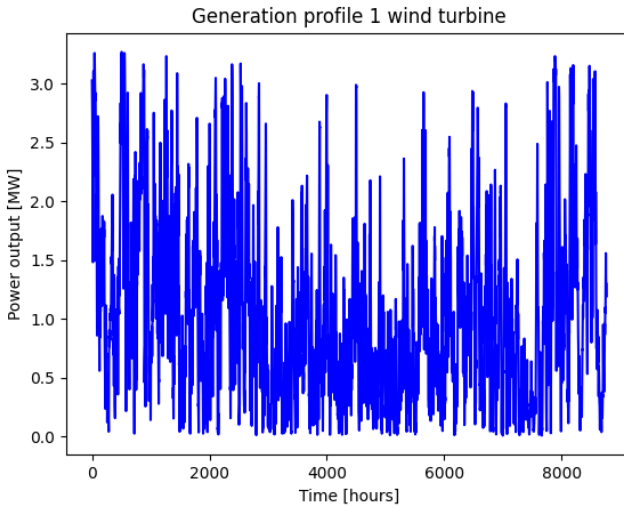


Figure 42 Wind power generation profile for one wind turbine (3.3 MW) using weather data for the year 2024.

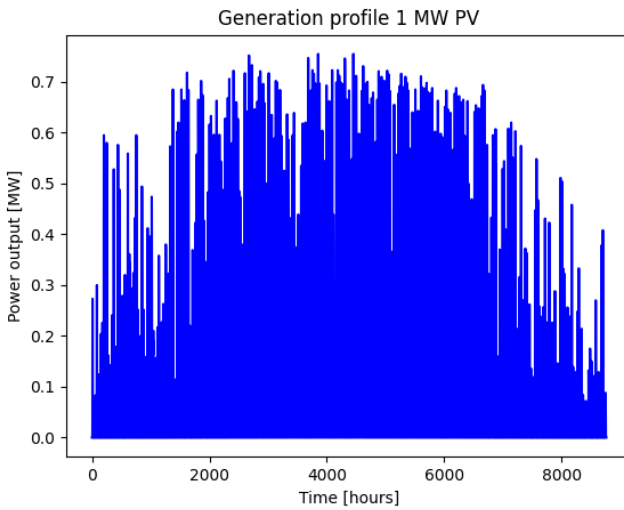


Figure 43 PV power generation profile for one MW capacity using weather data for the year 2024.

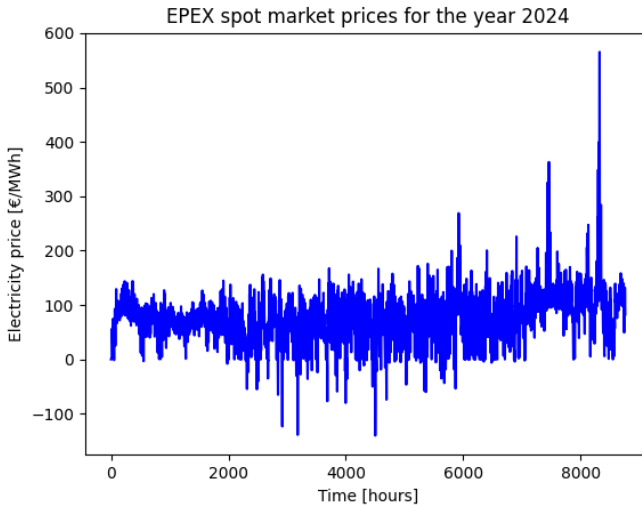


Figure 44 EPEX spot market data for the year 2024 for Belgium [266].

The optimisation is performed for a set of scenarios to explore the effects of RE sharing on the cluster (Figure 45). The first scenario models the cluster without RE sharing. The second allows for RE sharing in a no-taboo approach, assuming the amount of electricity exchanged between the sites to be unconstrained. Thirdly, the RE sharing in the cluster is modelled realistically, where any power flows have to be exchanged using the public grid. The fourth scenario maintains the grid constraints but relieves the fixed ownership of the newly installed RE capacities. To study the effect of grid congestion on the synergy, the grid connection capacity bottleneck is relieved in a fifth scenario. A sixth scenario completes the set by once again questioning the initial ownership of the RE potential in the situation with additional grid capacity. Depending on the scenario studied, the constraints defined in Section 5.2.2 need to be slightly altered, summarised by Table 21.

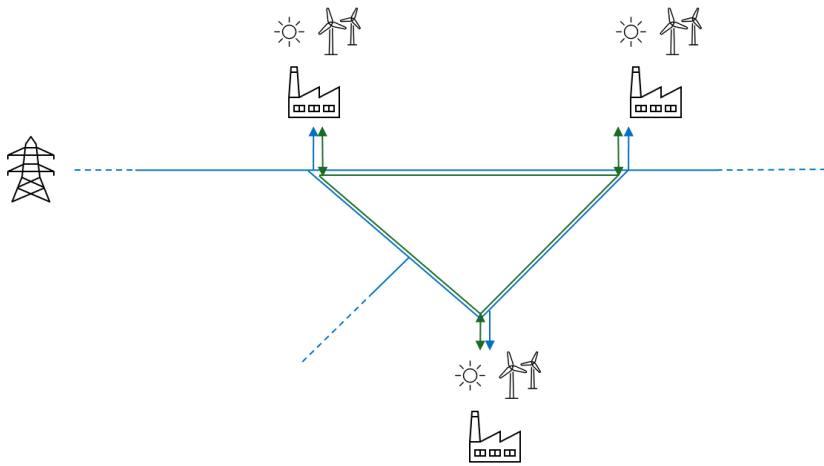


Figure 45 Schematic overview of the case study.

Table 21 Changes to the MILP optimisation model constraints according to the scenario modelled.

scenario	scenario description	altered constraints
1 V_1_ind	individual no RE exchange	$E_{tocluster}$ and $E_{fromcluster}$ are zero for all sites at all times
2 V_1_col	RE exchange no-taboo	model described as in Section 5.2.2
3 V_2_col	RE exchange realistic	$E_{grid,i,t} + E_{fromcluster,i,t} \leq Cap_{grid,i} \cdot y$ $E_{sold,i,t} + E_{tocluster,i,t} \leq Cap_{grid,i} \cdot (1 - y)$
4 V_2_col_own	RE exchange realistic ownership change	$E_{grid,i,t} + E_{fromcluster,i,t} \leq Cap_{grid,i} \cdot y$ $E_{sold,i,t} + E_{tocluster,i,t} \leq Cap_{grid,i} \cdot (1 - y)$ and $0 \leq \sum_i P_{i,k,new} \leq P_{k,cap} \text{ pooled}$ instead of $0 \leq P_{i,k,new} \leq P_{i,k,cap} - P_{i,k,existing}$

		with	$P_{k,cap\ pooled} = \sum_i (P_{i,k,cap} - P_{i,k,existing})$
5 V_3_col	RE exchange grid capacity extension		$E_{grid,i,t} + E_{fromcluster,i,t} \leq Cap_{grid,i} \cdot y$ $E_{sold,i,t} + E_{tocluster,i,t} \leq Cap_{grid,i} \cdot (1 - y)$ and $Cap_{grid,i} = [18, 20, 5]$
		instead of	$Cap_{grid,i} = [11, 14, 4]$
6 V_3_col_own	RE exchange grid capacity extension ownership change		$E_{grid,i,t} + E_{fromcluster,i,t} \leq Cap_{grid,i} \cdot y$ $E_{sold,i,t} + E_{tocluster,i,t} \leq Cap_{grid,i} \cdot (1 - y)$ and $Cap_{grid,i} = [18, 20, 5]$
		instead of	$Cap_{grid,i} = [11, 14, 4]$
		And	$0 \leq \sum_i P_{i,k,new} \leq P_{k,cap\ pooled}$
		instead of	$0 \leq P_{i,k,new} \leq P_{i,k,cap} - P_{i,k,existing}$
		with	$P_{k,cap\ pooled} = \sum_i (P_{i,k,cap} - P_{i,k,existing})$

5.3 RESULTS

In all six scenarios, the sites install additional RE capacity up until the remaining capacity limit. The results are shown in Table 22 and Table 23. Relieving the fixed ownership constraint changes the respective amounts of RE installed at sites A, B and C. In scenario V_2_col_own, the entire PV capacity of site C and a part of the PV capacity of site B shift towards site A. In return, one wind turbine originally destined for site A moves to site C. An explanation for this can be found in the design of the

objective function of the MILP model. Pooling and redistributing all remaining capacity to install the optimal RE portfolio at each site, maximising demand-supply profile complementarity, avoid to a large extent the exchange tariff T_c and reduces the total annual cost. Similarly in V_3_col_own, the RE capacity potential is redistributed. In this scenario, the grid connection capacity is no longer a bottleneck as it was rescaled to meet the updated electricity demand and there is no longer a penalty for load shedding. Hence, the optimal RE portfolio for each site changed again comparing to V_2_col_own. As a result, the PV capacity of site C shifts to site B, together with a marginal part of the capacity of site A. In return, one wind turbine of site A goes to site C.

Important to note here is that the costs related to the change of ownership have not been taken into account in the objective function. In reality, the coalition partners will have to make arrangements with respect to the land on which the turbines will be built, the roof renting scheme for the PV utilities and the lost income of selling surpluses to the grid. Such complicated agreements characterise IS negotiations and a change of ownership must be properly compensated for the coalition to sustain. The GT principles that offer support in those discussions are discussed in Section 5.4

Table 22 Newly installed PV capacity at each site for the different scenarios, in MW.

site	V_1_ind	V_1_col	V_2_col	V_2_col_own	V_3_col	V_3_col_own
A	5	5	5	9.5	5	4.7
B	5	5	5	2.5	5	7.3
C	2	2	2	0	2	0

Table 23 Newly installed wind capacity at each site for the different scenarios, in number of turbines.

site	V_1_ind	V_1_col	V_2_col	V_2_col_own	V_3_col	V_3_col_own
A	2	2	2	1	2	1
B	2	2	2	2	2	2
C	0	0	0	1	0	1

Table 24 reports the total amount of load shed for all sites combined over the whole year in each scenario. Once the grid connection capacity is updated in line with the electrified demand (scenarios V_3_col and V_3_col_own), load shedding no longer occurs. It is noted that the objective function of the MILP model contains a penalty

with a virtually large number to avoid load shedding. In the no-taboo scenario V_1_col, the amount of electricity demand not supplied is minimal, given the reference grid connection capacities. Of course, this way of RE sharing is not realistic as it is illegal to build parallel grids connecting sites behind the meter. The realistic way of sharing RE, scenario V_2_col, does not improve the load shedding in the cluster. As a response to this, scenario V_2_col_own was created to see how a change in RE ownership could resolve this issue. As can be seen from the table, the total amount of load shed in this scenario does not reach the minimum of scenario V_1_col, but comes rather close. These results illustrate that in a situation with grid congestion, an optimal onsite RE portfolio design can effectively make a difference and changing the RE ownership might be a worthwhile discussion.

Table 24 The total amount of load shed in each scenario.

scenario	total load shed [MWh]
V_1_ind	9149.83
V_1_col	5303.17
V_2_col	9149.83
V_2_col_own	6778.75
V_3_col	0
V_3_col_own	0

To complement Table 24, Figure 46 plots the cumulative load shedding profiles of the first four scenarios. The profiles of V_1_ind and V_2_col are identical. Comparing V_2_col_own to the two left ones, a clear improvement is visible as there are some time instances without any load shedding. Comparing the graph to V_1_col (the lowest amount of load shedding in the situation with reference grid connections), the increase of time instances with load shedding is noticeable. Comparing the plots in Figure 46 with the RE generation profiles of Figure 42 and Figure 43, an inverse relationship is identified between the load shed and the availability of wind power.

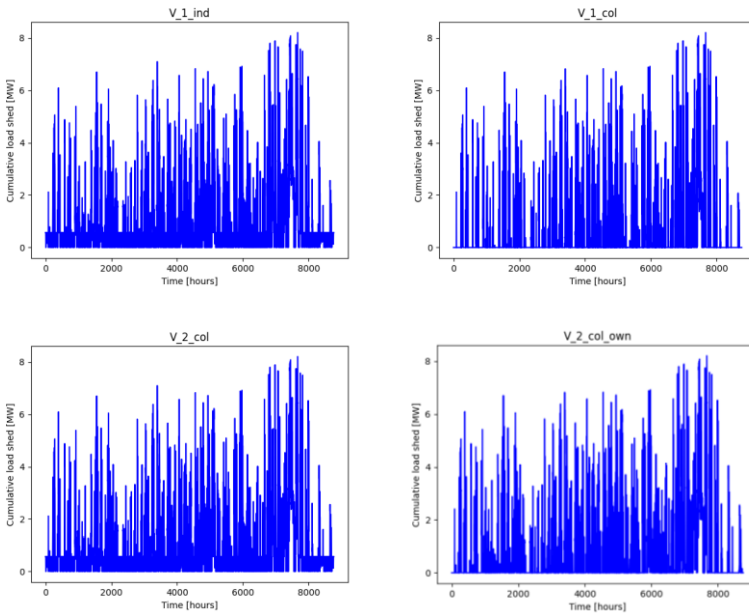


Figure 46 Cumulative load shed for the scenarios V_1_ind, V_1_col, V_2_col and V_2_col_own. V_3_col and V_3_col_own have no load shed.

Figure 47 to Figure 49 plot the electricity bought from the grid or sold back to the grid for sites A, B and C respectively for all six scenarios. Comparing the scenarios starting with V_1 and V_2 to the scenarios starting with V_3, the change in grid connection capacity is clear. Important to note here is that in the two scenarios V_1_ind and V_1_col the grid connection is only used for electricity exchange with the grid as the exchange of RE within the cluster is either non-existent or occurs using an imaginary parallel grid. This explains the consistently larger values for electricity sent to the grid by each site in V_1_col. All other scenarios have a trade-off in using the grid connection capacity to get electricity from the market or sell back to it, or to exchange with coalition partners. The selling-back profile of site A is comparable for V_1_ind and V_2_col, but drastically changes in the other scenarios, with more time instances of it being a net producer in V_2_col_own. Total quantities drop for selling electricity back in both scenarios starting with V_3 and electricity is bought at maximum volumes instead. This effect is also present at sites B and C. Aside from this, the behaviour of site B remains more or less similar. Site C only has electricity surpluses in the scenarios with a change in ownership or with an imaginary parallel grid (V_1_col).

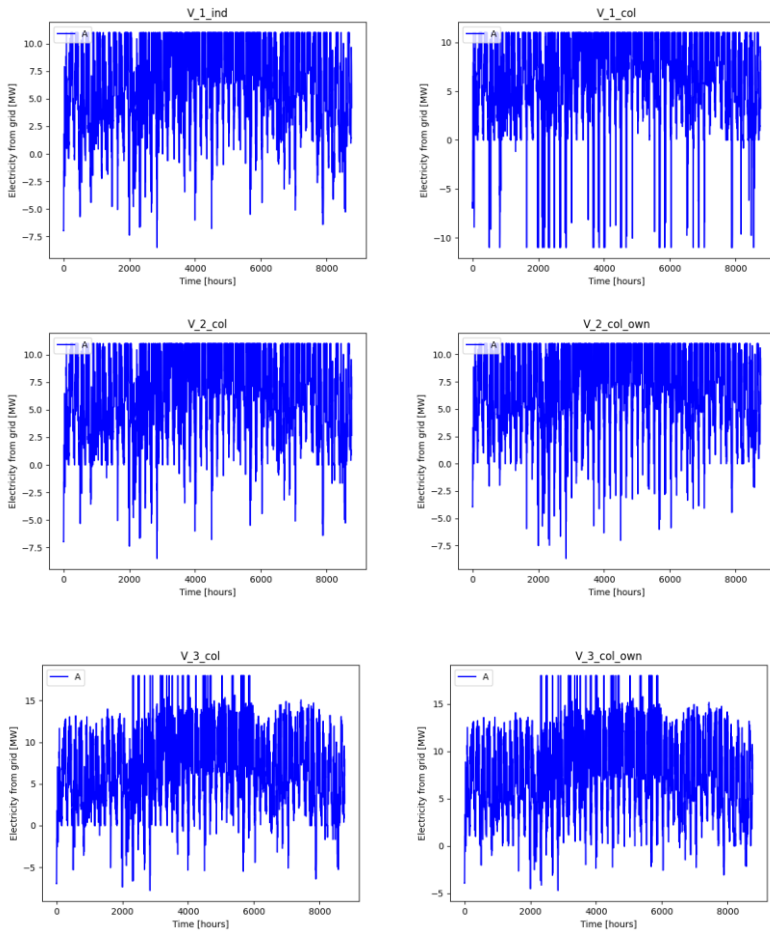


Figure 47 Electricity exchanged by site A with the grid in all scenarios (positive if bought from the grid, negative if sold).

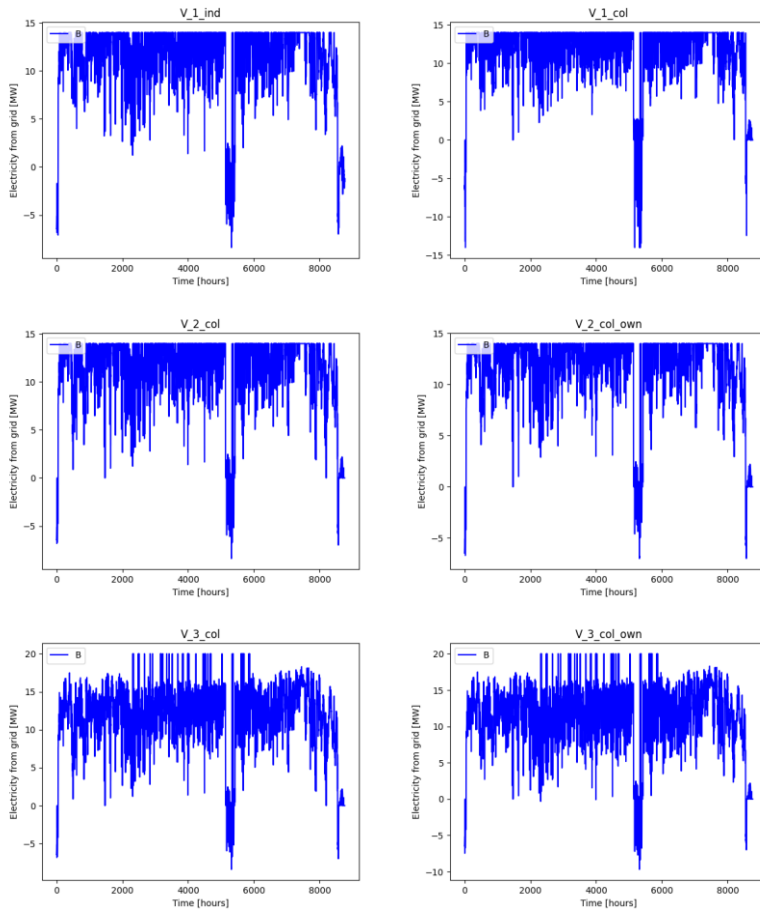


Figure 48 Electricity exchanged by site B with the grid in all scenarios (positive if bought from the grid, negative if sold).

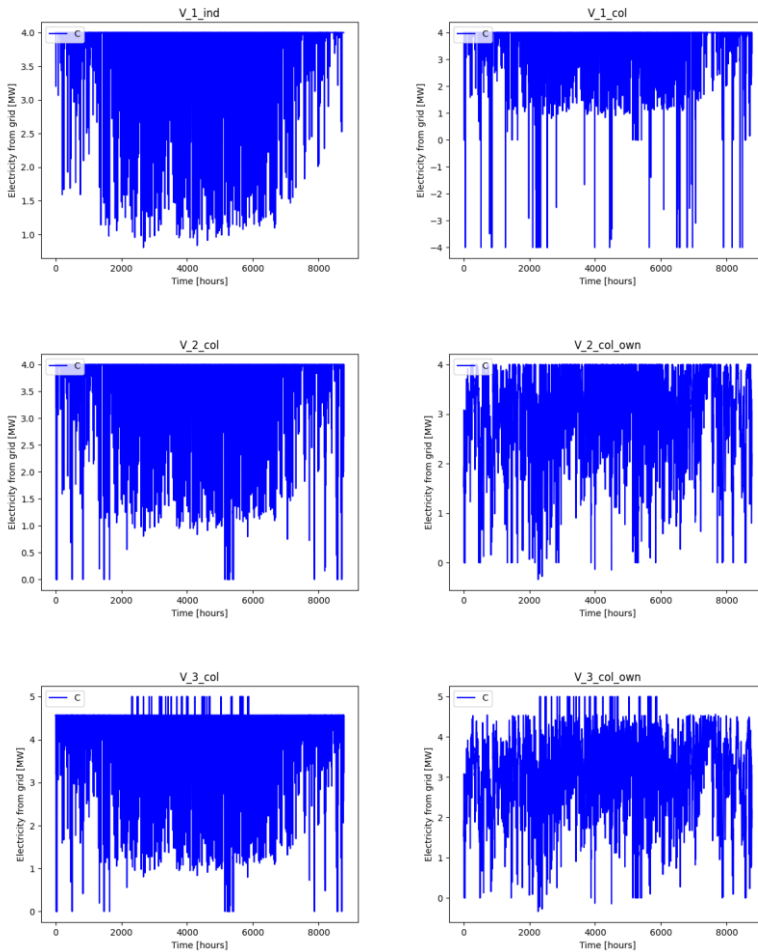


Figure 49 Electricity exchanged by site C with the grid in all scenarios (positive if bought from the grid, negative if sold).

The timing of maximum procurement of electricity from the grid coincides with negative electricity prices (see Figure 44). As a result, renewable energy production onsite is (partly) curtailed to respect the energy balances of the optimisation model (Figure 50 to Figure 52). Peak RE curtailment increases with larger grid connection capacities (scenarios starting with V_3). Ownership change lowers the peak RE curtailment at site A. At site B, ownership change increases peak RE curtailment in scenario V_3_col_own. This is due to the larger amount of PV installed (see Table 22). Similarly at site C, scenarios with ownership change exclusively increase RE curtailment.

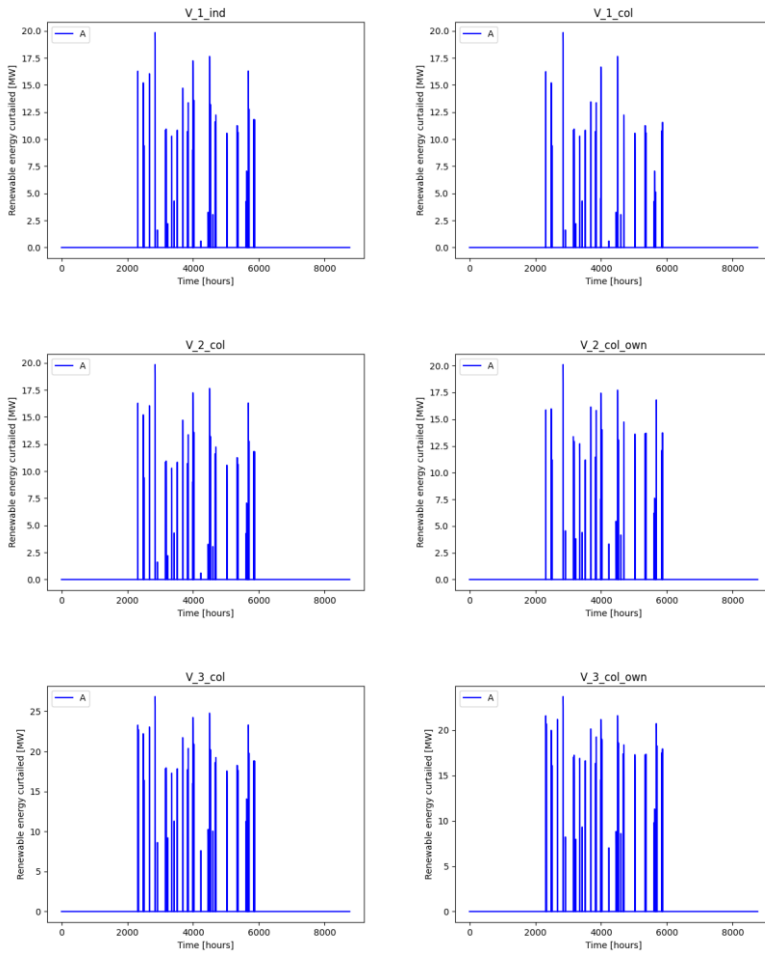
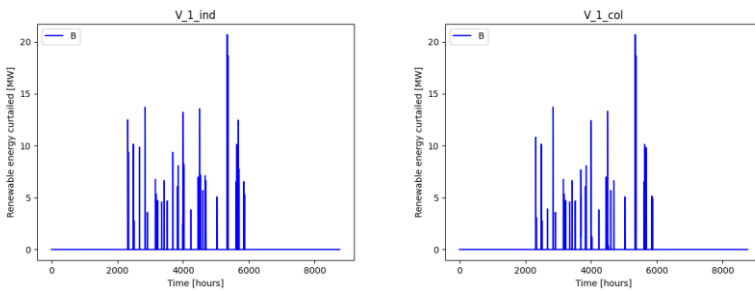


Figure 50 Onsite renewable energy curtailed by site A for all scenarios.



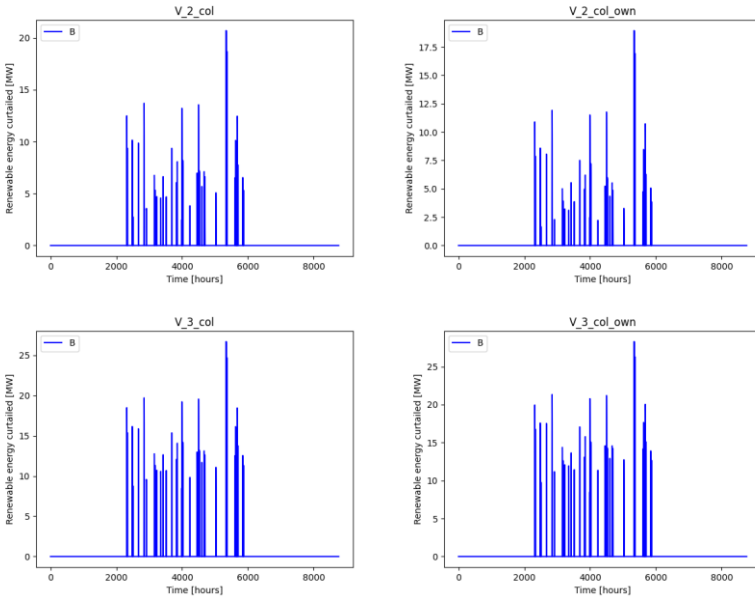
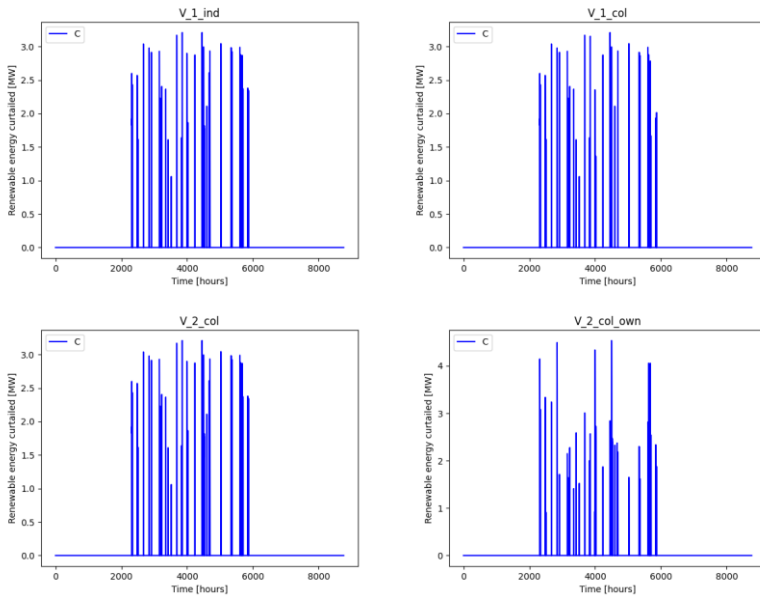


Figure 51 Onsite renewable energy curtailed by site B for all scenarios.



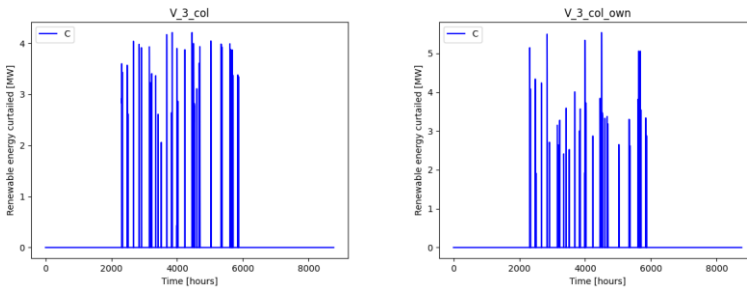


Figure 52 Onsite renewable energy curtailed by site C for all scenarios.

Figure 53 to Figure 55 show the exchange of electricity of each site within the grand coalition. There are only five graphs corresponding to scenarios 2-6 as the first scenario V_1_ind allows no RE sharing and the values $E_{\text{tocluster}}$ and $E_{\text{fromcluster}}$ for each site are zero throughout the entire year. It is noted that V_1_col assumes a parallel grid to facilitate the RE exchange within the cluster without any constraints, hence it is referred to as the no-taboo approach. This explains the strong difference between the load profiles corresponding to this scenario and those corresponding to the other four. V_2_col and V_3_col have similar profiles for all sites. Comparing the scenarios with and without a change of RE ownership, site A more frequently sends electricity to the cluster in V_2_col_own than in V_3_col_own. The same trend is present for electricity taken from the cluster by sites B and C. In all graphs, the shutdown period of site B during the summer is clearly noticeable, converting it into a net cluster producer and sites A and C into cluster consumers. Similar as to selling electricity back to the grid, sending surpluses to the cluster is only an option for site C in the scenarios with a change in ownership. Also for this site, the frequency of exchanges drops when comparing V_2_col to V_3_col. This leads to the conclusion that grid congestion affects RE sharing in the cluster, but not as much as the change of ownership.

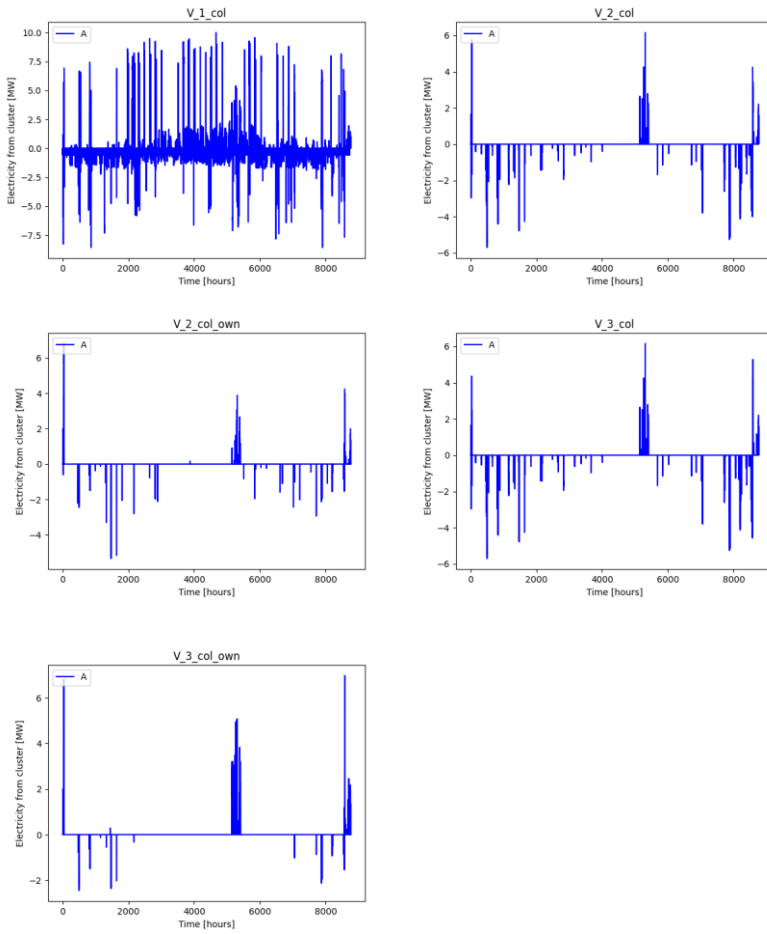


Figure S3 Electricity exchanged by site A with the cluster in all scenarios (positive if bought from the cluster, negative if sold).

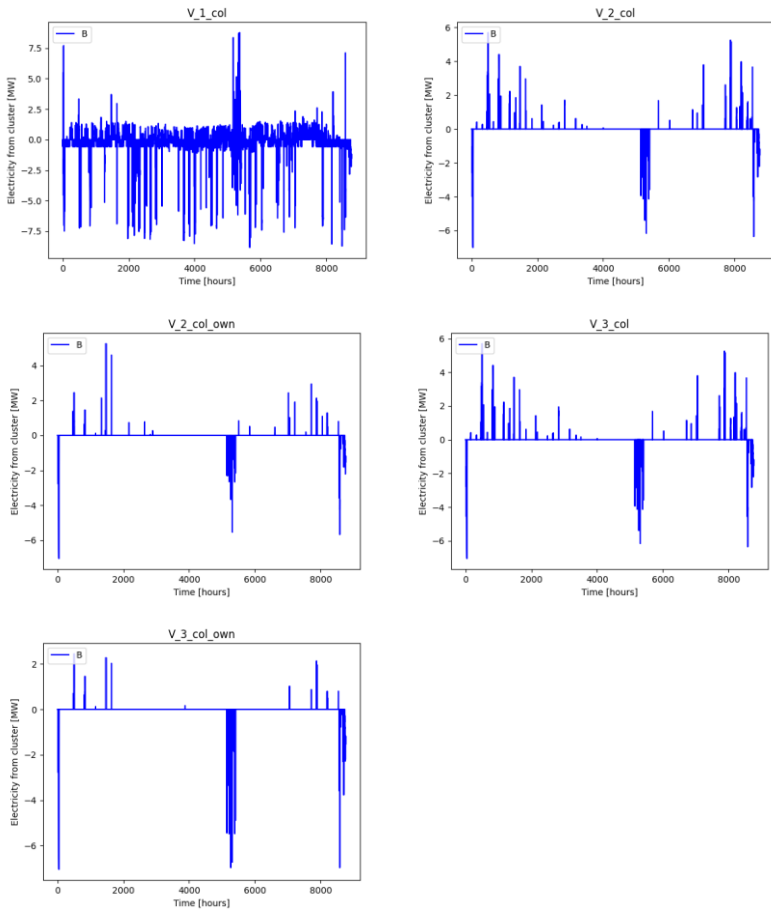
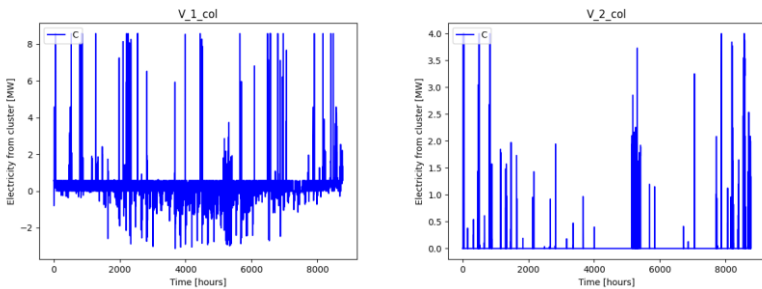


Figure 54 Electricity exchanged by site B with the cluster in all scenarios (positive if bought from the cluster, negative if sold).



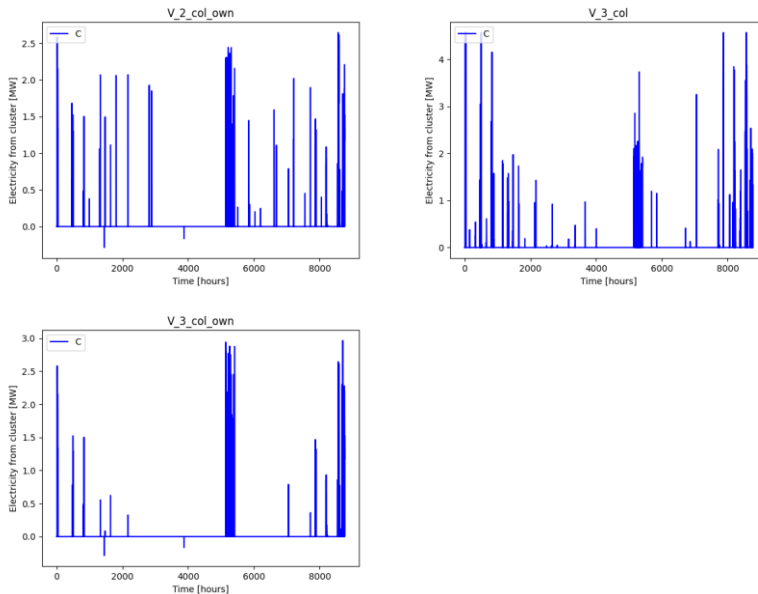


Figure 55 Electricity exchanged by site C with the cluster in all scenarios (positive if bought from the cluster, negative if sold).

5.4 COLLABORATIVE LAYER

In principle, a company aims to minimise costs at all times. In this case, the site strives to curtail its individual total costs. The second part of the methodology comprises GT principles to distribute the aggregated total cost, which is lower as a result of RE sharing, over the individual sites, and to validate the fairness and the stability of the coalition. It indicates the necessary side payments between the sites as the MILP model of the previous section does not include an electricity transfer cost related to RE sharing between the sites. This is because the model minimises the total cost of all sites combined and internal monetary exchanges would sum to zero. Hence, the transfer cost is not a decision variable in the model. Important to note is that the costs reported in this Section serve to illustrate the GT principles applied in the collaborative layer. In reality, electricity procurement by industry involves special contracts, tariffs, subsidies, etc. and PPAs, which were not included in this work.

The collaborative layer is applied to the fifth scenario, V_3_col. Since no load shedding occurs in this scenario, the objective function contains no penalty and

consists purely out of costs related to electricity procurement. In addition to solving the MILP optimisation model for the grand coalition {A, B, C}, the model is also solved for each site operating individually {A}, {B} and {C}, hence without RE sharing, and all possible sub-coalitions {A, B}, {A, C} and {B, C}. Table 25 shares the minimised total cost for each coalition.

Table 25 Minimal total cost for each possible coalition in scenario V_3_col.

coalition	minimal total cost [k euro]
{A}	6 007.99
{B}	9 728.74
{C}	3 025.24
{A, B}	15 711.19
{A, C}	9 019.04
{B, C}	12 742.18
{A, B, C}	18 734.30

Table 26 compares the total cost of each coalition to the sum of the individual costs of the coalition members. From this table it is clear that cooperation always reduces the total cost. In terms of pairwise coalitions, a synergy between sites A and B leads to the largest cost reduction. The grand coalition of all three sites still achieves the largest cost reduction, but the difference with the cost reduction of {A, B} is rather small.

Table 26 Total cost comparison between the coalitions and the sum of individual costs of the members.

coalition	coalition cost [k euro]	sum of individual costs [k euro]	savings [k euro]
{A, B}	15 711.19	15 736.73	25.54
{A, C}	9 019.04	9 033.23	14.19
{B, C}	12 742.18	12 753.98	11.80
{A, B, C}	18 734.30	18 761.97	27.67

The total cost reduction by the grand coalition is nearly 28 k€ compared to the sum of the individual costs. The next step is to distribute the total remaining cost of the

grand coalition over the individual sites. One way to achieve this is to allocate an equal share of the cost reduction to each of the sites. This corresponds to the Equal Sharing Point (ESP) of the case. Each site gets a discount of 9223.03 euro, or one third of 27 669.08 euro. Table 27 reports the individualised total costs for each site using various cost allocation methods. The question is whether the ESP cost/benefit allocation method is fair and stable. Intuitively, the odds of the ESP being a fair approach are slim. Members of the coalition might have the impression that they contribute more to the synergy than others and should thus receive a larger reward from it. Such reasoning was identified by the LESTS survey as one of the main barriers to RE sharing.

To verify the fairness, the results from the ESP allocation are compared to the Shapley values of the case. In the field of GT, the Shapley value is the most known example of a fair way to allocate the cost savings as it is based on the average marginal contribution of each site to the coalition. The general formula is given below and defines the Shapley value φ for player i :

$$\varphi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! (n - |S| - 1)!}{n!} (v(S \cup \{i\}) - v(S)) \quad (9)$$

with

- n the total number of players
- S the coalition used in the summation
- $|S|$ the number of players in coalition S
- N the grand coalition

For a case with three players, A, B and C, the Shapley values are defined as follows:

$$\varphi_A = \frac{1}{6} (2(v\{A\} - v\{\emptyset\}) + (v\{A, B\} - v\{B\}) + (v\{A, C\} - v\{C\}) + 2(v\{A, B, C\} - v\{B, C\}))$$

$$\varphi_B = \frac{1}{6} (2(v\{B\} - v\{\emptyset\}) + (v\{A, B\} - v\{A\}) + (v\{B, C\} - v\{C\}) + 2(v\{A, B, C\} - v\{A, C\}))$$

$$\varphi_C = \frac{1}{6} (2(v\{C\} - v\{\emptyset\}) + (v\{A, C\} - v\{A\}) + (v\{B, C\} - v\{B\}) + 2(v\{A, B, C\} - v\{A, B\}))$$

with

- $n = 3$
- $N = \{A, B, C\}$
- $v\{\emptyset\} = 0$ as the set is empty

The Shapley values for the case are added to Table 27. Comparing the ESP to the Shapley values confirms the intuition that dividing the benefits by three is an unfair way to allocate the costs. While the cost reduction of site B remains more or less similar, it is clear that site A contributes more to the coalition than site C and the Shapley value corrects this by changing the weights of the cost distribution. According to the Shapley value, site A is the most contributing member of the coalition.

Table 27 Comparison of various cost allocation methods.

cost method	allocation	total cost site A [k euro]	total cost site B [k euro]	total cost site C [k euro]
individual (benchmark)		6 007.99	9 728.74	3 025.24
ESP		5 998.77	9 719.52	3 016.02
		(-9.22)	(-9.22)	(-9.22)
Shapley		5 996.08	9 718.02	3 020.20
		(-11 .91)	(-10 .72)	(-5.04)

Just because a cost allocation is fair, does not mean it is stable. The Core is a GT principle that verifies the stability of the cost allocation. If an allocation method falls within the Core, no sub-coalition can do better on their own than the grand coalition, hence they do not have an incentive to break away. Two conditions need to be met for an allocation method like the Shapley value to fall within the Core, corresponding to the individual rationality and group rationality [247]. The group rationality ensures that the sum of the individual costs is equal to the minimal group cost, corresponding to the grand coalition:

$$\sum_i \varphi_i = v_{A, B, C} \quad (10)$$

The individual rationality verifies that no individual players or sub-coalitions can do better than the cost allocation of the grand coalition:

$$\sum_{i \in S} \varphi_i \leq v(S) \forall S \subset N \quad (11)$$

Table 28 verifies each of the Core constraints for the ESP and the Shapley values of sites A, B and C. One of the constraints is false for both allocation methods. Hence, both methods fall outside the Core and are not stable to support the grand coalition in this case. Sub-coalition {A, B} prefers to deviate from the ESP by 7094.63 euro and from the Shapley value by 2913 euro.

Table 28 Stability validation of the Shapley values using the core constraints.

Core constraint	ESP	Shapley
$\varphi_A + \varphi_B + \varphi_C = v\{A, B, C\}$	true	true
$\varphi_A + \varphi_B \leq v\{A, B\}$	false	false
$\varphi_A + \varphi_C \leq v\{A, C\}$	true	true
$\varphi_B + \varphi_C \leq v\{B, C\}$	true	true
$\varphi_A \leq v\{A\}$	true	true
$\varphi_B \leq v\{B\}$	true	true
$\varphi_C \leq v\{C\}$	true	true

Contrary to the Shapley value, the Nucleolus inherently guarantees a stable solution in a non-empty Core, but it is not an indicator for fairness [85]. To define the Nucleolus, a new parameter called the excess $e(S, x)$ needs to be introduced:

$$e(S, x) = v(S) - \sum_{i \in S} x_i \quad \forall S \subset N \quad (12)$$

x_i is a possible imputation for player i in the coalition S , or in other words, a possible allocation vector. Each imputation needs to fulfil the individual and group rationality constraints [247]. The excess measures the inequity (unhappiness) of an imputation and the Nucleolus minimises the worst dissatisfaction among all coalitions.

Lechtenberg *et al.* developed a python package called pyCoopGame to construct and solve cooperative games [85,271]. It contains modules that verify the non-emptiness of the Core and calculate the computationally intensive Nucleolus. By means of the python package, the Core of the case studied in this work is retrieved and seems to be empty. This means the case is nonconvex and the players have no clear incentive to form large coalitions. A convex game is also called a super-modular game and for this specific class in cooperative GT the Nucleolus and Shapley values coincide. Convexity is defined by the formula below together with Figure 56.

$$v(S \cup \{i\}) - v(S) \geq v(T \cup \{i\}) - v(T) \quad \forall S \subseteq T \subseteq N \text{ \& } \forall i \in N \setminus T \quad (13)$$

In wording, the marginal contribution of any player i to coalition S increases as more players join the coalition, where contribution is defined here as the reduction of the cost after collaborating. It illustrates a snowballing effect where the larger a coalition, the more beneficial it becomes for the members. [250] Table 29 verifies each convexity constraint of this case.

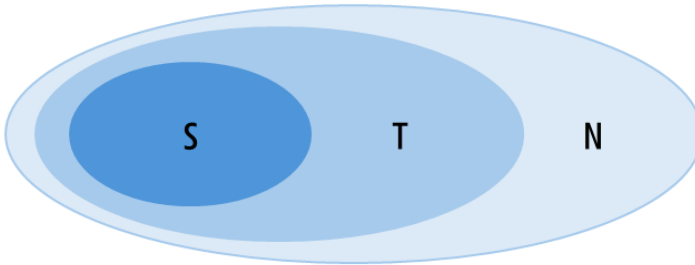


Figure 56 Coalition subsets in a convex game with N the grand coalition and T and S subcoalitions.

Table 29 Verification of the convexity of the case.

convexity constraint	i	true or false
$v\{A, B\} - v\{A\} \geq v\{A, B, C\} - v\{A, C\}$	B	false
$v\{A, B\} - v\{B\} \geq v\{A, B, C\} - v\{B, C\}$	A	false
$v\{A, C\} - v\{A\} \geq v\{A, B, C\} - v\{A, B\}$	C	false
$v\{A, C\} - v\{C\} \geq v\{A, B, C\} - v\{B, C\}$	A	true
$v\{B, C\} - v\{B\} \geq v\{A, B, C\} - v\{A, B\}$	C	false
$v\{B, C\} - v\{C\} \geq v\{A, B, C\} - v\{A, C\}$	B	true

Not all convexity constraints are fulfilled, confirming the empty Core of the case. More specifically, sites A and B are only inclined to join a larger coalition if the smaller coalition is with C. In other cases the marginal cost increases with the coalition size. This is in line with the earlier findings of Table 26 that illustrate the largest cost reduction to be a result of a coalition between sites A and B, and the lower added value of site C.

If the Core is empty, there still exists a Nucleolus. In this case, it corresponds to the allocation that is the least unstable. It symbolises the point of least dissatisfaction. The Nucleolus of this case is added to the overview of allocation methods in Table

30. This solution coincides with the ESP and diverges from the Shapley values of the case. The Core is always accompanied by an epsilon value which indicates the tolerance allowed in the coalition stability constraints to come to a solution. The epsilon value of this case is equal to 9223.03 euro. Ideally, the epsilon value is as low as possible.

Table 30 Comparison of various cost allocation methods, continued.

cost allocation method	total cost site A [k euro]	total cost site B [k euro]	total cost site C [k euro]
individual (benchmark)	6 007.99	9 728.74	3 025.24
ESP	5 998.77 (-9.22)	9 719.52 (-9.22)	3 016.02 (-9.22)
Shapley	5 996.08 (-11.91)	9 718.02 (-10.72)	3 020.20 (-5.04)
Nucleolus	5 998.77 (-9.22)	9 719.52 (-9.22)	3 016.02 (-9.23)

To see if an alternative version of the GT analysis of the cluster would improve the stability of the grand coalition, the principles above are repeated for the part of the objective function that corresponds to the electrification. Table 19 details the electricity demand of each site before and after electrification. Recall that the load increase of sites A, B and C are respectively 66%, 40% and 15%. This leads to the following cost calculation for site i :

$$\frac{\%_{\text{electrification}}}{1 + \%_{\text{electrification}}} \left(\sum_t \sum_i ((T_{\text{grid}} + C_{\text{grid},t}) \cdot E_{\text{grid},i,t} + T_{\text{shared}} \cdot E_{\text{fromcluster},i,t}) \right) \quad (14)$$

Table 31 shows the results of the cost calculation for all possible coalitions.

Table 32 compares the total costs for each coalition of at least two sites to the sum of its individual costs. Contrary to Table 26, the largest cost reduction does not correspond to the grand coalition but to sub-coalition {A, B}, reconfirming its importance over collaborating with site C bilaterally or in a grand coalition.

Table 31 Alternative cost calculation for each possible coalition in scenario V_3_col.

coalition	cost [k euro]
{A}	2 043.95
{B}	2 526.51
{C}	385.41
{A, B}	4 551.15
{A, C}	2 424.81
{B, C}	2 908.65
{A, B, C}	4 940.89

Table 32 Alternative cost comparison between the coalitions and the sum of individual costs of the members for scenario V3_col.

coalition	coalition cost [k euro]	sum of individual costs [k euro]	savings [k euro]
{A, B}	4 551.15	4 570.45	19.30
{A, C}	2 424.81	2 429.36	4.55
{B, C}	2 908.65	2 911.92	3.27
{A, B, C}	4 940.89	4 955.86	14.98

Table 33 again compares various cost allocation methods for the case with partial costs. Comparing the Shapley values to the ESP, sites A and B increase their share of benefits at the cost of site C which now experiences a disadvantage in joining the grand coalition. In fact, according to the Shapley values, site C is a burden to the grand coalition and a fair allocation method would require site C to compensate the other two sites. Unfortunately, the Core is again empty, meaning there is no possible stable cost allocation for the grand coalition. The Nucleolus, however, is more balanced over the sites compared to the Shapley value with an epsilon value equal to 5855.43 euro.

Table 33 Comparison of various cost allocation methods for scenario V3_col with alternative cost calculation.

cost allocation method	total cost site A [k euro]	total cost site B [k euro]	total cost site C [k euro]
individual (benchmark)	2 043.95	2 526.51	385.41
ESP	2 038.95 (-4.99)	2 521.51 (-4.99)	380.42 (-4.99)
Shapley	2 036.07 (-7.88)	2 519.27 (-7.24)	385.55 (+0.14)
Nucleolus	2 038.09 (-5.86)	2 521.29 (-5.22)	381.51 (-3.91)

Already put forward by Churkin *et al.*, many real-world applications, especially in the field of transmission expansion planning, tend to be nonconvex and lead to allocations that can never satisfy all members of the grand coalition [250]. According to the authors, the nonconvexity is related to the high dependency on the parameters defining the system and the interconnection topology.

GT principles have shown that the case under investigation here has a fair way to allocate the costs in the grand coalition, but that this solution is not at all stable. In fact, no stable solution exists for this case in particular and the grand coalition is likely to fall apart into sub-coalitions. The Nucleolus in this case corresponds to the least unstable allocation of costs. One could question the importance of stability over fairness, especially since the latter is not explicitly present in the LESTS survey outcomes, contrary to fairness. In the end, coalition formation requires trust between the parties, among other social effects that come into play. Such organisational dynamics can be the driver to prefer a grand coalition over sub-coalitions, despite the instability.

5.5 CONCLUSIONS

To investigate the potential of RE sharing in a cluster, this chapter runs through the first three steps of the IS life cycle. While the synergy was already identified long before by the EPOS and AIDRES projects, the LESTS assessment in this thesis gives a deeper view of the enablers and barriers to implementation. Conclusions from the survey are used in the barrier removal step, which consists of a MILP optimisation

model combined with GT principles to validate the added value of RE sharing in a cluster and to illustrate how to approach the benefit distribution in a fair and in a stable manner.

Literature on similar studies was consulted to develop the methodology described in this work and to outline the research gap it should tackle. Electrification of industry and grid congestion were, up until now, underrepresented in such studies, despite their significant influence nowadays on the energy system. The case study of a fictitious industry park that is planning to increase its electrical load was solved for six different scenarios, altering the constraints on RE capacity and grid connection availability to mimic grid congestion. Results from the MILP optimisation confirm the positive incentives to collaborate, highlighting collective and individual benefits. GT principles that allow users to find fair and stable outcomes for the coalition unfortunately confirmed the nonconvexity of the case. Hence, the Shapley values, corresponding to a fair allocation method, and the Nucleolus, corresponding to a stable allocation method, do not coincide with each other and the grand coalition is likely to fall apart. The Nucleolus for the above cases corresponds to the least unstable cost allocation. Authors in the literature review warned beforehand that cases based on real-life situations, e.g. energy system operations, frequently lead to nonconvex solutions because of the network constraints and parameter dependency.

Future work on this case study comprises more sensitivities, e.g. in terms of cost parameters (TIC RE, tariffs, price of electricity), weather years and the availability of onsite RE. The methodology is developed in a general manner with an adaptable superstructure to accommodate other case studies with different sets of industrial sites and profiles and the application to a real-life cluster. The case study presented here consists of three sites, and adding more sites to the coalition will increase the calculation time of the MILP optimisation model. Also the computational burden of the Shapley values and Nucleolus strongly increase when more players are added to the game. Luckily, the `pyCoopGame` python module of Lechtenberg *et al.* offers a user-friendly toolset to facilitate GT application in modelling exercises [85].

This work limits the modelling scope to exclusively investigate the RE sharing synergy. When expanding the RE sharing optimisation model, the first element to add should be the option for SES. Also presented as an IS opportunity in Chapter 2, mutualising a battery installation or coordinating the operation of multiple batteries on a cluster level is worthwhile to investigate. Installing a portfolio of PV, wind and storage assets is also in line with the current hybridisation trend of RE projects. Second element to add should be the option for demand-side response by the industry sites through load shifting and demand flexibility. Together, both SES and DSR measures improve the self-utilisation of RE within the cluster and allow the

sites to optimally benefit from low electricity prices. Including both elements not only affects the optimisation model, but also strongly redefines the synergy under investigation.

As a second area of improvement, the model would benefit from a deeper integration within the power grid to account for local grid topologies and respective power flows. Alternative scenarios could encompass leveraging non-firm grid connections which are currently used to free up hosting capacity. Contrary to firm grid connections, such connections no longer have a fixed power level up until energy can be withdrawn or injected and capacity limits are dynamic [272]. The current model framework does not include PPAs or any subsidies on the procurement of RE by industry. Recent findings from the EU study on industrial energy prices and costs confirm the strong interest of EIs in PPAs to hedge prices [267]. Future work should depart from the base assumption that each site buys electricity from the grid following the EPEX spot market and study the effect of PPAs on the synergy.

Lastly, future work on this synergy should explore the second category within GT: non-cooperative games. Recall that in this type of games the players set out their individual strategies as a reaction to the strategies selected by the others, or the game is designed in a leader-followers framework [244]. Contrary to cooperative game theory, the grand coalition is not assumed to be formed. This approach to RE sharing gives a different perspective on how the synergy could be managed to support the coalition management later in the IS life cycle.

An overview of the contributions of this dissertation to the research field are summarised in Table 34.

CHAPTER 6 GENERAL CONCLUSIONS

Given the current industrial context, characterised by uncertainties and a high pressure to remain competitive, Europe is revising its strategy. While the climate neutrality ambition remains a central pillar and key target to reach by 2050, the focus has shifted towards securing a more sustainable, reliable and affordable supply of clean energy and resources. The industry sector, especially the energy-intensive process industry, is strongly intertwined with the energy system. This interdependency is once again made clear by the current energy crisis due to conflicts in the Middle East, shortly following the crisis of 2022. The resulting price shocks deeply impact industrial operations.

Both the industry and energy transition towards climate neutrality are challenging on their own. However, given the strong linkage, both transitions require mutual coordination in order to succeed and maximise system value. The economic downturn of industry as a result of the high, currently surging, energy prices leads to deferred investment decisions on clean technologies and process modifications. This, in turn, results in postponing infrastructure developments in the power, hydrogen, CCUS, etc. supply chains, leaving industry and the energy system stranded in a chicken-and-egg situation. Necessary but capital-intensive network developments to prepare for the future—yet uncertain—industry needs, might be delayed without guaranteed demand. Conversely, if networks are not adequate at times when industry needs them, investments in cleaner processes can no longer be pursued.

As a central topic of the present work, industrial clusters (ICs) are put forward as a means to break the deadlock between the industry and energy transitions. Energy-intensive sectors such as steel, chemicals, refineries, cement, glass, etc. tend to co-locate, resulting in an industry-dense area operating an extensive web of material and energy flows and services. In line with the energy hub concept, ICs typically correspond to large demand centres in the energy system and function as coupling points between various energy carriers. This highlights their strategic significance. Hence, it makes sense to concentrate efforts on clusters, especially when industrial symbiosis (IS) cases are applied to enhance the transition towards climate and resource neutrality. Synergies are not only beneficial to the industrial stakeholders

but also to the energy system as a whole. They enhance energy and resource efficiency.

ICs provide a specific answer to Draghi's call to action for a joint plan forward without compromising industrial competitiveness. Published in September 2024, his report formulated a response to the, by now annually recurring, Antwerp Declarations where EU industries meet to voice their concerns on policy measures and global trends. According to Draghi, clustering can boost the uptake of local renewable energy and improve the business case of necessary infrastructure developments in support of EU industry and policy [1].

With the potential of industrial clusters and energy synergies increasingly recognised by both policy and decision makers, it is still unknown how and if this potential will ever be reached, nor how scalable and replicable the benefits will be. The central objective of this PhD is to explore the role of industrial clusters in the energy system, in support of the energy transition towards climate neutrality. It addresses some of the research gaps on IC research and strengthens the link with the energy system.

The present work is organised around two main research questions.

The first research question is purpose-driven and investigates the role ICs play in the energy system and how cluster dynamics transform over the coming decades. Work in this thesis enters the field of energy system modelling. A literature review to explore the research state-of-the-art uncovers the opportunity to improve industry representation in Energy System Models (ESMs) by means of clustering, both in terms of spatial and technical granularity. To facilitate this, a novel framework called the Industry-Infrastructure Quadrant (IIQ) is introduced in Chapter 3. This framework has been developed in the course of this PhD to qualitatively analyse the presence of both industry and energy infrastructure in a region. The IIQ consists of five distinct categories: cluster potential, infrastructure corridor, interconnection corridor, remote activities and out of scope for this work (no industry nor infrastructure present). A complementary node selection procedure, solely relying on open-source data and tools, is developed and is directly applied in multi-node ESMs to continue the study on cluster potential areas. This work proposes cluster-aligned nodes in multi-node ESMs to improve the spatial granularity, giving priority to demand-side heterogeneity in the system. This complements the extensive amount of research

that already went into supply-side, more precisely renewable energy, heterogeneity. To enhance the technical details behind industrial demand assumptions in ESMs, the AIDRES database [52] is leveraged to extract information from industry blueprints to create cluster-level transition pathways. Often, such demand assumptions are over-simplified or not convenient to alter. The AIDRES database offers a rich source of information, containing per-ton energy data on a vast array of production routes. This work aggregates the demand projections of various sectors to the cluster-level, proposing a more flexible and transparent alternative to the default assumptions.

Both the IIQ and the cluster-level transition pathways are tools that advance industry representation in ESMs and are proven to be useful for strategic energy planning. Governments and network operators rely on such models to take well-informed decisions about infrastructure investments based on future demand projections. Aligning ESMs with ICs creates more transparency in harmonising high-level EU ambition with local intra-cluster and inter-cluster needs.

Chapter 4 aims to illustrate the added value of both concepts and describes their integration in the open-source, sector-coupled ESM PyPSA-Eur [216]. An extension is developed, directly interacting with the workflow of the model, and is made open source again. Hence, this PhD contributes to the ESM community. As an example, the updated model is applied to a subset of three EU countries with a large presence of ICs: Belgium, the Netherlands and Germany. Chapter 4 contains the step-by-step procedure to identify the clusters, select the nodes and create the regions in the model and replace the original industry demand assumptions. For the latter, the RES2Go tool is leveraged to create the cluster-level transition pathways of interest [168]. A comparison of energy system developments with the original and updated industry assumptions confirms the influence of ICs and their transition on infrastructure requirements.

The second research question is means-driven. It looks at synergies and how exchanges and mutualisation have the potential to advance energy system integration to support industry clustering and optimise business and system value. Chapter 2 contains an updated overview of (potential) energy synergies in ICs in line with Draghi's recommendations. The work departs from the IS case-base from Mendez Alva [2] and enriches it with synergies involving mid- and high-TRL technologies that emerged after completion of the AIDRES project [58]. A brief reflection is made on the renewable energy landscape in Europe and the presence of ICs to assess the scalability of energy synergies. In addition, cluster-related policy

measures in other regions are compared to benchmark the European IC approach with the rest of the world.

To illustrate an effective use of the IS tools developed by ECM UGent in the past, one of the presented synergies in Chapter 2, renewables sharing, is explored in more detail in Chapter 5. The research plan follows the first three stages of the IS life cycle of Maqbool [47] and includes an exemplary LESTS survey to deepen our understanding of the drivers and barriers to collaboration. Afterwards, the theoretical framework is converted into a mixed-integer linear programming optimisation model combined with game theory (GT) principles to verify the fairness and stability of RE sharing. A case study on a fictitious IC aims to illustrate the methodology and nicely shows the added value of the GT layer to understand the individual benefits of each site in the synergy. Especially the LESTS survey deserves special attention. Such a multidisciplinary approach is crucial to correctly assess the feasibility of industrial symbiosis.

The contributions of this dissertation to the research field are summarised in Table 34.

In terms of future work, the remainder of this conclusions chapter suggests some research leads that directly depart from this dissertation. It is by no means an exhaustive, nor a definitive list. This is especially the case in the field of ESM which continuously advances to tackle existing or emerging challenges to the energy system. Future research should continue to improve industry representation, moving towards energy and material system models that truly capture the importance of industry and the implications of its distress. The extension to PyPSA-Eur developed in this work should expand its scope of industrial processes and include less energy-intensive sectors to improve its coverage.

Generally, this work centralised the most energy- and resource-intensive industry sectors to cover a significant share of energy demand and emissions and account for the largest drivers behind energy system developments. However, following the lead of Mendez Alva [2], the scope should be extended to include nearby cities to further enrich the list of synergy opportunities with urban-industrial symbiosis cases. Future work should also keep track of the technology readiness levels of upcoming clean technologies, such as small modular nuclear reactors, as they might offer new ways to collaborate within ICs in the future.

With respect to the IIQ, only two regions were further investigated in this work. Future studies could investigate the importance of transmission and interconnection corridors and how to support remote industries.

The power network in PyPSA-Eur covers the complete ENTSO-E territory [214], which would allow the extension to include all EU industrial clusters identified by Mendez Alva *et al.* [39]. Future work could move beyond the subset of EU industry-densest countries: Belgium, the Netherlands and Germany, investigated in this work. Chapter 2 illustrated the global interest in ICs. Hence, case studies should not be limited to European clusters. Chapter 4 successfully illustrated how ICs can be leveraged in an ESM to study cluster level transition pathways and respective implications for the energy system. This work used PyPSA-Eur as an example, but replication to other models is possible.

Future work could also deepen the time resolution aspect. In most ESMs, industrial energy demand is assumed as baseload. Future work could improve the industrial load profiles and the complementarity with local, variable RE resources.

Most interesting would be a soft-coupling between the RES2Go tool [168] and the PyPSA-Eur energy system model. Such an endeavour would require more far-reaching changes in the main workflow of the model but would allow clusters to diverge in terms of transition pathways to allow for geospatial distinctions that are system-optimal.

Going one level down from the larger energy system to the cluster level, more simulation-based research, total site analyses and case studies entailing all sorts of ICs are necessary to valorise the potential of IS. The MILP optimisation model described in Chapter 5 should be further developed to include options for demand flexibility and shared energy storage. With respect to the power grid, a deeper integration would account for grid topology and power flows and could explore the effects of non-firm grid connections on the transition in a cluster and the implementation of energy sharing synergies. Also an improved temporal detail at the level of the power grid would be beneficial, e.g. on available grid capacities and the flexibility potential of supply, demand and storage assets.

It can be concluded that ICs have significant untapped potential to become more integrated intra-cluster, as well as with the local/regional energy system. The findings of this dissertation underpin Draghi's recommendation. They illustrate how

industry clustering can advance Europe's path to climate neutrality while sustaining industry's competitiveness. The work improved the understanding of the leading role that ICs can play in sustainable energy systems and aims to inspire readers to pursue industry clustering in their work. It endorses the vision of various cluster-based initiatives like A.SPIRE, H4Cs and the WEF. The latter very recently published another report on transitioning industrial clusters and more precisely to promote shared energy infrastructure [273].

Clearly, the momentum is here and now to grasp the potential that industrial clusters offer. They have what it takes to reinvigorate industrial competitiveness while sustaining the climate goals in these uncertain times. Safeguarding the transition is crucial to reach climate neutrality and brings prosperity to society, now and in the coming decades.

Table 34 Overview of research contributions resulting from this dissertation.

Identified research gap	Contribution of this work	Added value
Techno-spatial representation of industry in energy system models	<p>Methodology to leverage the cluster algorithms in the node-selection procedure</p> <p>Integration of the AIDRES production routes database to define future energy demands</p>	<p>Contrary to the renewable energy potential, ESM still over-simplifies assumptions on industrial production and energy demand. The methodology presented in Chapter 3 is based on open-source data and applicable to any ESM with a user-defined node selection.</p>
Assumptions on industry in PyPSA-Eur	<p>Extension which interacts with PyPSA-Eur to align the node selection with the identified industrial clusters and updates industrial energy demand assumptions</p>	<p>Application of the general methodology of Chapter 3 to the PyPSA-Eur model improved the transparency of industrial energy demand assumptions. It offers a systemic approach in function of industrial clusters contrary to generalising trends which lose touch with the local context.</p>
Renewable energy sharing in an electrification context with grid congestion	<p>Explores the use of MILP optimisation combined with cooperative game theory principles to a range of renewable energy sharing scenarios</p>	<p>Complements the IS life cycle framework by confirming/disproving barriers and enablers to the synergy and verifying the fairness and stability of the coalition.</p>

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ANNEXES

APPENDIX 1 AUTHOR BIBLIOGRAPHY

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Publication I. Main author. Presenting author in international conference (extended abstracts).

Publication II. Second author. Main contribution to data collection and support on content discussion, analysis and review.

Publication III. Main author. Presenting author in international conference (extended abstracts).

Publication IV. Main author. Main contribution to data collection, conceptualisation, methodology development, discussion and final manuscript version and revision.

Publication V. Contributing author. Main contribution to data collection, support on content discussion, analysis and review.

Publication VI. Main author. Presenting author in international conference with proceedings.

Publication VII. Main author. Presenting author in international conference with proceedings.

Publication VIII. Main author. Main contribution to data collection, conceptualisation, methodology development, discussion and final manuscript version and revision.

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APPENDIX 2 DATASETS

Table 35 Overview of datasets and resources used per chapter.

Datasets / tools	Used in chapter	Geographical resolution	Source / organisation
E-PRTR	3	Europe	European Environment Agency [190]
ETS	3	Europe	European Commission [5]
AIDRES industry database	3, 4	Europe	AIDRES project [52]
AIDRES production routes database	3, 4	NA	AIDRES project [52]
Industrial symbiosis case base	2	NA	ECM UGent, Francisco Mendez Alva [2]
ENSPRESSO	2	Europe	European Joint Research Centre [163]
Hubs 4 Circularity industry hubs	2	Europe	A.SPIRE, Francisco Mendez Alva <i>et al.</i> [39]
Cluster policy overview	2	Global	IEA [169]
Backbone grid maps	3	Europe	ENTSO-E, ENTSO-G [195,197]
Hotmaps	4	Europe	Hotmaps project [219]
RES2Go	4	Europe	ECM UGent [168]
Renewables.ninja	5	Global	Imperial College London [259]

APPENDIX 3 CLUSTER-LEVEL TRANSITION PATHWAYS RESULTS

Table 36 Share of each resource in the total demand for energy and feedstock for all cluster transition scenarios.

Resource	Reference route	Electron route	Hydrogen route	CCS route
electricity	2%	87%	3%	3%
hydrogen	<<1%	<<1%	19%	<<1%
natural gas	13%		1%	18%
coal	10%			<<1%
cokes	1%			
biomass			18%	
crude oil	62%		58%	65%
naphtha	12%	13%		13%

Table 37 Total demand of a resource for each production route (except cokes), expressed in gigajoules per annum, per cluster transition scenario.

Scenario	Product	Electricity	Hydrogen	Natural gas	Coal	Biomass	Crude oil	Naphtha
reference route	steel	3.498.000			93.863.000			
	refinery	1.162.000		20.833.000			558.009.000	
	ammonia	3.952.000		53.827.000				
	nitric acid			9.100.000				
	urea	1.066.000		19.344.000				
	cracker	1.965.240						112.204.080
	PE	23.030	470	13.630				
	PEA	2.116.400		13.284.480				
	steel	76.002.000						
	refinery	493.269.000						
electron route	ammonia	72.257.000						
	nitric acid	12.978.000						
	urea	28.145.000						
	cracker	69.525.000						112.204.080
	PE	35.250	470					
	PEA	13.903.120						

APPENDIX 4 PYPSA-EUR EXTENSION

Link to Zenodo page: <https://doi.org/10.5281/zenodo.19511558>



Aerial view on wind turbines and Port of Antwerp in the far distance during sunrise.