



Industrial Symbiosis² Hubs 4 Circularity

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Abstract

In Task 2.1 “Identification, classification & analysis of key technologies” the aim is to enable a technology mapping for each hub. Therefore, the goal is a generic approach to facilitate the development of technology maps for identifying Industrial Symbiosis opportunities. The following aspects form the basis for developing the generic approach:

1. Industrial subsector-specific – Identification of the relevant main industrial processes of the industrial sub-sectors and estimation of according to input and output streams relevant for IS.
2. Technology-oriented – Identification of key technologies for maximising synergies will be identified, focusing on the technologies further developed within the project and represented by contributing technology providers. The technologies will be described, analysed, and classified in terms of their technical objective (e.g., electrification, electrolysis, green gases, CCU/CCS). To evaluate the technologies and their contribution to synergies, KPIs (e.g. TRL, useful life, efficiencies, specific CAPEX, and OPEX) will be defined and collected.

This deliverable focuses on presenting the generic approach and how it can be used to derive hub-specific technology maps. This includes a list of the necessary data which must be collected for each hub, to create the technology map. A timeline for data collection, which can subsequently occur within WP4, specifically Task 4.1, as well as for the creation of hub-specific technology maps, is also presented. To collect technology-specific data, particularly for the technologies developed, further developed or demonstrated within the project, a Technology Fact Sheet (TFS) was set up (see Appendix), which was sent to the technology providers. The evaluation of the TFSs will also take place within the framework of Task 4.1. To facilitate the creation of hub-specific technology maps, an initial literature review was conducted to identify relevant industrial processes and other potential key technologies, independent of the technologies already represented within the hubs. The results of the literature review are presented below.

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List of Abbreviations

Abbreviation	Definition
a	Year
AEL	Alkaline electrolysis
B	Exergy content
BF	Blast furnace
BOD	Biological Oxygen Demand
BOF	Basic Oxygen Furnace
CAPEX	Capital expenditures required for implementing a project or technology, crucial for financial planning and resource allocation.
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
d	day
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
g	gram
GWh	Gigawatt hours
h	Hour/Enthalpy
H4C	Hubs for circularity
I	Inhabitant
IEA	International Energy Agency
IS	Industrial symbiosis
IS2H4C	"From Industrial Symbiosis to Hubs for Circularity"
IURS	Industrial-Urban-Rural Symbiosis
K	Kelvin
kg	Kilogram
KPI	Key performance indicators
kWh	Kilowatt hours
l	Litre
m	Meter
mg	Milligram
MWh	Megawatt hours
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NG	Natural gas
NIPU	Non-Isocyanate Polyurethanes

OPEX	The operational expenditures associated with maintaining and running a project or technology, essential for assessing ongoing costs and financial sustainability
p	Pressure
Pa	Pascal
PE	Population Equivalent
PEMEL	Proton exchange membrane electrolysis
PFS	Process Fact Sheet
s	Entropy
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
t	ton
TFS	Technology Fact Sheet
TN	Total Nitrogen
TP	Total Phosphorus
TRL	Technology readiness level
TS	Total Solids
WP	Work package
θ	Temperature

1. Introduction

The mission of the project "From Industrial Symbiosis to Hubs for Circularity: IS2H4C" is to pave the way towards the development of Hubs for Circularity (H4C) based on the circularity and resilience requirements of existing and future industrial zones and their surrounding ecosystems. To achieve this mission, IS2H4C prioritizes resource efficiency, use of renewable energy, and waste prevention, and promotes Industrial-Urban-Rural Symbiosis (IURS) via reuse and recycling of unavoidable solid, liquid, and gas waste streams via deployment of innovative sustainable technologies and via systemic integration of existing and new infrastructure. Importantly, IS2H4C ensures societal and governmental engagement to Hubs for Circularity (H4C) via securing acceptance and trust among citizens based on clear communication, transparency, and inclusion, by proposing sustainable business and financial models, as well as respecting the planetary health boundaries. IS2H4C's biggest ambition is to become a reference for promoting H4C as Europe's future sustainable regional development model.

In Task 2.1 "Identification, classification & analysis of key technologies" the aim is to enable a technology mapping for each hub. Therefore, the goal is a generic approach to facilitate the development of technology maps for assessing Industrial Symbiosis (IS) opportunities. The following aspects form the basis for developing the generic approach:

- Industrial subsector-specific – Identification of the relevant main industrial processes of the industrial sub-sectors and estimation of according input and output streams relevant for IS.
- Technology-oriented – Identification of key technologies for maximising synergies will be identified, focusing on the technologies further developed within the project and represented by contributing technology providers. The technologies will be described, analysed, and classified in terms of their technical objective (e.g., electrification, electrolysis, green gases, CCU/CCS). To evaluate the technologies and their contribution to synergies, KPIs (e.g. TRL, useful life, efficiencies, specific CAPEX, and OPEX) will be defined and collected.

In this deliverable, the focus lies on presenting the generic approach and how it can be used to derive hub-specific technology maps. This includes a list of the necessary data which must be collected for each hub, to create the technology map. A timeline for data collection, which can subsequently occur within WP4, specifically Task 4.1, as well as for the creation of hub-specific technology maps, will also be presented. To collect technology-specific data, particularly for the technologies developed, further developed or demonstrated within the project, a Technology Fact Sheet (TFS) was created (see Appendix), which was sent to the technology providers. The evaluation of the TFSs will also take place within the framework of Task 4.1. To facilitate the creation of hub-specific technology maps, an initial literature review was conducted to identify relevant industrial processes and other potential key technologies independent of the technologies already represented within the hubs. The results of the literature review are presented below.

2. A subsector-specific, technology-oriented, generic approach for the development of a technology map for Industrial Symbiosis

As mentioned above the technology map adopts an industrial subsector-specific, technology-oriented, generic approach to assist the exploration of various hub structures. By being generic, this approach addresses concepts such as:

- **Flexibility:** The generic technology map should be adaptable to the specific hub context in which it is applied. Different hubs have varying industrial compositions, as well as different technology road maps for IS. The technology map needs to be flexible enough to efficiently deal with varying settings. For instance, the specific industrial sectors presented in a hub can significantly influence the applicability and effectiveness of certain technologies. The relevance of the resulting technology map depends on the availability of data for characterizing industrial in- and output streams as well as technologies for IS.

- **Intra- and cross-sectoral-synergy identification:** The generic approach also promotes the identification of potential synergies between different industry sectors. By analysing how different technologies can be applied in various sectors, the technology map can uncover opportunities for more effective and efficient industrial symbiosis networks. These synergies can lead to significant improvements in resource utilization, waste reduction, and energy efficiency.
- **Scalability and applicability:** The scalability and applicability of the key technologies is captured by two specific KPIs collected through the TFS. These are, the technology readiness level (TRL) and the applicability by industrial sub-sector. Hereby, the applicability aims to reflect whether a technology is relevant to several sub-sectors.

Figure 1 illustrates the concept of the proposed generic approach which is described in detail in the following sections. All relevant and available results and data that have been or will be determined as part of the literature research and hub analyses in Task 2.1 and 4.1 will be processed to develop a generic technology map in order to make it available for future research activities. Therefore, the generic technology map will be updated within the ongoing research in WP4 as a basis for modelling, simulation and/or optimisation steps.

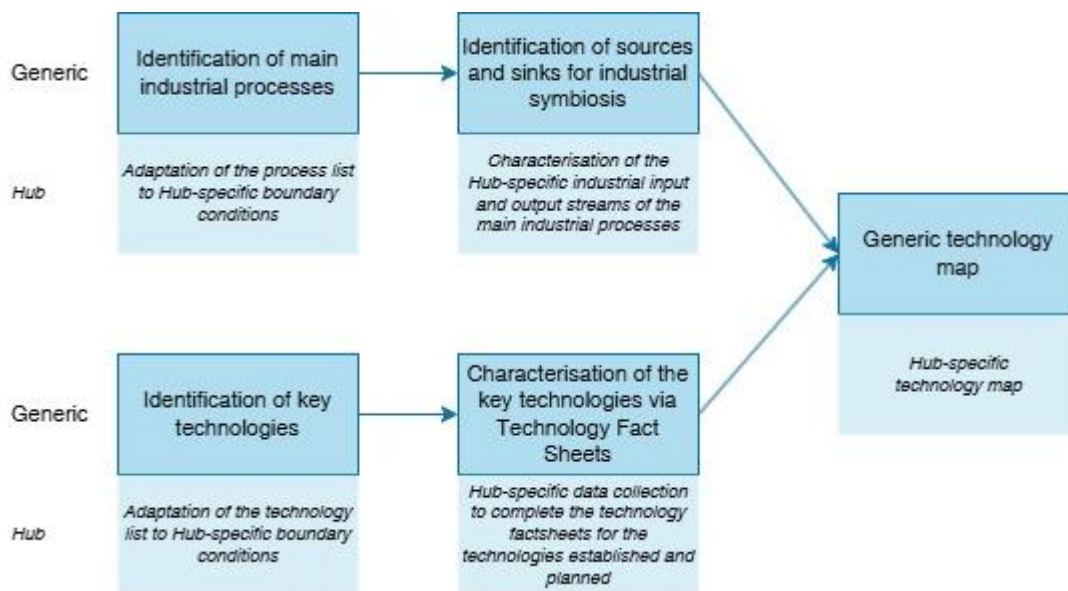


Figure 1: Industrial subsector-specific, technology-oriented approach for developing a technology map for industrial symbiosis

2.1 Industrial subsectors

The basis for analysing the structure of a given industrial sector is represented through a set of three interlinking classifications (Figure 2) [1]:

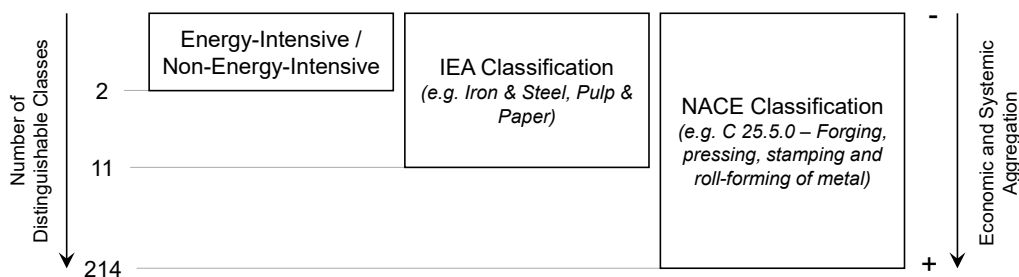


Figure 2: Level of detail and aggregation in the context of industrial classification schemes [1]

1. **Energy-intensive / non-energy-intensive subsectors:** This definition states two groups regarding the subsectors' respective energy consumption. The allocation of subsectors into these two groups varies depending on legislators, institutions and countries [2].
2. **IEA (International Energy Agency) classification [2]:** The IEA constitutes individual industrial subsectors based on their produced goods. These subsectors can be allocated to energy-intensive and non-energy-intensive groups from above. Table 3 lists the subsectors defined by the IEA including a classification by energy intensity.
3. **NACE (Nomenclature statistique des activités économiques dans la Communauté européenne) classification [3]:** Regarding the economic classification, the European Commission further utilises NACE codes within a graduated system. The first level describes the economic units themselves. Here, the class "C - Manufacturing" equals the industrial sector in its entirety. NACE codes including two digits are aligned with the aggregation level of the IEA classification, e.g. "C 24 – Manufacture of basic metals" and iron & steel. Two additional lower aggregation levels state more detailed classifications, e.g. NACE-3 class "C 24.4 – Manufacture of basic precious and other non-ferrous metals" and NACE-4 class "C 24.4.2 – Aluminum production".

All three classification schemes can be interlinked with each other and describe the structure of the industrial sector via different aggregation levels. Within Task 2.1 the IEA-classification [2] considering the energy intensity of the subsectors will build the basis for further investigations. At the present project stage, the focus is on analyzing a given industrial sector with its subsectors and main processes. If needed, this approach can be extended to allow the integration of parts of the transport and/or residential/commercial sectors into the technology map as additional sources or sinks.

Table 3: Industrial subsectors according to the IEA (International Energy Agency) classification [2]

Industrial subsectors	
Energy-intensive subsectors	Non-energy-intensive subsectors
<ul style="list-style-type: none"> • Iron and steel • Paper, pulp and print • Chemical and petrochemical • Non-metallic minerals • Non-ferrous metals 	<ul style="list-style-type: none"> • Wood and wood products • Machinery • Food and tobacco • Mining and quarrying • Construction • Textile and leather • Transport equipment • Non-specified

2.2 Methodology for the Identification of main industrial processes

Due to the high heterogeneity of the industrial sectors, the classifications of the industrial subsectors is applied to support the development of a holistic methodology for the identification of main industrial processes to derive relevant input- and output-streams for industrial symbiosis.

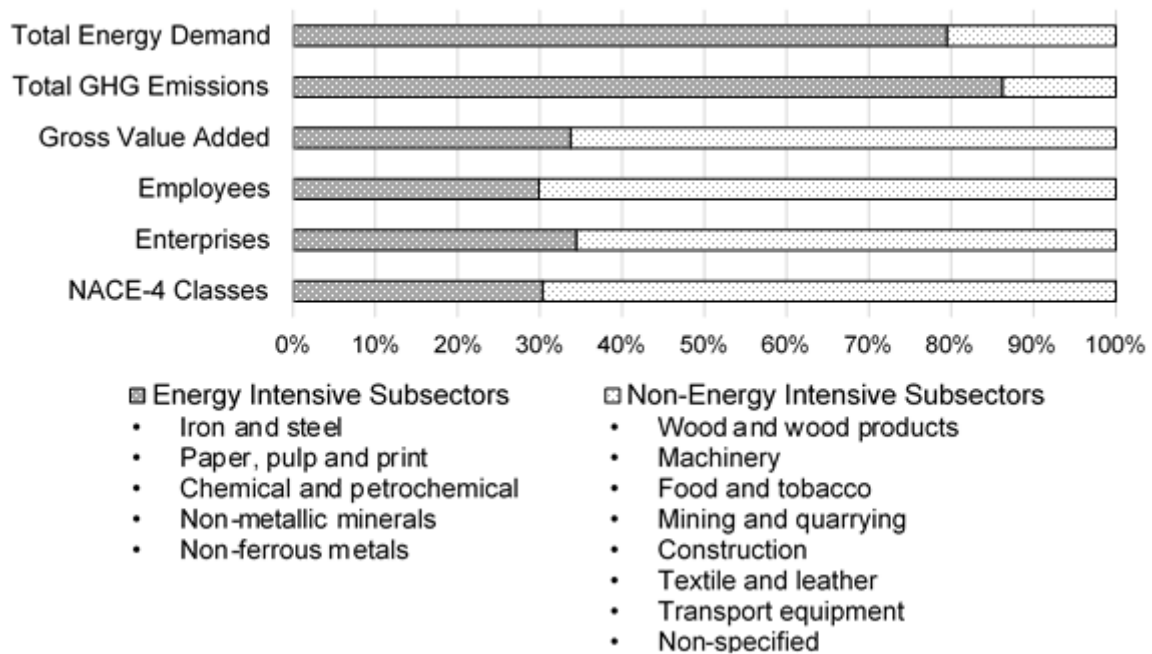


Figure 3: Comparison of energy-intensive and non-energy-intensive subsectors in regard to total energy demand, total greenhouse gas (GHG) emissions, gross value added, number of employees, number of enterprises and number of NACE-4 classes in Europe [1]

Figure 3 presents the comparison between the two subsector groups and the corresponding allocation of IEA subsectors. All parameters compared originate from European Commission (Eurostat) sources [4]. It is evident that the energy-intensive sub-sectors account for a much higher proportion of total energy consumption and greenhouse gas emissions than the non-energy-intensive sub-sectors. However, this trend does not hold for gross value added, number of employees, enterprises, and number of NACE-4 classes. These findings justify the need for distinct methodological approaches for representing energy-intensive and non-energy-intensive subsectors.

The limited variety of products and production processes in energy-intensive subsectors, indicated by the low number of NACE-4 classes, indicates the development of bottom-up methods. The advantage of this approach lies in a more detailed modelling at low aggregation levels (e.g., process level). Data and information on individual processes, especially for energy-intensive production routes, show a higher availability in literature or from dedicated research projects (e.g., time-resolved modelling of individual industrial plants). This also supports the application of bottom-up methods.

For non-energy-intensive industrial subsectors, where process-specific data availability is rather limited, top-down methods may be more advantageous. Here, highly aggregated data from industrial surveys and databases can be used to examine correlations, from which conclusions for individual industrial plants can be drawn. Based on these conclusions, for example time-resolved waste heat potentials may be generated stochastically.

Despite the methodological approach, the granularity of the industrial subsector analysis varies in accordance with the depicted systemic aggregation level, influencing the level of detail by analyzing the main industrial processes and their input- and output-streams. Standardized aggregation levels in industry are process, manufacturing, plant and subsector levels (see Figure 4; adopted by [1] based on [4]). Between these levels, energy can be generated, converted or consumed as a function of the selected level. Figure 4 also illustrates the implications of bottom-up and top-down methods within this system. The prominent touch point of the two selected approaches lies at plant level, therefore the main goal is to provide data for the characterization of the input- and output-streams of industrial subsectors at least on the plant level. If possible, data will be provided in more detail on manufacturing or process

level. Based on the bottom-up approach, a list of the identified main industrial processes of the energy-intensive subsectors is presented in chapter 5.1.

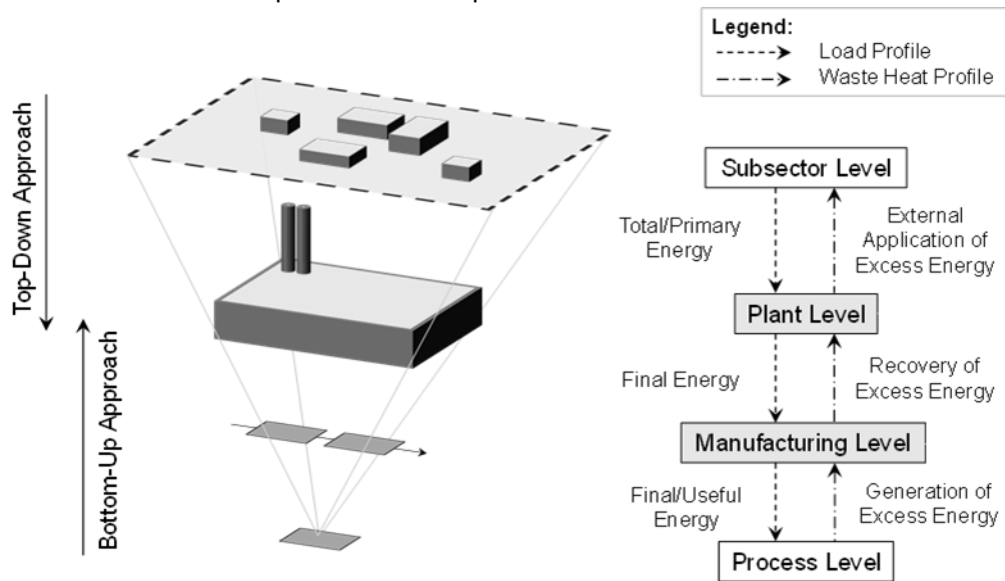


Figure 4: Systemic aggregation levels of the industrial sector including applied methodological approaches [adopted by [1] based on [4]]

2.3 Characterisation of industrial input & output streams: Identifying sources & sinks for IS

To ensure sufficient data quality for further modelling, simulation, and optimization tasks, the goal is to characterize the input and output streams of industrial processes (bottom-up approach) and sites (top-down approach) as detailed as possible according to the method explained above. Within the context of energy-intensive industrial subsectors, an analysis at the process or manufacturing level is planned. The list of data requirements, presented in Table 4, provides a basis for further data collection steps in cooperation with the hubs, the development of hub-specific technology maps, and additional literature research within the scope of Task 4.1 and 4.4 for generating subsector-specific synthetic load and waste heat profiles. The list does not claim to be exhaustive and can be adjusted as needed throughout the course of the project.

Table 4: List of parameters for characterising input and output streams to identify sources and sinks for IS

Classification	Parameter	Unit	Description/Comment
Energy and material stream	Type of stream	-	For defining an input flow following selection options are available: i) energy, ii) material or iii) others; for defining an output flow following selection options are available: i) Product, ii) By-product, iii) Waste, iv) Energy or v) others
	Flow rate (volume, mass)	m ³ /h, kg/h	Flow rate of the medium/material to be transported continuous / batch operation = typical / maximum flow rate of a process / device
	Pressure level/range	Pa	-
	Temperature level/range	K	-
	Flow continuity	-	Selection options: i) 100%, ii) 80%, iii) 60%, iv) 40%, v) 20% of runtime or vi) others
Energy streams	Energy form	-	Selection options: i) electric, ii) thermal, iii) chemical energy or iv) others
	Energy source	-	Selection options: i) coal, ii) oil, iii) natural gas, iv) biogas, v) hydrogen, vi) biomass, vii) biochar, viii) renewable electricity, ix) electricity, x) steam, xi) air, xii) water or xiii) other
	Energy consumption (thermal, electrical, chemical, others)	MWh	Average annual energy consumption of a process/device
	Energy density	kwh/m ³	Amount of electrical energy available per unit of either mass or volume
Material and waste streams	Composition	%	Description and percentage of the three main components of the stream
	State of aggregation	-	Selection options: i) Solid, ii) Liquid or iii) Gaseous
	Density	kg/m ³	The substance's mass per unit of volume
	Typ of waste	-	Selection options: i) Liquid waste (water), ii) Liquid waste (sludge), iii) Liquid waste (oil), iv) Solid waste, v) Organic waste, vi) Hazardous waste or vii) Other

2.4 Identification and Characterization of key technologies in the context of IS

The characterization and identification of key technologies are essential steps to create a comprehensive understanding of available technologies and their applications within industrial symbiosis networks. This process will be carried out at three distinct levels as shown in Table 5.

Table 5: Three Levels for the identification and characterisation of key technologies in the context of IS

Level	Description	Data gathering
Technology providers	Analysing the technologies further developed within the project and represented by contributing technology providers	Via Technology Fact Sheet, and discussions with the technology providers
Hubs	Analyzing existing and planned key technologies	Via existing hub flow sheets, interviews with the hub-leaders and hub-specific technology roadmaps or expansion plans (if available)
Broader search for potentially interesting technologies	Extending the search to a broader spectrum of potentially interesting technologies. These technologies may come from adjacent fields or represent novel approaches that can be adapted to the needs of industrial symbiosis.	Via literature research

Technology Fact Sheet inclusive relevant KPIs for the technology mapping

The Technology Fact Sheet (TFS) (see Appendix) was developed as part of Task 2.1 to systematically analyse the technologies being developed, enhanced, or demonstrated within the project. This fact sheet is used for gathering comprehensive data on various technological aspects, ensuring a structured approach for the technology assessment. Primarily, the TFS serves to collect detailed information about each technology's input and output streams. Thereby, the same parameters as listed in Table 2 are applied. In addition, the TFS can be used as data collection sheet at the two other levels of analysis. For example, at the hub level, the data in the TFS describes the specific technological landscape of each hub, including the identification of key technologies currently in use and their respective performance parameters. Moreover, the TFS can be an instrument for characterizing the input and output streams of the industrial processes. As the TFS encompasses all parameters in Table 2 it could also be handled as fact sheet to analyse single processes. To analyse industrial process routes and possible sinks and sources a further Process Fact Sheet (PFS) (see Appendix) was developed.

Additionally, the TFS captures process parameters and key performance indicators (KPIs) as outlined in Table 6. Furthermore, the TFS collects supplementary information, such as:

- Short technology description, graphical description and description of the technical function
- Technical objective (e.g., electrification, electrolysis, green gases, CCU/CCS)
- Potential fields of application and best practice application
- Subsector- and hub-specific applicability
- Relevant publications

Table 6: List of Process parameters and KPIs for Characterizing Key technologies

Classification	Parameter	Unit	Description/Comment
Process	Technical lifetime	a	The effective operational period of a technology in years, vital for assessing sustainability and viability.
	Process efficiency	%	The percentage of input effectively converted to desired output, essential for assessing technological performance and sustainability.
	Separation efficiency	%	The percentage of desired material successfully separated from a mixture, crucial for evaluating the performance and sustainability of separation technologies.
	Temperature level/range	K	The operational temperature span in Kelvin (K), critical for assessing the suitability and performance of a technology under different conditions.
	Pressure level/range	Pa	The operational pressure span in Pascals (Pa), crucial for assessing the suitability and performance of a technology under various conditions.
	Operation mode	-	The specified method or manner in which a technology functions or operates, defining its operational characteristics and capabilities
	Full-load hours	h/a	The total number of hours a technology or system operates at its maximum capacity or full load per year, indicating its annual utilization and efficiency.
	Warm start-up time	h	The time it takes, measured in hours (h), for a technology to reach operational readiness from a pre-warmed state.
	Cold start-up time	h	The time it takes, measured in hours (h), for a technology to become operational from a completely cold or inactive state.
KPIs	TRL	-	Metrics used to gauge the development progress and readiness of technologies across different TRL stages, helping evaluate performance and potential for deployment.
	CAPEX	€	Capital expenditures required for implementing a project or technology, crucial for financial planning and resource allocation.
	OPEX	€/a	The operational expenditures associated with maintaining and running a project or technology, essential for assessing ongoing costs and financial sustainability.

2.5 Technology mapping

To develop the generic technology map, the hub and literature data must be processed and integrated. An overview of the approach is shown in Figure 1. The detailed approach, organized into 6 steps, is described below.

Step 1: Identification of relevant industrial subsectors and related processes

The first task is to define the system boundaries of the potential IS network (e.g. an industrial park). For example, within the project, four H4C with clear system boundaries, defined within the proposal, represent the IS networks which should be analyzed in detail (see from Figure 6 to Figure 12). Subsequently, within these defined boundaries, the energy-intensive industrial subsectors and the related main process routes and specific processes are identified based on a process list. The process list (see from Table 25 to Table 28) is provided for the project and is based on literature research, industrial expert interviews and an analyze of the Austrian energy-intensive industrial sub-sectors. [1] Other relevant processes from non-energy-intensive subsectors can also be considered if datasets detailing the input and output streams of these processes are available. Otherwise, the non-energy-intensive subsectors are considered on plant level (see section 2.2).

Furthermore, other sectors can be integrated into the analysis, if they serve as potential sources or sinks in the context of IS. For example, the residential sector can act as a sink for waste heat via district heating systems, thereby contributing to the overall energy efficiency and sustainability of the industrial ecosystem.

Step 2: Classification of the output-streams and definition of the mapping criteria

Once the main processes have been identified, the output streams are characterized according to the parameters in Table 5. For this purpose, data is collected within the framework of the hubs (e.g. as part of WP4). Whenever data cannot be collected, literature data must enable a further procedure. An initial literature review has already been carried out (see Section 5.2). Further literature research is carried out within Task 4.1. In order to generate a transparent technology map, the output streams will be classified based on the five types of IS presented within the consortium meeting (February 2024). The five types are shortly described in Table 7.

The presented criteria have two main challenges are on the one hand the range of the mapping criteria within an output is considered, and on the other hand the identification of one significant mapping criteria for material- and water-based IS, due to the heterogeneity of waste and wastewater streams and respective treatment goals. Here, factors like organic content, energy density, dust load, hazardous components etc. can influence the usability of the source. However, in general, if the respective criteria are fulfilled, the output stream can be classified according to the respective type of IS and shows a potential for further utilization in the context of IS. For example, if a waste heat streams shows a high enough exergy ratio, the waste heat stream can be used in other processes or technologies, like heat pumps. However, it should be noted that only a preliminary estimation of the potential can be made at this stage. Only accurate measurements of the output flows allow the identification of the true potential of electricity for generation within the hubs.

Table 7: Five types of industrial symbiosis for classifying the output streams of main industrial processes

Class	Short explanation	Mapping criteria
Carbon-based IS	<p>Collaborative strategy among different industrial entities to use carbon resources (such as CO₂ emissions, organic waste, or other carbon-containing by-products) more efficiently and sustainably.</p> <p>Within the project we define a narrower scope for Carbon based IS focusing on carbon capture and utilisation (CCU).</p>	<p>Combined assessment of CO₂-concentration [%], CO₂ stream continuity [h], and CO₂'s stream origin</p>
Energy-based IS	<p>Energy cascade: This involves the use of waste energy (such as waste heat or steam) from one production process to another. The paper outlines different models of energy cascade based on business and technical dimensions, where energy can be directly used by another process or sent to an energy recovery unit first. [5]</p> <p>Fuel Replacement: Practice of using waste materials as alternative fuels in existing energy production processes. This approach aims to replace traditional fossil fuels (e.g., coal) with waste-derived fuels. It is possible to use the replacement fuel directly, or to have a treatment process, that does a processing step. [5]</p> <p>Bioenergy production: Generating energy from organic wastes, which can include agricultural, industrial, and urban waste materials. This type of synergy seeks to utilize biomass, such as animal manure, palm oil residues, and food waste, to produce bioenergy in the form of biogas, electricity, or heat. Bioenergy production can occur within a single company or through cooperation among multiple companies, forming a bioenergy production chain. [5]</p>	<p>Exergy content [%] or exergy ratio [-] [6]</p>
Material-based IS	<p>Exchange and reuse of waste materials between different industrial processes to reduce waste and enhance resource efficiency. In this context, waste materials from one process serve as inputs for another, creating a closed-loop system that minimizes the need for virgin raw materials [5]</p>	<p>Tbd, possible criteria: organic content [%], volume/mass flow [m³/h; kg/h]</p>
Water-based IS	<p>Shared use and recycling of water resources between different industrial processes to improve efficiency and sustainability. In this system, wastewater or surplus water from one process is treated and reused in another, reducing the overall demand for freshwater. [5]</p>	<p>Tbd, possible criterium: chemical oxygen demand [mg/l]</p>
Service-based IS	<p>Providing storage capacities in the form of electrical, thermal or chemical storage systems or storage areas. Sharing other services is not considered. [5]</p>	<p>Storage capacity</p>

Mapping Criteria for Carbon-based IS:

The selection of the most appropriate CO₂ capture technology for a given application depends on several factors, including [7] :

- Initial and final desired CO₂ concentration
- Flow rate and continuity of the gas stream
- CO₂-origin: biogenic, fossil, generic

Therefore, an assessment scheme for CO₂ streams is suggested to assess the usability potential of CO₂-streams within industrial symbiosis networks to reduce emissions and energy intensity. The assessment scheme for CO₂ streams involves evaluating the characteristics of various CO₂ emissions sources to determine their suitability for carbon capture and utilization (CCU) technologies. Key factors include the concentration of CO₂ in the stream, the stream continuity as well as the CO₂'s origin. Particularly CO₂ concentrations play a significant role because higher purities lead to lower separation efforts and thus lower separation costs [8, 9]. The CO₂'s origin significantly influences future Carbon Management (CM) Strategies. The CO₂ origin can be distinguished in fossil, biogenic and atmospheric CO₂, as well as CO₂ from waste incineration (mixture of fossil and biogenic carbon) [10]. The assessment approach illustrated in Table 8 may be validated with results of the modelling and optimization activities in WP4.

Table 8: Carbon-based is mapping criteria – assessment scheme for CO₂ streams

Assessment factor	Purity	Continuity	Origin
Weighting rate [%]	50%	25%	25%
High Usability potential	CO ₂ Concentration > 50% [7]	Availability > 6000 hours per year	Biogenic, geogenic
Low Usability potential	CO ₂ Concentration ≤ 50% [7]	Availability ≤ 6000 hours per year	Fossil

Mapping Criteria for Energy-based IS:

Exergy represents the maximum useful work obtainable from a system as it reaches equilibrium with its environment, effectively quantifying energy quality. In energy-based industrial symbiosis, exergy serves as a mapping criterion to assess the potential of energy streams for reuse or exchange between industrial processes and their urban surroundings. Unlike total energy, exergy accounts for both quantity and quality, making it ideal for identifying e.g. valuable heat potentials that can be transferred across facilities. High-exergy flows, often from high-temperature or high-quality waste streams, are prioritized for synergies, maximizing resource efficiency and minimizing energy loss. This exergy-based approach enables targeted matching of energy needs with available resources, fostering a sustainable, interconnected industrial ecosystem.

The exergy content B of a stream is calculated by summing up the embodied physical B_{ph} (deviation of pressure p and temperature ϑ from the environment p_0, ϑ_0), chemical B_{ch} (deviation of the chemical composition to the environment), kinetic B_{kin} (system velocity relative to the environment) and potential B_{pot} (system height relative to the environment) exergy, as shown by Equation 1. [11]

EQUATION 1:

$$B = B_{pot} + B_{kin} + B_{ch} + B_{ph}$$

While potential and kinetic energy are pure exergy, the chemical exergy can be approximated with the lower heating value. With Equation 2 the physical exergy of a mass m can be calculated by using the system enthalpy h and entropy s with p and ϑ compared to the ambient conditions. [11]

EQUATION 2:

$$B_{ph} = [(h - h_0) - (\vartheta_0 s - \vartheta_0 s_0)] \cdot m$$

Mapping Criteria for Material-based IS:

A potential assessment approach for designing mapping criteria in material-based industrial symbiosis involves evaluating material characteristics—such as composition, quality, and compatibility—to identify feasible exchanges between industrial processes. By assessing characteristics like contamination levels, recyclability, and handling requirements, the criteria prioritize materials with high reuse potential while minimizing environmental and safety risks. A scoring system may help evaluating each material’s symbiosis potential to facilitate optimal matches between waste streams and resource needs within industrial symbiosis hub. A suggestion for a scoring system is shown in Table 9. Hereby the preliminary suggested weighting rates can be adapted based on specific industrial goals. For example, if purity and recyclability are highly prioritized in the symbiosis network, these weights can be adjusted accordingly. The assessment scheme may provide a basis for further activities in WP 4.

Table 9: Material based is mapping criteria – assessment scheme for material streams

Characteristic	Description	Suggested weighting rates (%)
Composition & Purity	Determines material usability and compatibility in different processes.	30
Contamination Level	Assesses risk of contamination; important for safe handling and applicability.	20
Recyclability	Evaluates the ease of repurposing the material within other industrial processes.	15
Physical State	Solid, liquid, or gas; influences transport and storage requirements.	10
Energy Content	Measures embedded energy in material, supporting processes with energy needs.	10
Availability & Volume	Ensures material quantities align with demand for efficient symbiosis.	10
Environmental Impact	Considers material’s life-cycle impact, including toxicity and emissions, for sustainable practices.	5

Mapping Criteria for Water-based IS:

In Table 10 an assessment approach for designing a mapping criterion in water-based industrial symbiosis is summarized. The approach involves evaluating wastewater quality parameters, such as the Chemical Oxygen Demand (COD), the Biological Oxygen Demand (BOD), nitrogen, and phosphorus concentrations, to identify reuse or treatment opportunities between industrial facilities. The aim of the assessment scheme is to ensure safe and efficient water exchanges that align with treatment capabilities and environmental regulations. This targeted evaluation enables effective water reuse and promotes sustainable water resource management in industrial symbiosis networks. The assessment scheme may provide a basis for further activities in WP 4. Thereby, the weighting rates may be adjusted based on specific symbiosis objectives, such as prioritizing nutrient recovery or minimizing treatment costs.

Table 10: Water based IS mapping criteria – assessment scheme for water streams

Characteristic	Description	Suggested weighting rates (%)
Chemical Oxygen Demand (COD)	Measures the organic load; important for assessing treatment needs and compatibility.	20
Biological Oxygen Demand (BOD)	Indicates biodegradability; essential for determining reuse potential in biological processes.	20
Nitrogen Content	Assesses nutrient potential for reuse, such as in agricultural applications.	15
Phosphorus Content	Evaluates potential for nutrient recovery, supporting applications like fertilization.	15
Toxicity	Identifies harmful substances that may require specialized treatment before reuse.	15
Total Suspended Solids (TSS)	Measures particulate content, affecting suitability for filtration-based applications.	10
pH Level	Ensures compatibility with receiving processes, especially in industries sensitive to pH variations.	5

Mapping Criteria for Service-based IS:

By assessing storage system characteristics such as capacity, response time, efficiency, and compatibility with industrial processes are of importance, as shown in Table 11. The storage capacity (e.g., kWh or m³) determines the volume or energy amount the system can hold, while the response time reflects how quickly stored resources can be accessed or dispatched to meet demand. Efficiency considers energy losses during charging and discharging cycles for energy storage or leakage and degradation rates for material storage. Compatibility with various industrial demands, such as specific temperature or pressure requirements, is also crucial for smooth integration. By scoring or ranking these parameters, storage systems can be matched effectively to industrial requirements, enabling reliable energy and material exchanges and supporting efficient, resilient industrial symbiosis networks. The assessment scheme may provide a basis for further activities in WP 4.

Table 11: Service based is mapping criteria – assessment scheme for storage systems

Characteristic	Description	Suggested weighting rate (%)
Storage Capacity	Indicates the maximum volume or energy the system can store (e.g., kWh for energy, m ³ for materials).	30
Response Time	Measures how quickly the storage system can supply or withdraw resources to meet demand.	20
Efficiency	Assesses energy losses in charging/discharging cycles for energy or leakage rates for materials.	20
Scalability	Evaluates the system's potential for scaling to meet increasing demand.	10
Compatibility	Ensures alignment with specific industrial requirements, such as temperature, pressure, or purity.	10
Lifecycle & Maintenance	Considers the durability and maintenance needs of the storage system, impacting long-term reliability.	10

Step 3: Classification of the key technologies

Also, the technologies will be classified based on the five types of industrial symbiosis presented during the consortium meeting (see Table 12). The allocation is based on the output stream (classified in step 1) to be processed by the technology. For example, if the technology uses an output stream that is allocated to the energy-based IS, the technology is also allocated to this class. For example, a heat pump that is used to increase the temperature level of an industrial waste heat stream is classified as energy-based IS, as the waste heat stream is also classed into this category. The key technologies mapped are furthermore sorted according to their TRL. It is assumed that a higher TRL correlates with a higher integration potential.

Table 12: Five types of industrial symbiosis for classifying the key technologies

Class	Technology focus	Exemplary technologies	Mapping criteria
Carbon-based IS	Treatment of streams containing CO ₂	Pre-combustion CO ₂ capture or Oxyfuel combustion	CO ₂ -concentration [%]
Energy-based IS	Technologies facilitating energy cascades, fuel replacement or bioenergy production	High temperature heat pumps, gasification, pyrolysis	Exergy content [%] or exergy ratio [-] [6]
Material-based IS	Pre-treatment of waste streams for substituting a specific primary input	Infrared sorting or shredding	Tbd, possible criteria: organic content [%], volume/mass flow [m ³ /h; kg/h]
Water-based IS	Treatment of wastewater streams for resource recovery	Direct contact and vacuum membrane distillation	Tbd, possible criterium: chemical oxygen demand [mg/l]
Service-based IS	Storing electric, thermal or chemical energy	Batteries, boilers etc.	Storage capacity

To assess the key technologies regarding the integration potential into an industrial symbiosis hub, technical and economic factors may be considered. Key parameters are the Technology Readiness Level (TRL), which indicates the maturity of the technology, ensuring it is sufficiently developed for industrial applications. The net present value covers capital expenditure (CapEx), operational expenditure (OpEx), and potential savings or revenues from resource exchanges, establishing the economic feasibility of the technology. Scalability assesses the technology's capacity to meet future demand growth and efficiency is also considered. The assessment approach illustrated in Table 13 may be valeted with results of the modelling and optimization activities in WP4.

Table 13: Assessment scheme for key technologies

Assessment factor	TRL	Economic feasibility	Scalability	Efficiency
Weighting rate [%]	25%	25%	25%	25%
High Usability potential	TRL 8-9 (commercially ready, proven in industry)	Positive net present value regarding the period of use	Easily scalable, modular design	High efficiency, low losses
Low Usability potential	TRL 1-3 (basic research, experimental stage)	Negative net present value regarding the period of use	Limited scalability, complex to expand	Low efficiency, high losses

Step 4: Calculating the linking streams

The output streams of the linking key technologies, the linking streams, are determined based on the output stream of the industrial process (step 2) and the data of the TFSs or literature values (e.g. conversion factors) for the respective technology. Thereby, the output stream from the linking technology is considered in the context of the mapping criteria. For example, in the case of a heat pump, the exergy stream is determined after the temperature level has been raised.

Step 5: Identifying the sinks

The required input streams of relevant industrial processes of the energy-intensive subsectors, as well as other sectors considered (plant level), are also analysed on the basis of the mapping criteria (step 2) in order to be able to estimate the interchangeability with output streams from other industrial processes or from the linking key technologies investigated.

Step 6: Derivation of Hub-specific Technology Maps

By linking the sources directly via collection buses, or via linking key technologies, with sinks the Hub-specific technology maps can be derived. A generic illustration of the technology map is shown in Figure 5, the specific technology maps for the hubs are shown in the following sub chapter.

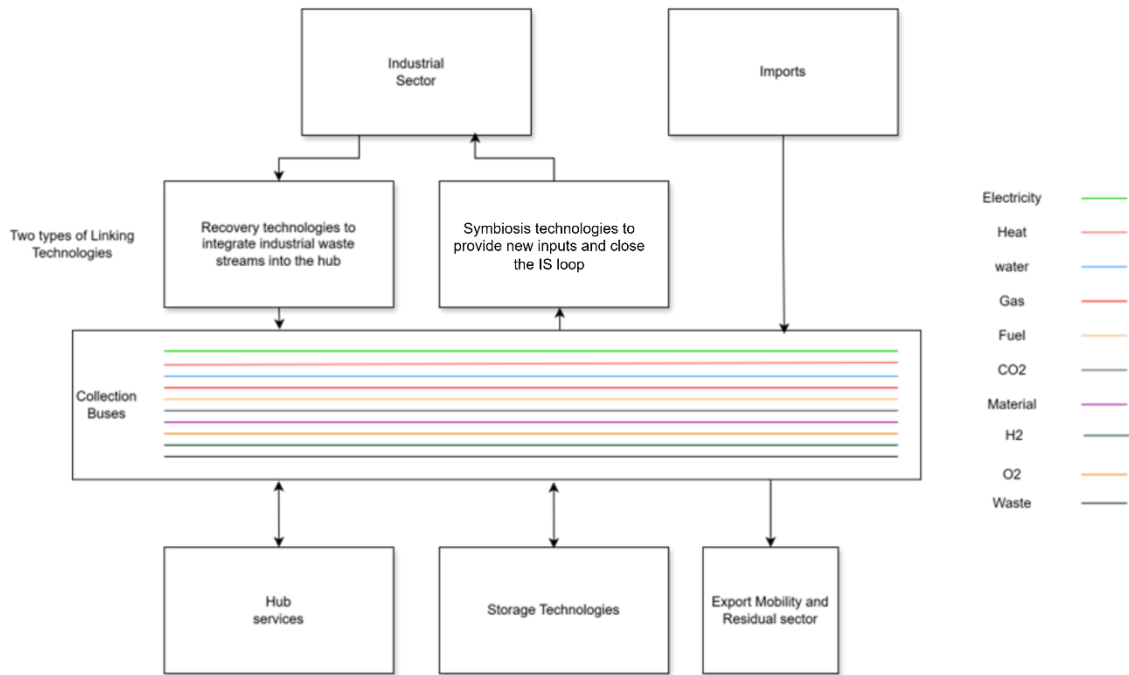


Figure 5: General hub map

The Generic illustration represents different components of the technology map that can enable industrial symbiosis. The industrial sector represents different types of industries and industrial processes, depending on the level of granularity of the data available. The classification of the industrial subsectors is described in detail in Section 2.1 and is used in the development of methodology for the identification of main industrial processes to derive relevant input- and output-streams for industrial symbiosis. Each hub involved within the project IS2H4C is unique, therefore, relevant industrial sector and stream are identified accordingly. Further, two types of linking technologies are defined for the purpose of fulfilling the necessary link between different process streams. Recovery technologies are used to recover, upgrade and process the available excess stream from relevant industrial process depending on the characteristics of the individual stream as classified in Step 2 of the technology mapping. Relevant technologies are classified according to Step 3 of the mapping criteria. These technologies are either already used for similar processes or have been tested to have the potential to be used. The symbiosis technologies are used to integrate the upgraded or available industrial streams to the relevant industrial processes. These technologies can potentially replace particular imports such as hydrogen or fuels for relevant industrial processes. Moreover, the collection buses are the central part of this technology map which represents all the important streams within the hub. They represent the central point of interaction between different components of the hub map. This also provides a general framework for implementing the energy and mass balance for all the relevant streams. This concept can also be used for the development of optimization model in WP4. Furthermore, Hub services represent the already existing infrastructure for energy production, waste processing, water treatment and building services as well as new technologies that can enable the utilization of the waste streams within these categories. Storage technologies can provide required flexibility and enable temporal balancing. Relevant storage technologies include electricity storage such as batteries, hydrogen storage and heat storage technologies. The export component is added to the map to represent the streams that cannot be fully utilized within the hub and is sold to the relevant user. This can include heat for district heating, fuels for mobility and residential sector etc.

3. Hub analyses

The results of the initial hub analyses are presented below. As part of the activities in WP4, data will be collected, exchanged with the project partners and communicated as well as discussed with the hub leaders. Based on the actual status quo of the data gathering process the main industrial sectors, hub specific output and input streams and relevant technologies which are already integrated or planned will be described. The system boundaries of each hub defined through the proposal phase is presented for each hub. Based on correspondence with the hub-coordinator, the technology map is an attempt to refine the existing flow sheets and propose synergies within the specific industrial hub.

3.1 H4C 1 – Izmir-Manisa – Turkish hub

Initial system boundaries

The system boundaries of the Turkish hub defined through the proposal phase are shown in Figure 6. This includes focus on key enabling technologies such as Electrolysis, CO₂ capture, E-methanol production and NIPU production.

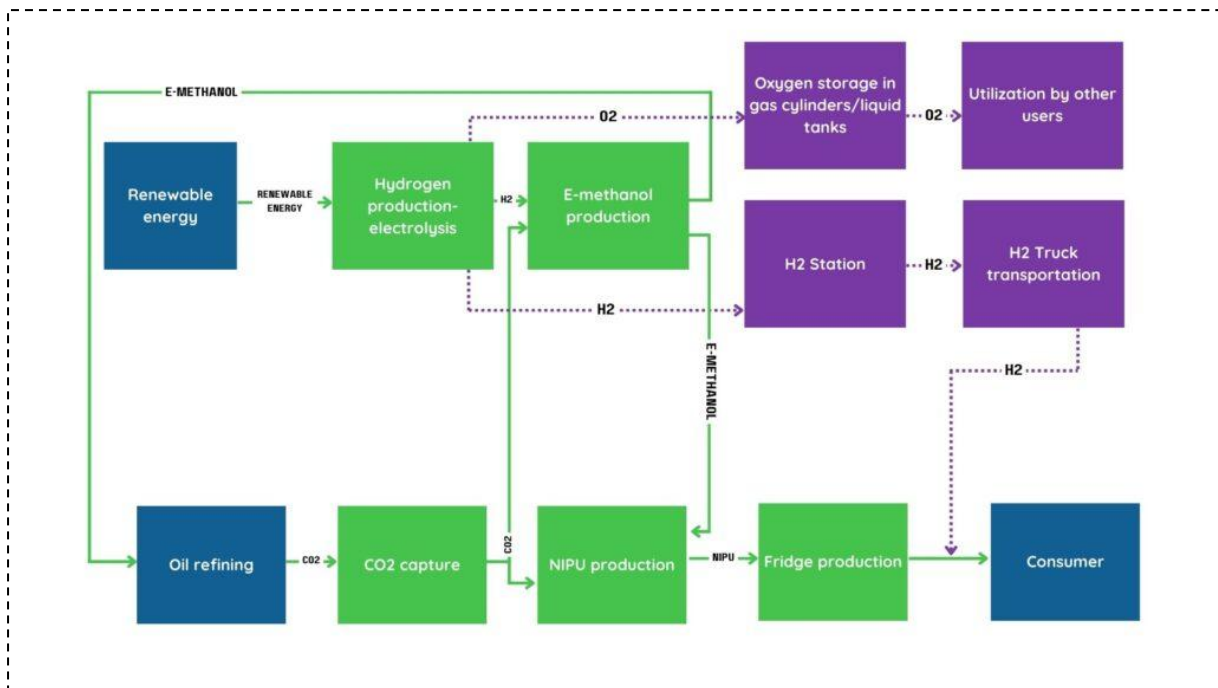


Figure 6: System Boundaries of the H4C 1 – IZMIR-MANISA – TURKISH HUB (magenta: synergies will be studied as hub expansion plan; [Home - IS2H4C PROJECT - GA. 101138473 \(is2h4c-project.eu\)](http://Home-IS2H4C-PROJECT-GA.101138473(is2h4c-project.eu)))

Following points will be relevant for the technology mapping:

- **Main subsector:** Energy (oil refining, renewable), Non-energy-intensive (Refrigerator Production)
- **Main technology focus:**
 - **Carbon Capture:** Capturing CO₂ emissions from oil refineries and utilizing them in various industrial processes.
 - **E-methanol Production:** Utilizing currently produced hydrogen to create e-methanol, which replaces traditional methanol in oil refineries.
 - **NIPU Production:** Using CO₂ from oil refineries in the production of Non-Isocyanate Polyurethane (NIPU) for fridge production, replacing traditional polyurethane.

- **Oxygen Storage:** Storing oxygen produced during hydrogen production for various industrial uses (feasibility study).
- **Hydrogen Fuel Stations:** Establishing hydrogen fuel stations and providing hydrogen trucks to consumers, promoting the use of hydrogen as a cleaner fuel alternative (feasibility study).

Hub specific technology map

Hub specific technology map for the Turkish hub is shown in Figure 7. As indicated in the initial system boundaries, the main industrial subsectors are petroleum and refrigerator production. Recovery technologies under different sub-categories include carbon capture technologies, energy recovery technologies, material waste and wastewater recovery technologies. Specific recovery technologies can be determined based on data collection via data collection instruments developed during task 2.1, i.e. PFS and TFS. According to the communication with the hub coordinator, the primary focus in the Turkish hub is the production of e-methanol and NIPU from oil refinery process emissions. The refinery process is not directly included within the defined hub boundaries.

For the carbon-based IS (Table 14), Steam Methane Reforming (SMR) flue gas is selected by Tupras as a CO₂ source because of its suitable CO₂ content and lower impurity levels. SMR is currently used to produce grey hydrogen for refinery processes such as hydrocracker reactors. There is also a plan to integrate green hydrogen production to reduce emissions. Depending on the project outcome, other CO₂ sources will also be evaluated for continuing e-methanol production once SMR is replaced. The appropriate recovery technology for Carbon base IS is indicated below:

Table 14: Carbon based IS recovery technologies

Industrial Sector	Source	CO ₂ Conc. [vol.%]	CCU Tech
Chemical & Petrochemical	Steam Reformer off gas	42.45	Chemical Absorption, Physical Absorption, Physical Adsorption

For Energy based IS (Table 15), waste heat recovery is possible for individual process streams provided that the process data is available. Based on the available data and literature research (see chapter 5.2), following can be determined for Energy based IS:

Table 15: Energy based IS recovery technologies

Industrial Sector	Source	Temperature level	Heat recovery technology
Chemical & Petrochemical	Steam Reformer off gas	High	Flat heat pipe, Rankine cycle, Regenerative/recuperative burner, Regenerator, Steam generator, Steam micro-turbine, Steam Rankine cycle, Stirling engine

Material based and Water based IS are not discussed in detail here since the specific relevant information has not yet been obtained. General description of these IS can be found in Literature section of this deliverable.

For the symbiosis technologies, E-methanol production, electrolyzes and NIPU technologies are of interest for the hub partners. In this context, the relevant data is collected via TFSs from the technology

providers as well as gathered via literature. Further, the hub services for the Turkish hub can include renewable energy production via solar and wind farms alongside providing remaining waste heat for heating purposes. Based on the required use, a hydrogen storage, methanol storage or an electrical storage can also be used for temporal balancing. An optimization study can determine which is more economical for the specific use-case. Additionally, oxygen and hydrogen produced can be exported for further use in other industrial and mobility sector.

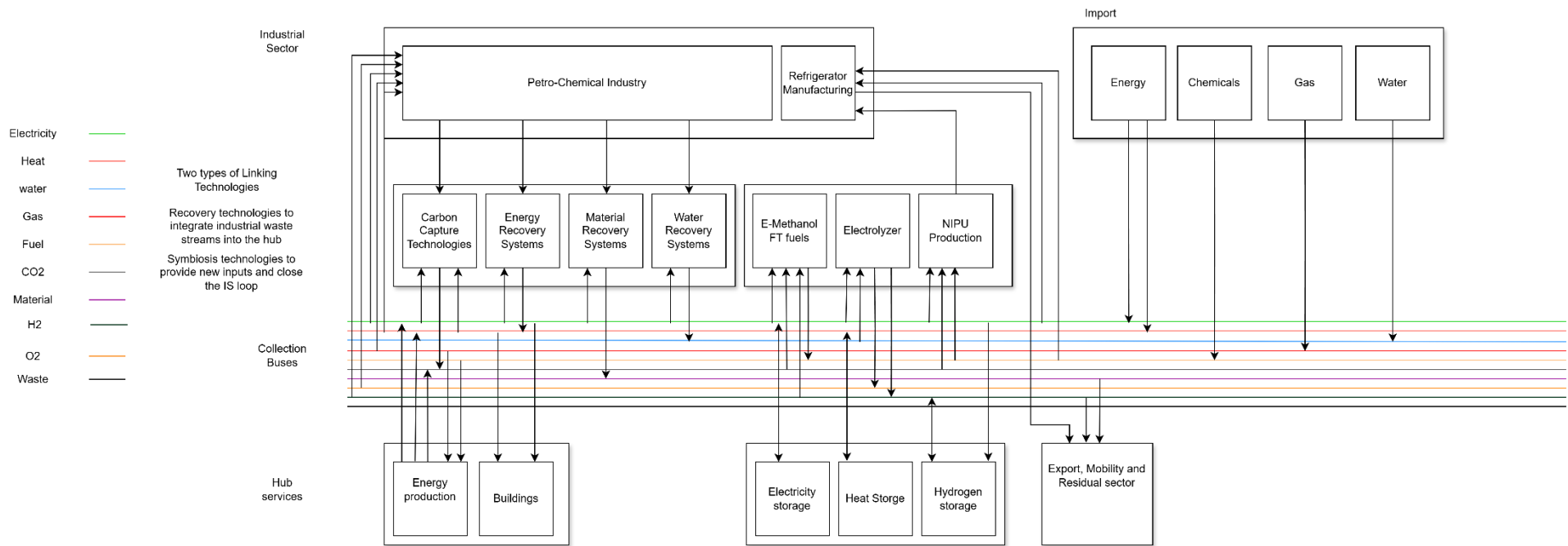


Figure 7: Turkish hub technology map

3.2 H4C 2 – Basque Industrial – Basque hub

The system boundaries of the hub are shown in Figure 8.

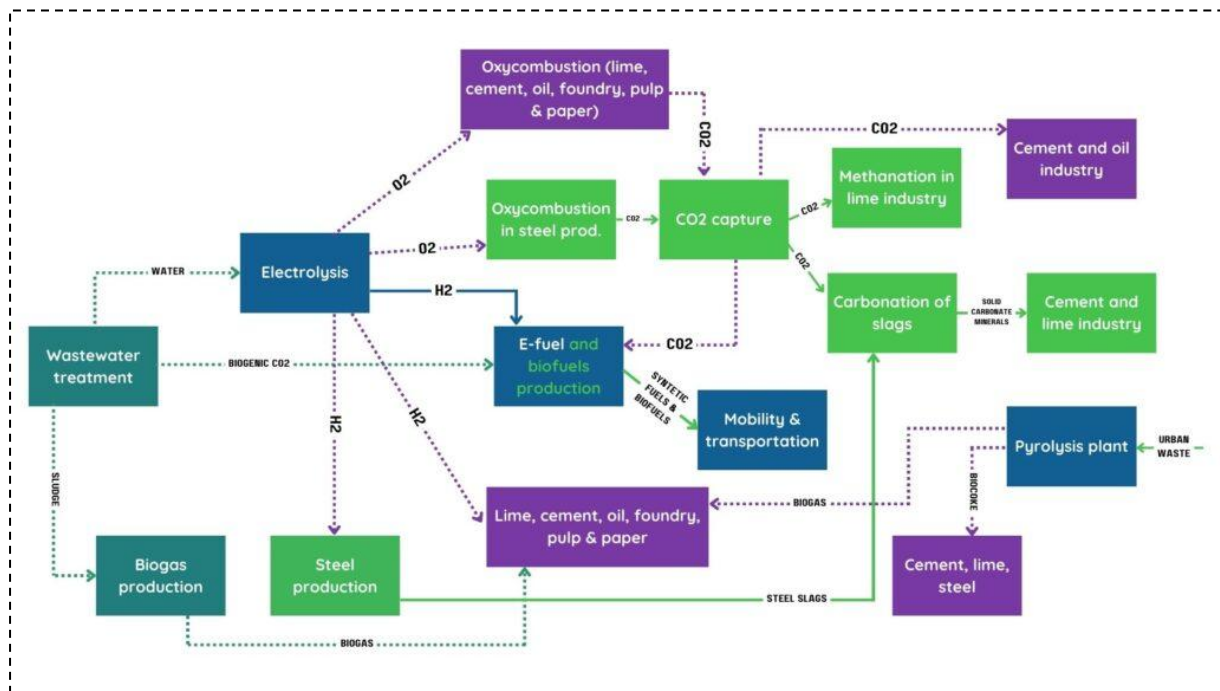


Figure 8: System Boundaries of the H4C 2 – BASQUE INDUSTRIAL – BASQUE HUB ([Home - IS2H4C PROJECT - GA. 101138473 \(is2h4c-project.eu\)](https://www.is2h4c-project.eu))

Following points will be relevant for the technology mapping:

- **Main subsectors:** Energy-intensive (Iron and steel; Paper, pulp and print; Non-metallic minerals), Energy (Oil Refining)
- **Main technology focus:**
 - **CCU:** Capture and utilization of CO₂ in various industries. For instance, CO₂ captured from the steel industry is used in the lime, cement, and oil refining industries.
 - **Oxy-Combustion:** Use of pure oxygen instead of air in combustion processes in the steel and other heavy industries to improve efficiency and reduce emissions.
 - **Electrolysis:** Production of hydrogen through electrolysis, a critical component for creating e-fuels and other industrial applications.
 - **Hydrothermal Cracking:** A process used for breaking down complex molecules in feedstocks to produce lighter and more valuable products.
 - **CO₂ Capture:** Specific focus on capturing CO₂ emissions from the steel and cement production; capturing CO₂ from flue gas of the rotary kiln including a subsequent methanation; using steel slag in carbonation processes to produce construction materials for the cement industry
 - **Biocoke and Biogas:** Production of biocoke and biogas from the pyrolysis of urban waste to replace traditional coke and natural gas in the cement, lime, and steel industries. Biogas also replaces natural gas in the oil refining and paper industries.
 - **Hydrogen Utilization:** Investigation into the uses of hydrogen in various industrial processes to enhance efficiency and reduce carbon emissions.

Hub specific technology map for the Basque hub is shown in Figure 9. As indicated in the initial system boundaries, the main industrial subsectors are Steel, Petro-chemical, Pulp and paper, lime and cement industry. Recovery technologies under different sub-categories include carbon capture technologies, energy recovery technologies, material waste and wastewater recovery technologies. Specific recovery

technologies can be determined based on data collection via data collection instruments developed during task 2.1, i.e. PFS and TFS. The process level data collection for the Basque hub is still on-going and will be further analyzed during WP4. Following hub level demand data has been collected during the data collection process (Table 16):

Table 16: Basque hub demand data

Demand	Quantity	Unit
Oxygen demand (expected)	73,700	m ³ /a
Electricity demand	768,000	MWh/a
Gas demand (Natural Gas)	433,000	MWh/a
Fuel oil	10,900	MWh/a
Biomass	278,000	MWh/a
Bark	70,000	t/a
Black-liquor	560	MWh/a
Sludge	8,500	t/a
Petroleum coke	240,300	MWh/a
Water	2,500,000	m ³ /a

At this stage, based on the industrial sectors identified in the proposal alongside possible waste streams, following can be concluded for the Basque hub. For the Carbon based IS, the amount of CO₂ available annually for each industry is not yet available. Therefore, based on literature (see chapter 5.2) a general overview of suitable recovery technologies is presented as follows (Table 17):

Table 17: Carbon based IS recovery technologies [according to [7]]

Industrial Sector	Product	Comment	CO ₂ Conc. [vol.%]	CCU Tech
Iron & Steel	Steel	Blend of BF-, BOF- and coke oven gas	23	Chemical Absorption
		EAF off gas	40	
		DRI flue gas	13-18	
Non-Metallic Minerals	Cement		14-33	Chemical Absorption, Oxy-Fuel, Calcium looping
	Lime		21	

For Energy based IS, waste heat recovery is possible for individual process streams provided that the process data is available. Based on the available data and literature research (see chapter 5.2), following can be determined for Energy based IS (Table 18):

Table 18: Energy based IS for basque hub [according to [18]]

Industry	Process or Waste Stream	Temperature level
Steel	Electric arc furnaces	Ultra-High
	Flue gas from continuous/forging/pit furnaces	Ultra-High
	Basic oxygen furnaces	High
	Blast furnaces	High
	Casting	High
	Coking	High
	Rolling	High
Non-metallic materials	Primary/secondary lead production	Medium
	Rolling	Medium
	Sintering	Medium
	Flue gas from glass-melting furnaces	Ultra-High
	Clinker	Ultra-High
	Lime	High
	Ceramic kilns	High
	Clinker	High
	Exhaust gas from cement kilns (dry process) or glass-melting furnaces	High
	Furnace heating and primary melting	High
	Kiln firing	High
Exhaust from cement kilns using a 5- or 6-stage preheater	Medium	
Pulp and Paper	Sintering	Medium
	Chemical/mechanical pulping	Low-High
	Papermaking and related processes	Low-High
	Furnace wall cooling water	Low
	Waste steam/water from slag flushing in furnaces	Low
Chemical and petrochemical	Conventional steam reforming	High
	Sulfuric acid process	High
	Thermal oxidation of VOCs	High
	Distilling	Medium-High
	Boiler exhaust	Medium
	Exhaust from ethylene furnaces	Medium
	Processing furnace exhaust	Medium
	Stack gas from crude/vacuum distillation	Medium
	Compressor cooling air/water	Ultra-Low
	Condensate	Ultra-Low
	Condenser cooling water	Ultra-Low
	Latex rubber	Ultra-Low
	Methane production (electrolysis, biomethanation)	Ultra-Low
	Process water	Ultra-Low
Soda ash	Ultra-Low	

Suitable heat recovery technologies are described in the literature section (see chapter 5.2) of this deliverable where different technologies are classified. Material based and Water based IS are not discussed in detail here since the specific relevant information has not yet been obtained. A general description of these IS can be found in Literature section of this deliverable.

For the symbiosis technologies, E-methanol production, electrolyzes, Methanation and Carbonation technologies are of interest for the hub partners. In this context, the relevant data is collected via TFSs from the technology providers as well as gathered via literature. Further, the hub services for the Basque hub can include energy production, Wastewater treatment, pyrolysis and providing heat and electricity to the industrial buildings. Based on the required use, a hydrogen storage, methanol storage or an electrical storage can also be used for temporal balancing. An optimization study can determine which is more economical for the specific use-case. Additionally, water, heat and fuel produced can be exported for further use in other industrial, residential and mobility sector.

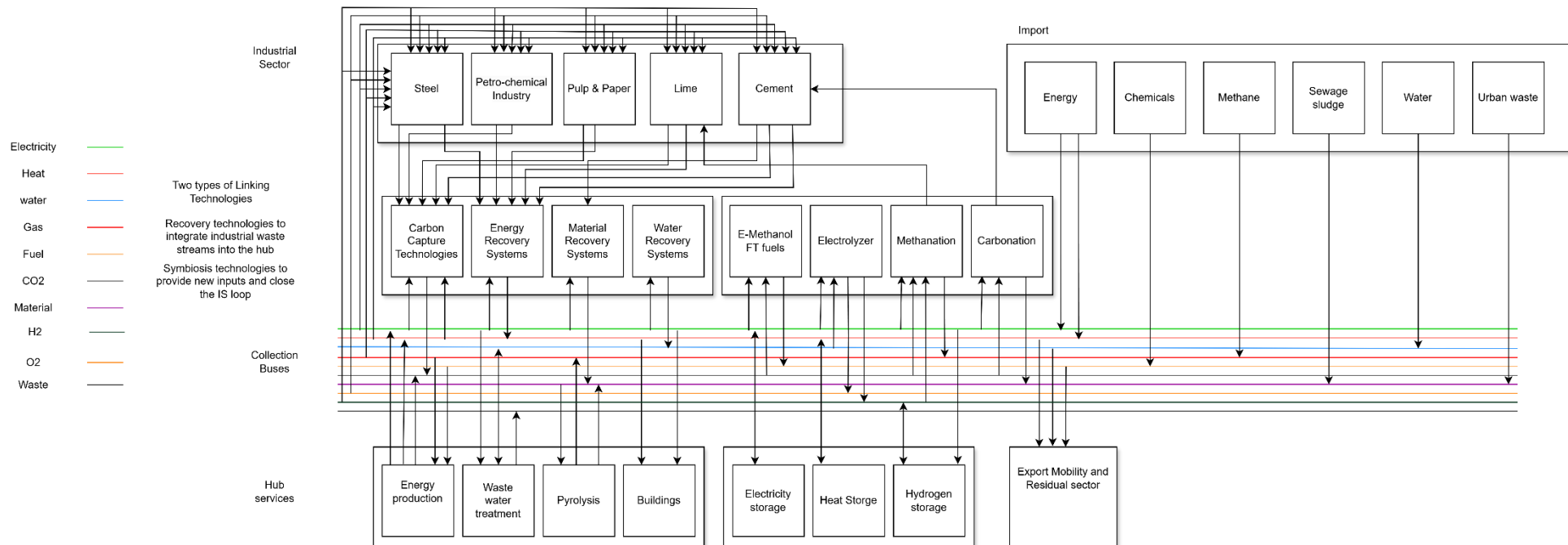


Figure 9: Basque hub map

3.3 H4C 3 – Almelo & H2C Twente – Dutch hub

The system boundaries of the hub are shown in Figure 10.

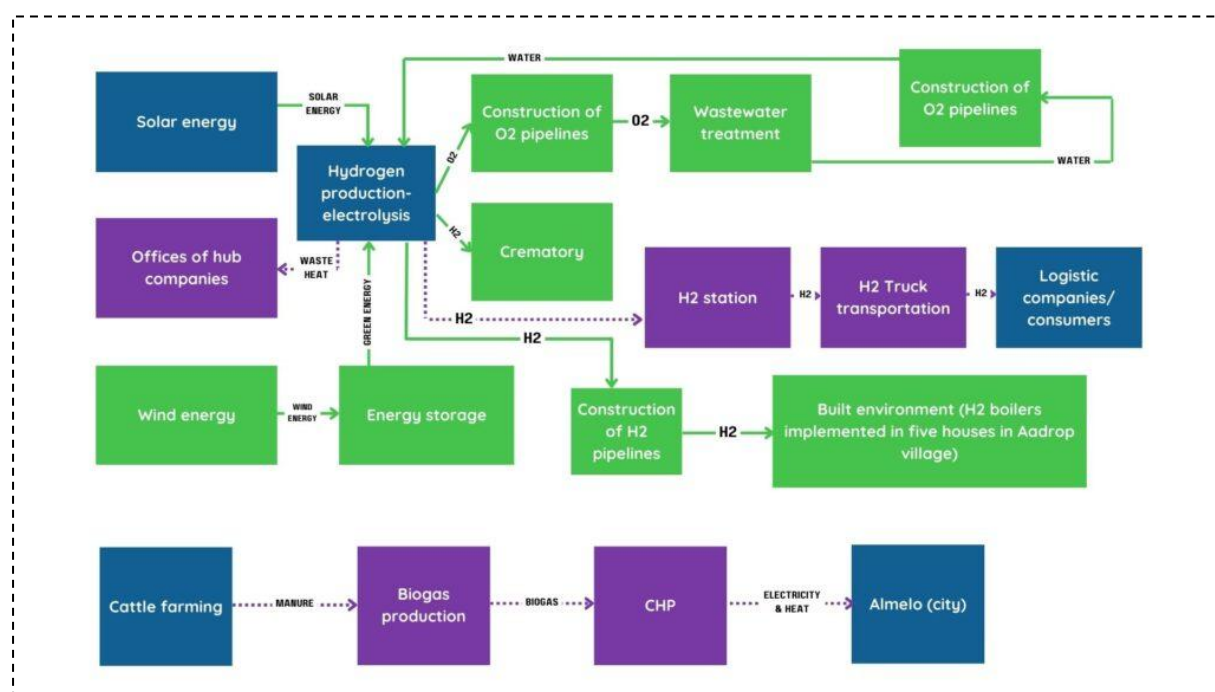


Figure 10: System Boundaries of the H4C 3 – ALMELO & H2C TWENTE – DUTCH HUB ([Home - IS2H4C PROJECT - GA_101138473 \(is2h4c-project.eu\)](https://www.is2h4c-project.eu/))

Following points will be relevant for the technology mapping:

- **Main subsectors:** Energy (Renewable), Residual (Office Buildings, City, wastewater treatment), Agriculture (cattle farming)
- **Main technology focus:**
 - **Electrolysis with Wind Energy:** Using wind energy for electrolysis to produce hydrogen, promoting sustainable energy storage and usage.
 - **Hydrogen Transport:** Development of infrastructure for transporting hydrogen to households via pipelines and to crematories via tube trailers as a natural gas replacement.
 - **Oxygen for Wastewater Treatment:** Using oxygen generated from electrolysis for wastewater treatment, which in turn supports the electrolysis process.
 - **Energy Storage:** Storing energy generated from wind using green hydrogen, which can be used during periods of low energy production.
 - **Biogas from Manure:** Producing biogas from manure to replace natural gas in combined heat and power (CHP) systems.
 - **Waste Heat Recovery:** Utilizing waste heat from electrolysis for space heating in residential and commercial buildings.
 - **Hydrogen Stations:** Establishing hydrogen fueling stations to supply hydrogen trucks for logistics companies, promoting cleaner transportation options.

Hub specific technology map for the Basque hub is shown in Figure 11. Dutch hub is unique in character from all the other hubs as it does not involve any industrial sector and serves as a collaborative space where entrepreneurs and educators work together on hydrogen technology research, development, and application, also known as the H2 Hub Twente—located near Aadorp, a small village with around 600 homes. Dutch hub includes a small-scale hydrogen facility - the H₂ Hub Twente. Aadorp aims to transition into a positive energy district by becoming independent from natural gas and fossil-based

electricity. As per the communication with the hub leader, the overview of the planned synergies in the Dutch hub is:

- Green hydrogen will be generated through electrolysis using solar energy and, in the future, wind energy. This hydrogen will be delivered to four homes and the community center in Aadorp via H₂ pipelines, which are still in the planning stages.
- Implementation of an energy storage solution in the H₂ Hub to stabilize the green energy supply and address variability in generation.
- The transport of Hydrogen to a crematorium in Twente using H₂ tube trailers as a potential substitute for natural gas.
- Oxygen produced during electrolysis will be sent to a nearby wastewater treatment facility for water purification, and the treated water will be routed back to the electrolyzes through two planned pipelines.

Since the Dutch hub relies on the external partners for information and are collaboration. for example, Aadorp depends on the distribution network operator, Cogas, for H₂ pipeline construction and on Remeha for installing H₂ boilers, the necessary data might not be available at this stage according to the hub leader. The available data for the Dutch hub includes a Solar PV plant of 1.1 MWp, a planned Wind power plant of 70 kW and alkaline electrolysis (AEL) with a hydrogen volume flow of 15 m³/h at 15 bar, 1.3 kg/h, 60-80 °C. Following demand data is also gathered from the Dutch hub (Table 19):

Table 19: Demand data for dutch hub

Demand	Quantity	Unit
Hydrogen demand	±3000kg H ₂ /a based on Aadorp	kg/a
Oxygen demand	7,875,240	kg/a
Electricity demand	1,530	MWh/a

For storage services, following data is collected (Table 20):

Table 20: Storage services for Dutch hub

Type of Storage	Description	Capacity	Unit
Electric Storage	Battery storage	1.4	MWh
Chemical Storage	H ₂ storage [planned]	60.0	kg
Thermal Storage	Geothermal field	450.0	kWh

Energy based IS is relevant here for the energy recovery from electrolysis. Since the temperature of heat recovered from electrolysis is classified as low temperature, this heat can be used for local heating/district heating purposes. This heat can be used either directly using a heat exchanger or indirectly with heat pumps and/or heat buffer in between depending on the intended usage [12]. The geothermal field in the dutch hub can be used as a heat buffer in this case. For wastewater treatment, the direct contact membrane distillation technology can be evaluated.

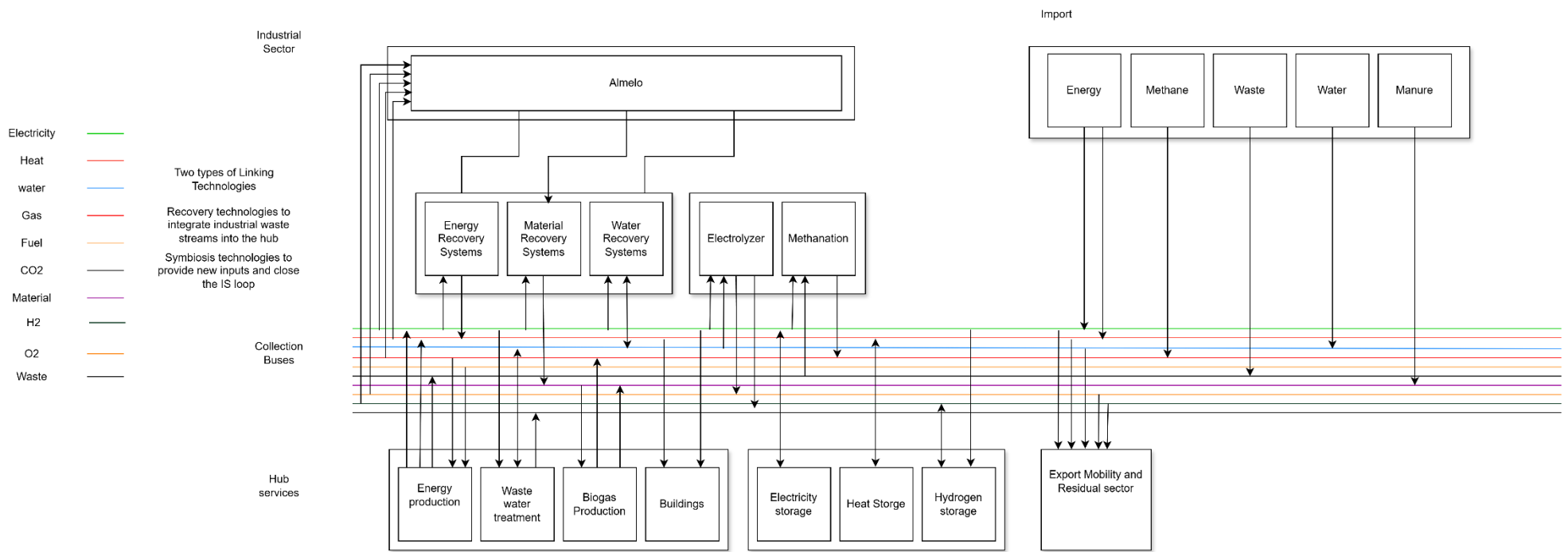


Figure 11: Dutch hub map

3.4 H4C 4 – Industriepark Höchst – German hub

The system boundaries of the hub are shown in Figure 12.

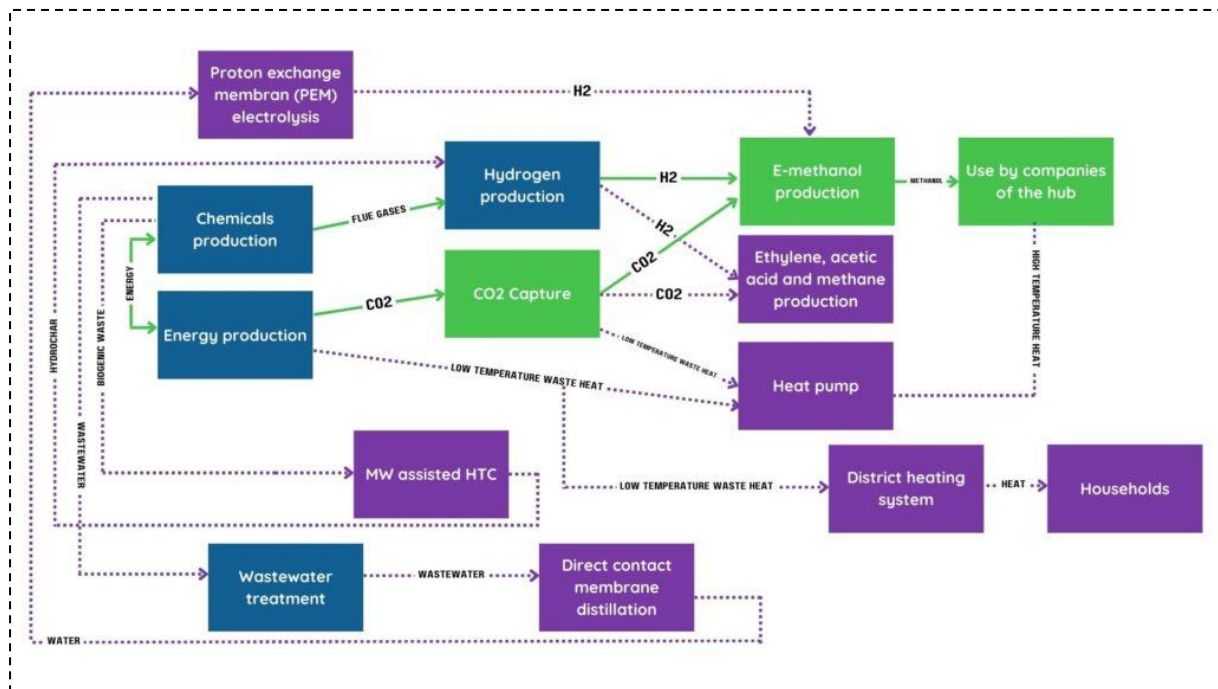


Figure 12: System Boundaries of the H4C 4 – Industriepark Höchst – german hub ([Home - IS2H4C PROJECT - GA_101138473 \(is2h4c-project.eu\)](https://www.is2h4c-project.eu/))

Following points will be relevant for the technology mapping:

- **Main Sub-sector:** Energy-intensive (Chemical and petrochemical incl. Pharmaceutical), Energy, Residual (wastewater treatment, City)
- **Main technology focus:**
 - **PEM Electrolysis:** Production of hydrogen (H₂) via Proton Exchange Membrane (PEM) electrolysis, a process that uses electricity to split water into hydrogen and oxygen.
 - **Carbon Capture Utilization (CCU):** Capture of carbon dioxide (CO₂) from Incineration plants. The captured CO₂ is then utilized for producing e-methanol, ethylene, acetic acid, and methane.
 - **E-fuels:** Utilization of H₂ and CO₂ to produce e-methanol, a synthetic fuel, and other chemicals such as ethylene, acetic acid, and methane.
 - **Heat Pumps:** Upgrading low-temperature waste heat from energy production and CO₂ capture processes to high-temperature waste heat, which can be used more efficiently in industrial processes and district heating networks.
 - **Direct Contact Membrane Distillation:** A method for wastewater treatment that involves direct contact membrane distillation, which helps in the efficient treatment of wastewater from chemical production.
 - **Microwave-Assisted Hydrothermal Carbonization:** A process for converting biogenic waste from chemical production into useful carbon products using microwave-assisted hydrothermal carbonization.

The Hub specific technology map for the German hub is shown in Figure 13. As indicated in the initial system boundaries, the main industrial subsectors are chemical industry and energy production. Recovery technologies under different sub-categories include carbon capture technologies, energy recovery technologies, material waste and wastewater recovery technologies. Specific recovery technologies can be determined based on data collection via data collection instruments developed during task 2.1, i.e. PFS and TFS. The process level data collection for the German hub is still on-going and will be further analyzed during WP4. Following hub level demand and production data has been collected during the data collection process (Table 21 to Table 23):

Table 21: German hub demand data

Input Raw materials	Quantity	Unit	Source	Remarks
Hydrogen	9,000	t/a	Chloralkali electrolysis	Full utilisation by customers
Methanol	300,000	t/a	imported to the HUB	several products
Ethylene	260,000	t/a	imported to the HUB	several products
River water	60,000,000	t/a	taken from the river Main	several water qualities
Well water	3,100,000	t/a	from own wells	only used where other water qualities are prohibited
Potable water	278,000	t/a	Municipal drinking water	for employees and pharmaceutical production
Natural Gas	4,700	GWh/a	imported to the HUB	for steam and electricity production

Table 22: German hub energy production data

Energy production type	Capacity	Unit	Source	Remarks
Electricity	1,679	GWh/a	on-site production and import	Carbon Footprint report 2022
thereof	571	GWh/a	external purchase	national grid
	1,024	GWh/a	Combined heat and power plant	on-site production
	84	GWh/a	RDF incineration plant	on-site production
Steam	3,400	GWh/a	on-site production	CHP and incineration plants
thereof	2,346	GWh/a	Combined heat and power plant	
	782	GWh/a	RDF incineration plant	
	272	GWh/a	Waste incineration plants ISH	Sewage sludge and residue incineration plants
Biogas	100	GWh/a	on-site production	Biogas Plant
biomethane	80	GWh/a	on-site production	Biogas Upgrading Plant

Table 23: German hub production data

Products	Capacity	Unit	Source	Remarks
POM polymer	160,000	t/a	methanol	Celanese
Bio-diesel	300,000	t/a	methanol	Cargill
PE polymer	210,000	t/a	ethene	LyondellBasell
Methylchloride	10,000	t/a	methane	Nobian
Dimethylether	20.000	t/a	methanol	Grillo-Werke
Sulphuric acid	258.000	t/a	sulfur	Grillo-Werke

The appropriate recovery technology for Carbon based IS is amine based chemical absorption carbon capture unit since the planned input CO₂ stream is from a waste incineration plant. Detailed data on the CO₂ stream is not available at this stage. For Energy based IS, several technologies can be of interest depending on the quality of available heat. Heat pumps and Organic Rankine cycle being one of the most interesting ones since according to literature most of the waste heat available from chemical industry is at low to medium temperature [13]. Data for industrial wastewater recovery is not available at the moment. The symbiosis technologies include E-methanol production and electrolysis. For electrolysis, PEM electrolysis can be of interest as a suitable technology for hydrogen production. Based on the required use, a hydrogen storage, methanol storage or an electrical storage can also be used for temporal balancing. An optimization study can determine which is more economical for the specific use-case. Additionally, water, heat and fuel produced can be exported for further use in other industrial, residential and mobility sector.

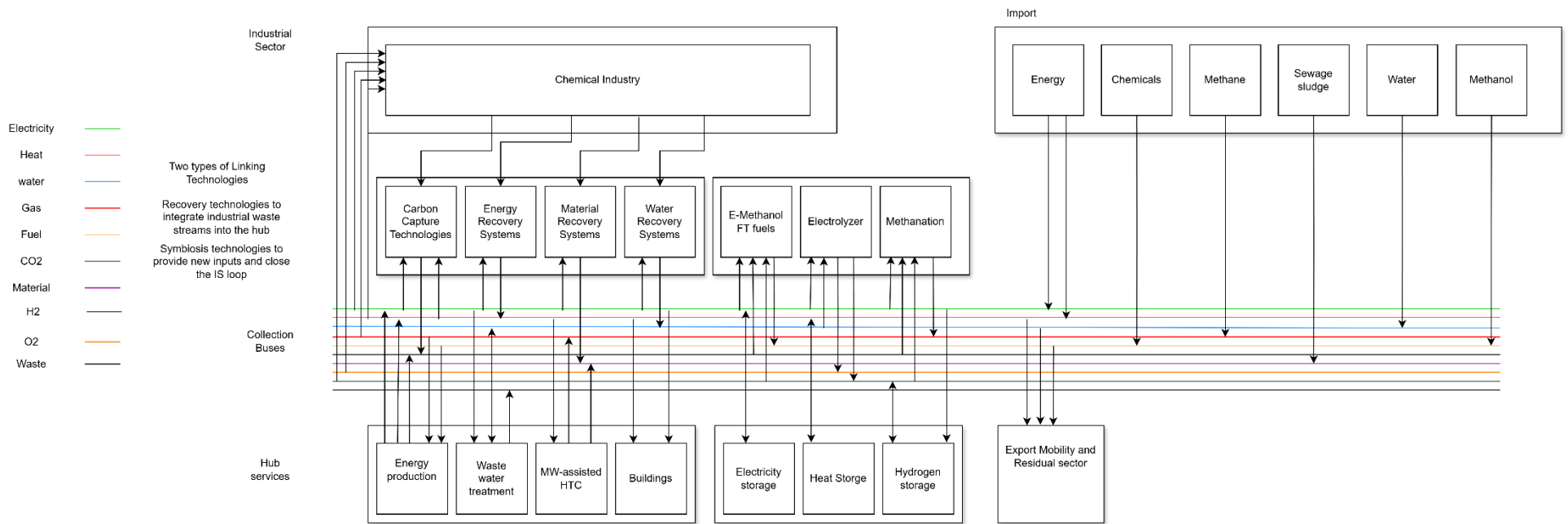


Figure 13: German hub map

4. Project-specific technology analyses

The technology fact sheets (TFS) are shared with the technology providers working together in WP2. Table 24 shows the technologies developed or to be further developed in the project and presents the current state of progress of the data collection via TFS. An update of the fact sheets will be considered for technologies that show changed parameters in a later phase of the project. These TFS can be provided for use in other WP's if the individual technology provider does not have any reservations

Table 24: State of progress of the technology analyses via the Technology Fact Sheet on technology provider level

Technology	Progress	Technology developed	TRL	Efficiency
CO ₂ methanation	TFS completed	The Sabatier reaction converts CO ₂ to CH ₄ using H ₂ and a Ru or Ni-based catalyst at 200–400 °C and 1–30 bar, achieving 80–90% CO ₂ conversion. Millichannel reactors enhance this conversion	TRL 5	- -
High temperature heat pump	TFS completed	The variable geometry ejector integrated high temperature heat pump with a temperature outout up to 150 °C.	TRL 4	300% Process -
Direct contact and vacuum membrane distillation	TFS completed	Direct contact membrane distillation (DCMD) and vacuum distillation (VMD) use a porous hydrophobic membrane to selectively pass water vapor and ammonia gas. Ammonia is recovered by adjusting pH or temperature, while DCMD forms ammonium sulfate in a sulfuric acid permeate, which can be utilized as a fertilizer.	TRL 6	85 % Process 95% Separation
NIPU-process	TFS completed	Non-isocyanate polyurethanes (NIPU) are produced using CO ₂ -based building blocks, polyols, and diols, providing a sustainable and safe alternative to traditional PU materials.	TRL 4	- -
One-Pot Synthesis	TFS – Technology parameters are missing	The technology converts CO ₂ , methanol, and diamines into dicarbamates for isocyanate-free polyurethanes, with dimethyl carbonate as an intermediate with various applications. It operates at over 50 bar and 100°C, requiring water removal."	TRL 2	- -
Green hydrogen production	TFS – Technology parameters, Publications, Best practice	Green hydrogen is produced via electrolysis using renewable energy, storing excess solar or wind power without CO ₂ emissions. This stored hydrogen	TRL 9	87 % Process -

	applications are missing	provides a reliable, year-round energy source, supports peak shaving, and serves as emergency power. It's 100% safe and only produces oxygen as a side product.		
Microwave-Assisted Hydrothermal Carbonization	TFS – General description is missing	-	-	70-85% Process N/A
Methanol Tupras	TFS 80% is missing	-	-	99,9 % -
Tüpraş	TFS best practice applications are missing	Tüpraş is introducing a PEM electrolyzer for efficient hydrogen production, an amine CO ₂ capture unit to reduce emissions, and a catalytic unit to produce methanol from captured CO ₂ and hydrogen. This methanol, along with CO ₂ , will be used to create NIPU, aiming to produce at least 2 kg of high-quality methanol per day.	TRL 9	- -
H2HT	TFS general description is missing	-	-	80 % -

5. Literature Research

5.1 main Processes of energy-intensive Industrial Subsectors

Based on the energy-intensive industrial subsectors within the system boundaries (see from Figure 6 to Figure 13) of the four H4C the following subsectors are investigated:

- Iron and steel
- Paper, pulp and print
- Chemical and petrochemical
- Non-metallic minerals

The process lists for these subsectors (see from Table 25 to Table 28) are provided for the project and is based on literature research, industrial expert interviews and a analyse of the Austrian energy-intensive industrial sub-sectors. [1] The selected processes and process routes represent those for which time-resolved synthetic load and generation profiles will be modelled via using and further expanding “Ganymed”, a software developed at the Chair of Energy Network Technology (Montanuniversitaet Leoben). Time-resolved profiles and specific process data will be estimated, modelled and analysed in subsequent activities of the chair within WP4. [1]

These lists do not claim to be exhaustive. If further relevant processes are identified as a result of the project, the lists can be extended.

Table 25: Process list for the iron and steel subsector [based on [1]]

Process route	ÖNACE code	Process unit	Type of processing
Blast Furnace Route (Gross Energy Consumption Boundary)	24.10 -Manufacture of basic iron, steel, and ferro-alloys	Sintering Plant	Thermal
		Coking Plant	Thermal
		Blast Furnace	Thermal
		Desulphurisation	Thermal
		Converter	Thermal
Blast Furnace Route (Final Energy Boundary)	24.10 - Manufacture of basic iron, steel, and ferro-alloys	Sintering Plant	Thermal
		Coking Plant	Thermal
		Blast Furnace	Thermal
		Desulphurisation	Thermal
		Converter	Thermal
		Ladle Furnace	Thermal
		Vacuum Oxygen Degasser	Thermal
		Continuous Casting	Thermal
		Hot Rolling	Thermal
Blast Furnace Route (Total Energy Boundary)	24.10 - Manufacture of basic iron, steel, and ferro-alloys	Sintering Plant	Thermal
		Coking Plant	Thermal
		Blast Furnace	Thermal
		Combined Heat & Power Plant	Special
		Desulphurisation	Thermal
		Converter	Thermal
		Ladle Furnace	Thermal
		Vacuum Oxygen Degasser	Thermal
		Continuous Casting	Thermal
Hot Rolling	Thermal		
Electric Arc Furnace Route Version 1 (Final Energy Boundary)	24.10 - Manufacture of basic iron, steel, and ferro-alloys	Buffer	Special
		EAF	Thermal
		Ladle Furnace	Thermal
		Vacuum Oxygen Degasser	Thermal
		Continuous Casting	Thermal
		Hot Rolling	Thermal
Electric Arc Furnace Route Version 2 (Final Energy Boundary)	24.10 - Manufacture of basic iron, steel, and ferro-alloys	Buffer	Special
		EAF	Thermal
		Ladle Furnace	Thermal
		Ladle Heater	Thermal
		Ingot Casting	Thermal
		Tubular Reactor	Thermal
		Separator	Chemical
		Extruder	Thermal
Dryer	Thermal		

Table 26: Process list for the paper pulp and print subsector [based on [1]]

Process route	ÖNACE code	Process unit	Type of processing
Chemical Pulp Production via Kraft	17.11 - Manufacture of pulp	Debarker	Mechanical
		Chipper	Mechanical
		Pulper & Digester	Thermal
		Washing & Screening	Mechanical
		Evaporator	Thermal
		Oxygen Delignification	Chemical
		Combined Heat & Power Plant	Special
		Bleach Plant	Chemical
		Lime Kiln	Thermal
Mechanical Pulp Production via RMP	17.11 - Manufacture of pulp	Debarker	Mechanical
		Chipper	Mechanical
		Pulp Refiner	Mechanical
		Washing & Screening	Mechanical
		Oxygen Delignification	Chemical
		Bleach Plant	Chemical
(Thermo-)Mechanical Pulp Production via TMP	17.11 - Manufacture of pulp	Debarker	Mechanical
		Chipper	Mechanical
		Pulp Refiner	Mechanical
		Oxygen Delignification	Chemical
		Bleach Plant	Chemical
Integrated Pulp (via Kraft) & (Printing & Writing) Paper Production	17.12 - Manufacture of paper and paperboard	Debarker	Mechanical
		Chipper	Mechanical
		Pulper & Digester	Thermal
		Washing & Screening	Mechanical
		Evaporator	Thermal
		Oxygen Delignification	Chemical
		Combined Heat & Power Plant	Special
		Bleach Plant	Chemical
		Lime Kiln	Thermal
		Stock Preparation	Mechanical
		Pressing & Forming	Mechanical
		Dryer	Thermal
		Calendering	Mechanical
Integrated Pulp (via Sulfite) & (Printing & Writing) Paper Production	17.12 - Manufacture of paper and paperboard	Buffer	Special
		Pulper & Digester	Thermal
		Washing & Screening	Mechanical
		Oxygen Delignification	Chemical
		Evaporator	Thermal
		Bleach Plant	Chemical

		Stock Preparation	Mechanical
		Combined Heat & Power Plant	Special
		Pressing & Forming	Mechanical
		Dryer	Thermal
		Calendering	Mechanical
		Wastewater Treatment	Chemical
		Miscellaneous	Special

Table 27: Process list for chemical and petrochemical subsector [based on [1]]

Process route	ÖNACE Code	Process unit	Type of processing
Chlorine Gas Production	20.13 - Manufacture of other inorganic basic chemicals	Ion Exchanger	Chemical
		General Heating Unit	Thermal
		Electrolyser	Chemical
		Chiller	Thermal
		Evaporator	Thermal
		Compressor	Mechanical
Oxygen Production	20.11 - Manufacture of industrial gases	Compressor	Mechanical
		Chiller	Thermal
		Molecular Sieve Unit	Chemical
		Rectification Column	Chemical
Ammonia Production	20.15 - Manufacture of fertilizers and nitrogen compounds	Turbo Compressor	Mechanical
		Primary Reformer	Thermal
		Buffer	Special
		Secondary Reformer	Thermal
		Boiler	Special
		CO Converter CO ₂ Separator	Chemical
		Synthesis Reactor	Thermal
Urea Production	20.15 - Manufacture of fertilizers and nitrogen compounds	Compressor	Mechanical
		Synthesis Reactor	Thermal
		Falling Film Heat Exchanger	Thermal
		Evaporator	Thermal
Diammonium Hydrogen Phosphate (Fertilizer) Production	20.15 - Manufacture of fertilizers and nitrogen compounds	Washing & Screening	Mechanical
		Synthesis Reactor	Thermal
		Granulator	Mechanical
		Dryer	Thermal
		Crusher	Mechanical
Ethylene Production	20.14 - Manufacture of other organic basic chemicals	Steamcracker	Thermal
		Boiler	Special
		General Quenching Unit	Thermal
		Turbo Compressor	Mechanical
		Distillation	Thermal

		Hydrogenation	Thermal
Polyethylene (LDPE) Production	20.16 - Manufacture of plastics in primary forms	Compressor	Mechanical
		Tubular Reactor	Thermal
		Separator	Chemical
		Extruder	Thermal
		Dryer	Thermal

Table 28: Process list for non-metallic minerals subsector [based on [1]]

Process route	ÖNACE code	Process unit	Type of processing
Cement Production	23.51 - Manufacture of cement	Crusher	Mechanical
		Raw Material Mill	Mechanical
		Buffer	Special
Flat Glass Production	23.11 - Manufacture of flat glass	Raw Material Mill	Mechanical
		Tub Oven	Thermal
		Glass Shaping Unit	Thermal
		Chiller	Thermal
Lime Production	23.52 - Manufacture of lime and plaster	Crusher	Mechanical
		Lime Mill	Mechanical
		Raw Material Mill	Mechanical
Brick and other Ceramic Production	23.32 - Manufacture of bricks, tiles and construction products, in baked clay	Raw Material Mill	Mechanical
		Pressing & Forming	Mechanical
		Dryer	Thermal
		Tunnel Furnace	Thermal

5.2 Subsector-specific Industrial Output and Input streams: Sources and Sinks

Carbon-based IS: CO₂-streams

Besides an actual ongoing data gathering process literature values might be helpful to understand the overall picture with regards to sector specific emissions. For instance, Table 29 describes specific process related emissions in kg per ton of product, summarized from different literature sources, like Austria's National Inventory Report, by Hochmeister et al [7].

Table 29: Specific process related CO₂ emissions (*geogenic CO₂ emissions) [7]

Industrial Sector	Product	Comment	Process-related CO ₂ (kg per ton)	
Chemical & Petrochemical	Ammonia		926.00	
	Nitric Acid		0.72	
	Urea		0.50	
	Fertilizer		40.00	
	Olefine		913.20	
	Methanol		554.01	
Iron & Steel	Steel	BF/BOF	1,487.00	
		EAF	54.00	
		DRI/EAF (CH ₄ reduction)	716.00	
		DRI/EAF (H ₂ reduction)	80.00	
Non-Ferrous Metal	Aluminum		0.01	
Non-Metallic Minerals	Brick		53.00	
		Cement	Per ton Clinker	517.00
		Cement	Per ton Cement	338.43
		Lime		746.00
		Glass		78.00
Mining & Quarrying	Magnesia	Per ton Magnesite	475.00	

Apart from specific emissions, CO₂ concentrations are also of importance in determining the right carbon capture technology. Table 30 describes different industrial sectors and their CO₂ concentrations. Appropriate carbon capture technologies are also suggested based on examples available in literature. The findings shown are based on a study assessing a methodology for the determination of future Carbon Management Strategies in Austria. [7]

Table 30: CO₂ concentration of various industrial sector streams and possible carbon capture technology [7]

Industrial Sector	Product	Comment	CO ₂ Conc. [vol.%]	CCU Tech
Chemical & Petrochemical	Ammonia, Nitric Acid, Urea, Fertilizer	H ₂ purification	98-100	CA, PAb, PAd
	Olefine			
	Methanol	Steam Reformer off gas	18-20	CA, PAb, PAd
Energy Supply	Bioethanol production	Fermentation process	98-99	
	Biogas production		25-50	
	Refinery	Refinery off gas	8-24	
	Natural Gas processing	Acid gas removal	96-99	
	Coal-fired CHP		10-15	CA
	Biomass CHP		14	CA
	CH ₄ CHP		3-5	CA

	Oil heating plant		3-8	
	Waste incineration plant		10	CA
	CH ₄ heating plant		7-10	
	CH ₄ pipeline compressor station		3-5	
Iron & Steel	Steel	Blend of BF-, BOF- and coke oven gas	23	CA, CL
		EAF off gas	40	
		DRI flue gas	13-18	
Non-Ferrous Metal	Aluminum		3-10	
Non-Metallic Minerals	Brick		1.5-4	
	Cement		14-33	CA, OF, CL
	Lime		21	
	Glass		13	
Paper, Pulp & Print	Pulp and Paper		7-20	

Energy based IS: Waste heat potentials

Waste heat potentials of different industrial subsectors can be calculated via different approaches. Subsector specific waste heat temperature levels are provided in a waste heat study of Fraunhofer ISI, this report also includes the description of several waste heat recovery technologies. [14] Within the EU-project sEnergies an open data platform has been generated. The platform provides industrial excess heat potentials data sets [15]. Timely resolved waste heat potentials of specific subsectors can be provided with “Ganymed” a software developed at the chair of energy network technology (MUL) [1]

To describe hub-specific waste heat streams for further simulation and optimization tasks in WP4 hub-specific waste heat streams are essential. In the absence of real data, literature-derived values are necessary to approximate hub- and subsector-specific waste heat potentials. To facilitate this estimation, three methods are analyzed in detail below.

The first method described in detail is using technical potentials recalculated according to a bottom up approach based on the Austrian heat map. In the framework of spec. technical potential, the term "potential" has been defined in a variety of ways in the literature, mostly in relation to renewable energy. Particular definitions have been created for the waste heat under consideration here [16]. Only physical restrictions are considered by theoretical (or physical) potential, which requires that the heat be above the reference temperature of 0°C and attached to a heat carrier (liquid, gas, or solid). Here, the technological viability of heat extraction or its use is not considered. Building on theoretical potential, technical potential takes into account constraints like heat extraction feasibility, which are contingent on technological considerations (e.g., scientific knowledge or the level of technology). The minimal temperature differential in heat exchangers (gradient), extreme heat carrier medium contamination, biological conditions in wastewater (biofouling), or operational safety are a few examples of technical limitations. It does not consider whether the usage is economically feasible or whether there is an imminent prospect of use (such as an industrial activity with heat demand or an existing heating network).

Waste Heat is categorized according to temperature ranges. The temperature ranges of >100°C, 50-100°C, and 0-50°C were selected. The lower limit of 0°C was chosen since it is lower than the average

yearly temperature in lowland regions. This was determined by the consortium, nevertheless, because it is economically and efficiently feasible to use heat for heating up to this degree using a heat pump. The rather narrow split in the lower temperature range, in contrast to earlier studies, shows the expected increasing significance of low-temperature sources and their application in anergy or low-temperature networks in combination with heat pumps. Temperatures lower than 50°C can power these applications. While the range over 100°C may feed traditional district heating networks, the range between 50 and 100°C is targeted at smaller networks, optimized, or new district heating networks with lower supply temperatures [16]. In the following table are spec. technical potentials recalculated according bottom up approach based on the Austrian heat map [17] with the corresponding ÖNACE code.

Table 31: Spec. technical potential according ÖNACE code [recalculation based on [16] and [17]]

ÖNACE Code and Description	Spec. technical potential kWh/t of product		
	>100 °C	50 - 100 °C	< 50 °C
8990 - Other mining; extraction of stone and earth n.e.c.	88.42	123.20	315.02
10510 - Dairy processing (excluding ice cream production)	0.00	1.14	31.81
17110 - Manufacture of paper, cardboard, and paperboard	35.41	233.81	1,014.82
17120 - Manufacture of corrugated paper and paperboard, and packaging made from paper, cardboard, and paperboard	15.08	67.21	422.88
17210 - Manufacture of household, hygiene, and toilet articles from pulp, paper, and paperboard	13.56	33.89	200.68
17220 - Manufacture of stationery and office supplies from paper, cardboard, and paperboard	0.00	65.74	883.00
17290 - Manufacture of other goods from paper, cardboard, and paperboard	13.33	33.32	197.22
20130 - Manufacture of dyes and pigments	614.23	150.79	582.49
20300 - Manufacture of paints, printing inks, and putty	55.33	19.63	53.29
20600 - Manufacture of chemical fibers	0.00	181.85	2,909.00
23130 - Manufacture of hollow glass	270.55	162.81	1,429.69
23190 - Manufacture, refinement, and processing of other glass including technical glass products	525.99	273.27	2,318.40
23200 - Manufacture of refractory ceramic materials and goods	209.87	53.52	136.19
23320 - Manufacture of bricks and other construction ceramics	18.45	12.73	193.03
23420 - Manufacture of sanitary ceramics	0.00	98.69	878.33
23510 - Manufacture of cement	69.88	48.80	51.69
23520 - Manufacture of lime and burnt gypsum	114.93	22.42	101.58
23610 - Manufacture of products made from concrete, cement, and lime sandstone for construction	13.59	131.03	68.14

23620 - Manufacture of plaster products for construction	14.53	131.60	63.95
23640 - Manufacture of mortar and other concrete (dry concrete)	130.76	37.36	113.01
24100 - Production of pig iron, steel, and ferroalloys	126.08	49.10	443.21
24200 - Manufacture of steel pipes, tube fittings, and pipe connectors made from steel	111.99	50.87	667.54
24310 - Manufacture of cold profiles	4.42	1.40	41.63
24420 - Production and primary processing of lead, zinc, and tin	82.24	44.99	208.76
24440 - Production and primary processing of copper	175.02	33.03	70.91
24510 - Manufacture of steam boilers (excluding central heating boilers)	72.85	42.37	547.51
24520 - Manufacture of radiators and boilers for central heating	77.95	45.33	585.96
24530 - Manufacture of containers, tanks, and similar metal containers	44.49	24.02	87.98
10810 - Manufacture of confectionery	31.91	27.66	246.78
16210 - Manufacture of furniture	7.71	23.22	310.34
19200 - Manufacture of optical instruments	18.49	15.24	202.74
20140 - Manufacture of pharmaceutical specialties and other pharmaceutical products	73.55	143.06	2,093.94
20150 - Manufacture of glass fibers and products made from them	59.54	14.71	98.59
20160 - Manufacture of pharmaceutical products	95.83	31.94	415.28
20590 - Manufacture of cosmetics	61.44	204.15	406.21
24330 - Manufacture of glassware	15.12	4.76	134.61

Another study supporting the application of the previously presented waste heat potentials and facilitates the estimation of hub-specific potentials is carried out by Benedetti et. al. [18]. Hereby, another way to classify the waste heat potential of different industrial sectors based on temperature level has been presented. In this regard, literature data available is shown in Table 32.

Table 32: Classification of waste heat based on temperature level [18]

Industry	Process or Waste Stream	Temperature level
Steel	Electric arc furnaces	Ultra-High
	Flue gas from continuous/forging/pit furnaces	Ultra-High
	Basic oxygen furnaces	High
	Blast furnaces	High
	Casting	High
	Coking	High
	Rolling	High
Non-metallic materials	Primary/secondary lead production	Medium
	Rolling	Medium
	Sintering	Medium
	Flue gas from glass-melting furnaces	Ultra-High
	Clinker	Ultra-High
	Lime	High
	Ceramic kilns	High
	Clinker	High
	Exhaust gas from cement kilns (dry process) or glass-melting furnaces	High
	Furnace heating and primary melting	High
	Kiln firing	High
	Exhaust from cement kilns using a 5- or 6-stage preheater	Medium
Pulp and Paper	Sintering	Medium
	Chemical/mechanical pulping	Low-High
	Papermaking and related processes	Low-High
	Furnace wall cooling water	Low
	Waste steam/water from slag flushing in furnaces	Low
Chemical and petrochemical	Conventional steam reforming	High
	Sulfuric acid process	High
	Thermal oxidation of VOCs	High
	Distilling	Medium-High
	Boiler exhaust	Medium
	Exhaust from ethylene furnaces	Medium
	Processing furnace exhaust	Medium
	Stack gas from crude/vacuum distillation	Medium
	Compressor cooling air/water	Ultra-Low
	Condensate	Ultra-Low
	Condenser cooling water	Ultra-Low
	Latex rubber	Ultra-Low
	Methane production (electrolysis, biomethanation)	Ultra-Low
	Process water	Ultra-Low
Soda ash	Ultra-Low	

This categorization is based on Benedetti et. al. [18] who have classified different temperature levels as shown in Table 33.

Table 33: Classification of temperature level according to Benedetti et al. [18]

Ultra-Low Level	Low Level	Medium Level	High Level	Ultra-High Level
< 120 °C	120-230 °C	230-650 °C	650-870 °C	>870 °C

According to the approach of Aydemir et al. [19] the excess heat potential specific for every industrial sector can also be calculated from the natural gas consumption using factors that have been identified in a study by Fraunhofer ISI. The study considered the excess heat of industries in Baden-Wurttemberg in the southeast of Germany, a highly industrialized region. Based on vast company data, the factors were deduced from the emission values in the flue gas streams. The estimation is rather conservative and only refers to excess heat in the flue gas leaving internal losses unconsidered. It therefore tends to underestimate the potential for excess heat. The excess heat potential is calculated in kWh/a based on the natural gas (NG) consumption of the company in kWh/a multiplied with a sector specific excess heat factor shown in Table 34.

Table 34: Factors for excess heat potential per industrial sector [19]

Sector	Excess heat factor
Food	0.05
Glass processing	0.13
Textile	0.23
Plastics	0.14
Battery Manufacturing	0.39
Metalwork	0.21
Foundry	0.27
Chemicals	0.08
Construction Materials	0.13
Shipyard	0.04
Paper	0.05
Mechanical Equipment	0.05
Fishery	0.18

Material-based IS: Material-streams

To facilitate ongoing surveys of hub-specific material flows, a comprehensive literature review was conducted to establish a foundation for identifying potentially accessible material flows. Notably, the report from the SCALER project, Technology Database for Synergy Setups, warrants particular attention. This report systematically identifies and characterizes a range of processes and technologies relevant to the valorization of 100 promising synergies across Europe. Within this context, distinct waste streams—termed "synergies"—are detailed in terms of their physical state, origin and destination sectors, and are associated with applicable recovery technologies or processes. The resulting technology database provides technical descriptions and characterizations, details on solutions

implemented at industrial scale, and information on emerging technologies. The report is available on the project homepage [20].

Water-based IS: Residual wastewater

The composition and flowrate of residual wastewater can be calculated via OPTIEVLEX, a software developed at the Chair of Energy Network Technology (Montanuniversitaet Leoben) [21]. The wastewater flow in OPTIEVLEX is specified by the average hourly wastewater volume flow as well as the average concentrations of COD, TN (Total Nitrogen in the homogenized sample as nitrogen), and TP (Total Phosphorus in the homogenized sample as phosphorus) in mg per litre. Additionally, the inert fraction of soluble and particulate COD, as well as the inorganic fraction of filterable substances according to DWA [22], can be optionally defined. These user specifications influence SS (suspended solids) and TS (total solids) generation and allow an approximation to the actual plant-specific conditions.

The literature values for municipal wastewater generation and municipal wastewater composition embedded in OPTIEVLEX [21] can be used for calculations if no specifications are provided and are shown in Table 35. The average values for wastewater generation include usage by commercial establishments, public services, and the waterworks' own needs, explaining the increase with population growth. The wastewater from these facilities is usually treated in municipal treatment plants and therefore forms part of the municipal wastewater. Thus, the wastewater composition also reflects municipal wastewater. It is assumed that one inhabitant (I) corresponds to one population equivalent (PE).

Table 35: Literature values for the daily wastewater quantity in liter per inhabitant (I) and composition in grams per population equivalent (PE) and day (d) [21]

Wastewater generation		Wastewater composition	
Population equivalent	Wastewater quantity [lI ⁻¹ d ⁻¹]	Substance	Load [gPE ⁻¹ d ⁻¹]
< 5,000	150.00	COD	120.00
5,001 – 10,000	180.00	BOD ₅ ¹	60.00
10,001 – 100,000	210.00	TS ²	70.00
100,001 – 250,000	240.00	TP	1.80
> 250,000	275.00	TN	11.00

1 Biochemical oxygen demand within 5 days
2 Concentration of substances filterable with a 0.45 µm membrane after drying at 105 °C

The inflow fractionation is conducted for both specified and literature values according to worksheet DWA-A 131 [22]. Standard values for municipal wastewater of 0.05, 0.25, and 0.20 are assumed for the inert fraction of soluble and particulate COD as well as the inorganic fraction of filterable substances.

5.3 Key technologies in the context of IS

This chapter presents the findings of a comprehensive literature review conducted to identify and summarize key technologies crucial for the advancement of industrial symbiosis. The projects reviewed focus on industrial symbiosis (IS) technologies with unique outputs and approaches:

1. Hubs4Circularity offers a collection of 93 technologies relevant for IS, 40 of which are at TRL 6-9, along with patents and publications. Its searchable database links users to

- broader project pages rather than specific technology solutions, making in-depth information gathering a bit challenging [23].
2. Processes4Planet (P4P) focuses on transitioning the European process industries to circularity and climate neutrality. The portal includes 181 EU-funded projects, with outputs such as project descriptions and limited access to specific technologies (88 outputs available). Similar to Hubs4Circularity, the platform emphasizes project-level information [24].
 3. Water Europe Marketplace provides technologies centered on water, energy, and nutrient/material recovery. This user-friendly, technology-centered platform enables searches by domain and features detailed technology descriptions, case studies, and performance indicators. However, its focus is mainly on water-related IS technologies [25].
 4. SCALER compiles a database of key-enabling technologies for realizing 100 analyzed synergies across Europe. Its lists are comprehensive but difficult to navigate due to format constraints. Although detailed with numerous parameters, the database is not optimized for search and requires significant effort for technology-specific queries. [20]
 5. CORALIS has developed technology solution briefs aimed at assisting need owners—such as industry experts and researchers—who are seeking industrial symbiosis solutions at Technology Readiness Levels (TRL) 4 to 9. These briefs are designed to facilitate matchmaking between need owners and technology solution providers by being easily searchable and providing quick access to relevant information. The goal is to advance solutions toward TRL 9+ and commercialization. Additionally, the CORALIS briefs aim to bridge gaps between existing databases like Hub4Circularity, Processes4Planet, and SCALERS, as well as address the limitations of the Water Europe Marketplace. However, as a project, CORALIS does not commit to the long-term administration of a web portal.

Each platform provides valuable but distinct insights into IS technologies, with varying degrees of accessibility and user-friendliness. Further literature researched for collecting data for key technologies relevant for the hubs is summarized in Table 36.

Table 36: Literature research on data bases for technology and process data

Topic	Reference
Technology data	[26–28]
Electrolysis	[29–41]
Power-to-fuel	[33, 40, 42–50]
Carbon capture	[51–55]
Oxyfuel combustion	[56–59]
Post-combustion	[57]
Heat pumps	[60, 61]

Carbon based IS technologies

Data generated for carbon capture technologies are shown in Table 37.

Table 37: Key parameters of carbon capture technologies [51–55]

Key Parameters	Unit	Pre Combustion	Post Combustion MEA	Oxyfuel Combustion
TRL		9	9	5-8
Development		+	+	+
CO ₂ concentration	%CO ₂ /flue gas	20-40	98	80
Performance		+	+	+
CAPEX		high capital cost	lower capital costs	high capital cost
Costs		-	+	-
Implementation		change of the process needed	CC units can be simply added	change of the process needed
Integration Feasibility	-	-	+	-
Flue gas		CO ₂ high concentrated	syngas which contains H ₂ and CO ₂ is produced	lower NO _x concentration, easier purification
Gas quality		+	+	+

Energy based IS technologies

Data generated for electrolysis technologies are shown in Table 38.

Table 38: Key parameters of electrolysis technologies [29–41]

Key Parameters	Unit	AEL	PEMEL	SOEC
TRL		9	8-9	5-6
Development		+	+	-
Efficiency	%	68%	63%	83%
Production rates per unit	Nm ³ /h	1000	460	5,7
Energy consumption	kWh/kg	50-51	55-58	40-41
Plant capacity range	MW	up to 130	up to 6	0,018
Performance		+	+	-
Load gradient	%/s	20-100	5-100	-
Part load range	%	<1	10	0,05
Current density	A/cm ²	0,2-0,4	up to 2	0,46-1,3
Flexibility		-	+	-
CAPEX	\$/kW	988	1182	1346
Costs		+	-	-
Stack lifetime	H	85.000	45.000	-
System lifetime	Years	20	20	-
Life duration		+	+	-
Characteristics		not fit in load- operation	quick response to fluctuating energy	usage of waste heat possible
Sector Coupling		-	+	+

For the available waste heat, it can be recovered with the help of waste heat recovery technologies. Zhang et al. [62] classified waste heat recovery technologies into three main categories, namely direct utilization, transformation into electricity, and cascading systems which involve direct use of the higher-

temperature heat, while the remaining portion is transformed to electricity. Similarly, Brueckner et al. [63] identified four modes of waste heat recovery: 1. Direct recovery (e.g., using heat exchangers or thermal energy storage); 2. Transformation to a higher temperature level (e.g., via heat pumps); 3. Transformation to a lower temperature level (i.e., cooling via absorption or adsorption chillers etc.); 4. Transformation to electricity (e.g., through an organic Rankine cycle). Heat recovery technologies and equipment sometimes also are classified as “active” or “passive” depending on the actual manner of energy recovery or transformation [13]. Figure 14 illustrates this classification as follows:

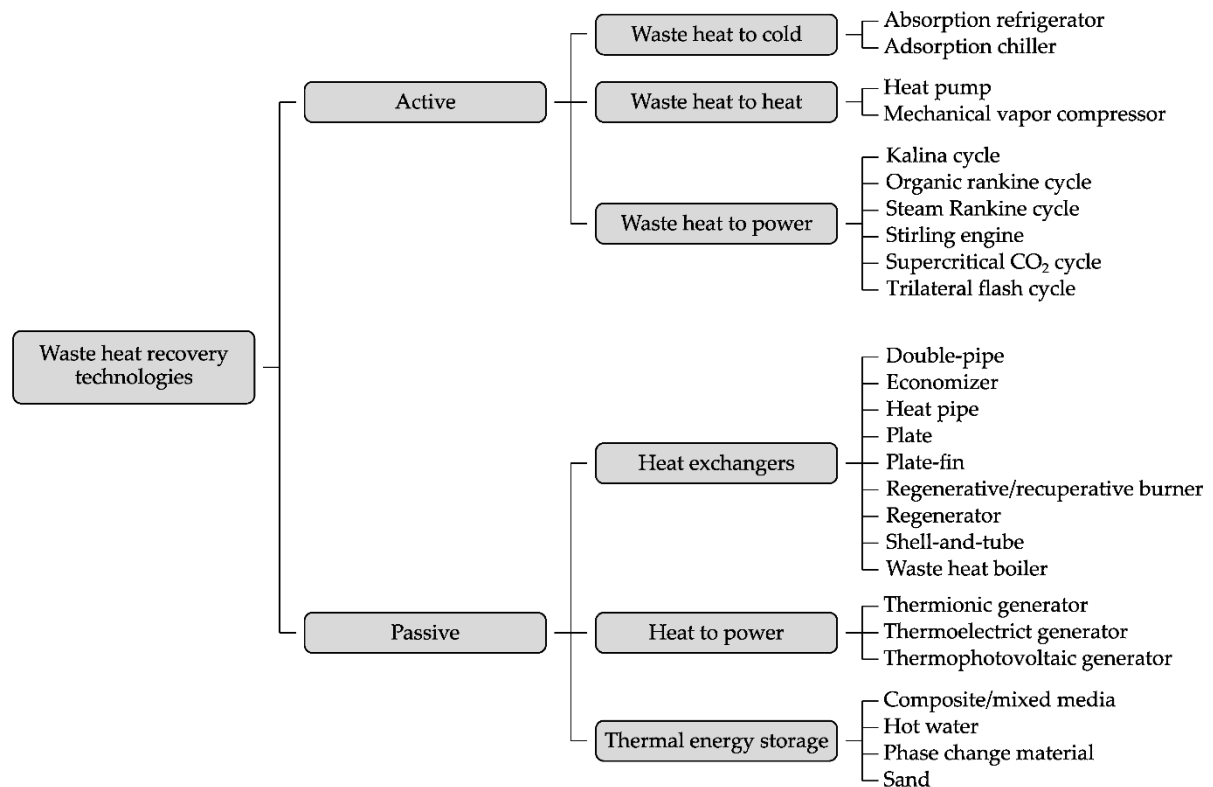


Figure 14: Classification of waste heat recovery technologies and equipment [13]

Based on this classification, Benedetti et. al. [18] have identified suitable technologies for waste heat recovery at different temperature levels as shown in Table 39. The classification of temperature level according to Benedetti et al. [18] is already presented in Table 33.

Table 39: Common waste heat recovery technologies [18]

Temperature Level	Applicable Technologies
Ultra-Low Level ($< 120^{\circ}\text{C}$)	Absorption refrigerator, Adsorption chiller, Air preheater, Economizer, Flat heat pipe, Heat pipe, Heat pump, Hot water building heating, Hot water storage, Kalina cycle, Organic Rankine cycle, Plate heat exchanger, Plate-fin heat exchanger, Recuperator, Shell-and-tube heat exchanger, Steam dehumidification, Stirling engine, Trilateral flash cycle, Waste heat boiler
Low Level ($120 - 230^{\circ}\text{C}$)	Absorption refrigerator, Adsorption chiller, Air preheater, Economizer, Flat heat pipe, Heat pipe, Heat pump, Hot water building heating, Hot water storage, Kalina cycle, Organic Rankine cycle, Plate heat exchanger, Plate-fin heat exchanger, Recuperator, Rankine cycle, Regenerator, Stirling engine, Supercritical CO_2 cycle, Trilateral flash cycle, Waste heat boiler
Medium Level ($230 - 650^{\circ}\text{C}$)	Air preheater, Economizer, Flat heat pipe, Heat pump, Kalina cycle, Organic Rankine cycle, Plate heat exchanger, Recuperator, Rankine cycle, Regenerator, Steam generator, Steam micro-turbine, Steam Rankine cycle, Stirling engine, Supercritical CO_2 cycle, Transcritical CO_2 cycle, Waste heat boiler
High Level ($650 - 870^{\circ}\text{C}$)	Flat heat pipe, Rankine cycle, Regenerative/recuperative burner, Regenerator, Steam generator, Steam micro-turbine, Steam Rankine cycle, Stirling engine, Supercritical CO_2 cycle, Transcritical CO_2 cycle
Ultra-High Level ($> 870^{\circ}\text{C}$)	Flat heat pipe, Recuperator, Regenerative/recuperative burner, Stirling engine

6. Outlook

The goal of task 2.1 to offer a generic approach for technology mapping in the context of IS is presented within this deliverable. This deliverable provides a basis for exploring synergies for industrial symbiosis by defining a generic hub structure suitable for hub specific IS. The hub specific technology maps are also discussed in the deliverable. The data collection instruments developed during this task i.e. Technology Fact Sheet (TFS) and Process Fact Sheet (PFS) have come out to be of critical importance for other partners and WP's as well. These fact sheets were circulated among the relevant partners. The TFS collected are listed in section 4. For the PFS, there are still some white spots that need to be filled as this information is also relevant for other work packages. White spots within the PFS data include process types, stream flow details etc. For the current deliverable, literature data are collected to support the investigation of hub specific technology maps. Actually data availability still needs to be increased in order to provide detailed technology maps at hub level. Since each hub is unique with respect to the industrial sector involved, relevant white spots are identified in this regard. Further, the data collection instruments developed during this task could also form the basis of work to be done in the successive tasks of the IS2H4C project. For instance, the data collected from the TFS and PFS can form the basis of modelling work to be performed in WP4 and further data on process streams within the hubs can be collected using the template provided. Moreover, this deliverable could also form the basis for the modelling of so-called artificial hub in WP4. Therefore, required steps to fill in the white spots can also be taken during task 4.1. The technology maps developed in Task 2.1 provide the necessary framework for the development of the model for artificial hub. In this deliverable we have delivered all the important Process definitions, identification and classifications that can aid the development of a generic industrial symbiosis hub model. The steps taken to develop the technology map framework and further suggested activities, are listed in Table 40.

Table 40: Development steps and suggested activities

Steps	Task	Progress	Suggested activities
Development of a generic approach for technology mapping in the context of IS	2.1	Finished	
Development of a Technology Fact Sheet	2.1	Finished	
Data collection at technology provider level via the Technology Fact Sheet	2.1, 4.1	Finished	Further development possible in WP4
Data collection at hub level via the Process Fact Sheet	2.1, 4.1	Finished	Further development possible in WP4
Further literature research to fill data gaps: industrial processes, technologies	2.1, 4.1	Finished	
Hub-specific technology maps	2.1, 4.1	Finished	Further development possible in WP4

Bibliography

- [1] BINDERBAUER, Paul Josef: *Synthetic Load and Generation Profiles in Industry*. Montanuniversität Leoben. 2024
- [2] GIELEN, Dolf ; TAYLOR, Michael: *Modelling industrial energy use: The IEAs Energy Technology Perspectives*. In: *Energy Economics* 29 (2007), Nr. 4, S. 889–912
- [3] EUROPEAN COMMISSION: *Classification of the Economic Sector : NACE Codes*
- [4] THIEDE, Sebastian: *Energy Efficiency in Manufacturing Systems*. 1st ed. Berlin, Heidelberg : Springer Berlin Heidelberg, 2012 (Sustainable Production, Life Cycle Engineering and Management)
- [5] FRACCASCIA, Luca ; YAZDANPANA, Vahid ; VAN CAPELLEVEEN, Guido ; YAZAN, Devrim Murat: *Energy-based industrial symbiosis: a literature review for circular energy transition*. In: *Environment, Development and Sustainability* 23 (2021), Nr. 4, S. 4791–4825
- [6] LUKAS KRIECHBAUM: *Exergy Efficient Municipal Multi Energy Systems*. Leoben, Montanuniversität Leoben, Chair of energy network technology. PhD thesis. 2020. URL [https://pureadmintest.unileoben.ac.at/portal/en/publications/exergy-efficient-municipal-multi-energy-systems\(672e62f2-e1ff-4295-acb3-37df765d0be6\).html?customType=theses](https://pureadmintest.unileoben.ac.at/portal/en/publications/exergy-efficient-municipal-multi-energy-systems(672e62f2-e1ff-4295-acb3-37df765d0be6).html?customType=theses) – Überprüfungsdatum 2024-06-26
- [7] HOCHMEISTER, Susanne ; KÜHBERGER, Lisa ; KULICH, Jakob ; OTT, Holger ; KIENBERGER, Thomas: *A methodology for the determination of future Carbon Management Strategies: A case study of Austria*. In: *International Journal of Sustainable Energy Planning and Management* 41 (2024), S. 108–124. URL <https://journals.aau.dk/index.php/sepm/article/view/8280>
- [8] BAINS, Praveen ; PSARRAS, Peter ; WILCOX, Jennifer: *CO2 capture from the industry sector*. In: *Progress in Energy and Combustion Science* 63 (2017), S. 146–172. URL <https://www.sciencedirect.com/science/article/pii/S0360128517300114>
- [9] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: *IPCC special report on carbon dioxide capture and storage*. 1. publ. Cambridge : Cambridge Univ. Press, 2005
- [10] RAMIREZ, Andrea ; EL KHAMLI, Aïcha ; MARKOWZ, Georg ; RETTENMAIER, Nils ; BAITZ, Martin ; JUNGMEIER, Gerfried ; BRADLEY, Tom: *LCA4CCU : Guidelines for life cycle assessment of carbon capture and utilisation*. Luxembourg : Publications Office of the European Union, 2022
- [11] KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation*. In: *Energies* 13 (2020), Nr. 1, S. 182
- [12] VAN DER ROEST, Els ; BOL, Ron ; FENS, Theo ; VAN WIJK, Ad: *Utilisation of waste heat from PEM electrolyzers – Unlocking local optimisation*. In: *International Journal of Hydrogen Energy* 48 (2023), Nr. 72, S. 27872–27891. URL <https://www.sciencedirect.com/science/article/pii/S0360319923015410>

- [13] TUREK, Vojtěch ; KILKOVSKÝ, Bohuslav ; DAXNER, Ján ; BABIČKA FIALOVÁ, Dominika ; JEGLA, Zdeněk: *Industrial Waste Heat Utilization in the European Union—An Engineering-Centric Review*. In: *Energies* 17 (2024), Nr. 9, S. 2084. URL <https://www.mdpi.com/1996-1073/17/9/2084>
- [14] SIMON HIRZEL, BENJAMIN SONTAG UND DR.-ING. CLEMENS ROHDE: *Industrielle Abwärmennutzung : Kurzstudie*. Karlsruhe, 2013
- [15] TOBIAS FLEITER (FRAUNHOFER ISI), PIA MANZ (FRAUNHOFER ISI), MARIUS NEUWIRTH (FRAUNHOFER ISI), FELIX MILDNER (FRAUNHOFER ISI), URBAN PERSSON (HU), KATERINA KERMELI (UU), WINA CRIJNS-GRAUS (UU), CATHELIJNE RUTTEN: *D5.1 Excess heat potentials of industrial sites in Europe : Documentation on excess heat potentials of industrial sites including open data file with selected potentials*. 2020
- [16] ANDREAS HAMMER, ELISABETH LACHNER, THOMAS KIENBERGER, WOLFGANG GRUBER-GLATZL, JASMIN PFLEGER, ANDREAS STÖGER, STEFAN REUTER, RALF-ROMAN SCHMIDT, SIMON MOSER, GABRIELA JAUSCHNIK: *Industrial Excess Heat – INXS : Erhebung industrieller Abwärmepotenziale in Österreich*. 2023
- [17] BUNDESMINISTERIUM KLIMASCHUTZ. UMWELT, ENERGIE, MOBILITÄT. INNOVATION UND TECHNOLOGIE: *Austrian Heat Map*. URL <https://austrian-heatmap.gv.at/startseite/>
- [18] BENEDETTI, Miriam ; DADI, Daniele ; GIORDANO, Lorena ; INTRONA, Vito ; LAPENNA, Pasquale Eduardo ; SANTOLAMAZZA, Annalisa: *Design of a Database of Case Studies and Technologies to Increase the Diffusion of Low-Temperature Waste Heat Recovery in the Industrial Sector*. In: *Sustainability* 13 (2021), Nr. 9, S. 5223. URL <https://www.mdpi.com/2071-1050/13/9/5223>
- [19] DR. ALI AYDEMIR (FRAUNHOFER ISI) HANNES DODERER (IKEM) FELIX HOPPE (BBHC) DR. SIBYLLE BRAUNGARDT: *ABWÄRMENNUTZUNG IN UNTERNEHMEN : Studie für das Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg*. Karlsruhe, 2019
- [20] JOÃO AZEVEDO, RUI DIAS, INÊS FERREIRA, JUAN HENRIQUES, MARCO ESTRELA, CRISTINA ASCENÇO: *Technology-database-for-synergies-setup-SCALER-D3.2*. 09/2019
- [21] KERSTIN PFLEGER-SCHOPF: *Kommunale Abwasserreinigungsanlagen mit optionaler thermischer Klärschlammverwertung als Flexibilitätsdienstleister in elektrischen Netzen*. Leoben, Montanuniversitaet Leoben, Chair of Energy Network Technology. Phd-Thesis. 10/2021. URL <https://pure.unileoben.ac.at/de/publications/kommunale-abwasserreinigungsanlagen-mit-optionaler-thermischer-kl> – Überprüfungsdatum 2024-11-02
- [22] ATV-DVWK, Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfall: *Bemessung von einstufigen Belebungsanlagen*. Entwurf, Frist zur Stellungnahme: 30. Juni 2015. Hennef, Deutschland : DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V, 2015 (DWA-Regelwerk Arbeitsblatt DWA-A 131)
- [23] HUBS4CIRCULARITY: *Hubs4Circularity*. URL <https://www.h4c-community.eu/>. – Aktualisierungsdatum: 2023-06-28 – Überprüfungsdatum 2024-11-05
- [24] *About Processes4Planet | A.SPIRE*. URL <https://www.aspire2050.eu/p4planet/about-p4planet>. – Aktualisierungsdatum: 2024-11-05 – Überprüfungsdatum 2024-11-05
- [25] *Water Europe Marketplace*. URL <https://mp.watereurope.eu/teb/>

- [26] DANISH ENERGY AGENCY: *Technology Data for Renewable Fuels*. URL <https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels>. – Aktualisierungsdatum: 2024-02-23 – Überprüfungsdatum 2024-03-28
- [27] HYJACK : HYDROGEN ONLINE: *Sizing & costing bricks - Hyjack : Hydrogen Online*. URL <https://hyjack.tech/components/>. – Aktualisierungsdatum: 2024-06-28 – Überprüfungsdatum 2024-06-28
- [28] TOM MEARES ; JAMES TYRRELL ; RUSSELL PENDLEBURY: *Hydrogen: the role of the hydrogen production industry in providing system services to the NEM*. URL <https://www.aemc.gov.au/hydrogen-role-hydrogen-production-industry-providing-system-services-nem>. – Aktualisierungsdatum: 2024-06-27 – Überprüfungsdatum 2024-06-28
- [29] *Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review*. URL <https://www.sciencedirect.com/science/article/pii/S136403211731242X#bib97>. – Aktualisierungsdatum: 2023-10-17 – Überprüfungsdatum 2023-10-17
- [30] REKSTEN, Anita H. ; THOMASSEN, Magnus S. ; MØLLER-HOLST, Steffen ; SUNDSETH, Kyrre: *Projecting the future cost of PEM and alkaline water electrolyzers; a CAPEX model including electrolyser plant size and technology development*. In: *International Journal of Hydrogen Energy* 47 (2022), Nr. 90, S. 38106–38113. URL <https://www.sciencedirect.com/science/article/pii/S0360319922040253>
- [31] GABRIELLI, Paolo ; GAZZANI, Matteo ; MAZZOTTI, Marco: *Electrochemical conversion technologies for optimal design of decentralized multi-energy systems: Modeling framework and technology assessment*. In: *Applied Energy* 221 (2018), S. 557–575. URL <https://www.sciencedirect.com/science/article/pii/S0306261918304872>
- [32] BLANCO, Herib: *Hydrogen production in 2050: how much water will 74EJ need?* URL <https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/>. – Aktualisierungsdatum: 2022-05-04 – Überprüfungsdatum 2022-06-21
- [33] ARNDT, Christoph ; NEULING, Ulf ; VORSATZ, Martin ; PRAUSE, Juliana ; MOLZBERGER, Uwe ; LE CLERCQ, Patrick ; FRECH, Guido ; WOLLENWEBER, Heiko ; TAUCHNITZ, Heiko ; JÄNISCH, Thorsten: *Konzeptionelle und technische Ausgestaltung einer Entwicklungsplattform für Power-to-Liquid-Kraftstoffe : Abschlussbericht* (2021)
- [34] FFE MÜNCHEN: *Elektrolyse – Die Schlüsseltechnologie für Power-to-X*. URL <https://www.ffe.de/veroeffentlichungen/elektrolyse-die-schlueseltechnologie-fuer-power-to-x/>
- [35] KAKOULAKI, G. ; KOUGIAS, I. ; TAYLOR, N. ; DOLCI, F. ; MOYA, J. ; JÄGER-WALDAU, A.: *Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables*. In: *Energy Conversion and Management* 228 (2021), S. 113649
- [36] MELANZI, Sarah ; SPILLER, Carla ; GROSSE, Benjamin ; HERMANN, Lisa ; KOCHEMS, Johannes ; MÜLLER-KIRCHENBAUER, Martin: *Technischer Stand und Flexibilität des Power-to-Gas-Verfahrens*. Berlin, 2018
- [37] PICHLMAIER, Simon ; HÜBNER, Tobias ; KIGLE, Stephan: *Elektrolyse – Die Schlüsseltechnologie für Power-to-X*. URL

<https://www.ffe.de/veroeffentlichungen/elektrolyse-die-schluesselftechnologie-fuer-power-to-x/>. – Aktualisierungsdatum: 2022-06-02 – Überprüfungsdatum 2022-06-02

- [38] ZHOU, Yuanrong ; SEARLE, Stephanie: *COST OF RENEWABLE HYDROGEN PRODUCED ONSITE AT HYDROGEN REFUELING STATIONS IN EUROPE*. In: *icct* (2022). URL <https://theicct.org/wp-content/uploads/2022/02/fuels-eu-cost-renew-h-produced-onsite-h-refueling-stations-europe-feb22.pdf> – Überprüfungsdatum 2022-06-21
- [39] CARMO, Marcelo ; FRITZ, David L. ; MERGEL, Jürgen ; STOLTEN, Detlef: *A comprehensive review on PEM water electrolysis*. In: *International Journal of Hydrogen Energy* 38 (2013), Nr. 12, S. 4901–4934. URL <https://www.sciencedirect.com/science/article/pii/S0360319913002607>
- [40] EGGEMANN, Lea ; ESCOBAR, Neus ; PETERS, Ralf ; BURAUDEL, Peter ; STOLTEN, Detlef: *Life cycle assessment of a small-scale methanol production system: A Power-to-Fuel strategy for biogas plants*. In: *Journal of Cleaner Production* 271 (2020), S. 122476
- [41] THE INTERNATIONAL RENEWABLE ENERGY AGENCY: *Green hydrogen cost reduction: Scaling up electrolyzers to meet the 1.5C climate goal*
- [42] DIETERICH, Vincent ; BUTTLER, Alexander ; HANEL, Andreas ; SPLIETHOFF, Hartmut ; FENDT, Sebastian: *Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review*. In: *Energy & Environmental Science* 13 (2020), Nr. 10, S. 3207–3252. URL <https://pubs.rsc.org/en/content/articlelanding/2020/ee/d0ee01187h>
- [43] HANNULA, Ilkka ; KAISALO, Noora ; SIMELL, Pekka: *Preparation of Synthesis Gas from CO₂ for Fischer–Tropsch Synthesis—Comparison of Alternative Process Configurations*. In: *C* 6 (2020), Nr. 3, S. 55. URL <https://www.mdpi.com/2311-5629/6/3/55>
- [44] BELLOTTI, D. ; SORCE, A. ; RIVAROLO, M. ; MAGISTRI, L.: *Techno-economic analysis for the integration of a power to fuel system with a CCS coal power plant*. In: *Journal of CO₂ Utilization* 33 (2019), S. 262–272. URL <https://www.sciencedirect.com/science/article/pii/S2212982019302550>
- [45] DIETERICH, Vincent ; BUTTLER, Alexander ; HANEL, Andreas ; SPLIETHOFF, Hartmut ; FENDT, Sebastian: *Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review*. In: *Energy & Environmental Science* 13 (2020), Nr. 10, S. 3207–3252. URL <https://pubs.rsc.org/en/content/articlelanding/2020/ee/d0ee01187h>
- [46] GAO, Ruxing ; ZHANG, Chundong ; JUN, Ki-Won ; KIM, Seok Ki ; PARK, Hae-Gu ; ZHAO, Tiansheng ; WANG, Lei ; WAN, Hui ; GUAN, Guofeng: *Transformation of CO₂ into liquid fuels and synthetic natural gas using green hydrogen: A comparative analysis*. In: *Fuel* 291 (2021), S. 120111. URL <https://www.sciencedirect.com/science/article/pii/S0016236120331082>
- [47] KISS, Anton A. ; PRAGT, J. J. ; VOS, H. J. ; BARGEMAN, G. ; GROOT, M. T. de: *Novel efficient process for methanol synthesis by CO₂ hydrogenation*. In: *Chemical Engineering Journal* 284 (2016), S. 260–269. URL <https://www.sciencedirect.com/science/article/pii/S1385894715011833>
- [48] WASSERMANN, Timo ; SCHNUELLE, Christian ; KENKEL, Philipp ; ZONDERVAN, Edwin: *Power-to-Methanol at Refineries as a Precursor to Green Jet Fuel Production: a*

Simulation and Assessment Study, Bd. 48. In: *30th European Symposium on Computer Aided Process Engineering* : Elsevier, 2020 (Computer Aided Chemical Engineering), S. 1453–1458

- [49] CHEN, Chao ; YANG, Aidong: *Power-to-methanol: The role of process flexibility in the integration of variable renewable energy into chemical production*. In: *Energy Conversion and Management* 228 (2021), S. 113673. URL <https://www.sciencedirect.com/science/article/pii/S0196890420311997>
- [50] PÉREZ-FORTES, Mar ; SCHÖNEBERGER, Jan C. ; BOULAMANTI, Aikaterini ; TZIMAS, Evangelos: *Methanol synthesis using captured CO₂ as raw material: Techno-economic and environmental assessment*. In: *Applied Energy* 161 (2016), S. 718–732. URL <https://www.sciencedirect.com/science/article/pii/S0306261915009071>
- [51] GARDARSDOTTIR, Stefania ; LENA, Edoardo de ; ROMANO, Matteo ; ROUSSANALY, Simon ; VOLDSUND, Mari ; PÉREZ-CALVO, José-Francisco ; BERSTAD, David ; FU, Chao ; ANANTHARAMAN, Rahul ; SUTTER, Daniel ; GAZZANI, Matteo ; MAZZOTTI, Marco ; CINTI, Giovanni: *Comparison of Technologies for CO₂ Capture from Cement Production—Part 2: Cost Analysis*. In: *Energies* 12 (2019), Nr. 3, S. 542
- [52] MIKULČIĆ, Hrvoje ; RIDJAN SKOV, Iva ; DOMINKOVIĆ, Dominik Franjo ; WAN ALWI, Sharifah Rafidah ; MANAN, Zainuddin Abdul ; TAN, Raymond ; DUIĆ, Neven ; HIDAYAH MOHAMAD, Siti Nur ; WANG, Xuebin: *Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO₂*. In: *Renewable and Sustainable Energy Reviews* 114 (2019), S. 109338. URL <https://www.sciencedirect.com/science/article/pii/S1364032119305465>
- [53] PEI, Peng ; BARSE, Kirtipal ; GIL, Andres J. ; NASAH, Junior: *Waste heat recovery in CO₂ compression*. In: *International Journal of Greenhouse Gas Control* 30 (2014), S. 86–96
- [54] SONG, Chunfeng ; LIU, Qingling ; DENG, Shuai ; LI, Hailong ; KITAMURA, Yutaka: *Cryogenic-based CO₂ capture technologies: State-of-the-art developments and current challenges*. In: *Renewable and Sustainable Energy Reviews* 101 (2019), S. 265–278
- [55] YANG, F. ; MEERMAN, J. C. ; FAAIJ, A.P.C.: *Carbon capture and biomass in industry: A techno-economic analysis and comparison of negative emission options*. In: *Renewable and Sustainable Energy Reviews* 144 (2021), S. 111028
- [56] ENARGUS: *Oxyfuel-Verfahren*. URL https://www.enargus.de/pub/bscw.cgi/d8360-2/*/*Oxyfuel-Verfahren.html?op=Wiki.getwiki. – Aktualisierungsdatum: 2022-05-11 – Überprüfungsdatum 2022-05-11
- [57] GERBELOVÁ, Hana ; VAN DER SPEK, Mijndert ; SCHAKEL, Wouter: *Feasibility Assessment of CO₂ Capture Retrofitted to an Existing Cement Plant: Post-combustion vs. Oxy-fuel Combustion Technology*. In: *Energy Procedia* 114 (2017), S. 6141–6149
- [58] HAN, Sang Heon ; LEE, Yeon Seung ; CHO, J. R. ; LEE, Kyun Ho: *Efficiency analysis of air-fuel and oxy-fuel combustion in a reheating furnace*. In: *International Journal of Heat and Mass Transfer* 121 (2018), S. 1364–1370
- [59] NEMITALLAH, Medhat A. ; HABIB, Mohamed A. ; BADR, Hassan M. ; SAID, Syed A. ; JAMAL, Aqil ; BEN-MANSOUR, Rached ; MOKHEIMER, Esmail M. A. ; MEZGHANI, K.:

Oxy-fuel combustion technology: current status, applications, and trends. In: *International Journal of Energy Research* 41 (2017), Nr. 12, S. 1670–1708

- [60] ADAMSON, Keri-Marie ; WALMSLEY, Timothy Gordon ; CARSON, James K. ; CHEN, Qun ; SCHLOSSER, Florian ; KONG, Lana ; CLELAND, Donald John: *High-temperature and transcritical heat pump cycles and advancements: A review*. In: *Renewable and Sustainable Energy Reviews* 167 (2022), S. 112798. URL
<https://www.sciencedirect.com/science/article/pii/S1364032122006827>
- [61] MARINA, A. ; SPOELSTRA, S. ; ZONDAG, H. A. ; WEMMERS, A. K.: *An estimation of the European industrial heat pump market potential*. In: *Renewable and Sustainable Energy Reviews* 139 (2021), S. 110545. URL
<https://www.sciencedirect.com/science/article/pii/S1364032120308297>
- [62] ZHANG, Qi ; ZHAO, Xiaoyu ; LU, Hongyou ; NI, Tuanjie ; LI, Yu: *Waste energy recovery and energy efficiency improvement in China's iron and steel industry*. In: *Applied Energy* 191 (2017), S. 502–520. URL
<https://www.sciencedirect.com/science/article/pii/S0306261917300909>
- [63] BRUECKNER, Sarah ; MIRÓ, Laia ; CABEZA, Luisa F. ; PEHNT, Martin ; LAEVEMANN, Eberhard: *Methods to estimate the industrial waste heat potential of regions – A categorization and literature review*. In: *Renewable and Sustainable Energy Reviews* 38 (2014), S. 164–171. URL
<https://www.sciencedirect.com/science/article/pii/S1364032114003165>

Appendix

The following appendix describes the Technology Fact Sheet (TFS), a detailed template that serves as the data collection instrument for the developed technology concepts within the framework of the project. The TFS is an Excel-Sheet and supports the systematic collection and harmonised documentation of technological information, ensuring comparability across different processes, sectors and hubs. Furthermore, the Process Fact Sheet (PFS) to analyse industrial process routes in more detail is presented. The PFS is an Excel-Sheet and supports the data gathering process for modelling and analysing industrial demand and production profiles via Ganymed. Moreover, possible sources and sinks for industrial symbiosis technologies and activities, like waste heat streams, can be identified.

Technology Fact Sheet

The first part of the TFS is designed to collect general information on the technology, including a graphical description, technical function, and main technical objectives. It also records data on the technology readiness level (TRL), relevant scientific publications, and the industrial sectors in which the technology can be applied. This should offer the basis for a first evaluation of possible symbiosis applications. The design and structure of the first part of the TFS is shown in Figure 15 and Figure 16.

The second part of the TFS focuses on the technological parameters of the processes and the process flows. It includes both technical and financial data relevant to process operation and performance. The number of defined input and output flows can be extended as required when the process involves multiple material or energy streams. This part of the TFS should provide data to for characterising input and output streams to identify sources and sinks, as well as linking streams for enabling industrial symbiosis. The design and structure of the second part of the TFS is illustrated in Figure 17 and Figure 18.

Process Fact Sheet

The PFS focuses on the input and output flows within industrial process routes, as well as on relevant process parameters for estimating synthetic demand and production profiles of industrial process routes. The detailed structure of the PFS is presented in Figure 19.

Technology Fact Sheet - General Description

Short technology description

[Please include a publishable description of the technology.]

Graphical description

[Please include a picture describing the technology f.ex. a flow sheet, schematic layout etc.]

Technical function

[Please include a technical description of the technology, including an explanation of the graphical description above.]

Technical objective

[Please mark applicable with x]

- Alternative material
- Material efficiency
- Electrification of processes
- Energy efficiency
- CCU/S
- Green gases especially hydrogen
- Flexibilisation
- Industrial Symbiosis
- Circular economy

Technology readiness level

[Please mark applicable with x]

- TRL 1 - Basic principles observed
- TRL 2 - Technology concept formulated
- TRL 3 - Experimental proof of concept
- TRL 4 - Technology validated in lab
- TRL 5 - Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 - Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 - System prototype demonstration in operational environment
- TRL 8 - System complete and qualified
- TRL 9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 15: Technology Fact Sheet - general description (1/2)

Potential fields of application	Best practice applications
<i>[Please give up to 5 examples]</i>	<i>[Please give up to 5 already demonstrated application examples]</i>
<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>
Applicable in following industrial sectors	<input type="checkbox"/> Iron and steel <input type="checkbox"/> Chemical and petrochemical <input type="checkbox"/> Non-ferrous metals <input type="checkbox"/> Non-metallic minerals <input type="checkbox"/> Paper, pulp and printing <input type="checkbox"/> Transport equipment <input type="checkbox"/> Machinery <input type="checkbox"/> Mining and quarrying <input type="checkbox"/> Food, beverages and tobacco <input type="checkbox"/> Wood and wood products <input type="checkbox"/> Construction <input type="checkbox"/> Textile and leather <input type="checkbox"/> Other
<i>[Please mark applicable with x]</i>	
Applicable in following hubs	<input type="checkbox"/> Izmir-Manisa <input type="checkbox"/> Basque Industrial <input type="checkbox"/> Almelo & H2Hub Twente <input type="checkbox"/> Industriepark Höchst
<i>[Please mark applicable with x]</i>	
Relevant publications	<p style="text-align: center;"><i>[Please list the scientific literature already available.]</i></p>

Figure 16: Technology Fact Sheet - general description (2/2)



Technology Fact Sheet - Technology Parameters

0		0
0		0
0		0
0		0
0		0

[Please include a picture describing the technology f.ex. a flow sheet, schematic layout etc.]

Process

[Please define technology specific process parameters. Only fill in the green fields that are suitable for your technology.]

Process data:

Financial data:

CAPEX €
OPEX €/a

Technical data:

Technical lifetime a
Process efficiency %
Separation efficiency %
Temperature level/range K
Pressure level/range Pa
Operation mode
Full-load hours h/a
warm start-up time h
cold start-up time h
Comments on environmental effects
Further comments

Figure 17: Technology Fact Sheet - technology parameters (1/2)



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Input		Output	
<i>[Please define up to 5 input streams. Only fill in the green fields that are suitable for your technology.]</i>		<i>[Please define up to 5 output streams. Only fill in the green fields that are suitable for your technology.]</i>	
Details input flow 1:		Details output flow 1:	
Name of flow 1		Name of flow 1	
Type	Please select	Type	Product
<i>Please fill in if energy has been selected as type:</i>		<i>Please fill in if energy has been selected as type:</i>	
Energy form	Please select	Energy form	Please select
Energy source	Please select	Energy source	Please select
Amount		Amount	MWh/a
Energy density		Energy density	kWh/m ³
<i>Please fill in if material has been selected as type:</i>		<i>Please fill in if product, by-product or waste has been selected as type:</i>	
Main components	Name	Share [%]	
#1			
#2			
#3			
State of aggregation	Please select		
Density			kg/m ³
<i>Please fill in for energy and material flows when available:</i>		<i>Please fill in for all kind of output flows when available:</i>	
Volume flow		Volume flow	m ³ /h
Mass flow		Mass flow	kg/h
Pressure level/range		Pressure level/range	Pa
Temperature level/range		Temperature level/range	K
Flow continuity	Please select	Flow continuity	Please select
Comments on material quality		Comments on critical substances	
Further comments		Comments on dust loading	
		Comments on potential application of waste streams	

Figure 18: Technology Fact Sheet - technology parameters (2/2)





Process Fact Sheet - Industrial Process Parameters

Goal within the project

The goal is to map industrial processes within hub models to identify industrial symbiosis (IS) synergies and generate mutual benefits for both industrial partners and hubs. This approach aims to enhance resource efficiency, optimize energy use, and improve overall system performance by creating interconnected and collaborative industrial ecosystems.

Benefit for industrial partners

System analysis can help industrial partners to:

- Identify waste heat recovery potentials
- Estimate energy efficiency potentials
- Identify synergies with other industrial partners or urban areas
- Estimate potentials for the integration climate neutrality technologies (e.g. battery storages, heat storages, heat pumps, electrolyzers)
- Evaluate flexibilities of processes to integrate renewable energy.

Method (Ganymed)

To achieve this goal, we use Ganymed, an advanced simulation tool that models time-resolved energy load profiles for industrial processes. It combines powerful simulation models with a dynamic user interface, enabling the creation and optimization of production chains.

Please click here for more info:

[Doctoral Thesis P.J. Binderbauer Ganymed](#)

Process line 1

	Process block 1	Process block 2	Process block 3	Process block 4	Process block 5	Process block 6	Process block 7	Process block 8	Process block 9	Process block 10
Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined	Please select from the dropdown box or write if it is not predefined
Type of process (thermal etc.)	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
Continuity of the process	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select
1) Continuous process: Throughput	t/h	t/h	t/h	t/h	t/h	t/h	t/h	t/h	t/h	t/h
2) Batch process: Unit Size	t	t	t	t	t	t	t	t	t	t
Turnover time	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.
Process duration for chosen unit size	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.
Product intake temperature	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Operating temperature	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Specific consumption of electricity:	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t
Specific consumption of direct fuel:	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t
Specific consumption of steam:	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t
Specific consumption of waste heat:	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t
Type of consumed waste heat:	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
When available, consumption time series kWh/t per minute	Please provide	Please provide	Please provide	Please provide	Please provide	Please provide	Please provide	Please provide	Please provide	Please provide
Input material for process block	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
Output material for process block	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
How much input is needed for 1 tonne of output for process block	t/t output	t/t output	t/t output	t/t output	t/t output	t/t output	t/t output	t/t output	t/t output	t/t output
Probability of bypassed products	%	%	%	%	%	%	%	%	%	%
Excess heat energy carrier:	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
Excess heat - output temperature of process	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Available excess heat	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t	kWh/t
Connect fluctuation of excess heat to:	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write	Please select or write
Full load hours	h/a	h/a	h/a	h/a	h/a	h/a	h/a	h/a	h/a	h/a
Is it possible to adjust the performance of the process?	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select
Is it possible to shift the process timely?	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select	Please select
Peak consumption	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
Average power consumption	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
Nominal power	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW

Figure 19: Process Fact Sheet



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