INITIATE
A STEPWISE PROJECT

PUBLIC

DELIVERABLE 6.4:
INVENTORY OF SUCCESSFUL SYMBIOTIC RELATIONSHIPS

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Version Management

VERSION	DETAILS
V20220919	Draft Version
V20220923	First review revision
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Disclaimer

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List of abbreviations

CAPEX	Capital Cost
CCS	Carbon capture and storage
CO_2	Carbon dioxide
H2	Hydrogen
IEA	International Energy Agency
IRR	Internal rate of return
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCOE	Levelized cost of electricity
LCOP	Levelized cost of product
PMC	Product-Market combination
KPI	Key-Performance Indicator
BFG	Blast Furnace Gas
BOFG	Basic Oxygen Furnace Gas
DALY	Disability-adjusted life years
DRI	Direct Reduced Iron
TRL	Technology Readiness Level

INITIATE
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Executive Summary

INITIATE proposes a novel symbiotic process to produce urea from steel residual gases. The project consists of demonstrating the innovations at TRL7, assessing the impact of the technology, developing a commercial implementation roadmap and designing a bankable commercial plant. The symbiosis is enabled using SEWGS (Figure 1). In this report an inventory of Product-market combinations (PMCs) and symbiotic relationships which can be enabled by the SEWGS technology is presented. Product-market combinations suitable for application of the SEWGS technology, broader than urea production (i.e., INITIATE process), are considered in this inventory. As long-term roll-out will be defined by collaboration between stakeholders, inventory of the key performance indicators (KPIs) on suitability for industrial symbiosis and on a multi-stakeholder methodology development is part of this report. The inventory of PMCs and KPIs will be used in Task 6.4 of the project, where three PMCs will be selected for in-depth evaluation.

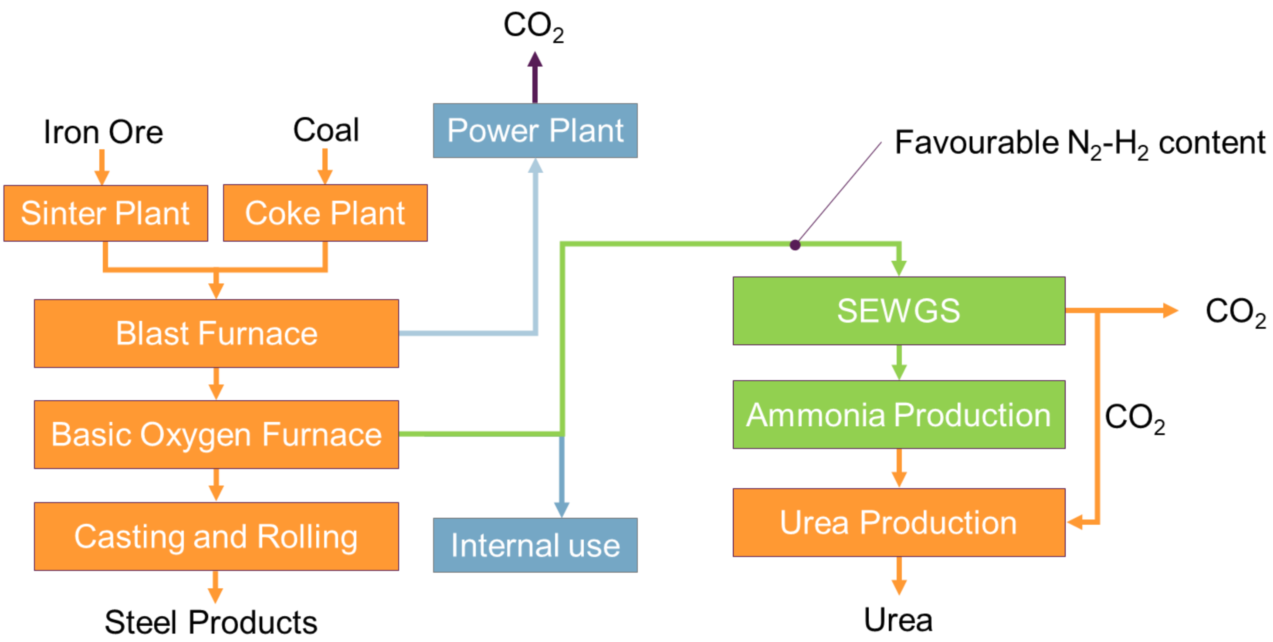

Figure 1: Schematic description of the symbiotic process enabled with SEWGS

The long-list of product-market combinations contains products based on the hydrogen content of the streams (such as ammonia, methanol [1]) and products based on the CO_2 content of the residual gases (such as Polyurethane [2]). The scope of the project is to use the hydrogen content of residual gases, therefore synergies based solely on the CO_2 content are not considered for the final selection of Product Market Combinations. Products which use both the hydrogen and the CO_2 content, such as Urea, are placed in scope of the long-list. The final selection of product market combinations is shown in Table 1.

Table 1: Selected Product market combinations

Product	Market
Hydrogen	Energy – external
	Energy – internal
	DRI
	Feedstock
Urea	Fertilizer
	Animal feed
	Diesel Exhaust Fluid
	Resins
Methanol	(Syn-)fuels
	Chemical
Ammonia	Fertilizer
	Fuel
	Energy
	Chemical

A long list of 106 KPIs to support strategic decision making was formed, these KPIs assess the feasibility of industrial symbiosis in the context of INITIATE or the level to which a PMC supports the development of a multi-stakeholder decision making methodology. The selected KPIs are specifically tailored to compare the identified PMCs. The following criteria applied to the selection of KPIs:

- Recognized by industry stakeholders and methodology developers
- Information availability
- Able to compare on PMC level, not only on case level.

The KPIs for all clusters are ranked by their importance by stakeholders from the steel, chemical and knowledge industry. The six KPI clusters and their corresponding KPIs were discussed. The KPIs were ranked between 1 (low) and 5 (high) for strategic decision making. These results will be used in selection of the most interesting PMCs in Task 6.5 and are the basis for the long-term strategy development. In order to assess the relevance of the KPI ranking, the results from the steel and chemical industry were compared. This results in one big difference between these industries regarding the market potential KPIs:

- The chemical industry ranks the EU market low (16th) and the global market high (5th)
- The steel industry ranks the EU market high (4th) and the global market low (15th)

Therefore, to consider both perspectives, both market potential KPIs are ranked on their highest location, respectively 4th and 5th for the EU and global market.

In Table 2 the results for the business KPI ranking are shown, based on the results from Steel & Chemical company participants. Per criteria, the results are sorted from the most important, to least important.

Table 2: Results of ranking the business KPIs

Rank	KPI	Cluster
1	Levelized cost of product	Economic
2	Legislation	Societal
3	CO2 abatement cost	Economic
4	Market size EU	Economic
5	Market size Global	Economic
6	GHG Emission	Societal
7	Cost distribution	Innovation ecosystem
8	Governance	Innovation ecosystem
9	Scale of accessible infrastructure	Business model
10	Alternatives	Economic
11	Utilization of residual gases	Business model
12	Significant Air Emissions	Societal
13	Community development	Innovation ecosystem
14	Contribution to Sustainable Development Goals	Societal
15	Job creation and retention	Societal
16	Access to knowledge	Business model
17	Ease of distribution	Business model

Main takeaways for inventory of PMCs in an industrial symbiosis are:

- High level characterization of PMCs is facilitated by the “Synergy classification” part of the SCALER approach.
- The main denominators in the characterized PMCs are the **element of interest**, which are with associated the **receiving industry**, and the **resource exchanged**, which is split between material and energy.
- In the case of SEWGS, the relevant business model criteria were specific to the stakeholders and specific case. KPIs in the other clusters were raised and proposed in literature.
- Next to making an inventory of evaluation criteria, it is important to assess for each party involved the relative importance of these criteria for decision-making.

- The ranking of importance differs with the subset of PMCs that are studied (example ease of distribution) and the parties in the consortium.

The results of the inventory of PMCs and KPIs will be considered in the multi-stakeholder decision support process to develop a long-term strategy:

- The ranked KPIs will be weighed and assessed for each PMC, leading to a selection of promising PMCs.
- The associated longlisted KPIs will be used in development of the long-term strategy
- The KPI assessment and interviews will be used in the multi-stakeholder methodology development.

Introduction

The following report describes the method and findings from a study into symbiotic relationships as part of the Horizon 2020 funded INITIATE project on behalf of the European Commission. This study has been conducted as part of WP6 “Commercial implementation plan”, and specifically Task 6.3 “Inventory of successful symbiotic relationships”.

INITIATE proposes a novel symbiotic process to produce urea from steel residual gases, based on the SEWGS technology [3] as shown in Figure 2. The considered residual gases emerge from the blast furnace (BFG) or from the basic oxygen furnace (BOFG). The project consists of demonstrating the innovations at TRL7, assessing the impact of the technology, developing a commercial implementation roadmap and designing a bankable commercial plant. The SEWGS process consists of a water-gas shift reaction and a carbon capture process in one reactor. Applying the SEWGS process to residual steel gases results in a CO_2 rich gas stream and a hydrogen rich gas steam. These streams can be used to make several products, including urea. This report assesses the full scale of symbiotic relationships which the core SEWGS technology can enable. It aims to contribute to the commercial implementation roadmap for the INITIATE process. The inventory is structured by working with Product-Market combinations, which allows for a clear and structured method to identify and compare different symbiotic options that can be facilitated by the SEWGS technology. As long-term roll-out will be defined by collaboration between stakeholders, an inventory of the key performance indicators on suitability for industrial symbiosis and multi-stakeholder methodology development is part of this report. The inventory of PMCs and KPIs will be used in Task 6.4 of the project, where three PMCs will be selected for in-depth evaluation.

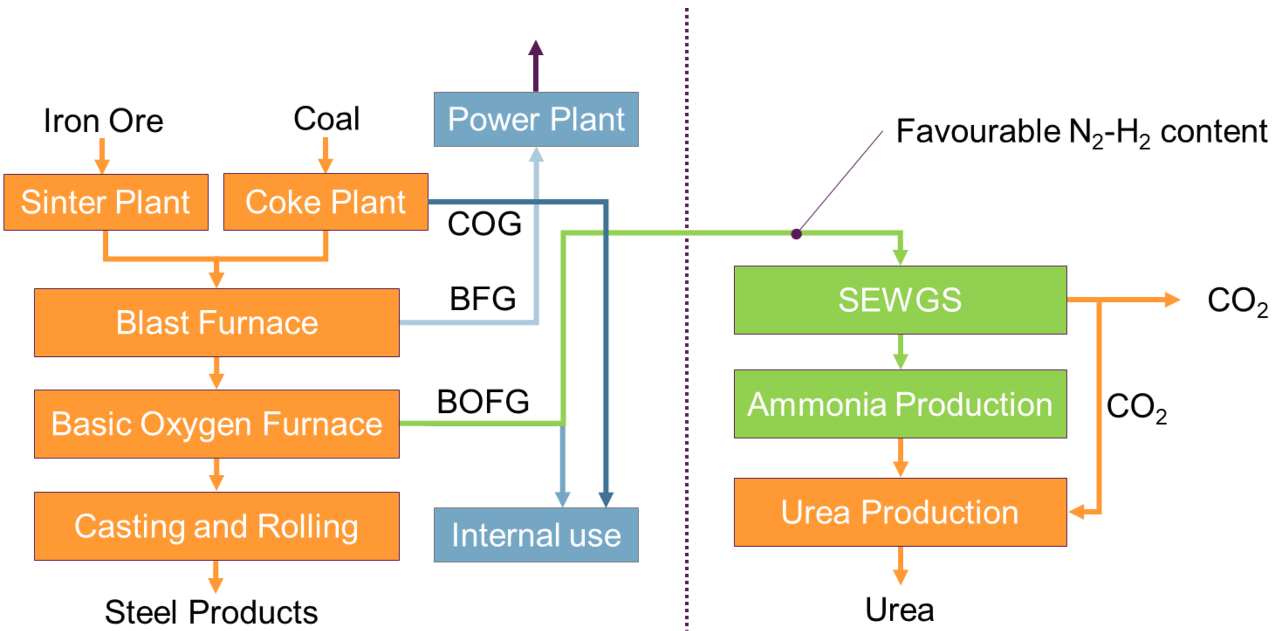

Figure 2: Schematic description of the symbiotic process enabled with SEWGS

In Chapter 1, an inventory of alternatives (PMCs) is developed based on the utilization of residual steel gases. These PMCs are classified according to specific metrics and in alignment with the SCALER classification model. A selection of key performance indicators (KPIs) to assess the suitability for industrial symbiosis is presented in Chapter 2. These KPIs are ranked based on input from key stakeholders in the chemical, steel and knowledge industry regarding the SEWGS technology, thereby considering the full value chain. In Chapter 3, conclusions regarding industrial symbiosis in general and follow-up towards the long-term strategy are discussed.

The results of this study are used in Tasks 6.4 and 6.5, in which a selection will be made of the identified PMCs using the KPIs from this report. The long list of KPIs will be used to develop a long-term strategy. The results of business model development and innovation ecosystems will be part of the development for a multi-stakeholder decision support methodology.

1. Product-Market combinations

INITIATE proposes a novel symbiotic process to produce urea from steel residual gases, based on the SEWGS technology [3]. Applying the SEWGS process to residual steel gases results in a CO_2 rich gas stream and a hydrogen rich gas steam. These streams can be used to make several products, including urea. This report assesses the full scale of symbiotic relationships which the core SEWGS technology can enable. The inventory is structured by working with Product-Market combinations, which allows for a clear and structured method to identify and compare different symbiotic options that can be facilitated by the SEWGS technology. This Chapter describes the identification and classification of these PMCs.

1.1. Identification

14 product-market combinations have been identified as potential symbiosis options between steel and other industries. The symbiosis is enabled using the SEWGS technology. These PMCs have been selected from a long list of combinations generated through workshops, interviews, data from previous projects and Task 5.4 of the INITIATE project.

In order to allow for structural comparison of PMCs guided by a multistakeholder decision making methodology, boundary conditions were set to include PMCs. These boundary conditions are based on the Value Case Methodology [4]. Synergies with regards to SEWGS can contain products consuming hydrogen (such as ammonia and methanol [1]) and carbon dioxide (such as Polyurethane [2]). The scope of the study is to use the hydrogen content of residual gases. Therefore, synergies based solely on the CO_2 content are not considered for the final selection of PMCs. Products which use both the hydrogen and the CO_2 content, such as urea, are placed in scope of the long-list. The boundary conditions leading to the final selection (Table 3) are:

- The decision has to be made by multiple stakeholders, as this is required for methodology development later on in the project.
- The end-product has clear alternatives.
- The end-product is based on the hydrogen content of steel residual gases.

In the following sections, the selected product market combinations are described.

Table 3: Selected Product market combinations

Product	Market
Hydrogen	Energy – external
	Energy – internal
	DRI
	Feedstock
Urea	Fertilizer
	Animal feed
	Diesel Exhaust Fluid
	Resins
Methanol	(Syn-)fuels
	Chemical
Ammonia	Fertilizer
	Fuel
	Energy
	Chemical

1.1.1. Hydrogen

Hydrogen (Chemical formula: H_2), is a chemical element which is currently produced in two ways: by natural gas reforming or by electrolysis as described in Figure 3. In the reformer, natural gas reacts with steam under pressure using a catalyst to produce hydrogen and carbon monoxide. Next, the produced carbon monoxide and steam are reacted in the water-gas shift reaction to create hydrogen and CO_2. An electrolyzer uses electricity to split water into hydrogen and oxygen. The hydrogen produced from electrolysis has a higher purity compared to the hydrogen from a reformer.

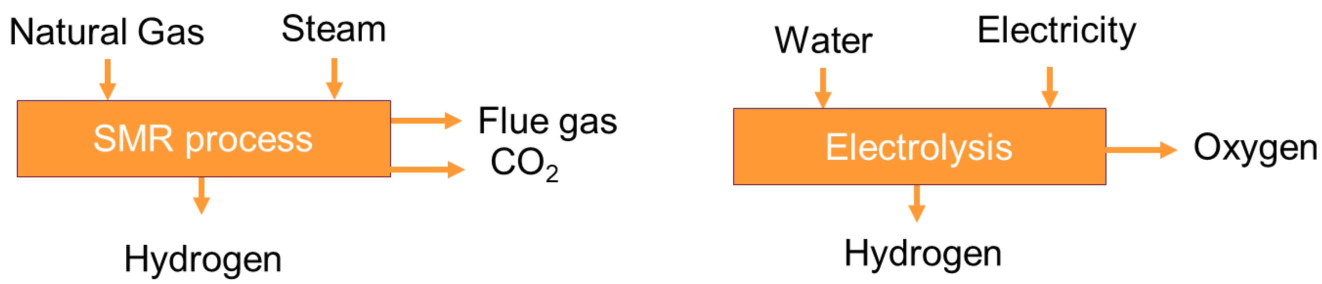

Figure 3: Stand-alone hydrogen production

Hydrogen can be produced from residual gases of steel production by capturing CO_2 from the residual gases and purifying the left-over hydrogen rich gas. The residual gas from the steel process is fed through a pre-water gas shift section before entering the SEWGS section, in which the remaining CO is converted to CO_2 and H_2. The CO_2 is removed from the gas phase. The exiting gas stream is a mixture of hydrogen and nitrogen, which can be purified for specific applications of hydrogen. The complete process is described as part of the STEPWISE project ([5], Figure 4).

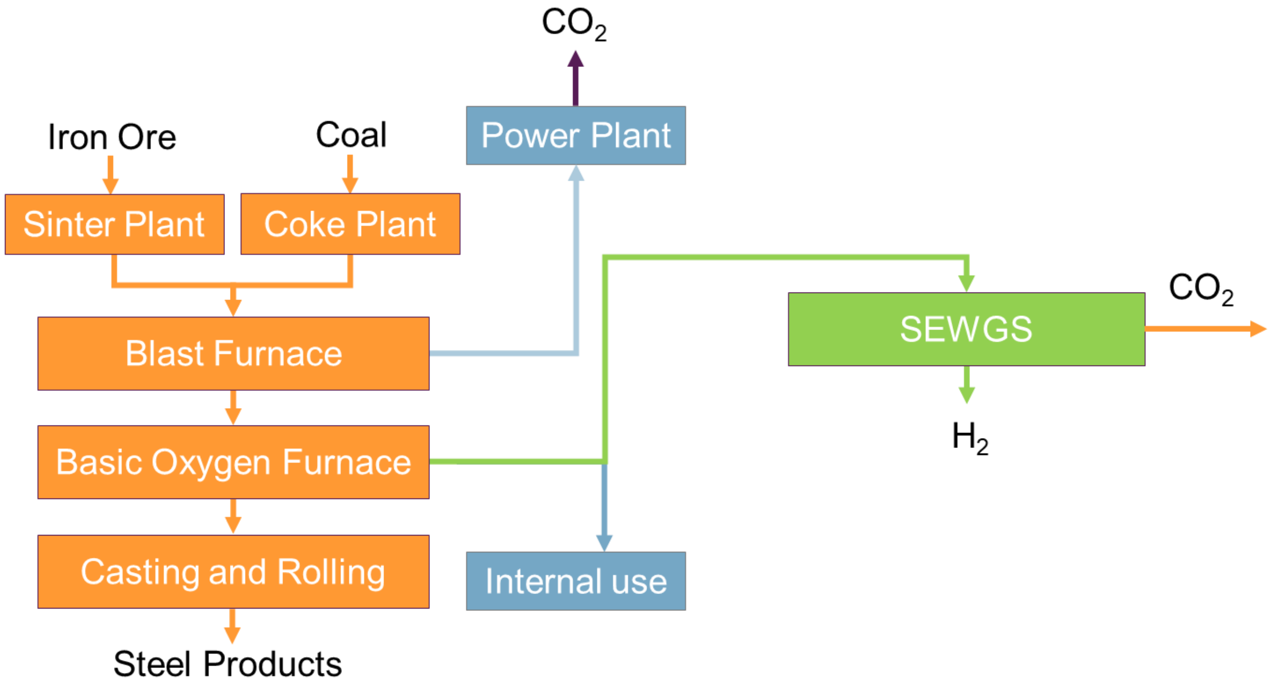

Figure 4: Hydrogen production from residual steel gases (based on STEPWISE [5])

The main application of hydrogen is as a base chemical for (petro-)chemistry. It is expected that the hydrogen market will change drastically due to the energy transition. This change applies to the current application as a base chemical and foresees markets for hydrogen as energy carrier or fuel. The Sustainable Development Scenario of the IEA specifically sees hydrogen used as feedstock for synfuel in aviation and shipping by making methanol and ammonia. Furthermore, direct fuel applications in short-distance shipping and road transport are foreseen. In the energy sector, the IEA expects applications in direct power generation, refining and heating of buildings [6]. Hydrogen can also be used in the steel-making process itself; the STEPWISE project [7] analyzed the use of SEWGS technology to decarbonize the local electricity production and deep decarbonization of its internal use. Within the INITIATE project Task 5.4, poses the use of produced hydrogen for DRI as application. In this application, the natural gas feed of an NG-DRI plant is replaced with hydrogen produced from the residual gases using SEWGS.

1.1.2. Ammonia

Ammonia (Chemical formula: NH_3) is a chemical which is produced from hydrogen and nitrogen. In the reference case natural gas is used as hydrogen source, using steam reforming. With this method ammonia is manufactured by: (1) catalytic steam reforming, where hydrogen is produced and nitrogen is introduced in the process, (2) clean-up of the reformed stream, removing CO_2 and (3) producing ammonia from the nitrogen and hydrogen stream as described by Zecca et al. [8]. In this process CO_2 is emitted or should be captured and stored (**Error! Reference source not found.**).

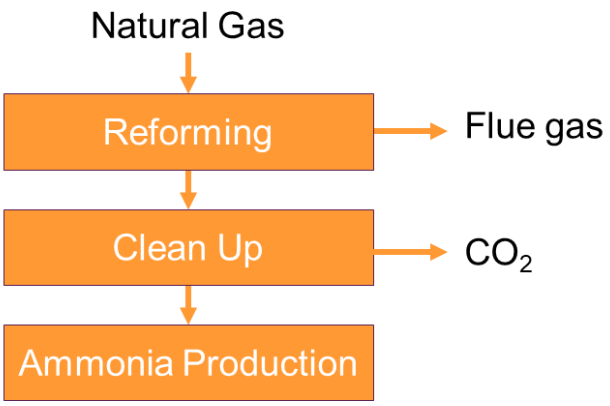

Figure 5: Stand-alone ammonia production (based on [8])

Ammonia can also be produced residual steel gases by capturing CO_2 and using the remaining hydrogen rich gas to produce ammonia. The complete process is described in the BOF2UREA project, where the process includes urea production (**Error! Reference source not found.**, [9]). The residual gas from the steel process is fed through a pre-water gas shift section before entering the SEWGS section, in which the remaining CO is converted to CO_2 and H_2. The CO_2 is removed from the gas phase. The exiting mixture of hydrogen and nitrogen is purified and fed into the ammonia loop. The yield of the ammonia depends on the ratio of H_2 and N_2.

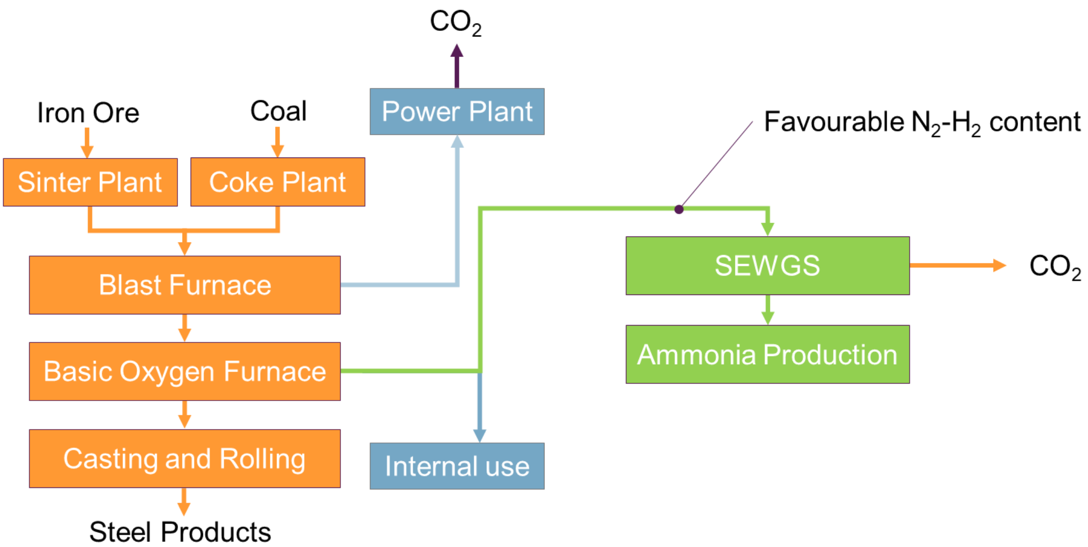

Figure 6: Ammonia production from residual steel gases (based on BOF2UREA [9])

The main application of ammonia is as a source for nitrate-based fertilizers, which adds up to 47% of the total EU fertilizer use in 2019/2020, ammonia for urea production is not considered [10]. Another prevalent application of ammonia is as a base chemical for producing plastics, explosives and synthetic fibers [11]. Besides these existing markets and applications, ammonia is a future low-carbon energy carrier and fuel. The Sustainable Development Scenario of the IEA specifically sees ammonia fuel for shipping, covering half of the total fuel demand from ships [6]. As an energy carrier, ammonia can fit the same role as foreseen for hydrogen. It can compete in this sector, which will mean a possible application for heating in industry and electricity generation [12].

1.1.3. Urea

Urea (Chemical formula: $CO(NH_2)_2$) is a chemical produced from ammonia and carbon dioxide. Urea is conventionally produced by combining ammonia from natural gas with carbon dioxide. The carbon dioxide is removed during the production of ammonia. The production process for producing urea from natural gas is shown schematically in Figure 7. Ammonia is produced using the steam reforming method. Urea is synthesized from the ammonia and the CO_2 captured in the clean-up step. Ammonia and CO_2 react at high pressure in ammonium carbamate and dehydrates to form urea and water, as described in INITIATE Deliverable 5.3 [8].

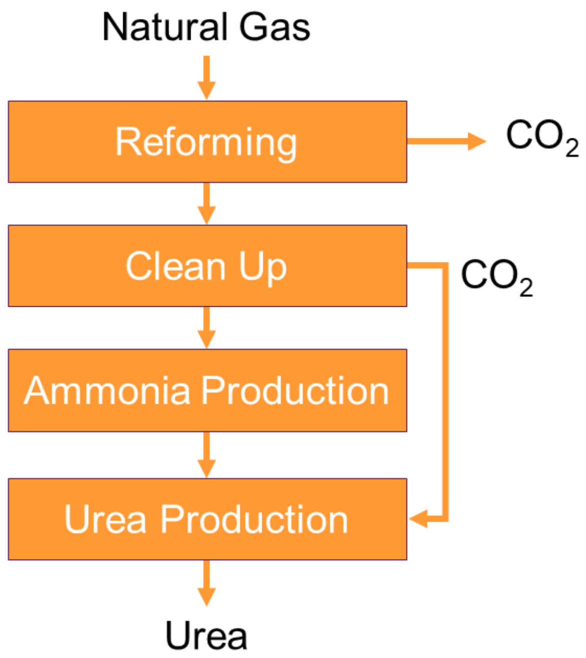

Figure 7: Ammonia plant coupled with urea plant (based on [8])

Urea can be produced from residual steel gases by capturing CO_2 from the residual gases and using the hydrogen rich gas to produce ammonia. The part of ammonia production is described in the previous section (Figure 7). The resulting ammonia is cooled to a liquid and stored. This ammonia is compressed and mixed with part of the captured CO_2 in the SEWGS step to produce urea. Remaining CO_2 is transported and stored. The complete process is described in the BOF2UREA project (**Error! Reference source not found.**, [9]).

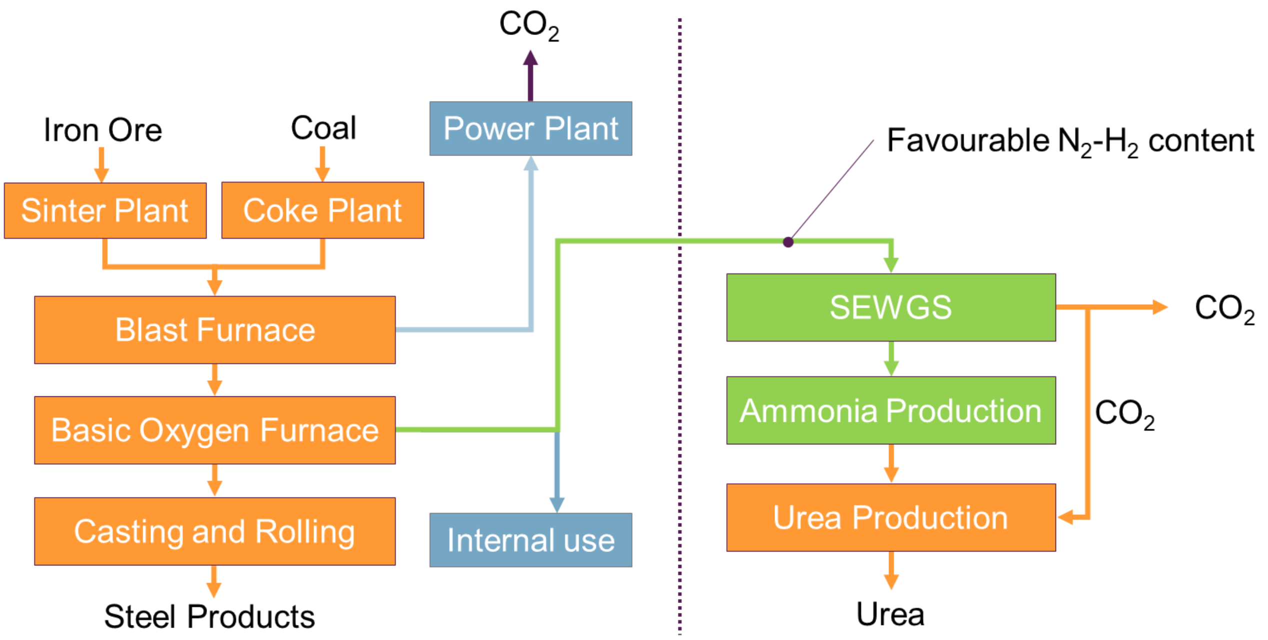

Figure 8: Urea production from residual steel gases (based on BOF2UREA [9])

The main application of urea is as fertilizer or as a source for nitrate-based fertilizers, direct use of urea is 20% of the total EU fertilizer use. Nitrate based fertilizers adds up to 47% of the total EU fertilizer use in 2019/2020, but also includes ammonia-based fertilizers [10]. Other applications of urea are as an additive in animal feed, as resin (urea-formaldehyde) mainly used in wood products. Lastly, diesel engines use urea dissolved in water as Diesel Exhaust Fluid (DEF) to reduce NO_x emissions.

1.1.4. Methanol

Methanol (Chemical formula: CH_3OH), is a chemical which is conventionally produced from natural gas. In the reference case natural gas is used as hydrogen source, using steam reforming. This case is described as part of the FReSMe project (**Error! Reference source not found.**, [13]). Compressed gas and steam is fed in to the reformer where syngas is produced, consisting of hydrogen and carbon oxides. The compressed syngas is delivered to the methanol reactor in which hydrogen and carbon oxides are converted to methanol.

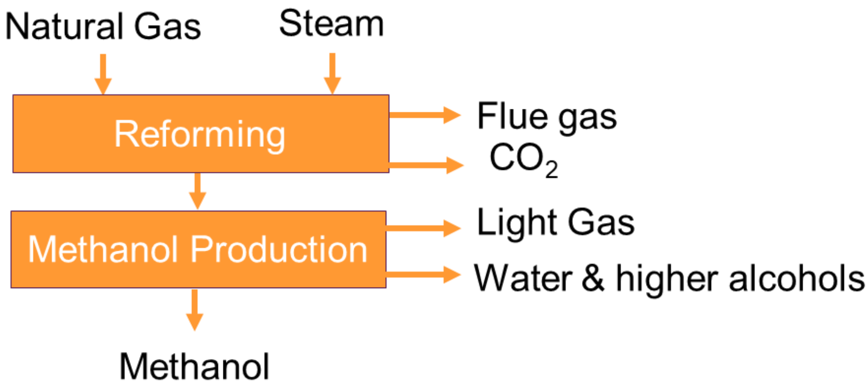

Figure 9: Stand-alone methanol production from natural gas

The product can be produced from residual gases of steel production by capturing CO_2 from the residual gases and purifying the left-over hydrogen rich gas. The complete process is described as part of the FReSMe project (**Error! Reference source not found.**, [7]). The residual gas from the steel process is fed through a pre-water gas shift section before entering the SEWGS section, in which the remaining CO is converted to CO_2 and H_2. The SEWGS section produces two main streams which are sent to the methanol production plant. One is rich in hydrogen and the other rich in CO_2. The hydrogen rich stream is purified to increase the hydrogen concentration. The residual gases have a higher carbon content with respect to the hydrogen. This means that either additional hydrogen is added to the process, or part of the CO_2 is captured and stored. All these streams are fed into the methanol reactor which is the same as in the reference case.

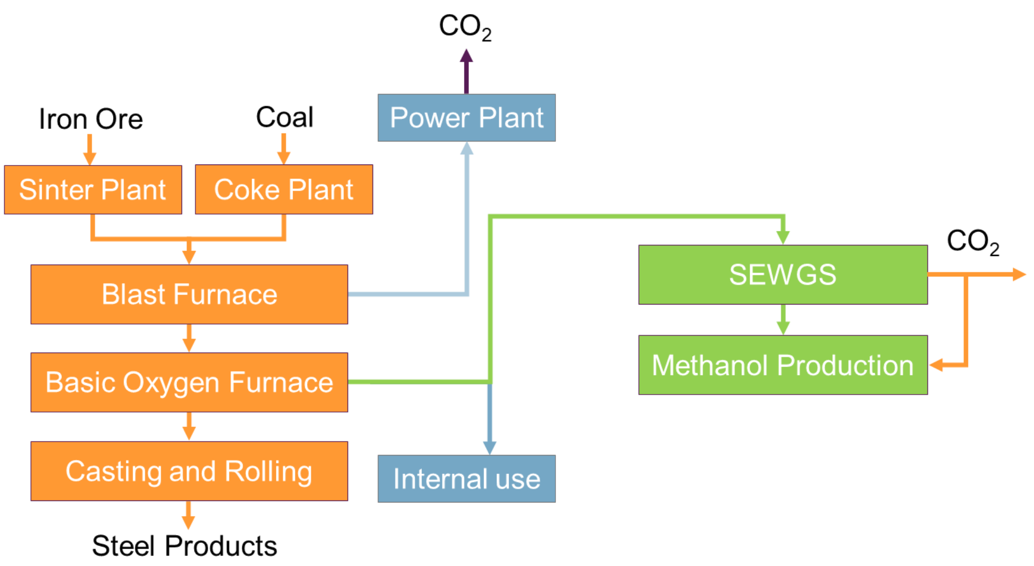

Figure 10: Methanol production from residual steel gases (based on FReSMe [13])

The main application of methanol is as a base chemical for (petro-)chemistry. Besides this existing market, methanol is a future low-carbon energy carrier or fuel. The Sustainable Development Scenario of the IEA specifically sees methanol used as feedstock for synfuel in aviation [6]. Furthermore, methanol can also be used as fuel in the shipping industry, which is a competitor to ammonia and hydrogen [14].

1.2. Classification

The scale-up of potential symbiotic relations has been the topic of the SCALER project [15]. In order to promote industrial symbiosis, a classification method for industrial symbiotic synergies was developed in the SCALER project [16]. To align with previous industrial symbiosis analysis, the identified PMCs have been classified according to this methodology. The methodology consists of “Synergy characterization”, “Procedure and Technology description” and “Transport” . The procedure and technology description section is covered by the process descriptions in the previous section. In this section the “Synergy characterization” category is presented. This classification shows which differences exist between the PMCs. The transport classification is part of the KPI selection in the following chapter. The full classification results are reported in Appendix A.

The main differentiators of the synergy characterization are:

- The **element of interest** and associated the **receiver sector**, and
- The **resource exchanged**, which is split between material and energy.

This leads to classification results, as shown in Table 4.

Table 4: Synergy characterization, based on the SCALER synergy classification [16]

#	Element of Interest	Sender Sector & Process	Receiver Sector & Process	Technical Objective	Resource exchanged
1	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food sector P: Fertilization	Recover BFG/BOFG from furnaces and produce urea to provide fertilizer industry.	Material
2	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food sector P: Animal Feed	Recover BFG/BOFG from furnaces and produce urea to provide animal feed.	Material
3	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Automotive P: Diesel Exhaust Fluid	Recover BFG/BOFG from furnaces and produce urea to provide automotive industry.	Material
4	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Construction P: Resins	Recover BFG/BOFG from furnaces and produce urea to provide in resin production.	Material
5	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food P: Fertilization	Recover BFG/BOFG from furnaces and produce ammonia to provide fertilizer industry.	Material
6	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Transport P: Fuel combustion	Recover BFG/BOFG from furnaces and produce ammonia to provide transport industry.	Energy

#	Element of Interest	Sender Sector & Process	Receiver Sector & Process	Technical Objective	Resource exchanged
7	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Energy P: Fuel combustion	Recover BFG/BOFG from furnaces and produce ammonia to provide energy.	Energy
8	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemistry P: Feedstock	Recover BFG/BOFG from furnaces and produce ammonia to provide chemical industry.	Material
9	Methanol	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Transport P: Fuel combustion	Recover BFG/BOFG from furnaces and produce methanol to provide as fuel to transport industry.	Energy
10	Methanol	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemistry P: Feedstock	Recover BFG/BOFG from furnaces and produce methanol to provide chemical industry.	Material
11	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Energy P: Fuel combustion	Recover BFG/BOFG from furnaces and extract hydrogen to provide energy.	Energy
12	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Steel P: Fuel combustion	Recover BFG/BOFG from furnaces and extract hydrogen to provide energy.	Energy
13	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Steel P: DRI	Recover BFG/BOFG from furnaces and extract hydrogen to provide input for DRI.	Material
14	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemical P: Feedstock	Recover BFG/BOFG from furnaces and extract hydrogen to provide feedstock for the chemical industry.	Material

2. Key Performance Indicators

In order to support strategic decision-making, the next step is to identify criteria by which the list of PMCs can be evaluated. This chapter describes the method by which criteria were collected and elaborates on these criteria in general.

2.1. Identification and selection

An initial list of KPIs was generated by gathering information from project partners on aspects considered important in commercial and strategic decision-making. These results were complemented with additional interviews and a literature review, creating a long list of 106 KPIs to support strategic decision-making (Appendix B). The KPIs assess the feasibility of industrial symbiosis by using the SEWGS technology, next to several KPIs that assess their case to support the development of a multi-stakeholder decision-making methodology.

In order to get towards a shortlist of KPIs and asses these for several PMCs, seven interviews were held. This included interviews with four consortium partners from the steel, chemical and knowledge industry. Two Interviews with external organizations to incorporate their learnings of earlier industrial symbiosis Horizon projects, namely Carbon4PUR [2] and FReSMe [1]. One interview was conducted with regards to the applicability of a multi-stakeholder decision support methodology to obtain learnings from the Value Case Methodology [17]. With the collected information, 22 KPIs made it to the shortlist grouped in six different clusters. Five of these clusters are related to the business ecosystem, as shown in Table 5. The last cluster is related to the applicability and development potential of a multi-stakeholder decision support methodology and is shown in Table 6. In order to facilitate the long-term strategy (T6.4) and methodology development (T6.5) in the INITIATE project, both the business and methodology perspectives are considered. More information on these 22 KPIs is found below the tables.

The selected KPIs are specifically chosen to compare the PMCs which were identified in the previous chapter. The following criteria were applied to the selection of KPIs through an online workshop:

- Recognized by industry stakeholders and methodology developers
- Information availability
- Able to compare on PMC level, not only on case level.

Table 5: Business related KPIs to asses viability of industrial symbiosis

KPI Cluster	KPI	Unit
Economic	Levelized cost of residual gas used	€/ton BOFG or BFG
	Cost of CO_2 avoidance	€/ton CO_2
	Market Size EU	% of potential BOFG or BFG
	Market Size Global	% of potential BOFG or BFG
	Competition	Number of competitors
Business model	Utilization of residual gasses	Average utilization rate (%)
	Scale of accessible infrastructure	Local - Global
	Access to knowledge	Low-High
	Ease of distribution	Hazard classification
Innovation Ecosystem	Governance	Central – Decentralized
	Community Development	Ad-hoc - Excellent
	Cost Distribution	$\frac{LCOP_{Steel}}{LCOP_{Total}}$ (%)
Societal	GHG Emission	CO_2-equivalent
	Significant Air Emissions	DALY/ton BOFG or BFG
	Job Creation & Retention	# FTE added
	Contribution to SDGs	# SDGs
	Symbiotic Legitimacy	High, Medium, Low

Table 6: Methodology related KPIs to assess viability for multi-stakeholder decision support

KPI Cluster	KPI	Unit
Methodology	Maturity	Yr
	Uncertainty	%
	Transparency	Low, Med, High
	Number of stakeholders	#
	Willingness to participate	%

2.1.1. Economic

The economic criteria have been developed in collaboration with the economic evaluation in work package 5; therefore, the definition of the KPIs is also in line with these results.

Levelized cost of residual gas used

The “levelized cost of residual gas used” is evaluated as the levelized cost per ton used BOFG or BFG. This is to be able to compare PMCs in which the end products have different values and masses. The KPI is considered to evaluate the economic potential of the PMC. The levelized cost is computed by dividing the Total Annualized Cost by the amount of BOFG or BFG consumed per year. These calculations are described in depth in Deliverable 5.3 [8] and will be summarized here.

$$LCORG\left[\frac{€}{ton}\right] = \frac{TAC}{m \cdot \tau}$$

The following formulas are used to calculate the total annualized cost:

$$TAC\left[\frac{M€}{y}\right] = TCR \cdot FCF + C_v + C_f$$

$$TCR\,[M€] = TPC + C_{co} + C_{oc}$$

$$TPC\,[M€] = TDPC + C_{EPC}$$

$$FCF\,[\%] = \frac{r(1+r)^T}{(1+r)^T}$$

The variable and operational cost variables are based on the following cost categories, which have to be determined specifically for each technology:

- Feedstock (residual gas or natural gas)
- Electricity
- CO_2 storage
- O&M

The description and values of the variables in these calculations are listed in Table 7.

Table 7: Variables in calculating the total annualized cost

Variable	Description	Value
m	Ton residual gas per year	Calculated
τ	Plant availability	90%
TPC	Total Plant Cost	Calculated
TDPC	Total Direct Plant Cost	Calculated
C_v	Variable operational cost	Calculated
C_f	Fixed operational cost	Calculated
C_{EPC}	Engineering, procurement and construction cost	20% of TDPC
C_{co}	Contingencies	35% of TPC (contingencies + onwer's cost)
C_{oc}	Owner's cost	
FCF	Fixed Charge Factor	9.37 %
r	Interest rate	8 %
T	Project lifetime	25 years
O&M	Operational & Maintenance cost	3%

Cost of CO_2 avoidance

The "cost of CO_2 avoidance" compares the PMC with a chemical production plant and steel plant without CCS. The KPI is considered to evaluate the investment compared to other CO_2 mitigation options. Calculation of the KPI uses the additional Total Annualized Cost for the SEWGS integrated plant and divides this cost by the yearly avoided CO_2 by applying SEWGS. The detailed definition of this calculation can be found in Deliverable 5.3 [8] and is defined by the following equation.

$$CCA\left[\frac{€}{t_{CO_2}}\right] = \frac{LCORG_{SEWGS} - LCORG_{reference}}{CO_{2_{SEWGS}} - CO_{2_{reference}}}$$

The reference cases of the PMCs are defined in Chapter 1.

Market size

The market size KPI indicates the amount of product that can be expected to be sold yearly. This KPI is used to evaluate the scalability of the PMC. The KPI is split into an EU market potential to indicate the local potential of the PMC and Global market potential, which is the main market indicator for large chemical producers. The market potential will be estimated based on projections and publicly available scenarios, such as the IEA Sustainable Development Scenario [6].

In order to compare the PMCs, the market size KPI is evaluated in Mt BOFG or BFG. This is done by converting the market size of the product to Mt residual steel gas by the conversion factors as shown in Table 8. The conversion uses the efficiencies of producing ammonia, urea and methanol. The efficiency of ammonia production is assumed to be 63-91%, dependent on the scale of the process, and the methanol production has an assumed H_2 efficiency of 62% [18]. The conversion factors are based on the assumed composition of residual gases as shown in Table 9.

Table 8: Indicative conversion of product volumes to residual steel gases

Product	Kg BOFG/kg product	Kg BFG/kg product
Hydrogen	27	65
Ammonia	8	13
Urea	5	7
Methanol	8	20

Table 9: Assumed composition of residual gases

Element	Kg/kg BOFG	Kg/kg BFG
CO	0.52	0.21
N_2	0.17	0.49
CO_2	0.30	0.31
O_2	0.0002	0
H_2	0.0022	0.0016
Ar	0.0082	0

The value of the KPI is determined by evaluating the market size to the potential BFG and BOFG production if 50% of EU and global steel plants switch to producing chemicals with 100% of their available residual gases. This potential is estimated based on the total crude steel production per year and the estimated amount of residual gases produced. The assumptions of this calculation are shown in Table 10.

Table 10: Assumptions in calculation potential residual gas production

Assumption	Value	Unit	Reference
EU crude (BOF/BFG)	92	Mt steel/yr	[19], data from 2019
Global Crude (Total)	1875	Mt steel/yr	[20]
Global Crude (BOF/BFG)	70%	%	[21]
BOFG	9	kNm^3/hr per ton steel/yr	[22]
BFG	180	kNm^3/hr per ton steel/yr	[22]

The KPI is low when the market size is less than 50% of the potential residual gas production. The highest value is from 200% of the potential residual gas production onward. The calculated potential residual gas production is shown in Table 11.

Table 11: Results of potential residual gas production

	EU (Mt/year)	Global (Mt/year)
BOFG	4	53
BFG	68	960

Competition

The KPI “competition” assesses the amount of alternatives that compete with the product made from residual gasses. This KPI is considered to evaluate whether the estimated market size can actually be captured. With desk research and stakeholder interviews the inventory of alternatives is formed. The KPI scores high for a low number of alternatives and low for a high number of alternatives. A low number of alternatives is an indication that the industrial symbiosis route can capture a significant part of the market.

2.1.2. Business model

Utilization of residual gasses

The residual gases from steel production (BOF and BF gas) are composed of nitrogen, CO_2 and hydrogen. The assumed composition in this deliverable in shown in Table 9. Depending on the PMC, these components are used in different amounts. This entails a difference in the utilization of the residual gasses. For all products, the amount of hydrogen is a limiting factor. This means that mainly the utilized amount of nitrogen and CO_2 differs between PMCs. Adding additional hydrogen to the production process can increase the utilization rate at the cost of additional hydrogen and the need for green electricity. The KPI is scored according to the average molar utilization rate of all components in the residual gas, where a higher utilization rate leads to a higher score.

Scale of accessible infrastructure

The KPI “scale of accessible infrastructure” evaluates the scalability of transport infrastructure through which the product will be transported to the customer. The KPI result is obtained by listing available transport modes. For the assessment within INITIATE these modes are ship (global), train (EU), truck (local) or pipeline (local or EU). In the evaluation of the KPI local transport scores low, EU wide transport scores medium and global transport scores high.

Access to knowledge

This KPI assesses whether the knowledge required to participate in a PMC is accessible. The following components are considered:

- Technology knowledge: Is the knowledge for the technology easy to obtain?
- Effectiveness of knowledge processing between different levels of the business ecosystem: How well is the required knowledge within a PMC shared among stakeholders?

The output of this KPI is defined as high, medium or low. When the required knowledge is internally present in the organizations of the business ecosystem, the KPI scores high. When not all required knowledge is internally present, but can easily be accessed or bought, the KPI scores medium. It scores low when the required knowledge is difficult to obtain. Information to score the KPI is gathered through interviews and workshops.

Ease of distribution

The KPI “ease of distribution” evaluates the effort required to transport a product. Based on exploratory interviews, it was concluded that the main determining factor in the ease of transport is the product's safety. The safety labels and their category, which indicate hazards and risk factors that have the potential to cause harm, are leading in this KPI. This information can be found on the safety sheets required for transport. The KPI scores low for high risks for safety and high for lower risks for safety.

2.1.3. Innovation Ecosystem

Governance

The KPI “governance” mainly aims to answer the question on how power between all the stakeholders of an ecosystem is distributed. To do this a first step is to compose the business ecosystem by mapping all stakeholders. Next, power relationships are revealed by identifying possible channels of influence, as well as risks of conflict. The result of the KPI is defined as either a central or decentralized network. If one stakeholder of the business ecosystem has significantly more power and hence more interdependencies than others, it is defined as a centralized ecosystem. When the power of the stakeholders is distributed between multiple partners, it is a decentralized ecosystem.

Community development

The KPI “community development” assesses the level of relationships within the innovation ecosystem of a certain PMC. The levels of this KPI are defined by the Digital Innovation Hub capability model [23]:

- **Ad-Hoc:** The community is not involved in explicit collaboration or structured engagement with the regional (EU) innovation ecosystem. Relationships are often based on shorter-term and/or operational purposes.
- **Low:** There are some existing relationships, but they are irregularly used. The ecosystem is extended as a response to demand from outside the community.
- **Intermediate:** Current relationships are known and exploited. Potential partners are regularly scanned and selected for collaboration.
- **High:** A diverse range of external partner relations is present and exploited, and potential partners are scanned and selected continuously.
- **Excellent:** The community constantly evaluates and revises partnerships and has an attractive image in the ecosystem as partners. The community promotes new innovations and collaborations among different stakeholders

Cost distribution

The “cost distribution” KPI is calculated by allocating the CAPEX and OPEX to the several stakeholders in the project. The selection of this KPI follows from industrial symbiosis development, in which the cost and value distribution between stakeholders can be a barrier for implementation. This allocation is presented in a calculation of levelized cost of residual gas. The levelized cost of residual gas is calculated by the following equation

$$LCORG\left[\frac{€}{ton}\right] = \frac{TAC}{m \cdot \tau}$$

Where TAC is the Total Annualized Cost, m is the ton residual gas per year and τ is the plant availability. In the context of INITIATE the calculation of the total annualized cost is done for both the steel and chemical actor. These actors are divided as shown in Figure 11. The SEWGS investment and operation is accounted to the steel actor, and the investment and operation of the integrated urea plant is in scope of the chemical actor.

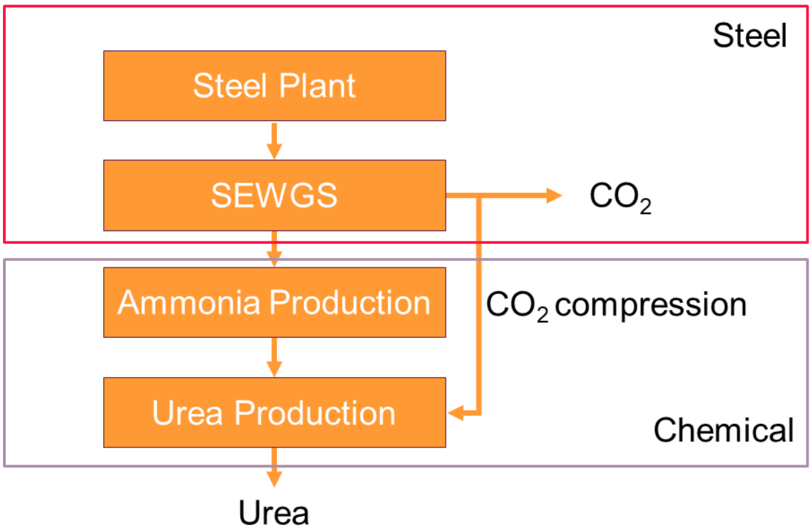

Figure 11: Division of cost scope between steel and chemical for urea production

For both scopes a levelized cost of residual gas calculation is performed as defined in the levelized cost KPI. The cost distribution KPI measures the equality of investment stakeholders must make in the product. Equal distribution is deemed more favorable for realizing industrial symbiosis; deviating from an equal distribution results in a lower score. The calculation of the KPI is as follows:

$$Cost\ distribution = \frac{LCORG_{Steel}}{LCORG_{Steel} + LCORG_{Chemical}}$$

2.1.4. Societal

GHG Emission

This KPI measures the GHG emissions for all PMCs compared to the base-case scenario. This base-case scenario is defined as the business-as-usual case, where the steel production plant uses the residual gasses for electricity production. Thus, when the residual gasses are used for other purposes than electricity production, the additional production of electricity also contributes to the GHG emissions. Moreover, in the base case the conventional production process and corresponding emissions of the product (of the PMC) is considered, resulting in a comparable output of kg CO_2-eq for the reference-case to the base-case scenario. To determine the GHG emissions for every product of the selected PMCs, a life cycle assessment (LCA) is conducted for the base-case and the reference-case.

Significant Air Emissions

This KPI measures the significant air emissions for all PMCs compared to the base-case scenario. The approach of the base-case and the reference case of the PMC is similar to the GHG emission KPI. In this KPI the output is measured in disability-adjusted life years (DALY) per ton of residual gasses. This unit is used in LCA to determine the impact on human health. All fine particulate matter ($PM_{2.5}$, NO_x and SO_x) can be summed with this unit to determine the effect of fine particulate matter on human health for the reference-case and base-case of all PMCs. The score of the KPI improves when the DALY impact decreases.

Job Creation & Retention

This KPI is an estimation of the jobs (in FTE) that will be created or lost for the PMC compared to the case where no industrial symbiosis takes place. The estimation is based on the number of new FTE resulting from operating SEWGS, construction of a new plant, and operating the plant for the PMC.

Contribution to SDGs

The sustainable development goals (SDGs) adopted by the United Nations are a call for action to address a series of global challenges such as: poverty, inequality, climate, environmental degradation, and justice. Many corporations use the SDGs to report on their CSR activities. Therefore, number of SDGs that a PMC can contribute to is used as KPI to assess public perception [24].

Symbiotic legitimacy

In order to evaluate the strengths and weaknesses of each PMC in the inventory, the potentially different impact of European legislation is of importance. Therefore it is essential to determine which legislations have most influence and what exact elements in the legislation have an impact.

Carbon Border Adjustment Mechanism

The consortium indicated that the carbon border adjustment mechanism (CBAM) implemented by the EU is of importance for the INITIATE project.

CBAM is a climate measure that is intended to prevent the risk of carbon leakage. Carbon leakage happens when companies based in the EU replace products by more carbon-intensive imports to take advantage of lax standards. Such carbon leakage can shift emissions outside of Europe and therefore seriously undermine EU and global climate efforts. The CBAM will equalize the price of carbon between domestic products and imports, ensuring that the EU's climate objectives are not undermined by production relocating to countries with less ambitious policies [25].

Products that are at high risk of carbon leakage are: iron and steel, cement, fertilizer (ammonia, urea, nitric acid, ammonium nitrate), aluminium and electricity generation. The system implemented by CBAM will work as follows: EU importers will buy carbon certificates corresponding to the carbon price that would have been paid, had the goods been produced under the EU's carbon pricing rules. Conversely, once a non-EU producer can show that they have already paid a price for the carbon used in the production of the imported goods in a third country, the corresponding cost can be fully deducted for the EU importer [25].

Renewable Energy Directive

The second legislation that has been indicated as potentially important is the Renewable Energy Directive. This directive is aimed at helping the EU to meet its emission reduction commitments (32% renewables in energy mix by 2030) under the Paris Agreement. Renewable energy is the collective name for energy, that is produced using the earth’s natural resources: sunlight, wind, water resources (rivers, tides and waves), heat from the earth’s surface, or biomass. The process, by which these renewable resources are converted into energy, emits no net greenhouse gases. In order to help member countries deliver on the target, the directive introduces premiums for various sectors of the economy, particularly on heating and cooling and transport, where progress has been slower [26].

2.1.5. Methodology

The criteria to assess methodology development relate to the degree of uncertainty and the quality of available information.

Maturity

The KPI “maturity” assesses the time horizon until a concrete investment decision is made by the companies involved in industrial symbiosis. This KPI is considered from a methodology perspective, because it has an influence on the accessibility of information and the uncertainty involved in the decision. PMCs with high as well as PMCs with low maturity are requested to ensure diversity. The moment of decision is assessed with the key stakeholders.

Uncertainty

The KPI uncertainty measures the proportion of KPI results (% out of total) which is expected to have a 25% or more deviation. This KPI is selected because of the impact uncertainty has on the decision process. The methodology should be able to account for uncertainty in KPIs, and therefore selection of a PMC with high uncertainty is recommended.

Transparency

Transparency relates to whether the information of a PMC matches the FAIR principle. The KPI is differentiated between low, medium and high. The FAIR principle assesses if information is findable, accessible, interoperable and reusable. Findability entails that it is possible to find information regarding the PMC, whether this information is accessible. Accessibility entails that the information is as open as possible, as closed as necessary (trade-off between maximizing research potential and protecting confidential information). Interoperability entails that the information is in a formal, accessible, shared and broadly applicable language for knowledge representation. Reusability entails that the collected information can be used for other scientific research [27].

Amount of stakeholders

This KPI counts the number of stakeholders involved in the innovation ecosystem of a PMC. The higher this number, the more complex strategic decision making gets. It affects methodology development as it influences how much (variable) data can be collected.

Willingness to participate

The KPI willingness to participate measures the proportion stakeholders (%) that want to invest time to participate in a study to develop a new methodology. This information is obtained through interviews and workshops. In order to develop the methodology and assess the PMC a high amount of participating stakeholders is recommended.

2.2. Ranking

As the final part of this task, the KPIs for all clusters are ranked by their importance. First, the approach for the KPI ranking is described. Second, the results for the KPI ranking are discussed. Important findings that can influence the decision-making for the long-term and the upcoming tasks of work package 6, are evaluated.

2.2.1. Approach

For the KPIs ranking, stakeholders provided input through a workshop and interviews. The six clusters were discussed with their corresponding KPIs, and the latter were ranked between 1 (low) and 5 (high) for strategic decision making.

The results of this analysis, based on 11 participants, consist of an average number between 1 and 5 and a ranking of the KPIs. From these participants, 6 represent companies from the steel and chemical industry and 5 are representatives from knowledge industry. The companies from the steel and chemical industry are representative parties for long-term strategy formation, hence results from these parties are used to rank the business related KPIs. The results of the knowledge industry are considered for ranking the methodology related KPIs.

The result of this section elaborates on the difference in KPI importance between steel and chemical representatives, the most important business related KPIs according to the company participants and the most important methodology KPIs according to the knowledge industry. Lastly, the difference between the business oriented and knowledge oriented participants are discussed.

2.2.2. Results

The main results for organizing industrial symbiosis are the scoring of the 17 business KPIs. These results will be used in selection of the most interesting PMCs in Task 6.5 and form the basis for long-term strategy development. In order to assess the relevance of the KPI ranking, the results emerging from the steel and chemical companies were compared. This revealed one relevant difference between these sectors regarding the market size KPIs:

- The chemical industry ranks the EU market low (16^{th}) and the Global market high (5^{th})
- The steel industry ranks the EU market high (4^{th}) and the global market low (15^{th})

Therefore, to consider both perspectives, both market potential KPI are ranked on their highest location, respectively 4^{th} and 5^{th} for the EU and Global market.

The results for the business KPI ranking are shown in Table 12. This ranking is based on the average ranking score from steel and chemical company participants. In this table, the market size KPIs have been reordered based on the bias from the different sectors. The results are sorted from most important, to least important.

Table 12: Results of ranking the business KPIs

Rank	KPI	Cluster
1	Levelized cost of product	Economic
2	Legislation	Societal
3	CO2 abatement cost	Economic
4	Market size EU	Economic
5	Market size Global	Economic
6	GHG Emission	Societal
7	Cost distribution	Innovation ecosystem
8	Governance	Innovation ecosystem
9	Scale of accessible infrastructure	Business model
10	Alternatives	Economic
11	Utilization of residual gases	Business model
12	Significant Air Emissions	Societal
13	Community development	Innovation ecosystem
14	Contribution to Sustainable Development Goals	Societal
15	Job creation and retention	Societal
16	Access to knowledge	Business model
17	Ease of distribution	Business model

The biggest differences between the ranking of the KPIs from a company perspective and the knowledge institutes are, from a knowledge perspective:

- A higher value for job creation and retention and scale of accessible infrastructure
- A lower emphasis on legislation, market potential and alternatives.

From the results for the stakeholders in the INITIATE project, economic criteria are valued highly having 4 of the 5 highest ratings. The attendees mentioned that an economic competitive product with sufficient market potential is a pre-requisite for the industrial symbiosis to develop. The top 5 is complemented by legislation which is mainly viewed as a potential barrier for adoption of the process.

The stakeholders consider KPIs related to industrial symbioses, such as cost distribution (7th) and governance (8th), relevant. However, the economic and legal aspects have a higher impact on decision-making than the ease to develop industrial symbiosis.

The least relevant KPIs are access to knowledge and ease of distribution. The ranking of these KPIs is mainly specific to the SEWGS technology, as the partners see the knowledge already as accessible and the products as sufficiently easy to be transported for successful implementation of the PMCs. While public perception is important to the stakeholders, measuring this is viewed to be a more project level action while the SDG KPI is not deemed sufficient to measure the impact on the public.

The ranking of the 6 methodology criteria, as shown in Table 13, is based on the input of the knowledge stakeholders in the workshop and the interviews.

Table 13: Ranking of the methodology KPIs

Ranking	**KPI**
1	Maturity
2	Willingness to participate
3	Uncertainty of KPIs
4	Access to information
5	Number of stakeholders
6	Transparency

A significant difference between the ranking of the KPIs from a company perspective and the knowledge institutes is that the companies assigned a higher value to transparency compared to knowledge representatives.

Most important KPIs from a methodology perspective are Maturity, Willingness to participate and Uncertainty of KPIs. The willingness to participate KPI is perceived as a barrier, as the information sharing between the sectors can be inadequate. Maturity and uncertainty seen to be related to the amount of public finance needed to develop the project, lower score on these will make a company more reluctant to invest.

3. Conclusion

INITIATE proposes a novel symbiotic process to produce urea from steel residual gases. The project consists of demonstrating the innovations at TRL7, assessing the impact of the technology, developing a commercial implementation roadmap and designing a bankable commercial plant. As part of development of the commercial implementation roadmap, this report assesses the full scale of Product-market combinations (PMCs) and symbiotic relationships which can be enabled by the core SEWGS technology. Therefore, PMCs suitable for application of the SEWGS technology broader than urea production are considered. As long-term roll-out will be defined by collaboration between stakeholders, assessment of the PMCs on suitability for industrial symbiosis and multi-stakeholder methodology development is a key part of this report. This deliverable explains the process that was followed to explore how strategic decision making can be supported in the context of industrial symbiosis involving the steel and chemical industry.

The main takeaways for inventory of Product-Market combinations in an industrial symbiosis setting are:

- High level characterization of PMCs is facilitated by the “Synergy classification” part of the SCALER approach
- The main denominators in the characterized PMCs are the **elements of interest**, which are associated with the **receiving industry**, and the **resource exchanged**, which is split between material and energy.

The identification and ranking of key performance indicators developed insights into the importance of parameters regarding the SEWGS technology. In Table 14 the top 5 of the business KPI ranking are shown, based on the results from steel and chemical company participants. For each criteria, the results are sorted from most important, to least important.

Table 14: Top 5 of ranking the business KPIs

Rank	KPI	Cluster
1	Levelized cost of product	Economic
2	Legislation	Societal
3	CO2 abatement cost	Economic
4	Market size EU	Economic
5	Market size Global	Economic

The main results of the inventory and ranking of KPIs are:

- In the case regarding SEWGS technology, the relevant business model criteria were specific to the stakeholders and specific case. KPIs in the other clusters were raised and proposed in literature.
- Next to making an inventory of evaluation criteria, it is important to assess for each party involved the relative importance for decision making of these criteria.
- The ranking of the KPIs from a business perspective show a preference towards economic performance indicators, followed by social and ecosystem KPIs.
- The ranking of importance differs with the subset of PMCs that are studied and the parties in the consortium. In multi-stakeholder decision making, the individual ranking of each stakeholder should be considered.

The results of the inventory of PMCs and KPIs will be considered in the multi-stakeholder decision support process to develop a long-term strategy:

- The ranked KPIs will be weighed and assessed for each PMC, leading to a selection of promising PMCs.
- The associated longlisted KPIs will be used in development of the long-term strategy
- The KPI assessment and interviews will be used in the multi-stakeholder methodology development.

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Appendix A – Synergy classification

#	By-Product	State of Matter	Element of Interest	Sender Sector & Process	Receiver Sector & Process	Technical Objective	Resource exchanged	Type of Synergy	Identification source
1	BFG/BOFG	Gas	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food sector P: Fertilization	Recover BFG/BOFG from furnaces and produce urea to provide fertilizer industry.	Material	Indirect	Workshops Use cases
2	BFG/BOFG	Gas	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food sector P: Animal Feed	Recover BFG/BOFG from furnaces and produce urea to provide animal feed.	Material	Indirect	Workshops Use cases
3	BFG/BOFG	Gas	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Automotive P: Diesel Exhaust Fluid	Recover BFG/BOFG from furnaces and produce urea to provide automotive industry.	Material	Indirect	Workshops Use cases
4	BFG/BOFG	Gas	Urea	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Construction P: Resins	Recover BFG/BOFG from furnaces and produce urea to provide in resin production.	Material	Indirect	Workshops Use cases
5	BFG/BOFG	Gas	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Food P: Fertilization	Recover BFG/BOFG from furnaces and produce ammonia to provide fertilizer industry.	Material	Indirect	Workshops Use cases

#	By-Product	State of Matter	Element of Interest	Sender Sector & Process	Receiver Sector & Process	Technical Objective	Resource exchanged	Type of Synergy	Identification source
6	BFG/BOFG	Gas	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Transport P: Fuel combustion	Recover BFG/BOFG from furnaces and produce ammonia to provide transport industry.	Energy	Indirect	Workshops Use cases
7	BFG/BOFG	Gas	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Energy P: Fuel combustion	Recover BFG/BOFG from furnaces and produce ammonia to provide energy.	Energy	Indirect	Workshops Use cases
8	BFG/BOFG	Gas	Ammonia	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemistry P: Feedstock	Recover BFG/BOFG from furnaces and produce ammonia to provide chemical industry.	Material	Indirect	Workshops Use cases
9	BFG/BOFG	Gas	Methanol	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Transport P: Fuel combustion	Recover BFG/BOFG from furnaces and produce methanol to provide as fuel to transport industry.	Energy	Indirect	Workshops Use cases
10	BFG/BOFG	Gas	Methanol	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemistry P: Feedstock	Recover BFG/BOFG from furnaces and produce methanol to provide chemical industry.	Material	Indirect	Workshops Use cases
11	BFG/BOFG	Gas	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Energy P: Fuel combustion	Recover BFG/BOFG from furnaces and extract hydrogen to provide energy.	Energy	Indirect	Workshops Use cases
12	BFG/BOFG	Gas	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Steel P: Fuel combustion	Recover BFG/BOFG from furnaces and extract hydrogen to provide energy.	Energy	Indirect	Workshops Use cases

#	By-Product	State of Matter	Element of Interest	Sender Sector & Process	Receiver Sector & Process	Technical Objective	Resource exchanged	Type of Synergy	Identification source
13	BFG/BOFG	Gas	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Steel P: DRI	Recover BFG/BOFG from furnaces and extract hydrogen to provide input for DRI.	Material	Indirect	Workshops Use cases
14	BFG/BOFG	Gas	Hydrogen	S: Steel P: Blast Furnace/Blast Oxygen Furnace	R: Chemical P: Feedstock	Recover BFG/BOFG from furnaces and extract hydrogen to provide feedstock for the chemical industry.	Material	Indirect	Workshops Use cases

Appendix B – KPI Longlist

Name KPI	Category	Cluster
Higher added value	Economical	Business Case
Business case	Economical	Business Case
Levelized cost	Economical	Business Case
Cost of CO2 avoided	Economical	Business Case
Financing	Economical	Business Case
Operational Cost	Economical	Business Case
Capital Cost	Economical	Business Case
Product Quantity	Economical	Business Case
Turnover	Economical	Business Case
Net Value added	Economical	Business Case
Carbon tax	Legal	Business Case
Subsidy	Legal	Business Case
Feedstock price	Price	Business Case
Ease of relocation 'giver'	Economical	Business Case, Value Creation
Ease of relocation 'receiver'	Economical	Business Case, Value Delivery
Primary energy consumption	Technological	Business Case, Environmental Impact, Public Perception
SPECCA	Technological	Business Case, Environmental Impact, Public Perception
Utility	Circularity	Environmental Impact
Transport method	Place	Value Delivery
Production Location	Place	Value Creation, Value Delivery
Consumption location	Place	Value Delivery
Geographical proximity	Place	Value Delivery
Resources	Technological	Value Creation
Distribution and logistics	Commercial	Value Delivery
Quality materials	Technological	Value Creation
Number of 'new' companies	Commercial	Value Creation, Value Delivery
Number of 'new' relations	Commercial	Value Creation, Value Delivery
Flexibility	Commercial	Value Creation, Value Delivery
Change in governance	Commercial	Ecosystem
Internal and external networks	Network	Ecosystem
Promotion of networks	Network	Ecosystem
Participative networks	Network	Ecosystem
Reciprocity	Network	Ecosystem

Name KPI	Category	Cluster
Intensity	Network	Ecosystem
Creation of IS	Social	Ecosystem
Community development	Social	Ecosystem
Betweenness and closeness	Network	Ecosystem
Value Distribution	Economical	Ecosystem
Number of stakeholders	Methodology	Ecosystem
Trusting environment	Social	Ecosystem
Environmental awareness	Social	Ecosystem
Community awareness	Social	Ecosystem
Involvement of R&D	Social	Ecosystem
Promotion by regional and national entities	Social	Ecosystem
Mistrust	Social	Ecosystem
Conflicts of interest	Social	Ecosystem
Lack of knowledge	Social	Ecosystem
Poor communications	Social	Ecosystem
Innovation and investment in R&D	Social	Ecosystem
Natural resource optimization	Circularity	Environmental Impact
Circular "R" performance	Circularity	Environmental Impact
CO2 avoided	Environmental	Environmental Impact
Carbon storage	Environmental	Environmental Impact
Material use	Environmental	Environmental Impact
Energy and Exergy consumption	Environmental	Environmental Impact
Water consumption	Environmental	Environmental Impact
Land use	Environmental	Environmental Impact
Air emissions	Environmental	Environmental Impact
Wastewater	Environmental	Environmental Impact
Solid wastes	Environmental	Environmental Impact
Environmental impact momentum	Circularity	Environmental Impact
Environmental cost effectiveness	Circularity	Environmental Impact
CO2 capture	Technological	Environmental Impact
Process carbon intensity	Technological	Environmental Impact
By products	Environmental	Environmental Impact, Business Case
Waste Heat	Environmental	Environmental Impact, Business Case
Willingness to participate	Methodology	Quality of Information
Clear investment decision	Methodology	Quality of Information
Information availability	Methodology	Quality of Information
Production size	Technological	Input
Available legislation	Legal	Legislation

Name KPI	Category	Cluster
Complicated bureaucratic procedures	Legal	Legislation
Legitimacy of current practice	Legal and social	Legislation
Legitimacy of symbiotic practice	Legal and social	Legislation
Substitutes/Competition	Economical	Market potential
Market size Global	Economical	Market potential
Market size Europe	Economical	Market potential
Alternative markets	Economical	Market potential
Public Perception	Social	Public Perception
Trust in developers	Social	Public Perception
Safety	Social	Public Perception
Public perception of 'giver'	Social	Public Perception
Public perception of 'receiver'	Social	Public Perception
Well-being & the SDGs	Social	Public Perception
Social inertia	Social	Public Perception
Manpower	Social	Public Perception
Job creation and retention	Social	Public Perception
Social responsibility	Social	Public Perception
Lifelong learning	Social	Public Perception
Health and Safety	Social	Public Perception
Rate of community participation	Social	Public Perception
Level of social acceptance	Social	Public Perception
Transparency and reporting	Methodology	Quality of Information
Independence of monitoring	Methodology	Quality of Information
Feasibility of scaling up	Commercial	Uncertainty, Business Model
Uncertainty reduction	Commercial	Uncertainty
Instable demand	Economical	Uncertainty, Market potential
Maturity of market	Economical	Uncertainty, Market potential
Uncertainty in policies	Legal	Uncertainty, Legislation
Maturity	Methodology	Uncertainty, Ecosystem
Technology Readiness Level	Technological	Uncertainty, Business Model

Table 15 Sources: **[8]**, **[28]**, **[29]**, Workshop 1, Interviews & Project team