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Development and definition of Key Resource Indicators

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GLOSSARY

This glossary complements the document "Definition of terms" produced in the frame of the project TOP-REF.

Energy Input: all types of energy (provided in the form of electricity, heat or fuel) that are necessary for the manufacture of a good or for the provision of a service. Direct energy consumption is the energy used within the studied process[1]. Indirect energy consumption is the energy consumed outside of the process, for the provision of services or goods by the suppliers.

Environmental aspect: element of an activity, product or service that can interact with the environment during its life cycle.

Environmental impact: any change to the natural environment, natural resources or human health, whether adverse or beneficial, wholly or partially resulting from socio-economic activities.

Indicator: a quantifiable, qualitative or descriptive measure[2].

Index: a numerical scale by means of which variables can be compared with each other or with some base number[3].

Metric: a defined measurement method and the measurement scale[4].

Key Resource Indicator (KRI): variable that represents an **index** for evaluating the **resource efficiency of a process** and/or impacts associated with their consumption.

Life cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal[5].

Material Input: all materials that are necessary for the manufacture of a good or for the provision of a service and used as feedstock[6]. Material Input covers directly used, indirectly used and unused materials. Directly used materials are those materials that enter into the studied process. Indirectly used materials are those materials that are used in processes in the value chain but outside the

[1] Here, "studied process" refers to the industrial process performed onsite, and not to the system that would be studied from an LCA perspective for a cradle-to-gate assessment of the main outputs of the process.

[2] Source: ISO 15392:2008

[3] http://www.collinsdictionary.com

[4] Source: ISO/IEC 14598-1:1999

[5] Source: ISO 14040:2006

[6] As opposed to the materials used to produce energy (fossil/biomass fuels).

process. Unused materials are sub-products of any process in the value chain, such as mining, excavated soil for constructions or soil erosion in agriculture[7].

Natural resources: Natural resources are biotic and abiotic raw materials as well as water and land, which, due to their material or energetic characteristics or the overall technological requirements, are extracted from the natural environment for socio-industrial purposes[7].

The European Commission identified the following main categories of resources in the "Roadmap to a Resource Efficient Europe"[8]: **metals, minerals, fuels, fish, timber, water, soil, clean air, biomass, biodiversity and land and sea** (Roadmap to a Resource Efficient Europe, 2011). Within its Flagship Initiative for a Resource Efficient Europe[9] under the Europe 2020 Strategy the European Commission states the importance of using all types of natural resources (including energy) efficiently for the European economy and environment.

As stated in the document "Definition of terms" produced in the frame of the TOP-REF project, the relevant natural resources included within the scope of this project are the following:

- Energy (renewable and non-renewable)
- Fuels (fossil and biotic)
- Minerals[10]
- Biomass
- Water

[7] Based on Schütz H. and Bringezu S. (2008) Resource consumption of Germany – indicators and definitions. Federal Environmental Agency (Umweltbundesamt), Dessau-Rosslau/Germany. UBA-Texte 08/08

[8] European Commission (2011) Roadmap for a Resource Efficient Europe

[9] European Commission (2011), A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy. COM(2011) 21.

[10] Including metals

EXECUTIVE SUMMARY

This document presents the work and results of task 2.3 of the TOP-REF within the framework of the EC Grant Agreement no 604140. The aim of this task was to define the most suitable set of Key Resource Indicators for monitoring and control the resource efficiency of industrial processes.

The selection of appropriate KRIs should help in the preservation and use of natural resources in an efficient way, serving as standards not only for the industry itself, but also for policy makers, public authorities and even the civil society. It should be mentioned that this deliverable is a living document throughout the project. Accordingly, all proposed KRIs will be tested and validated against different industrial sectors in following work packages, thereby ensuring that the final aim has been appropriately met. In the end of the project the KRIs will be the basis of new standards or a supplement to existing standards to be used by EU stakeholders.

A Key Resource Indicator (KRI) is a variable that represents an index for evaluating the resource efficiency of a process or the impacts associated with the consumption of resources. The first step of the selection of Key Resource Indicators was a review of existing indicators in the industry and in the literature. This work is reported in the Deliverable 2.2 of TOP-REF, which precedes the present report. The Deliverable 2.2 presents a first shortlist of the existing indicators and provides a general picture of what can be measured with the current practices. The present Deliverable 2.3 contains an in-depth comparative analysis of the selected indicators, based on the criteria of the TOP-REF partners, stakeholders and the overall objectives of the TOP-REF project.

In order to define the criteria for selecting the Key Resource Indicators, the project team interviewed the different partners involved in the project TOP-REF, as well as stakeholders external to the project. The objective of the interviews was to gather the possible uses and needs of the users of these indicators to measure resource efficiency in the industry. The criteria expressed by the interviewees were used to define a RACER evaluation framework to assess all the indicators (RACER stands for Relevant, Accepted, Credible, Easy and Robust). The results of the RACER evaluation oriented the selection of the most suitable indicators of resource efficiency, and this was complemented with some additional indicators in order to have a coherent and complete set of KRIs that could be used to evaluate different industrial processes in different industrial sectors. The set of KRIs for the TOP-REF Project should fulfil the following characteristics:

- Completeness in the coverage of objectives and resources in the scope of the TOP-REF project;
- Low redundancy;
- Consistency;
- Reduced number;
- Being valid for different sectors and at the same time relevant for the specific industrial processes.

The final set of KRIs proposed includes a few headline indicators of resource efficiency, which are complemented by some indicators of environmental impacts. This set of KRIs will be tested and validated during Work Package 7 of the TOP-REF project, where the project team will calculate the full set of indicators for three pilot cases of industrial processes. The specific scope of each indicator, calculation methods and data inputs needed will be clearly defined for the application of the three pilot cases.

The proposed set of KRIs is presented in the following table.

Key Resource Indicators	
Headline indicators	Material efficiency (kg/FU[11]) Direct primary energy consumption (J/FU) Gross water use (m3/FU) Net water use (m3/FU) Resource Exergy indicator (resources: materials, energy and water) (J/FU)
Complementary indicators	Direct GHG emissions (kg CO2 eq./FU) Indirect GHG Emissions (kg CO2 eq./FU) Acidification (Accumulated Exceedance - AE) (mole H+ eq./FU) Ecotoxicity (freshwater) (USEtox) (Comparative toxic unit for ecosystems - CTUe/FU) Eutrophication, terrestrial (Accumulated Exceedance - AE) (mole N eq. /FU) Eutrophication, freshwater and marine (ReCiPe) (kg P eq. /FU) Human toxicity, cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU) Human toxicity, non-cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU) Ionizing radiation (Human Health effects model) (kg U235 eq./FU) Ozone depletion potential (kg CFC-11 eq./FU) Particulate matter / respiratory inorganics (RiskPoll) (kg PM2.5 eq. /FU) Photochemical ozone formation (ReCiPe) (kg C2H4 eq. /FU)

[11] FU: Functional unit, defined as a unit of use that characterises the result attended linked to the function studied. This unit is measurable and verifiable, and is the reference to which the quantities of the indicators are measured (based on ISO 14040).

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1 Introduction

1.1 Reminder of the objectives of TOP-REF

The objective of the project TOP-REF – Innovative tools, methods and indicators for optimizing the resource efficiency in process industry - is to increase the competitiveness and efficiency of the EU resource-intensive process industry, focusing in the chemical, agrochemical and petrochemical sectors. TOP-REF will help improving the efficiency in the use of energy, water and raw materials, and reducing production costs. Within the framework of the TOP-REF project, the relevant natural resources are: energy (renewable and non-renewable), fuels (either used as feedstock or as source of energy), minerals, biomass and water.

To achieve this goal, TOP-REF will develop and demonstrate a robust, resource-efficiency-focused and cross-sectorial methodology that will be validated through demonstration under real conditions in three pilots, one in each sector.

1.2 Objective of this task and position in the frame of Work Package 2

An important part of the methodology is the use of indicators to measure the improvements in resource efficiency. With that objective, this task aimed to define the most suitable set of Key Resource Indicators (KRIs) for the three industrial processes studied in the project TOP-REF. KRIs will be used as objective function for the optimisation of the Critical Process Parameters in Work Package 7 of the project.

A Key Resource Indicator (KRI) is a variable that represents an index for evaluating the resource efficiency of a process or the impacts associated with the consumption of resources. These indicators will directly serve to measure the improvements in terms of resource efficiency in industrial processes.

The first step of the development of specific Key Resource Indicators was a review of existing relevant indicators of resource efficiency in industry and in the academic and grey literature. This work is reported in the Deliverable 2.2 of TOP-REF, which precedes the present report.

The Deliverable 2.2 presents a first screening of the existing indicators and provides a general picture of what can be measured with the current practices. The present Deliverable 2.3 contains an in-depth comparative analysis of the selected indicators, as well as the possibility of developing new indicators for TOP-REF. The different subtasks within this Work Package 2 are summarised in Figure 1.

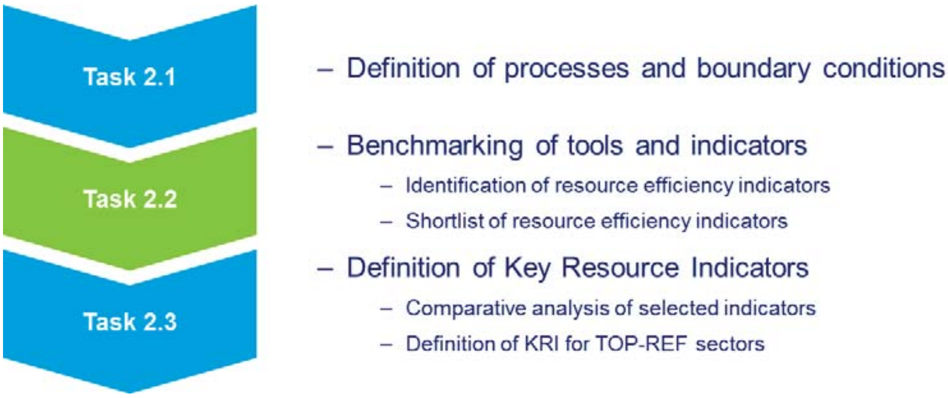

Figure 1: Task structure to define Key Resource Indicators for TOP-REF

The Key Resource Indicators should have certain common qualities such as a being valid for different sectors and being easily identifiable and measurable or easy to calculate. The indicators should also serve to reflect the advancement towards environmental and resource efficiency performance objectives. They could cover general aspects like the rejection rate, the cost of energy per product or the tons of CO_2 per ton of fuel.

2 METHODOLOGY

The aim of this task was to define the most suitable set of Key Resource Indicators (KRIs) for the three industrial processes studied in the project TOP-REF. This selection of indicators was based on the boundary conditions described in Task 2.1, and on the analysis of existing resource efficiency indicators identified in Task 2.2. The shortlist of indicators selected in Task 2.2 is reminded in Table 1 below.

Table 1: Resource indicators identified in Task 2.2

Material consumption	Abiotic Depletion Potential (CML)
Material cost	Abiotic Depletion Potential – elements (CML)
Material Input per Service Unit (MIPS)	Abiotic Depletion Potential – fossil fuels (CML)
Material Intensity	Fossil Depletion Potential (ReCiPe endpoint)
Recycled Content	Mineral Depletion Potential (ReCiPe endpoint)
Material efficiency / Specific consumption	Carbon Footprint of a product
Cumulative Energy Demand	Emissions of GHG
Direct energy consumption / Energy consumption within the organisation	Indirect GHG Emissions
Indirect energy consumption / Energy consumption outside the organisation	Acidification (Accumulated Exceedance - AE)
Energy Cost	Cost effectiveness (Keff)
Energy Intensity Factor	Eco-efficiency indicator
Exergy Indicators associated to Energy consumption, Emissions, Water consumption, Raw materials, and Residues[12].	Ecotoxicity (freshwater) (USEtox)
Specific Energy Consumption (SEC)	Eutrophication, terrestrial (Accumulated Exceedance - AE)
Water use / Water abstraction / Water withdrawal	Eutrophication, freshwater and marine (ReCiPe)
Water cost	Human toxicity, cancer effects (USEtox)
Water Footprint of products	Human toxicity, non-cancer effects (USEtox)
Water recycled or reused	Ionizing radiation (Human Health effects model)
Generation of waste	Ozone depletion potential
Share of waste treatment and disposal	Particulate matter / respiratory inorganics (RiskPoll)
Waste management cost	Photochemical ozone formation (ReCiPe)

The methodology for defining the most suitable set of indicators was as following:

1. **Definition of the objectives of the Key Resource Indicators in the project TOP-REF and the criteria for the selection of indicators**: in order to define the objectives and criteria of the KRIs, the project team consulted a few stakeholders from a range of backgrounds and with different intended uses of the KRIs to be developed. This consultation gathered the different views and needs from the possible users and public target of the indicators.
2. **Analysis of the indicators selected in task 2.2**: based on the objectives and criteria defined in the previous step, the project team applied a RACER evaluation framework[13] for the

[12] See Annex III:for a detailed description of the Exergy indicators

[13] Best et al, 2008

evaluation of indicators. RACER is the most appropriate evaluation framework found for this task, although this analysis contains some degree of subjectivity[14]. The selected parameters were analysed by using the RACER criteria to assess the appropriateness of each indicator to fulfil the objectives of the TOP-REF project. RACER stands for Relevant, Accepted, Credible, Easy and Robust. These criteria are detailed further in this report.

3. **Selection of Key Resource Indicators**: based on the results of the RACER evaluation in the previous step, the project team selected the most suitable indicators to propose a set of Headline Key Resource Indicators and some complementary Key Resource Indicators that fulfil the needs of the TOP-REF project. Some of the existing indicators were slightly modified to better suit the needs of the TOP-REF project (e.g. inclusion of the functional unit, definition of the scope of the indicator), but it was not deemed necessary to create new indicators.

The selected set of indicators will be tested on three pilot projects in future Work Packages of TOP-REF. The tests will serve to validate the usefulness of the information provided by the selected indicators and the accuracy of the calculation methods. Based on the analysis of the results of these tests, the set of KRIs could be amended.

3 Definition of criteria for the selection of Key Resource Indicators

A questionnaire carried out between a number of stakeholders helped the project team to gather the needs of possible users of Key Resource Indicators. The questionnaire is presented in Annex I, and the stakeholders that were interviewed in this step are presented in Table 2. Although the sample of the interviews is rather limited, its aim was to cover a few of the possible users and public related to the Key Resource Indicators that would be used in the project TOP-REF.

[14] There exist other similar evaluation methods, such as SWOT, which is used to analyse the situation in a given time of projects or organisations; or SMART, intended to evaluate targets, but none of these methods are suitable for the needs of this task.

Table 2: Interviews with stakeholders

Type of stakeholder	Organisation
TOP-REF industrial partner	Dow Chemical Iberia
TOP-REF industrial partner	Fertinagro
TOP-REF partner	Inosim
TOP-REF partner	TUDO
Auditors or standard managers	Danish standards
Policy makers or EC agencies	EASME
Information and support programme managers	Motiva

According to the responses collected, the main objective of the set of KRIs for all the respondents is to monitor internally and improve resource efficiency of processes over time. Most of the stakeholders would also use the KRIs to compare the resource efficiency of processes at different sites, and use the indicators to disclose environmental information of the company. The least important objective seems to be to compare the resource efficiency between different companies.

Objectives of KRIs	Number of responses			
	Main objective	Important objective	Preferable but not mandatory	Not important
To monitor and improve resource efficiency of processes internally over time.	6	0	0	0
To allow comparison of the resource efficiency of similar processes at different sites.	0	4	2	0
To allow comparison between companies of the resource efficiency of similar processes.	0	2	1	2
To report and disclose to the public resource efficiency improvements (e.g. sustainability reports).	0	3	2	1

Normalisation and weighting across indicators for the calculation of a single indicator is an optional step in e.g. ISO 14044 (2006). It can be helpful in communication or for optimisation purposes but this would imply supplementary calculation steps and a clearly documented aggregation methodology. Regarding the number and characteristics of the KRIs, most of the stakeholders consider more suitable to use a set of indicators rather than a single indicator. The opinions on the need of external databases to calculate the KRIs were divided: while some stakeholders preferred that the KRIs do not need of external databases and can be calculated based solely on company data, others accepted the need of databases to calculate the indicators.

Characteristics of KRIs	Replies
Would you recommend the use of a single Key Resource Indicator, or a set of a limited number of Key Resource Indicators?	4 respondents said KRI should be a set of indicators; 1 respondent said it should be a single indicator.
Would it be acceptable to use Key Resource Indicators that need the utilisation of public or commercial databases? (e.g. IPCC emission factors, LCA background datasets e.g. ecoinvent)	3 respondents said the use of databases is necessary; 2 respondents said that it would be preferable not to use databases; and 1 respondent said KRIs should not use external databases.

According to the results of the survey, the project team built a RACER framework for analysing the indicators shortlisted in Task 2.2. The three main objectives pointed out by the stakeholders were included as components of the aspects for analysis (i.e. relevant, accepted, credible, easy and robust), and specific criteria were defined for each of the aspects (i.e. an indicator is credible if the results of the indicator are verifiable and the means of reporting or calculation are transparent). The RACER matrix of criteria and **the results of the RACER analysis can be seen in Annex II.** The objective of this analysis was to obtain a classification of the indicators and to be able to choose a reduced number of them that better fulfil all the objectives.

4 Discussion – selecting a first set of KRIs for the three industrial sectors in TOP-REF

The RACER analysis is an appropriate methodology for selecting the KRIs as it highlights the strengths and weaknesses of each type of indicator. However, other methods may be used for refining this selection. In this sense, we have investigated the possibility of eliminating some indicators that might be correlated to others – and therefore, providing similar evidence for decision making. This discussion is based on results from the literature and it covers the energy and LCA-related indicators.

4.1 Correlation among indicators

A first approach was to investigate the relation between the energy indicators and the indicators associated to the emission of pollutants to the ecosphere. In Huijbregts et al. (2005), 226 energy production processes from the Ecoinvent database were analysed. The correlation between the fossil cumulative energy demand (CED) and eight other LCA indicators is presented in the following Table 3:

Table 3: Correlation between fossil CED and other LCA indicators for 226 energy production processes (adapted from Huijbregts et al. (2005))

Indicators	Coefficient of determination (R^2)
Global warming (GWP)	$R^2 = 0.97$
Abiotic depletion (ADP)	$R^2 = 0.98$
Eutrophication (EP)	$R^2 = 0.56$
Photochemical ozone creation (POCP)	$R^2 = 0.74$
Ozone depletion (ODP)	$R^2 = 0.49$
Acidification Potential (AP)	$R^2 = 0.71$
Land use (LU)	$R^2 = 0.00$
Human toxicity (HT)	$R^2 = 0.51$

These results show that, as expected, fossil CED is highly correlated to GWP (for the analysed set of processes) and ADP – $R^2 = 0.97 – 0.98$; and it is moderately correlated to other potential environmental impacts (AP, EP, POCP, ODP and HT) – $R^2 = 0.49 – 0.74$. LU has very small correlation with fossil CED. This is because LU plays an important role in relation to the production of renewable energies (especially biomass) but far less for fossil fuel extraction. Huijbregts et al. (2005) have achieved similar results in the analysis of 750 material production processes from ecoinvent.

Similar results are presented in Berger & Finkbeiner (2011). In this study, the correlation between several indicators is calculated for 100 materials from the ecoinvent database. An extract of the results is presented in the following Table 4:

Table 4: Correlation among different LCA indicators for 100 material production processes (adapted from Berger & Finkbeiner (2011))

Coefficient of determination (R^2)	CED	ADP	GWP	EP	POCP
CED	1	0.97	0.77	0.39	0.63
ADP		1	0.71	0.37	0.60
GWP			1	0.50	0.58
EP				1	0.40
POCP					1

In this study, CED is an indicator covering all primary energy uses and not just fossil energies but, once again, CED is highly correlated to ADP – $R^2 = 0.97$. This is explained by the fact that ADPs of the 100 selected materials are dominated by the consumption of fossil energy carriers to a magnitude of more than 95%. GWP, however, has a moderate (but significant) correlation with CED and ADP – $R^2 = 0.71 – 0.77$. The main sources for these differences are the non-energy related emissions that may occur in some processes (e.g. N_2O emissions from the field in an agricultural process).

Furthermore, the results indicate moderate correlations between emission-oriented indicators (GWP, EP, POCP) – R^2 = 0.40 – 0.60.

The results presented in this section were used in the indicators selection which is described in the following paragraphs. It is worth mentioning that both of the studies reviewed have selected processes that are fairly representative of the processes considered in TOP-REF for their analysis. The processes in a refinery (Petrogal), in the petrochemical industry (DCI) and in the fertilizer production (Fertinagro) are all energy intensive and therefore related to the energy production processes from Huijbregts et al. (2005). Also, the products and raw materials from TOP-REF industrial partners are linked to those analysed by Berger & Finkbeiner (2011) – 25 ores, metals and alloys; 25 monomers and polymers; 25 organic intermediates; 25 inorganic intermediates. Therefore, the conclusions of these studies can be used for recommendations with regards to indicators selection in the TOP-REF project.

4.2 Selection of a set of KRIs

As an additional step to the analysis of the candidate indicators considered individually, the following rationale was used for grouping KRIs together in a consistent set of KRIs. Overall, a set of KRIs for the TOP-REF Project would fulfil the following characteristics:

- Completeness in the coverage of objectives and resources in the scope of the TOP-REF project
- Low redundancy
- Consistency
- Reduced number
- Being valid for different sectors and at the same time relevant for the specific industrial processes.

In order to select the most suitable KRIs, the project team based its choice on the results of the RACER analysis and on the characteristics presented above for the selection of a suitable set of indicators. The validation task that will be carried out within WP7 will be used to polish the KRI list by focusing their attention on the results obtained from the demonstration activities.

The objective of selecting several indicators is to be able to analyse easily the resource efficiency of industrial processes and monitor its evolution over time, and at the same time have the possibility to identify which aspects of the process are relevant. A few headline indicators would allow users to evaluate and monitor the resource efficiency of the process, and a number of complementary indicators will serve to assess in detail the environmental aspects of the process.

The use of several headline and complementary indicators allow also measuring different aspects of resource efficiency, such as the quantities of resources used and the environmental impacts caused by the use of these resources. A single indicator summing up all these aspects would be beneficial for optimization purposes, since the calculation and interpretation of the results would be simplified. However, a single indicator would not give much detailed information other than a general trend of the resource efficiency of the process, and would not be useful if the users need to identify inefficiencies in the process. With this aim, it is proposed to use four headline indicators: one per type of resource covered (i.e. materials, energy and water) and one aggregated indicator that accounts for all three resources. Additionally, a number of complementary indicators that provide more detailed information on specific aspects of resource efficiency are proposed.

4.2.1 Indicators on material consumption

Between the indicators of material consumption, the ones best qualified in the RACER analysis are “material consumption” and “material efficiency”. Material consumption is in fact a part of material efficiency, which gives a ratio between the input materials and the output of the process. However, material efficiency does not explicitly include the concept of functional unit to ease comparison of results between processes or sites. For the objectives of this project, it would be preferable to use an indicator for material consumption calculated as a ratio of the functional unit of the process. This indicator would give enough information to the users to assess which aspects of the process can be improved in order to increase its resource efficiency. **Therefore, the indicator of material efficiency is proposed as headline indicator**, but this will be calculated as a ratio of the functional unit of the process.

It should be noted that material efficiency only captures the quantity of materials consumed, meaning that it does not account for the quality or scarcity of resources. Accordingly, environmental impacts and benefits of material consumption are not only related to the quantity of materials consumed but also to the quality of these.

In order to address this issue, the **Resource Exergy is proposed as additional indicator.** This indicator covers the consumption of resources in the form of materials, energy and water. In the case of a material input, exergy accounts for its composition, concentration and scarcity degree. A more detailed analysis of the Resource exergy indicator is provided in Annex III.

Table 5: Indicators on material consumption

Indicators	Headline indicator	Complementary indicator
Material consumption (kg/functional unit) (EC, 2009)		
Material cost (€/functional unit) (ISO 14051)		
Material Input per Service Unit - MIPS (kg/functional unit) (Schmidt-Bleek, 1993)		
Material Intensity (kg/€) (UN, 2007)		

Indicators	Headline indicator	Complementary indicator
Recycled Content (%) UNEP (2011)		
Material efficiency / Specific consumption (kg/kg) (UNEP, undated)	✓	
Resource Exergy indicator (including Cumulative exergy consumption, Exergy of materials and Exergy of water consumption) (J/functional unit) (Szargut and Morris, 1987; Dewulf et al. 2007; Valero, 2006)	✓	

4.2.2 Indicators on energy consumption

Among the indicators of energy consumption, the RACER analysis pointed out the "direct energy consumption" and the "specific energy consumption" as the most suitable energy indicators. The direct energy consumption is an indicator used in the Global Reporting Initiative. However, these two indicators do not explicitly include the concept of functional unit to ease comparison of results between processes or sites. On the contrary, the specific energy consumption is calculated per output of the process.

Similarly as in the case of material efficiency, it would be preferable to use an indicator for direct energy consumption calculated as a ratio of the functional unit or output of the process. **Therefore, the indicator of direct energy consumption is proposed**, but this will be calculated as a ratio of the output of the process, and expressed as primary energy consumption by using average conversion factors for the EU-28.

In addition, the **Resource Exergy indicator** proposed in the previous section is a general indicator that includes energy consumption and covers several aspects of the quality of resources consumed for the production of energy.

Table 6: Indicators on energy consumption

	Headline indicator	Complementary indicator
Cumulative Energy Demand/Embodied Energy (J/functional unit) (Valero, 2006; Sciubba, 2009)		
Direct energy consumption / Energy consumption within the organisation (J/functional unit) (GRI, 2013)	✓	

	Headline indicator	Complementary indicator
Indirect energy consumption / Energy consumption outside the organisation (J/functional unit) (GRI, 2013)		
Energy Cost (€/functional unit) (KPI library)		
Energy Intensity Factor / Economical Energy Efficiency (J/€ turnover) (EC, 2009)		
Exergy Indicator (Cumulative exergy consumption) (J/functional unit) (Szargut and Morris, 1987, Dewulf et al. 2007)	✓*	
Specific Energy Consumption (SEC) / Energy Efficiency Ratio (J/functional unit) (EC, 2009)		

* Included in the "Resource Exergy indicator presented in section 4.2.1"

4.2.3 Indicators on water consumption

Within the indicators of water consumption, the most suitable indicator according to the results of the RACER analysis is the "**water use**", which is proposed as headline indicator. This indicator can be calculated as gross water use per functional unit (i.e. all water inputs into the process) or as net water use per functional unit (i.e. all water inputs minus all water outputs from the process, also potentially taking into account the fact that the water can be rejected in the same environmental "compartment" or not, which does not have the same impact on the water cycle). We propose not to account for the water which is recirculated within the process (e.g. water used in a refrigeration circuit).

As in the previous cases, the main drawback of the indicator of water use is that it does not measure the quality of water resources; it focuses exclusively on quantities of water use and availability. The standard ISO 14046 proposes a wider definition of Water Footprint than that of Galli et al. (2011), including all metrics that quantify the potential environmental impacts related to water caused by an activity (e.g. water withdrawal, water scarcity, water degradation). Although this definition of Water Footprint is complete, some of the aspects included can be analysed separately by individual indicators (e.g. water use, eutrophication, ecotoxicity).

On the other hand, the Exergy indicator applied to water allows evaluating water resource degradation by means of a reduction of flow, height or quality. This **indicator is already included in the aggregated Resource Exergy indicator presented in section 4.2.1.**

Table 7: Indicators on water consumption

	Headline indicator	Complementary indicator
Exergy Indicator associated to water consumption (J/functional unit) (Valero, 2006)	✓*	
Water use / Water abstraction / Water withdrawal (m3/functional unit) (GRI, 2013)	✓	
Water cost (€/functional unit) (ISO 14051)		
Water Footprint of processes (m3/functional unit) (Galli et al., 2011)		
Water recycled or reused (%) (GRI, 2013)		

* Included in the "Resource Exergy indicator presented in section 4.2.1"

4.2.4 Indicators on waste generation and treatment

The indicators of waste generation can give information about the amount of materials that are inputs of the process but not finally used to produce a product or service. These indicators can give information indirectly on the efficiency of the materials consumed. However, the efficiency of the use of materials can be analysed directly by using the indicators of material flows (e.g. material consumed per functional unit or value created), and the environmental impacts of the waste generated can be assessed with environmental impact indicators (e.g. Ecotoxicity, Eutrophication, Human toxicity).

Indicators of waste treatment (e.g. recovery, reuse) are generally related to company management rather than to the efficiency of the process. Although strategies of reuse or valorisation of waste can improve the resource efficiency of a company or site, they do not improve the efficiency of the process itself. Therefore, none of these indicators on waste generation and treatment are considered relevant for the objectives of the KRIs in the TOP-REF project. For this reason, no indicator of this group is proposed as KRI.

Table 8: Indicators on waste generation and treatment

	Headline indicator	Complementary indicator
Exergy Indicator associated to residues		

	Headline indicator	Complementary indicator
(J/functional unit) (Valero, 2006)		
Generation of waste / Generation of hazardous waste (kg/functional unit) (UN, 2007)		
Share of waste treatment and disposal (%) (UN, 2007)		
Waste management cost (€/functional unit) (ISO 14051)		

4.2.5 Indicators on resource depletion

From the indicators of resource depletion, the three indicators developed by CML present the best evaluation in the RACER analysis. The aggregated ADP indicator includes ADP for elements and for fossil fuels. The previously presented results from the literature (section 2.1) show that the aggregated ADP is highly correlated to the cumulative energy demand (total or fossil) and to ADP fossil fuels as well – therefore cumulative energy demand, ADP (aggregated) and ADP fossil fuels would provide redundant information. In this context, only CML's ADP elements would be relevant for selection as a KRI, but as resource depletion and scarcity are already accounted for in the Resource Exergy indicator, including ADP is not necessary.

Table 9: Indicators on resource depletion

	Headline indicator	Complementary indicator
Abiotic Depletion Potential (CML) (kg Sb eq. /functional unit) (Van Oers et al., 2002)		
Abiotic Depletion Potential – elements (CML) (kg Sb eq. /functional unit) (Van Oers et al., 2002)		
Abiotic Depletion Potential – fossil fuels (CML) (kg Sb eq. /functional unit) (Van Oers et al., 2002)		
Exergy Indicator associated to raw materials (J/functional unit) (Valero, 2006)	✓*	
Fossil Depletion Potential (ReCiPe		

	Headline indicator	Complementary indicator
endpoint) (€/functional unit) (Goedkoop et al., 2009)		
Mineral Depletion Potential (ReCiPe endpoint) (€/functional unit) (Goedkoop et al., 2009)		

* Included in the "Resource Exergy indicator presented in section 4.2.1"

4.2.6 Indicators on climate change potential

The three indicators of climate change or GHG emissions present the same results in the RACER evaluation. However, it may be useful to present two different indicators that distinguish between direct and indirect GHG emissions (similarly to what was proposed for the energy indicators). These two indicators would give additional information to the users regarding the relevant aspects that could be improved in the process. **Therefore, the direct emissions of GHG and the indirect emissions of GHG are proposed as complementary KRIs.**

Table 10: Indicators on climate change potential

	Headline indicator	Complementary indicator
Carbon Footprint of a process (kg CO2 eq. /functional unit) (Wiedmann and Minx, 2008)		
(Direct) Emissions of GHG (kg CO2 eq. /functional unit) (UN, 2007)		✓
Indirect GHG Emissions (kg CO2 eq. /functional unit) (GRI 2013)		✓
Exergy Indicator associated to emissions (J/functional unit) (Valero, 2006)		

4.2.7 Indicators on other environmental impacts

Regarding other environmental impacts, there exist a number of impact categories not covered by the rest of the indicators analysed. These impact categories can be evaluated separately, with individual indicators, or combined in a single aggregated indicator.

The literature results presented in section 2.1 shows that the pollution-oriented indicators are (unsurprisingly) only moderately correlated. Therefore, all of them should be analysed separately and are proposed as complementary KRIs – they provide important information in different environmental decision making areas.

The aggregation of environmental impact indicators is a still debated step in the scientific community and there is no consensus on the best methodology to be used for this calculation step – weighting, monetising, etc. (Huppes et al. 2012, Ardente & Mathieux 2014). However, decision makers, which are used to uncertain and multidimensional situations, usually prefer to understand all the different trade-offs than relying in a single score (Baitz et al. 2012). Aggregation can be done to ease the handling of multiple environmental impact categories and is also useful for communication purposes. The different categories of impact can be merged in a single indicator that could be used for the calculation of the eco-efficiency indicator, which is a ratio between the economic value generated and the environmental impacts created. This indicator is proposed as a complementary KRI as well.

The aggregation can be done in multiple ways, including monetisation of environmental impacts (i.e. conversion of impacts into monetary value), or normalization and weighting.
In this project, our proposal is to use the normalization and weighting procedures proposed in the frame of the PEF-OEF initiative led by the European Commission, aiming at developing a harmonised framework for the environmental footprinting of products and services across Europe.

Table 11: Indicators on other environmental impacts

	Headline indicator	Complementary indicator
Acidification (Accumulated Exceedance - AE) (mole H+ eq. /functional unit) (Seppälä et al., 2006)		✓
Cost effectiveness (Keff) (kg/€) (EC, 2003)		
Eco-efficiency indicator (€/environmental impact) (EC 2013)		
Ecotoxicity (freshwater) (USEtox) (Comparative toxic unit for ecosystems - CTUe/functional unit) (Rosenbaum et al., 2008)		✓
Eutrophication, terrestrial (Accumulated Exceedance - AE) (mole N eq. /functional unit) (Seppälä et al., 2006)		✓
Eutrophication, freshwater and marine (ReCiPe) (kg P eq. /functional unit) (Struijs et al., 2009)		✓
Human toxicity, cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/functional unit) (Rosenbaum et al., 2008)		✓
Human toxicity, non-cancer effects (USEtox)		✓

	Headline indicator	Complementary indicator
(Comparative toxic unit for humans - CTUh/functional unit) (Rosenbaum et al., 2008)		
Ionizing radiation (Human Health effects model) (Kg U235 eq. to air/functional unit) (Dreicer et al., 1995)		✓
Ozone depletion potential (kg CFC-11 eq. /functional unit) (WMO, 2003)		✓
Particulate matter / respiratory inorganics (RiskPoll) (kg PM2.5 eq. /functional unit) (Rabl and Spadaro, 2004)		✓
Photochemical ozone formation (ReCiPe) (kg C2H4 eq. /functional unit) (Van Zelm et al., 2008)		✓

5 Summary of selected KRIs

In order to select the most suitable KRIs, the project team based their choice on the results of the RACER analysis. This facilitated the selection of one **headline indicator** per type of resource covered (i.e. materials, energy and water); a global headline indicator that aggregates these three types of resources; and a number of **complementary indicators** that provide more detailed information on specific aspects of environmental impacts.

At this stage of the project, the definition of the proposed indicators and the methods of calculation are not precisely defined. In particular, the scope of resources, processes covered and functional units could be defined in more detail. These aspects will be improved in Work Package 5 of the TOP-REF project.

Table 12: Selection of Key Resource Indicators

Key Resource Indicators	
Headline indicators	Material efficiency (kg/FU[15])
	Direct primary energy consumption (J/FU)
	Gross water use (m3/FU)
	Net water use (m3/FU)
	Resource Exergy indicator (resources: materials, energy and water) (J/FU)
Complementary indicators	Direct GHG emissions (kg CO2 eq./FU)
	Indirect GHG Emissions (kg CO2 eq./FU)
	Acidification (Accumulated Exceedance - AE) (mole H+ eq./FU)
	Ecotoxicity (freshwater) (USEtox) (Comparative toxic unit for ecosystems - CTUe/FU)
	Eutrophication, terrestrial (Accumulated Exceedance - AE) (mole N eq. /FU)
	Eutrophication, freshwater and marine (ReCiPe) (kg P eq. /FU)
	Human toxicity, cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU)
	Human toxicity, non-cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU)
	Ionizing radiation (Human Health effects model) (kg U235 eq./FU)
	Ozone depletion potential (kg CFC-11 eq./FU)
	Particulate matter / respiratory inorganics (RiskPoll) (kg PM2.5 eq. /FU)
	Photochemical ozone formation (ReCiPe) (kg C2H4 eq. /FU)

The headline and complementary indicators proposed in Table 12 aim to cover a wide range or aspects of resource efficiency and environmental impacts. Because of that, there might be some overlap between the indicators that measure the consumption of resources and those that measure

[15] FU: Functional unit, defined as a unit of use that characterises the result attended linked to the function studied. This unit is measurable and verifiable, and is the reference to which the quantities of the indicators are measured (based on ISO 14040).

the impacts of the consumption of resources. For example, the quantification of the energy consumption can be used as input data for the calculation of the GHG emissions. This means that the indicators of environmental impacts include somehow the information on resources consumed, although that is not their main function: the indicators of environmental impacts and the indicators of exergy quantify the *effects* of resource consumption on the environment; whereas the indicators of resource consumption measure the *inputs* of resources and the *efficiency* of the industrial process.

In some cases, the quantity of resources used per functional unit could be enough to monitor the resource efficiency of the process. For example, a reduction on resource input per functional unit would mean an increase of the resource efficiency. However, this correlation cannot be taken as a rule if the KRI should be valid to be applied in a wide range of industrial processes and sectors, which is the case of the TOP-REF project. In the case of substitution of resources, the quantification of inputs per functional unit may not be enough, since the consumption of different resources may imply different environmental impacts. For example, a substitution of the source of energy from fossil fuels to biomass would imply different environmental impacts.

For this reason, it is important to select a set of indicators that are complementary, cover all aspects of resource efficiency and avoid leaving any possible loopholes in the assessment of industrial processes.

6 NEXT STEPS

As explained in section 5, the methods of calculation of the proposed indicators are not unambiguously defined at this stage of the project. This will be developed in Work Package 7 of the project, and as explained in section 2, the proposed set of KRIs will be tested in the three pilot projects in Work Package 7 of TOP-REF.

One of the aspects to be clarified is the scope of each of the KRIs proposed. Some of the KRIs proposed relate to the resources used or the environmental impacts caused within the industrial process (e.g. direct primary energy consumption, direct GHG emissions), whereas other KRI have a larger scope, including the value chain of the resources consumed (e.g. indirect GHG emissions). The focus on the industrial process allows users to analyse only those aspects that can be controlled by the organisation (e.g. resources, emissions, waste). On the other hand, enlarging the scope to the value chain of the resources used may help to avoid the transfer of environmental impacts to other stages of the value chain, as well as to have a broad view of the main environmental aspects of the process and its value chain. For example, reducing the consumption of water may be possible but not worthwhile if it only accounts for a negligible part of the water consumed throughout the value chain of the resources. This issue will have to be clarified in order to harmonise the scope of the entire set of KRIs, and to provide clear instructions for the calculation of the indicators.

As explained in section 1.1, the resources included in the scope of the TOP-REF project are energy, fuels, minerals, biomass and water. Fuels can be considered as energy sources but also as non-energy materials if they are used as feedstock (e.g. hydrocarbons used in refinery processes). Classifying fuels based on the use made of them has the advantage that the results may reflect the real fate of the resources, but it requires a thorough knowledge of the process. If fuels are classified as energy sources independently of their use, the calculation and comparison of the KRI between different processes or sites would be easier. As the proposed set of KRIs covers both materials and energy inputs, the category in which the fuels are included should be clear and homogeneous for all the indicators.

All these aspects will be clarified before testing the KRI in the three pilot studies in TOP-REF in Work Package 7. These tests will serve to validate the practicability of the set of KRIs and to identify any possible amendments needed.

7 Suitability of the KRIs to support the objectives of the Public-Private Partnership SPIRE

The Sustainable Process Industry through Resource and energy Efficiency (SPIRE) is a Public Private Partnership aligned with the strategic goals of Europe in 2020 of the European Commission. In this initiative a pathway is given for the European process industry to create more jobs and to make industry more sustainable and competitive by decoupling human wellbeing from resource consumption SPIRE (2013).

The main aim of this section is to analyse the suitability of the headline indicators selected per type of resource, to measure the progress of the different actions that need to be taken in order to accomplish the goals proposed by the SPIRE.

This roadmap is divided in six Key Components: FEED, PROCESS, APPLICATIONS, WASTE2RESOURCE, HORIZONTAL and OUTREACH. Each of these components will be broken down into its Key Actions (KA) and for each Key Action a specific characteristic of the headline indicators will be suggested in order to help monitor and track the performance of the processes in the industry.

7.1 Key Component 1: FEED

The first component of the Spire is called FEED and it is intended to measure the increase of energy and resource efficiency through optimal valorisation and smarter use and management of existing, alternative and renewable feedstocks.

The Key Actions proposed for the accomplishment of component FEED and the applicability of indicators to measure the progress are summarized next.

7.1.1 KEY ACTION 1.1 Enhancing the availability and quality of existing resources

Direct Energy Consumption indicator will help quantify the energy efficiency of existing operations and facilities, and will give information regarding the efficiency increase or decrease accomplished through changes made in the processes. Exergy is an indicator that allows measuring the quantity and quality of a resource and provides a method to quantify irreversibilities, and detect where they are occurring (Valero and Valero, 2006). Material efficiency and water use indicators will give straightforward information about the reduction of material and water use and will help measure resource availability.

7.1.2 KEY ACTION 1.2 Optimal valorisation of waste, residue streams and recycled end-of-life materials as feed

The set of Key Resource Indicators proposed does not include indicators of waste streams, since these are generally related to company management rather than to the efficiency of the process. Although strategies of reuse or valorisation of waste can improve the resource efficiency of a company or site, they do not improve the efficiency of the process itself. Therefore, the KRI of the TOP-REF project would not contribute directly to this Key Action of the SPIRE programme.

7.1.3 KEY ACTION 1.3 Optimal and integrated (re) use of water

The exergy indicator is able to track and determine the exergy that is contained in different water streams. It can help in the evaluation of the possible re-use of water flows in processes. Through this methodology it is possible to simulate and assess the systems in terms of water quality, costs and quantity (Zaleta, Ranz, & Valero, 1998) (Martínez, Uche, Rubio, & Carrasquer, 2010). In addition, the water use indicator will reflect the decrease in water use per functional unit and is an easily understandable indicator.

7.1.4 KEY ACTION 1.4 Advancing the role of sustainable biomass/ renewables as industrial raw material

Material consumption and therefore the material efficiency indicator, will play an important role in the measurement of the progress of this key action. It will give information about the amount of biomass used in a process per functional unit. Depending on the approach, it will measure biomass as raw material or as fuel. In a complementary way, exergy indicator will help measuring the progress in the development and optimization of biomass processing technologies.

7.2 Key Component 2: PROCESS

The second component of the Spire roadmap is called **PROCESS** and focuses on solutions for more efficient processing and resource and energy efficient systems for the process industry, including industrial symbiosis. The way in which the selected indicators will contribute to the measurement of the KAs of this component are summarised next.

7.2.1 KEY ACTION 2.1 Novel advanced energy technologies

Through the calculation of the exergy indicators, it is possible to determine the location of irreversibilities and therefore the location of inefficiencies in the different processes (Rocco, Colombo, & Sciubba, 2013). New technologies can be developed to improve these weak points and increase energy and resource efficiency. The energy consumption indicator can be used to assess in terms of energy efficiency, reduction of energy costs and therefore advancement in competitiveness.

Novel energy technologies are expected to be more efficient also towards material and water use.

7.2.2 KEY ACTION 2.2 Energy harvesting, storage and reuse

Exergy data will also inform about the possibilities of energy harvesting and storage in a system. Energy, material and water use indicators will reflect the reuse of recycled material, energy and waste streams.

7.2.3 KEY ACTION 2.3 Process monitoring, control and optimization

Process monitoring, control and optimization is required to model the systems carefully and determine where potential improvements and savings can be made. All these savings will have an impact on material, water and energy consumption that will be measured by the Material Efficiency, Direct Energy Consumption and Water use indicators among others.

7.2.4 KEY ACTION 2.4 More efficient systems and equipment

Through the exergy analysis it is possible to compare the operation efficiency (in terms of exergy) of a system with its optimal performance values, and determine which equipment is presenting a malfunctions[16] and dysfunction[17] and then decide which actions to take in order to improve resource and energy consumption. The understanding of the process and the ability to qualitatively and quantitatively define the system allows improving and optimizing processes. As well as for the other key actions, the improvement in the efficiency of the equipment and the system in general terms will manifest itself in the selected indicators.

7.2.5 KEY ACTION 2.5 New energy and resource management concepts (including industrial symbiosis)

This key component is especially addressed by the exergy indicator, in the sense that as it is a measure of the quality of the resources used, it decouples from traditional accounting methodologies. As such for instance, if a certain industry uses recycled material instead of primary one (for instance via industrial symbiosis), exergy will be able to detect it.

[16] A malfunction is defined as the increase of the resource consumption of the component itself

[17] A dysfunction is defined as the irreversibility increment due to the malfunction of other processes, which causes more local resources consumption to obtain the additional production required

7.3 Key Component 3: APPLICATIONS

The key component **APPLICATIONS** is meant to track the development of new processes for sustainable materials and market applications that boost energy and/or resource efficiency across the value chain. The key actions proposed for this component and the contribution of the selected indicators for its measurement are summarized next.

7.3.1 KEY ACTION 3.1 New materials contributing to develop energy and resource efficient processes

To develop and produce a new material many resources like water, raw materials and energy need to be consumed and a lot of waste and residues are generated (e.g. GHG emissions thrown to the environment, among others). The selected indicators give valuable information on energy, material and water consumption and indirectly wastes generated do to the implementation of new materials. They give also important information regarding resource and energy use during treatment and disposal if used in a LCA approach.

7.3.2 Key Action 3.2 New processes for energy and resource efficient materials applied in sectors down the value chain

This Key Action can be measured by modelling different types of processes for the production of a specific material using the aggregated exergy indicator. As explained before, this will allow choosing the most energy and resource efficient process of the ones analysed. If one wants to know details about which resources have been improved one can then go on to check the different headline indicators chosen.

7.4 Key Component 4: WASTE2RESOURCE

Another component that can be measured with the help of the indicators selected is **WASTE2RESOURCE**. This component summarizes the actions needed for the valorisation and re-use of waste streams. The KAs for this component and the application of headline indicators for their measurement are analysed in the following section.

7.4.1 KEY ACTION 4.1 Systems approach: understanding the value of waste streams

The generation of residues is an inseparable part in a production process. Along with the desired product, some remaining flows of matter and energy will appear. These residues can be considered as wastes and be thrown to the environment or reused as resources in other parts of the processes. The avoidance, valorisation and reuse of residues are one of the main goals of the European Commission defined in the “Roadmap to Resource efficient Europe, 2011” (EC, 2011). By achieving these goals processes will inevitably be more efficient in terms of energy, material and water use. In order to accomplish this it is imperative to understand the value of waste streams and understand possible synergies in order to develop Industrial Symbiosis Concepts. Industrial Symbiosis allows a reduction of both natural resources and energy consumption as well as waste production (Valero et al,. 2013).

7.4.2 KEY ACTION 4.2 Technologies for separation, extraction, sorting and harvesting of gaseous, liquids and solid waste streams and KEY ACTION 4.3 Technologies for (pre)treatment of process and waste streams (gaseous, liquids, solids) for re-use and recycling

For this Key Action the exergy methodology as well as the Direct Energy Consumption indicator will help measure the energy and resource efficiency of all types of technologies developed for material and waste handling and processing. In this line the Material Efficiency indicator is able to quantify the recovery of critical and valuable material by reducing primary material consumption and enlarging recycled content.

7.4.3 KEY ACTION 4.4 Value chain collection and interaction, reuse and recycle schemes and business models

For this Key Action, all headline indicators need to be addressed in a more global approach. The implementation of value chain interactions between companies and their processes combined with the information of the headline indicators, will allow having more efficient processes. Energy, material consumption and waste generation in the entire Life Cycle of a product can be decreased.

7.5 Key Component 5: HORIZONTAL

The main aim of this component is to identify efficient resource and energy solutions and practices implemented in one sector and transfer them to another in order to promote new practices and products that have a significantly better environmental impact performance. The Key Actions for this component and the importance of the selected headline indicators are summarized next.

7.5.1 KEY ACTION 5.1 Identification, benchmarking and dissemination of cross-sectorial transfer of good energy and resource efficiency solutions and practices

The main objective of the indicators mentioned throughout this document, is to help identify the best processes and solutions to increase and optimise resource and energy efficiency in the industries. Regardless of the specific action taken, all headline indicators will give valuable information about the performance of the systems analysed.

7.5.2 KEY ACTION 5.2 Methodologies and tools for cross-sectorial Life Cycle and Cost Assessment as well as novel social Life Cycle Assessment of energy and resource efficiency solutions

The idea of the analysis of the indicator is to have appropriate assessment tools and methodologies to evaluate processes and identify the most resource and energy efficient ones. As mentioned before, each chosen indicator is focused in giving specific information about energy and resource consumption.

7.6 Key Component 6: OUTREACH

The component OUTREACH is meant to give information to the companies about the economic factors, the environmental impact and social aspects of the activity they perform.

7.6.1 KEY ACTION 6.1 Analysis and establishment of efficient technology dissemination methodologies and mechanisms and frameworks

The headline indicators selected are easy to understand and straight forward, this allows to efficiently distribute the knowledge generated from projects. The use of simple definitions, calculation methodologies and scores are key for achieving dissemination and to inform society, industries and people in general.

8 Conclusions

The aim of this task was to define the Key Resource Indicators (KRI) from the boundary conditions and benchmarking of the existing indicators carried out in the previous task 2.2. The indicators selected in task 2.2 were analysed against the criteria of the partners of the TOP-REF project and additional stakeholders in order to find the most suitable indicators for monitoring resource efficiency in the process industry.

The proposed set of KRIs (see Table 12) is based on indicators currently used in the industry and extensively defined in the literature. All the indicators are calculated in relation to the functional unit of the process, which facilitates the monitoring of the resource efficiency of the process and the comparison between different processes and sites.

The set of KRI includes a few headline indicators or resource efficiency accompanied by some complementary indicators of environmental impacts. This set of indicators was selected to be valid for different industrial sectors and be easily identifiable and measurable. The selected indicators should serve to reflect the advancement towards environmental and resource efficiency performance objectives. The proposed set of KRIs is presented in the following table.

Key Resource Indicators	
Headline indicators	Material efficiency (kg/FU[18]) Direct primary energy consumption (J/FU) Gross water use (m3/FU) Net water use (m3/FU) Resource Exergy indicator (resources: materials, energy and water) (J/FU)
Complementary indicators	Direct GHG emissions (kg CO2 eq./FU) Indirect GHG Emissions (kg CO2 eq./FU) Acidification (Accumulated Exceedance - AE) (mole H+ eq./FU) Ecotoxicity (freshwater) (USEtox) (Comparative toxic unit for ecosystems - CTUe/FU) Eutrophication, terrestrial (Accumulated Exceedance - AE) (mole N eq. /FU) Eutrophication, freshwater and marine (ReCiPe) (kg P eq. /FU) Human toxicity, cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU) Human toxicity, non-cancer effects (USEtox) (Comparative toxic unit for humans - CTUh/FU) Ionizing radiation (Human Health effects model) (kg U235 eq./FU) Ozone depletion potential (kg CFC-11 eq./FU) Particulate matter / respiratory inorganics (RiskPoll) (kg PM2.5 eq. /FU) Photochemical ozone formation (ReCiPe) (kg C2H4 eq. /FU)

[18] FU: Functional unit, defined as a unit of use that characterises the result attended linked to the function studied. This unit is measurable and verifiable, and is the reference to which the quantities of the indicators are measured (based on ISO 14040).

The proposed set of KRI will be validated in Work Package 7 of the TOP-REF project, where these indicators will be calculated for three pilot cases. The specific scope of each indicator, calculation methods and data inputs needed will be clearly defined for the application of the three pilot cases.

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10 ANNEX I: QUESTIONNAIRE FOR STAKEHOLDER CONSULTATION

TOP-REF - Innovative tools, methods and indicators for optimizing the resource efficiency in process industry

Questionnaire for identification of needs and requirements for Key Resource Indicators

Introduction of the project

TOP-REF – Innovative tools, methods and indicators for optimizing the resource efficiency in process industry – is an international collaborative project funded by the European Commission under the 7th Framework Programme.

The project objective is to increase the competitiveness and efficiency of the EU resource-intensive process industry, focusing in the chemical, agrochemical and petrochemical sectors. TOP-REF will help improving the efficiency in the use of energy, water and raw materials, and reducing production costs. Within the framework of the TOP-REF project, the relevant natural resources are: energy (renewable and non-renewable), fuels (fossil and biotic), minerals, biomass and water.

To achieve this goal, TOP-REF will develop and demonstrate a robust, resource-efficiency-focused and cross-sectorial methodology that will be validated through demonstration under real conditions in three pilots, one in each sector.

The final goal is to contribute to drive Europe to a leadership position in energy efficiency in industries by means of the promotion of a more efficient, greener and competitive economy based on knowledge and innovation.

Objective of this task

An important part of the methodology is the use of indicators to measure the improvements in resource efficiency. With that objective, the project team will define Key Resource Indicators (KRI) for industrial processes. A Key Resource Indicator (KRI) is a variable that represents an index for evaluating the resource efficiency of a process or the impacts associated with the consumption of resources. These indicators will directly serve to measure the improvements in terms of resource efficiency in industrial processes.

The indicators should have certain common qualities such as a being valid for different sectors and be easily identifiable and measurable or easy to calculate. The indicators should also serve to reflect the advancement towards environmental and resource efficiency performance objectives. They could cover general aspects like the rejection rate, the cost of energy per product or the tons of CO_2 per ton of combustible.

Objective of this questionnaire

This questionnaire aims to gather the needs of possible users of Key Resource Indicators. The project team will define the set of KRI that fulfil best these needs.

Questionnaire

1. Please comment on the objectives of Key Resource Indicators for the industry:

Should the KRI be developed:	Reply
To monitor and improve resource efficiency of processes internally over time?	
To allow comparison of the resource efficiency of similar processes at different sites?	
To allow comparison of the resource efficiency of similar processes at different sites, only within the same company?	
To allow comparison of the resource efficiency of similar processes at different sites, across an industrial sector?	
To report and disclose to the public resource efficiency improvements (e.g. in sustainability reports)?	
To report and disclose resource efficiency improvements to other audience? please specify:	
Other (please specify):	

2. The Key Resource Indicators should have the following characteristics:

Characteristics of KRI:	Are these criteria important for you to select the Key Resource Indicators? Why?
Relevant: the indicators should give accurate information about the resource efficiency of processes. E.g.: amount of materials consumed per economic value of the output of the process.	
Accepted: the indicators should be easy to understand by the target audience and scientifically sound. E.g.: emissions of kg. CO_2-eq. (assessed	

according to IPCC factors).	
Credible: the results of the indicators should be verifiable. E.g.: consumptions and emissions are tracked and available for audits of sustainability reporting.	
Easy: the indicators should be easy to measure or calculate. E.g.: no complicated modelling is required and all necessary data are available.	
Robust: the results of the measurement or calculation should be reproducible in the same conditions. E.g.: if the same method is followed, the deviation of the result is low.	
Would you suggest any additional criteria for the Key Resource Indicators?	

3. How should the Key Resource Indicators measure resource efficiency?

The KRI should measure:	Reply
Amount and type of natural resources used (e.g. electricity consumption)?	
Amount of natural resources necessary from a life cycle perspective (e.g. primary energy consumption, embodied energy, extracted primary material)?	
Environmental impacts of the use of natural resources (e.g. GHG emissions, water footprint)?	
Economic performance of processes (e.g. added value created)?	
Generation of waste (e.g. amount per type of waste and treatment)?	
Resource efficiency as a ratio between two of the aspects above?	
Other (please specify):	

4. Would you recommend the use of a single Key Resource Indicator, or a set of a limited number of Key Resource Indicators?

5. Would it be acceptable to use Key Resource Indicators that need the utilisation of public or commercial databases? (e.g. IPCC emission factors, LCA background datasets e.g. ecoinvent)

6. Should the scope of the system (e.g. process, site, company, supply chain) and the functional unit of the process (e.g. kg of output, economic value) be specified and constant for Key Resource Indicators?

11 ANNEX II: RACER MATRIX OF ANALYSIS

racer matrix.xlsx

Table 13: Matrix of RACER criteria

	Relevant for the following objectives:			Accepted by the main stakeholders:			Credible	Easy	Robust
	To monitor and improve resource efficiency of processes internally over time.	To report and disclose to the public resource efficiency improvements (e.g. sustainability reports).	To allow comparison of the resource efficiency of similar processes at different sites.	Technical staff in the company: to monitor and improve resource efficiency of processes internally over time	General public and auditors: to report and disclose to the public resource efficiency improvements (e.g. sustainability reports).	Technical staff in industry and policy makers: allow comparison of the resource efficiency of similar processes at different sites			
High	The indicator is relevant and sufficient to fulfil the mentioned objective.			The indicator is scientifically sound and well understood by the main users (i.e. technical staff).			The results of the indicator are verifiable, and the means of reporting or calculation are transparent.	The indicator is easy to measure or calculate. No complicated modelling is required and all necessary data are available.	The results of the measurement or calculation are reproducible in the same conditions.
Medium	The indicator is somehow relevant for the objective but presents some drawbacks.			The indicator is scientifically sound and well understood by the main users and target audience, but characteristics of the indicator (e.g. its unit) make it hard to understand by non-experts.			The results of the indicator are verifiable but the reporting is not entirely transparent or objective.	The measurement or calculation of the indicator is possible with some resources and data.	The results of the measurement or calculation require some assumptions and thus can present some deviation from one assessment to another.
Low	The indicator is not relevant at all.			The indicator is not scientifically sound or it is difficult to understand by the main users and target audience.			The results of the indicator cannot be verified or they are not objectively reported.	The measurement or calculation of the indicator is not easy and requires significant resources, time or external data.	The data is not reproducible and/or the results vary. The indicator includes a number of assumptions and/or estimations that make it not repeatable.

12 Annex III: Exergy indicators for resource consumption

12.1 Exergy Indicator associated to energy consumption

This indicator forms part of the global exergy of resources. It can be divided into two components: electricity and fuels.

12.1.1 Electricity, EEC

In order to calculate this indicator all electricity consuming devices of the process need to be taken into account. This indicator can be calculated as follows. Note that in this case, the energy and exergy values are equivalent, as the exergy of electricity is equal to its energy content.

$$EEC = \frac{kWh\ of\ electricity\ consumed}{functional\ unit}$$

Note that as in the case of the "direct energy consumption" indicator, the EEC should be then converted into primary energy consumption by using average conversion factors for the EU-28.

12.1.2 Fossil fuels, EFF:

This indicator gives information about the amount of fossil fuels that are used in a process compared with the amount of final product obtained. In this case, the exergy of fossil fuels can be roughly obtained through the High Heating Values of each substance. Alternatively, a more accurate conversion for the following fuels can can be used: 39,394 kJ/Nm3 for natural gas; 45,517.4 for an average fuel oil; 31,624.2 for anthracite; 29,047.1 for bituminous coal; 24,276.5 for subbituminous coal; 17,351.1 for lignite. In addition, this indicator could be used to assess also biomass use (again, through the corresponding HHV). Note that it has no sense to add in mass or volume terms fossil fuels, as these have all different qualities and cannot be compared that way.

$$EFF = \frac{Exergy\ of\ fossil\ fuels\ (kJ\ or\ kWh)}{kg\ of\ final\ product}$$

12.2 Exergy Indicator associated to water consumption, EWC:

This indicator is based on the water consumption that takes place in a process. The exergy of any water body *represents the maximum mechanical work that can be obtained from it until reaching the complete equilibrium with the reference environment (that is, it is totally diluted* *into the ocean)*. The thermodynamic status of water can be characterized through six parameters: temperature, pressure, composition, concentration, velocity and altitude. The indicators can be calculated as follows.

$$\boldsymbol{EWC = \frac{Exergy\ contained\ in\ water\ body\ used\ in\ the\ process}{kg\ of\ final\ product}}$$

12.3 Exergy Indicator associated to raw materials, ERM

For the calculation of this indicator we need to know the exergy of the raw materials entering the system. The exergies of the raw materials are calculated taken into account the concentration and chemical components of the flows as well as the so called exergy replacement cost, which accounts for abiotic resource depletion. For the latter, a weighting factor for each element measured in J/ton of chemical element is applied. Such values have been published in the literature (Valero and Valero, 2014)

$$\boldsymbol{ERM = \frac{Exergy\ of\ the\ raw\ materials\ entering\ the\ system}{kg\ of\ final\ product}}$$