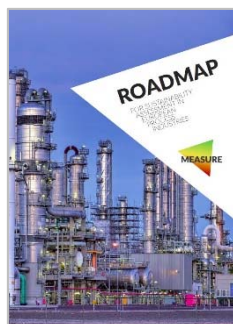


Background document

supplementing the
“Roadmap for
Sustainability Assessment in
European Process Industries”



Current state in resource efficiency evaluation

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Table of Content

1	Introduction	4
2	Choice of the goal and scope	6
3	Quantification of resources: calculation of the resource efficiency denominator	8
3.1	Resource accounting methods	8
3.2	Impact assessment methods	10
4	Points of attention for resource efficiency evaluation in process industry	12
4.1	Choice of the level of the evaluation	12
4.2	Resource covered by life cycle based methods.....	12
4.3	Definition of the benefits from resource use (functionality)	13
4.4	Consideration of criticality in resource efficiency evaluation	13
5	Evaluation of the resource efficiency of innovative products and processes	14
6	Conclusion	16
7	Abbreviations	17
8	References.....	18

1 Introduction

Today, there is no consensus on how to define resource efficiency. The resource efficiency platform of the European Commission (EC) defines resource efficiency as ‘using the Earth’s limited resources in a sustainable manner while minimizing impacts on the environment’ (EC-OREP, 2014). This is however a very broad definition that requires further clarification to allow quantification. Several methods have been developed to evaluate the resource efficiency of products and processes. For example, the ESSENZ method (Integrated method to assess/measure resource efficiency) combines a broad range of indicators related to resource use, i.e. indicators characterizing resource availability (divided into indicators characterizing physical availability and socio-economic availability), societal acceptance and environmental impacts (Bach et al., 2014). Another approach, developed in the framework of the TOP-REF project, defines resource efficiency of processes and products based on a set of five headline indicators (material efficiency, direct primary energy consumption, gross and net water use, resource exergy indicator) completed by 12 emission-oriented environmental impacts indicators (BIO by Deloitte & CIRCE, 2014). Therefore, many approaches are gathered behind the terms ‘resource efficiency’ in literature and reframing the concept is needed.

From a general point of view, efficiency is the comparison of the ‘efforts’ put in a process or system and the benefits obtained from this process or system (a product or a service). Resource efficiency is thus expressed as a ratio between efforts and benefits:

$$\text{Resource efficiency} = \frac{\text{Benefits from resources}}{(\text{Impact from}) \text{ Resources used}}$$

Whereas this concept is easily agreed upon, the exact definition of the numerator and denominator is less clear. Generally, the benefits are more easily understandable, namely the useful output from a system, often delivered to an end user, which can be in kg, MJ, €, or other units.

The denominator can be defined as the amount of resource used to produce the studied product or service, or as the impact from resource consumption. In the context of the MEASURE project, the impact from resource consumption is limited to the environmental context and thus labor, capital cost, time, etc. are not considered in our definition of resource efficiency. Within the environmental dimension, a general distinction can be made between resources in *sensu lato* (broad sense) and *sensu strictu* (in the strict sense). The first one is mainly used by environmental policies taking into account the effects of emissions, whereas the latter is mainly used in (process) industry and engineering (Huysman et al., 2015b), where resources are defined as an ‘input’ in a system and indirect effects of emissions on resources are not considered. Therefore, whereas both viewpoints are interesting, this document addresses resource efficiency evaluation within European process industries and in this context, we consider resources in *sensu stricto*.

Even within this viewpoint, many definitions of resources are followed in industry. These definitions differ on the number and types of resources considered. The SPIRE Roadmap defines resources as 'energy, raw materials and water'. The advantage of this definition is that it allows considering waste as a resource, as it does not only define resources as directly extracted from the natural environment. Moreover, it explicitly considers water as a resource, as it is a key resource in process industries. However, the definition provided by SPIRE does not consider land. This resource is considered as a key resource in scientific literature (Alvarenga et al., 2013; EC, 2014a; Klinglmair et al., 2014) and should also be considered.

2 Choice of the goal and scope

The indicators applied to quantify (impact from) resource use depend on the scale of the system to be analyzed (micro and macro level). Figure 1 gives an overview of a typical industrial system in which a distinction can be made between the natural environment and the industrial production system. The latter consists of production processes which are structured in ‘the foreground’ system and their supporting/background processes (e.g. their supply chain or waste treatment facilities). The scale of the studied system can depend on the goal and scope of the study. This can be:

- One single unit operation
- A chain of processes
- A production plant
- An industrial sector
- A country/region

A choice can then be made to account for the life cycle of the studied product or service, or to conduct a gate-to-gate analysis, i.e. to focus on the foreground system. The gate-to-gate analysis generally starts with a Material (and Energy) Flow Analysis. When following a life cycle perspective, data on background processes can be gathered by using Input-Output tables at country or sector level (e.g. Exiobase (Tukker et al., 2009) or the World Input-Output database (Dietzenbacher et al., 2013)), or life cycle assessment (LCA) databases such as ecoinvent (Frischknecht & Rebitzer, 2005), ELCD (JRC, 2014) or Gabi (PE International, 2013) for evaluation of resource efficiency at process or product level.

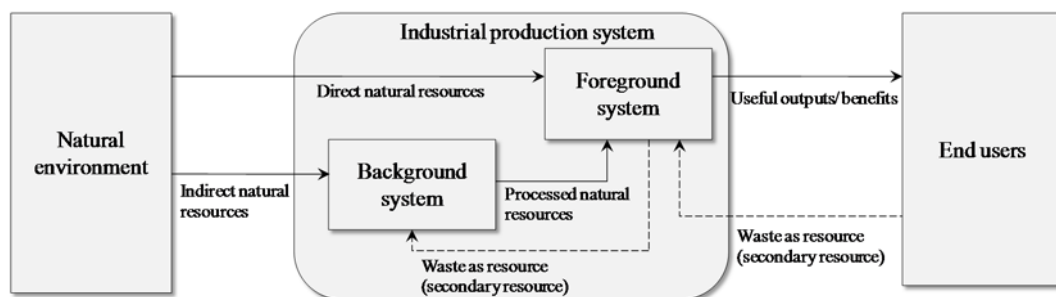


Figure 1: Simplified system diagram related to resource use (Sfez et al. (2016))

The inclusion of waste as a resource is a discussion that is linked to the choice of the goal and scope. Generally all three resource types, i.e. processed natural resources (already converted by the industrial production system), direct natural resources (virgin energy, raw materials, water and land) and waste as resource (which can be either post-consumer or post-industrial), are included when studying the foreground process at gate-to-gate level:

$$\text{Resource efficiency at gate-to-gate level} = \frac{\text{Benefits from resources}}{\text{Processed natural resources} + \text{direct natural resources} + \text{waste as resource}}$$

When accounting for resource efficiency at the level of the life cycle, generally waste as a resource is not accounted for and seen as gratuitous.

$$\text{Resource efficiency at life cycle level} = \frac{\text{Benefits from resources}}{\text{(Impact from) Natural resources}}$$

3 Quantification of resources: calculation of the resource efficiency denominator

The quantification of resource use is subject to more discussion as many options are available. Generally, this can be done in two different ways:

- By accounting for resources, i.e. by systematically accounting/booking the quantity of resources used based on a certain property of the resource.
- By assessing the impact of resource use, which is mostly done by considering the amount of resource available in the Earth's crust, predefined targets, future consequences of resource extraction, or willingness-to-pay (Klinglmair et al., 2014).

Both approaches are discussed herewith.

3.1 Resource accounting methods

Resource flows can be accounted for in different ways, and considering different chemical and/or physical properties of resources (Swart et al., 2015). These accounting methods have sometimes been integrated in the LCA framework to account for resources at the level of the industrial production system. Examples of methods are given in Table 1.

Resource property	Resource accounting at the production process (applied at gate-to-gate level)	Resource accounting at the industrial production system (applied at life cycle level)
Mass; Volume	Material flow analysis; substance flow analysis	Material Input Per Service unit (MIPS) (Ritthoff et al., 2002) Water footprint (Hoekstra et al., 2011)
Energy	Energy analysis: accounting of input energy flows, primary energy flows, energy embedded in materials...	Cumulated Energy Demand (CED) (Hischier et al., 2009) Primary Energy Demand (PED) (PE International, 2013)
Exergy	Exergy analysis: accounting of exergy content of materials and energy flows	Cumulated Exergy Consumption/Demand (CExC/CexD) (Bösch et al., 2007) Cumulative Exergy Extraction from the Natural Environment method (CEENE) (Dewulf et al., 2007)
Area	Direct land use accounting	Ecological footprint (Global Footprint Network, 2009)

Table 1: Examples of typically used resource accounting methods

At macro level, an example of resource efficiency indicator based on resource accounting method at macro level is the ratio of the Gross Domestic Product divided by the Domestic Material Consumption (GDP/DMC) proposed by the European Commission as the lead indicator of the Resource Efficiency Roadmap. It considers an economic benefit over an accounting of mass at gate-to-gate level. Several other resource efficiency indicators based on material flow accounting can be calculated at macro level, e.g. based on resource use indicators such as the Net Addition to Stocks (NAS), the Physical Trade

Balance (PTB) or the Total Material Outputs (TMO). Note that alternatives to such indicators have been proposed, e.g. the one proposed by Valero et al. (2015) as an alternative to the indicator GDP/DMC. Instead of using mass terms (i.e. DMC), the authors propose to use exergy replacement costs, i.e. the exergy that would be required to return minerals from the most dispersed state to their original conditions. However, macro level resource efficiency indicators are of limited interest for process industry.

Examples of resource efficiency indicators at production process level are the functional exergy efficiency defined as the ratio between the exergy of the product of interest and the exergy inputs of the system, or the energy efficiency e.g. as calculated through the R1 formula defined by the European Commission for waste-to-energy plants (for more details on the R1 formula, see section 2.3.2 of the MEASURE report D3.1).

Several resource accounting methods following the life cycle perspective exist. They are based on different resource properties (Table 1). For example, the Material Input Per Service unit (MIPS) considers resources in terms of mass, whereas the Cumulated Energy Demand method (CED) accounts for resources in terms of energy content.

One characteristic of resource accounting methods is that they can be applied at both gate-to-gate and life cycle levels. All resource accounting methods do not consider the same resources, e.g. land is not accounted for by mass accounting methods. Moreover, methods do not all account for the same resources within one resource category. For example mass accounting methods can only account for a fraction of energy carriers, e.g. typically not for wind energy or electricity. Similarly, resource accounting methods do not account for non-renewable, abiotic and biotic renewable resources in the same way (Sfez et al., 2016). Exergy based accounting methods are able to account for the largest number of resources as they are able to account for both materials and energy carriers.

Exergy accounting has first been integrated in the LCA framework through the Cumulated Exergy Consumption (CExC), which is the total exergy of natural resources extracted during the life cycle of a product or service. This approach has been coupled with the ecoinvent database in the Cumulative Exergy Demand method (CExD) (Bösch et al., 2007). Further, the CEENE (Cumulative Exergy extraction from the Natural Environment) method was developed by Dewulf et al. (2007) to overcome some limitations of the CExD methods. The main difference between CEENE and CExD is that CEENE also includes land as a resource, whereas CExD does not. The CEENE method was later updated by Alvarenga et al. (2013) who proposed a new approach to account for land resource by differentiating human-made and natural land use, as well as by calculating spatially differentiated characterization factors for land occupation. Moreover, the CEENE method was more recently updated to take into account resource consumption due to marine areas occupation (Taelman et al., 2014).

By using resource accounting methods, resource efficiency can be expressed unitless, as the benefits from resources can often be expressed in terms of mass/volume, energy

or exergy. This is typically the case for exergy based methods, since the numerator (benefits) can also be expressed in MJ exergy whether it is a material or energy flow. Furthermore, it can be combined with exergy analysis, which determines the efficiency of a production process. A disadvantage is the bad comprehensibility of the concept of exergy within process industry (EC, 2009). However, when using it for resource efficiency, this bottleneck is partly overcome by obtaining a result in ‘%’.

3.2 Impact assessment methods

There are four main types of methods assessing the impact from resource use (Klinglmair et al., 2014; Swart et al., 2015):

- *Methods based on reserves quantity/quality:* these methods consider the fact that the quantity and/or quality of resources available in the natural environment is decreasing. Some methods consider the decrease of ore grade as an indicator of resource availability in the natural environment (e.g. Swart and Dewulf (2013) and Vieira et al. (2012)), while other methods such as the Abiotic Depletion Potential (ADP) method (Guinée & Heijungs, 1995) put the amount of resources consumed in perspective with the reserves remaining in the natural environment. This approach is mostly followed in literature. One limitation of methods based on reserves quantity/quality is that they only consider non-renewable resources. Other limitations are regularly discussed in the scientific community and industry (Drielsma et al., 2016).
- *Methods based on distance-to-target:* these methods compare the amount of resources consumed to targets previously defined. This is for example the case of the Ecological Scarcity method (Frischknecht & Büsler Knöpfel, 2013).
- *Methods based on willingness-to-pay:* these methods estimate the monetary costs that people are ready to pay to restore damages caused to natural resources. An example is the EPS 2000 method (Steen, 1999).
- *Methods based on future consequences:* these methods consider the impact of the current resource consumption on future parameters (typically surplus energy (Jolliet et al., 2003) and surplus cost (Goedkoop et al., 2013; Vieira et al., 2016)) due to ore grade quality decrease in the natural environment.

Impact assessment methods are only applied at the level of the life cycle. Similar to accounting methods, they do not all consider the same resources and flows (Swart et al., 2015). Note that several methods consider land as a resource, but quantify the impact from land use to biodiversity, and therefore quantify the impact on another so-called Area of Protection (AoP) than the AoP ‘Natural Resources’, i.e. the AoP ‘Ecosystems quality’ (Dewulf et al., 2015; Sfez et al., 2016).

The ADP is widely used in industry (Schneider et al., 2014). It has been recommended by the Dutch LCA handbook (de Bruijn et al., 2002) and the ‘reserve base’ ADP has been selected as an impact assessment method in the Product Environmental Footprint (PEF)

guide to account for resource depletion (EC, 2012). Aside from PEF, instead of considering economic reserve as done in e.g. the EDIP method, the previous version of ADP considers the ultimate reserve, i.e. the total amount of a given substance on Earth (Guinée & Heijungs, 1995). This has often been criticized by industry as these reserves are not always extractable by humans and thus, the method developed by Guinée and Heijungs (1995) does not consider any scarcity issue. The ADP method has been revised by van Oers et al. (2002) to take into account this limitation by introducing ADP characterization factors based on different reserves types, i.e. ultimate reserve, reserve base and economic reserve.

Impact assessment methods, including ADP, only considers a limited set of resources, and mainly focus on abiotic non-renewable resources. Today, by accounting for different resource properties (mass/volume, energy, exergy and area), resource accounting methods integrated in the LCA framework are able to consider a wider range a resource types than impact assessment methods. These methods are therefore of high interest for the evaluation of resource efficiency.

4 Points of attention for resource efficiency evaluation in process industry

4.1 Choice of the level of the evaluation

When evaluating the resource efficiency of a system, the choice needs to be made between gate-to-gate and life cycle based analysis to evaluate the denominator of the resource efficiency ratio. Both approaches have limitations and advantages.

Gate-to-gate analysis is useful to calculate intermediary indicators for continuous process improvement and to understand the functioning of the studied process. It actually provides information on the conversion efficiency of a process. However, gate-to-gate analysis is unable to consider resources consumed downstream and upstream the process. In this way, life cycle based analysis allows a more complete and broader understanding of all the challenges associated with the resource use of a process. Both approaches can be followed and bring different information. However, an LCA should always be performed or, at least, a life cycle approach (i.e. which does not necessarily imply quantification) should be followed based on gate-to-gate data.

4.2 Resource covered by life cycle based methods

As aforementioned, existing life cycle based methods used to evaluate resource use do not all consider the same resources. This can be an issue when evaluating the resource efficiency of processes consuming biomass, for which significant amounts of land, water and fossil fuels can be used upstream. Therefore, the chosen method should at least cover the key resources consumed by the process and at best the largest number of resources. Note that it is advised to present results with a differentiation between biotic and abiotic renewable (e.g. wind energy) resources, as the latter are inexhaustible.

Some methods do not consider the same set of resources within a same resource category. For example, some methods consider peat as a fossil fuel while others do not. Moreover, some methods classify resources differently among resource categories, e.g. uranium is sometimes classified within metals, sometimes within fossil fuels.

Another important aspect is the coverage of metals and minerals by LCIA methods. In addition of being present in the natural environment, metals and minerals are present in the anthropogenic system, e.g. as building materials in some infrastructures (e.g. power grids). This stock becomes available at the end of the lifetimes of these installations. This anthropogenic stock is currently not covered by life cycle based methods. The Anthropogenic stock extended Abiotic Depletion Potential (AADP) method tries to include this stock (Schneider et al., 2011), but it is not yet operational as data is still missing to quantify the anthropogenic stock. The authors propose to include this stock in the ADP formula. Moreover, the stock 'ultimate reserves' is replaced by the stock 'resources', included in the ultimate reserves but which only includes resources which are economically

or potentially economically extractable today. This method was further updated to replace the stock 'resources' by the stock 'extractable geological stock' (Schneider et al., 2015).

4.3 Definition of the benefits from resource use (functionality)

Even though functionality is often better defined in life cycle analyses, its definition is important for both gate-to-gate and life cycle approaches. Lifetime and quality of the output product should be considered in this definition. This is however not always an easy task, especially in the case of processes processing waste, as such processes have a double function, i.e. the treatment of the waste and, in most cases, the delivery of secondary material and/or energy to the economy. The handling of recycling in life cycle based analyses is especially complex. Several approaches have been developed to consider the benefits from recycling. Sensitivity analysis is a useful step to strengthen the results obtained for recycling processes. Moreover, other metrics than the resource efficiency ratio have been recently developed to better account for the benefits from recycling, e.g. the Recyclability Benefit Rate (RBR), defined as the ratio of the potential environmental savings achieved from recycling over the environmental burdens of virgin production followed by disposal (Ardente & Mathieux, 2014; Huysman et al., 2015a).

4.4 Consideration of criticality in resource efficiency evaluation

Today, life cycle based methods only consider resource availability as dependant on their availability in the Earth's crust. However, it has been shown that the availability of resources for industry also highly dependents on a set of socio-economic parameters such as market stability or geopolitical issues (Dewulf et al., 2015b). These parameters can only be considered in a criticality assessment. The criticality of resources characterizes their importance in the economy and the risk of resource supply disruption (EC, 2014b). Such information should be considered. However, today criticality assessment goes beyond life cycle assessment, and no method has been fully developed to account for criticality parameters in the LCA framework. Such approaches are still needed.

5 Evaluation of the resource efficiency of innovative products and processes

Research and innovation is one of the strategies of regions and countries to tackle the challenge of resource supply worldwide and to increase resource efficiency of process industry. Thus, several regions and countries have launched their own research and innovation programs. It is the case of the EU and the Horizon 2020 funding program, which frames the SPIRE calls. Most of the project calls associated with these programs require project developers to reach specific targets regarding resource efficiency. In addition to the general points of attentions mentioned above and which also concern research and innovation projects, there are several bottlenecks that limit the evaluation of the resource efficiency of innovative products and processes. These are detailed below:

- *Vocabulary related to resources*: the vocabulary related to resources should be coherent in policy documents (e.g. EU documents) and project calls (e.g. SPIRE calls). For example, the indicator GDP/DMC defined by the EC in the framework of the resource-efficient Europe Flagship Initiative includes both fossil fuels and non-energy carriers but on the other hand programs such as SPIRE define targets for raw materials and energy intensities separately.
- *Level of the expected impacts*: the level of the expected impacts of projects on resource efficiency improvements should be clearly defined in project calls. These improvements can be achieved at two levels: the level of the region/country or of the process itself. Both levels are interesting and the link between them should be made, e.g. by considering the market share of the studied service or process.
- *Definition of product or service functionality*: a part of research and innovation projects develops new applications. In this case, the choice of the benchmark process or product considered to evaluate improvement of resource efficiency can be challenging. Project developers should look for the possibility to consider a 'basket' of products or services that fulfills the newly developed application.

In general, calls should be more specific when requiring project developers to report on improvements of resource efficiency. Guidelines and recommendations should be given regarding several points mentioned in part 4 (e.g. choice of the method, resources to consider) as well as in the paragraph above. Depending on the specificity of the call (i.e. if the call is sector or product specific or if it is more general), these recommendations should be clearly mentioned in the call, or project developers should be asked to justify their own choices in the proposal.

Today, the evaluation of resource efficiency in research and innovation projects is often conducted at the end of the project, and seen as a step needed to fulfill the call's requirements. However, resource efficiency evaluation could be useful to exclude certain options at the early stage of project development. At the beginning of the project, life cycle aspects (i.e. following a qualitative approach) and simple indicators or indexes could be

considered. The complexity of these indicators could increase at the end of the project, i.e. by considering LCA based indicators.

6 Conclusion

SPIRE aims at increasing the so-called resource efficiency of EU process industries within a defined time frame. However, to achieve this goal, it is necessary to clearly define what is meant by resource efficiency. Today, there is no consensus on the definition of such terms, leaving industries calculating resource efficiency following their own approach.

For a better estimation of resource efficiency within EU process industries, a better definition of the terms, scale and assessment practices should be agreed on and clear guidance on how to calculate resource efficiency should be provided if resource efficiency targets are set. This is especially the case when projects are conducted in the framework of research and innovation funding programs. In this case, comparability between projects is needed, and the link between the improvement of resource efficiency at micro and macro levels should be made.

7 Abbreviations

AADP	Anthropogenic stock extended Abiotic Depletion Potential
ADP	Abiotic Depletion Potential
AoP	Area of Protection
CED	Cumulated Energy Demand
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExC	Cumulated Exergy Consumption
CExD	Cumulated Exergy Demand
DMC	Domestic Material Consumption
EC	European Commission
ELCD	European Life Cycle Database
ESSENZ	Integrated method to assess/measure resource efficiency
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MIPS	Material Input Per Service unit
NAS	Net Addition to Stocks
PED	Primary Energy Demand
PEF	Product Environmental Footprint
PTB	Physical Trade Balance
RBR	Recycling Benefit Rate
SPIRE	Sustainable Process Industry through Resource Efficiency
TMO	Total Material Outputs

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