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Methodology to measure and improve the resource efficiency of resource intensive processes

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European foreword

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Introduction

The efficient management and use of limited resources have always been part of a successful economic activity. Achieving the goal of a safe, reliable, economical and environmentally friendly resource supply also requires the efficient use of available resources in order to increase the competitiveness and efficiency of the resource-intensive process industry. In recent years, focus has increased on resource efficiency. Stakeholders such as investors, NGOs or end users are demanding more environmental friendly products and services.

To ensure this, reliable indicators are essential for measuring and controlling environmental performance. In economic terms, standardization contributes to improve Europe's competitiveness in world markets with a better use of raw materials, natural resources and renewable energies. The current policy framework has set the way for more environmental friendly laws and regulations, and this fact has incentivized companies to improve their environmental and resource efficiency performance.

This CWA is an opportunity to further improve resource efficiency by introducing economy-wide resource efficiency indicators that will contribute to better informed decisions from both industrial agents and policy makers. The determination of comparable, reliable, accurate and globally accepted eco-efficiency indicators will be essential in the near future for the evaluation of the eco-efficiency of companies.

This CWA presents a cross-sectorial methodology for the identification and characterization of the critical process parameters (CPP) in order to establish and improve resource efficiency measures.

The application of this CWA will allow companies to have better knowledge of their environmental performance and footprint and their related financial impact which will allow a real comparison between companies and initiatives, ensuring the competitiveness of EU companies in global markets.

1 Scope

This European CWA specifies a cross-sectorial methodology for identifying, characterizing and implementing a set of indicators whose purpose it is to enable an organization to improve the resource use efficiency of a process or the impacts associated with the consumption of these resources.

It specifies a methodology applicable to resource use and consumption efficiency, including measurement, performance and optimization, and applies to all industries, but particularly to the resource-intensive process industry.

This European CWA has been designed to be used independently, but it can be aligned or integrated with other standards or management systems.

This European CWA also provides, in Annex A, informative guidance on its use.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
critical Process Parameter
CPP
operational variable of the system directly related to Key Performance Attribute values; the modification of the CPPs values along the utilities and product plants ensuring that the Key Performance Attributes are kept on range due to the influence of CPPs on Key Performance Attributes

3.2
exergy
maximum amount of work a system may theoretically perform by bringing a resource into equilibrium with its surrounding environment by a sequence of reversible processes

3.3
global sensitivity analysis
methodology to identify and rank the inputs according to their impact on the model's outputs; the term “global” describing that the impact is determined over the entire value range of inputs and that no assumptions are made about the linearity or additivity of the underlying model

3.4
In Site Battery Limit
fence of a production plant that is going to be considered as the system boundary in the methodology

3.5
Key Performance Attribute
KPA
variable directly related to products, by-products or interconnections between plant and utility systems which magnitude must be in a range of values that ensures quality, safety or production rates; which should be defined ad hoc for each process.

3.6
Key Resource Indicator
KRI
variable that represents an index for evaluating the resource efficiency (raw material, water and energy) of a process or transformation associated with the consumption of resources.

3.7
meta-model
model relating inputs and outputs, which are generated by a sampling, in a mathematical way

Note 1 to entry: It is important to note that a meta-model is data-driven and is not based on chemical or physical fundamentals.

3.8
Output Unit
OU
unit representing the quantity of the main economic output(s) of the process under study

3.9
process model
representation of a production process and the occurring phenomena in the apparatuses by physical and chemical laws

Note 1 to entry: By using a process model it is possible to describe the behaviour of a production plant at different operational states.

3.10
Process Parameter
PP
process control parameters for a process plant or utility system in regard to the KRIs

3.11
process plant
collection of process equipment which performs chemical or biochemical reactions and/or separation processes to produce valuable chemical or biochemical products

3.12
utility system
subsection in industrial frameworks responsible for power and/or heat generation and distribution interconnected with others process plants

4 Measuring resource efficiency

4.1 The methodology's stakeholders

4.1.1 General

It is important that stakeholders are involved throughout the implementation of the methodology. Each of these stakeholders have different roles in the use and success of the methodology.

4.1.2 Public authorities and policymakers

Public authorities may incorporate a resources efficiency methodology to measure and monitor resource efficiency in a tender or in the legislation. This may affect the whole value chain, since the raw materials price is linked to the public acceptance of the final product in the market.

These entities will put forward resource efficiency requirements in the market.

This group includes remarkable pan-regional institutions such as the European Commission and the European Parliament, as well as the national and local governments.

Policymakers' role is to advise and/or set new voluntary and/or mandatory standards and regulations to ensure compliance within an industry or sector.

4.1.3 Citizens, public opinion and users' associations

In line with the previous point, the perception of the citizens and the actions of the user associations directly affects the behaviour of the public authorities. The effect in the value chain is mostly in the final product, where the impact on the citizen, the capacity of decision, and the information is higher.

The role of these stakeholders is to raise awareness of the methodology and claim for its use in the market with actions addressing this improvement in the products on the market and their whole value chain.

4.1.4 Industry

Companies are the main users of the methodology to improve their resource efficiency and their position in the market. Thus, industry will decide on the implementation of the methodology. In addition, the impact of these companies in the workforce and in the Gross Domestic Product[1] provide them with the resources to influence the decisions of the public authorities, bringing a potential cooperation or conflict with the public opinion. Manufacturing industries are subject to the direct influence of the public opinion, which might provide further incentive to implement the methodology.

There are several persons within an industrial company's structure that have direct influence on the implementation of the methodology.

The <u>sustainability directors</u> have the responsibility to set and define strategies, regarding resource use and efficiency.

The <u>chief technical officer</u> has to ensure and facilitate the resources needed for the application of the strategies defined by the Sustainability Director. He/she also has the responsibility to superintend the application of this methodology.

In addition to this, the <u>utilities and logistics and supply chain and operations managers</u>' role is to commit and inspire their organization to continuously pursue new and innovative ways of being more resource efficient across the whole value chain.

4.1.5 Research and technology entities

Finally, research and technology entities (e.g. technology centres and universities) will provide the service for the implementation and updating of the methodology and related tools. These can help raise awareness of the methodology.

4.2 General overview of the methodology

The approach described here is a stepwise methodology to increase the efficiency of resource intensive industrial processes. The approach is based on a detailed process analysis of a defined production system to:

- select the Key Resource Indicators (KRIs) and enable their measurement or calculation for further improvement or minimization.

[1] Gross domestic product (GDP) at market prices is the expenditure on final goods and services minus imports: final consumption expenditures, gross capital formation, and exports less imports. Source: OECD

- define the process' constraints and requirements as Key Performance Attributes (KPAs)

- identify the Process Parameters (PP) and select the Critical Process Parameters (CPPs) for process control and optimization.

In order to apply the methodology, the system boundaries for the main system and optional subsystems have to be defined to apply all consecutive steps based on the same scope to ensure comparable results for all executed analysis. Definition of the system boundaries will be explained in 4.3.

A thorough process analysis will result in a set of product and process requirements or limitations which are crucial with respect to e.g. plant operation, product specification or safety and environmental issues. In order to define and correlate the KRIs, KPAs and PPs, a process model should be used. A process model is a representation of a production process and the occurring phenomena in the apparatuses by physical and chemical laws. By using a process model it is possible to describe the behaviour of a production plant at different operational states.

Using the process model, a set of KRIs will be selected, and for all selected KRIs the method for direct measurement or calculation based on secondary parameters will be defined. The requirements and constraints, defined as KPAs, will set the overall framework for all process optimization and improvement actions. Finally, the PPs will be identified which represent the process control parameters in regard to the KRIs.

Hereafter, a meta-model based on the process model(s) can be set up to reduce the computational effort for the sensitivity analysis and optimization actions. A meta-model relates inputs and outputs, which are generated by a sampling, in a mathematical way. It is important to note that a meta-model is data-driven.

For the identification of the CPPs, several methodologies and approaches are applicable which can be based upon recorded process data or process modelling. In any of these approaches, the parameters with greatest impact must be identified which can be done e.g. by sensitivity analysis or similar methods.

The selected set of KRIs should enable a continuous monitoring of plant operation. Thereby, the evolution of the KRIs in operation can be analysed, and actions on operational settings, which can improve the efficiency, can be initiated. To guide this action, the monitoring should be supplied by a set of optimized CPPs, suggesting more efficient operating parameters with respect to the KRIs and taking into account the constraints given by the KPAs.

For an overview of the methodology, see Figure 1.

Figure 1 — Overview of the methodology

If an organization does not already use a process model, meta-model, and sensitivity analysis, these should be set up, as they are a prerequisite for using the methodology in this CWA.

4.3 System boundaries

Two levels of system boundaries, represented in Figure 2, are defined in this methodology:

- **In Site Battery Limit (ISBL)**, which corresponds to the fence of a production plant. Raw materials and energy inputs are introduced over this fence; products and wastes leave the system delimited by this fence. It includes the process plant and the corresponding utility system. The processes within this first level of system boundaries are those that are under direct control of the producer of the good – the industrial party applying this methodology.

- **Cradle-to-gate**, which is a system boundary based on a Life Cycle perspective including all the processes from raw materials extraction, transportation and transformation steps until the production unit's output gate – the use phase of the product and its end-of-life are not in the scope of this methodology.

These system boundaries are complementary for the methodology. In a preliminary step, the cradle-to-gate system boundaries are advised to be applied; this allows for a holistic view of the resource consumptions and related environmental impacts associated with the industrial activity under study. 'Resource consumption factors' and 'impact factors', taking into account all the upstream processes (or downstream processes for what concerns e.g. waste treatment), are associated to all inputs of the ISBL. The cradle-to-gate system boundaries requires the availability of LCA databases in the user's organization (and possibly data collection on the processes within the cradle-to-gate boundaries).

After this preliminary step where the relevance and feasibility of adopting a cradle-to-gate approach are evaluated, the focus shifts to the processes under direct control by the methodology user. The resource consumption optimization, which is the core of this methodology, is performed using the ISBL as a system boundary: the optimization is done by changing parameters within the ISBL as explained in 4.2, considering eventually also those resources from the cradle-to-gate analysis that have been identified as relevant and feasible.

- Relevant: Significant resource consumptions takes place in upstream processes – it is, therefore, relevant to consider these processes for any resource efficiency actions. The preliminary step of this methodology, based on the cradle-to-gate system boundaries, can be discarded if no major resource consumptions are identified in the upstream processes.

- Feasible: LCA data on upstream processes is available or may be collected from suppliers – it is, therefore feasible to include these processes in the analysis. If LCA data on upstream processes is not available, it is acceptable to rely only on the second step of this methodology. This is, however, not recommended since significant resource consumptions are likely to occur in the upstream processes[2].

[2] For example, in a polyethylene polymerisation plant, the inputs would be ethylene, steam, electricity, etc. However, it has been verified that most of the mineral depletion occurs during ethylene production due to the use of a catalyst containing Palladium in the cracker. This catalyst is a consumable, upstream from the polymerisation plant, that strongly impacts resource depletion (because it is a rare mineral) and should be taken into account by placing the system boundaries covering all the steps from resource extraction to the polymerisation plant.

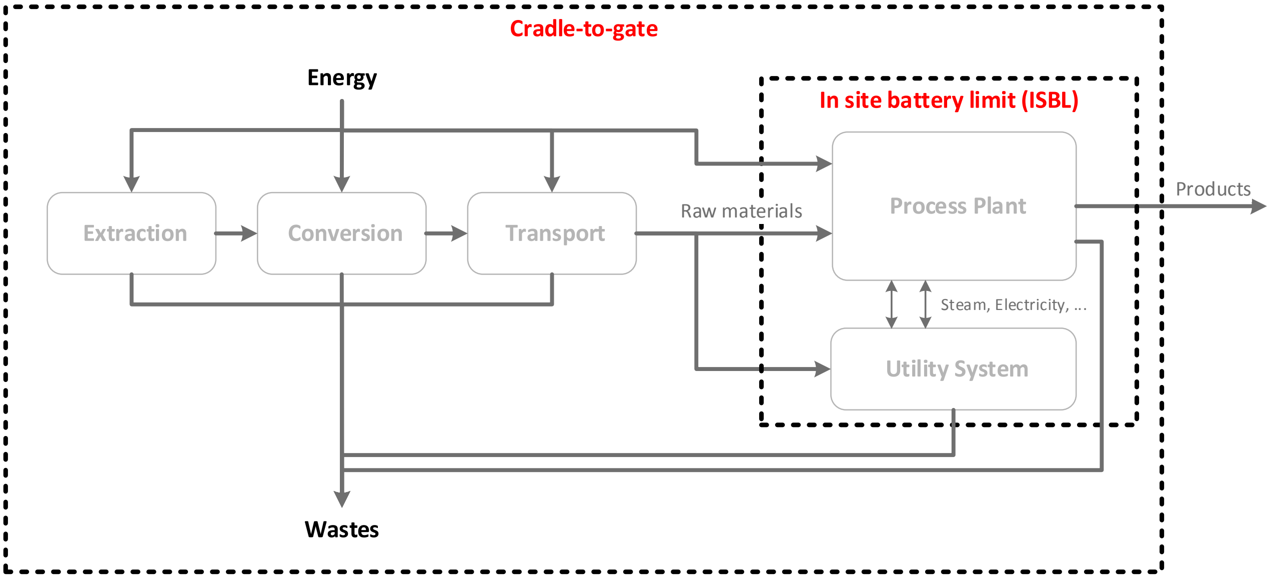

Figure 2 — Schematic overview of the system boundaries

4.4 Process analysis

An essential step for process control and optimization is the definition of indicators, which can be maximized or minimized depending on their nature (used as objective function for optimization). The methodology recommends the use of KRIs, KPAs and CPPs – these are described in the following sections and are represented schematically in Figure 3.

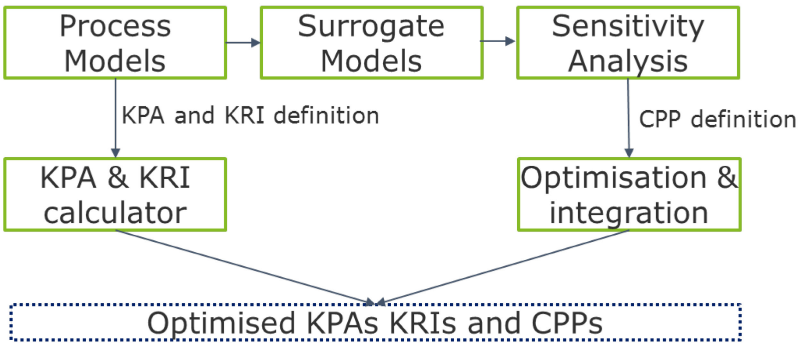

Figure 3 — Illustration of variables used for process control and optimization: CPPs, KPAs and KRIs

4.4.1 Key Resource Indicators

4.4.1.1 general

KRI is a variable that represents the **resource efficiency of a process**. These parameters should provide comprehensible, reliable and comparable information that can be used to improve resource efficiency in industrial processes.

A **KRI** should be developed taking into account the following characteristics (RACER criteria [3]):

— **R**elevant, i.e. the indicator should be closely linked with the overall objectives (e.g. monitoring, reporting, communication, and comparison of industrial sectors' performance)

— **A**ccepted (e.g. by main stakeholders)

— **C**redible, i.e. unambiguous and able to be verified

— **E**asy to measure / calculate and to monitor (e.g. data collection does not imply high costs or burdens)

— **R**obust against manipulation and interpretation

In addition, KRIs are broadly defined to allow for multi-sectorial application. In other words, KRIs can be used to monitor and improve resource efficiency and to report and disclose to the public the benefits of resource efficiency measures.

Since the KRIs are sensitive to the boundary conditions and the physical scale of the system, the system boundary where the methodology is applied should be clearly defined, as described in 4.3.

Two sets of indicators may be used within the methodology: Headline Indicators, which focus on resource consumption, and Complementary Indicators, which focus on environmental impacts associated with resource consumption.

Five Headline Indicators are proposed to constitute the main KRIs in the methodology:

— Unit material cost [kg/OU]

— Direct Primary Energy Consumption [kJ/OU]

— Gross Water Use [m^3/OU]

— Net Water Use [m^3/OU]

— Resource Exergy Indicator [kJ/OU]

Where OU stands for 'output unit' which represents the quantity of the main economic output(s)[3] of the process under study. This represents the reference to which all the parameters used to calculate the indicators will be normalized to. OU can be expressed in kg/s, kW or m3/s if it is referred to a material flow, energy flow or water flow, respectively.

These headline KRIs provide information on the three main resources used: raw materials, energy and water. The exergy indicator alone covers all of these resources and provides a quality-weighting factor based on rigorous thermodynamics. However, the other indicators (Unit Material Cost, Direct Primary Energy Consumption, Gross Water Use and Net Water Use) allow to focus on one specific type of resource and have been selected to ease the communication. The four Headline Indicators other than the exergy indicator have been proposed because they are commonly reported and are well accepted in industry. They complement the exergy indicator which is scientifically more robust but may be less easy to communicate about. All of these indicators are detailed in the following sections.

4.4.1.2 Unit Material Cost (UMC)

This indicator is defined as the ratio between the sum of all input materials expressed in mass terms and the predefined Output Unit. Water and fuels are not considered in this category, as they are included in other indicators.

[3] Economic outputs are all the flows leaving the system boundaries, which have an economic value – it is important to take into account all the products and co-products for the calculation of KRIs.

$$UMC = \frac{\sum \dot{m}_{raw\ material}}{OU}\left[\frac{kg}{OU}\right]$$

where

UMV	is the unit material cost
$\dot{m}_{raw\ material}$	is all input materials expressed in mass terms in kg/s
OU	is the predefined output unit i.e. the quantity of the main economic output(s)

4.4.1.3 Direct Primary Energy Consumption (DPEC)

All types of energy vectors (electricity, heat or fuels) can be found in manufacturing processes of industrial facilities. The Direct Energy Consumption would be the addition of the energy content of these energy vectors through the proper productive process (only those that are not generated within the productive process should be taken into account).

Rather than the Direct Final Energy Consumption, the Primary Energy Consumption is recommended as an indicator for resource efficiency in industrial processes, since it takes into account the efficiency of the conversion of energy in its raw state (primary energy) into energy vectors (final energy). Conversion factors (CF) from final energy into primary energy can be found in the literature[4].

Accordingly, Direct Primary Energy Consumption is calculated as the Primary Energy used divided by its Output Unit (as per the boundary conditions defined in 4.3 of this CWA).

$$DPEC = \frac{CF * EE + \left(\dot{m}_{fossil\ fuel} * HHV_{fosil\ fuel}\right)}{OU}\left[\frac{kJ}{OU}\right]$$

where

$DCEP$	is the Direct Primary Energy Consumption
CF	is the conversion factor in kW/kW
EE	is the electrical energy consumed in kW
$\dot{m}_{fossil\ fuel}$	is the kg/s of fossil fuels introduced (i.e. fuel oil, natural gas, diesel…)
$HHV_{fosil\ fuel}$	is the High Heating Value of the given fossil fuel in kJ/kg
OU	is the predefined output unit i.e. the quantity of the main economic output(s)

Note that if a given heat flow enters the system boundaries, it will need to be converted into primary energy, taking into account the technology used to produce it, i.e. for a natural gas boiler, the natural gas that was required for producing the steam. If the heat flow is generated within the system boundaries, it will not be considered.

[4] A conversion factor for EU-28 would be 2,5 kW/kW. This factor is an average thermal-electrical energy conversion of Europe. Nevertheless, a more precise figure for the specific country where the given industry is located is advisable, since electricity production technologies are different, depending on the county. [7]

4.4.1.4 Gross Water Use (GWU)

This indicator can be defined as the ratio of the overall water input into the processes and the Output Unit. Only water entering the system boundaries is accounted for and hence recirculated water is not considered.

$$GWU = \frac{\sum(\frac{\dot{m}_{water}}{\rho_{water}})}{OU}\left[\frac{m^3}{OU}\right]$$

where

GWU	is the Gross Water Use
$\dot{m}\_water$	is a given water flow entering the system in kg/s
ρ_water	is the density of the given water flows in kg/m^3
OU	is the predefined output unit i.e. the quantity of the main economic output(s)

Note that some of the water can enter with the raw materials themselves, i.e. as a solution.

4.4.1.5 Net Water Use (NWU)

Net Water Use differs from Gross Water Use as it only considers the amount of water strictly consumed within the process. It is defined as water inputs minus all water outputs from the processes. Note that some of the output water can be embedded into the final product. As in the previous case, only water entering and leaving the system boundaries is accounted for and hence recirculated water is not considered.

$$NWU = \frac{\left(\frac{\dot{m}_{water} input - \dot{m}_{water}\ output}{\rho_{water}}\right)}{OU}\left[\frac{m^3}{OU}\right]$$

where

NWU	is the Net Water Use
$\dot{m}_{water} input$	is the water input in kg/s
$\dot{m}_{water}\ output$	is the water output in kg/s
ρ_water	is the density of the given water flows in kg/m^3
OU	is the predefined output unit i.e. the quantity of the main economic output(s)

4.4.1.6 Resource Exergy Indicator (REI)

Technically, exergy is defined as the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surrounding environment by a sequence of reversible processes. The exergy of a system gives an idea of its evolution potential for not being in thermodynamic equilibrium or dead state with the environment. At the dead state, a system is at the temperature and pressure of its surroundings; it has no kinetic or potential energy and it does not react with the surroundings.

All substances have a definable and calculable exergy content, with respect to a defined external environment. Once the environment is specified, a value can be assigned to exergy in terms of property values for the system only, and exergy can be regarded as a property of the system. Unlike mass or energy, exergy is not conserved but destroyed by irreversibility. It is an extensive property, with the same units as energy. In all physical transformations of matter or energy, it is always exergy that is lost. Exergy analysis is thus a powerful tool for improving the efficiency of processes and systems. This leads to fewer resources being used and the emission of fewer wastes to the environment.

Moreover, the universality of exergy allows applying it to different stream categories, i.e. water, energy or materials with the same units, and can thus be used as a resource efficiency indicator for industries. A further advantage is that since efficiency can be assessed with a single indicator, different industrial processes can be easily compared and benchmarked.

The specific exergy, b, of a system is characterized by a set of thermodynamic parameters that define its quality. Commonly, it is calculated as the sum of the thermo-mechanical exergy, the kinetic exergy, the potential exergy and the chemical exergy as shown in the following equation.

$$b = \left(u - u_0\right) + p_0\left(v - v_0\right) - T_0\left(s - s_0\right) + \frac{1}{2}\left(C^2 - C_0^2\right) + g\left(z - z_0\right) + \left(\Delta G_{fi} + \sum_j r_{j,i} b_{ch\,j}\right)$$

where

- b is the exergy in J/mol
- u denotes specific energy in J/mol
- p is pressure in Pa
- v is the specific volume in kg/m^3
- T is the temperature in K
- s is the entropy in J/mol K
- C is the velocity in m/s
- g is gravity of the Earth: 9,81 in m/s2
- z is height in m
- ΔG_f is the Gibbs free energy of the given substance i in J/mol
- j is the chemical element in the given substance i
- $r_{j,i}$ is the number of moles of each chemical element *j* per mole of substance i
- b_{chj} is the chemical exergy of the chemical element, obtained from a given reference environment[5] in J/mol

This is a general formula valid for any kind of substance, mixed or pure, reactive or not, at a different pressure, temperature, velocity and height with respect to a reference environment characterized by properties sub-indexed as 0.

In addition to “pure exergy”, one needs to consider an exergy derived indicator to have a complete picture of the process: the *exergy cost* [5] or *cumulative exergy consumption*, [8] also recognized as *embodied exergy*. This is an emergent property of a given manufactured good and is defined as the actual exergy expenditure in its production process, once the limits of the analysis, the process itself and the efficiencies of each process component have been defined.

[5] Such as the one proposed by Szargut and Morris (1985). [8]

The exergy cost or embodied exergy (kJ) is not a property of a piece of matter, since it depends on its production process. However, it has precise rules for its calculation, particularly those relating to the allocation of co-products, by-products and residues which is done in proportion to the exergy content of the different streams.

In summary, the Resource Exergy Indicator incorporates both approaches (exergy and exergy cost). In order to obtain them, it will be necessary to know the flows within the system boundaries: the power, the temperature and pressure of the heat flows, the composition of the raw materials or consumables or water flows and a reference state to compare with.

The Resource Exergy Indicator (REI) as defined in this CWA will be the inverse of the exergy efficiency of the processes, calculated as the exergy inputs divided by the Output Unit.

$$REI = \frac{B_{energy} + B_{water} + B_{raw\ material}}{OU} \left[\frac{kJ}{OU} \right]$$

where

REI	is the resource exergy indicator measured in kW
B_{energy}	is the exergy from energy flows measured in kW
B_{water}	is the exergy from water flows measured in kW
$B_{raw\ material}$	is the exergy from raw materials measured in kW
OU	is the predefined output unit i.e. the quantity of the main economic output(s)

4.4.1.6.1 Exergy from energy flows - B_{energy}

There are different types of energy flows in industrial systems: Fossil fuels and Electricity. As it has been explained in 4.4.1.3, Primary Energy Consumption is recommended as indicator, because it allows to assess the efficiency of the conversion of energy in its raw state to final energy. Therefore, it is necessary to calculate the exergy of the primary energy consumed by these energy flows.

Fossil fuels are assessed by means of their chemical exergy content. It has been largely demonstrated that the chemical exergy of fossil fuels can be satisfactorily approximated to the **High Heating Value (HHV)** in many cases [6]. Table 1 shows typical exergy values of different types of coals (anthracite, bituminous, subbituminous and lignite), fuel-oils (1, 2 and 4), and natural gas. As can be seen in the table, the error made in assuming the chemical exergy of the fuel (b_{ch}) as its HHV is less than 6 % (i.e. the difference between HHV and b_{ch} values are small). Hence, for our purposes, we will use the approximation of the HHV.

Table 1 — Chemical exergies of different types of fossil fuels

Fuel	HHV	b_{ch}
Anthracite	30675	31624
Bituminous	28241	29047
Subituminous	23590	24276
Lignite	16400	17351
Fuel-Oil 1	46365	46259
Fuel-Oil 2	45509	45517
Fuel-Oil 4	43920	44002
Natural gas	42110	39393

Values are expressed in kJ/kg except for natural gas (in kJ/Nm3). The exergy of electricity coincides with its energy content. Yet it is necessary to take into account, that such electricity came from a primary source. The exergy of Primary Energy Consumed can be calculated by means of the conversion factor (CF) given in section 4.4.1.3

In the case of heat flows, the reasoning is similar to that used for electricity, i.e. obtaining the exergy of the fuels used to produce this flow. Accordingly, a heat flow would be assessed through the exergy of the primary energy used, such as natural gas or coal burned to produce it. If heat is produced simultaneously with electricity, then cost allocation based on exergy should be accomplished [9]. Note that waste heats should not be included in order to avoid it being accounted for twice.

Therefore, exergy from energy flows would be equal to the Direct Primary Energy Consumption:

$$B_{energy} = CF * EE + \left(\dot{m}_{fossil\ fuel} * HHV_{fosil\ fuel}\right) \qquad \left[kW\right]$$

where

B_{energy}	is the exergy from energy flows
CF	is the conversion factor in kW/kW
EE	is the electrical energy consumed in kW
$\dot{m}_{fossil\ fuel}$	is the kg/s of fossil fuels introduced (i.e. fuel oil, natural gas, diesel…)
$HHV_{fosil\ fuel}$	is the High Heating Value of the given fossil fuel in kJ/kg

4.4.1.6.2 Exergy from water flows - B_{water}

Exergy of water flows is defined as the maximum work that can be obtained from the flow until reaching the complete equilibrium with the reference environment - RE. Note that the chemical exergy of water is obtained together with the exergy of raw materials[6].

Flow exergy: It represents the specific exergy change by means of the following equation.

$$b_{water} = \left(h_1 - h_0\right) - T_0 \cdot \left(s_1 - s_0\right) + \frac{C_1^2 - C_0^2}{2} + g \cdot \left(z_1 - z_0\right) \qquad \left[kJ / kg\right]$$

where

b_{water}	is the exergy from water flows in kJ/kg
h_i	is the specific enthalpy in kJ/kg
T	is the temperature in K
s_i	is the specific entropy in kJ/kgK
$C_i^2\ /\ 2$	is related to the kinetic energy of the flow, with velocity C expressed in m/s x10^{-3}

[6] Other exergy components associated to water such as concentration exergy or treatment exergy costs could be potentially incorporated. For more information, see Carrasquer et al. [1] or Carrasquer et al. [2]

$g \cdot z_i$ is related to the potential energy in m^2/s^2 x10^{-3}, with g the gravity of the Earth and z_i the height

Usually kinetic and potential energy are neglected in common industrial processes. Subscript 0 denotes the reference environment, meaning the conditions of the surrounding ambient. Accordingly, if a given water flow remains unchanged with respect to the ambient, B_{water} will be zero.

The exergy of a water flow can thus be obtained through the sum of the flow exergy and water exergy cost, multiplied by the specific water flow[7]:

$$B_{water} = b_{water} \cdot \dot{m}\_water \quad [kW]$$

where

B_{water} is the exergy from water flows

$\dot{m}\_water$ is a given water flow entering the system expressed in kg/s

4.4.1.6.3 Exergy from raw materials ($B_{raw\ material}$)

The exergy of material flows is represented by chemical exergy and exergy replacement cost.

Chemical exergy expresses the exergy associated to the chemical composition of a substance at ambient temperature and pressure. The chemical exergy of any compound *i* can be calculated by means of:

$$b_{ch,i} = \Delta G_{f,i} + \sum_j r_{j,i} \cdot b_{chj,i} \qquad [kJ / mol]$$

where

$b_{chj,i}$ is the standard chemical exergy of element *j* contained in substance *i* (kJ/mol)

$\Delta G_{f,i}$ is the Gibbs free energy of substance *i* (kJ/mol)

$r_{j,i}$ is the amount of mole of element *j* per mole of substance *i*

Note that chemical exergies can be directly obtained from the “Exergoecology Portal”[8] by introducing the name or the chemical formula of the substance.

Concentration exergy represents the minimum theoretical work needed to concentrate a substance from an ideal mixture of two components. It is:

$$b_c = -R \cdot T_0 \left[\ln x_i + \frac{(1 - x_i)}{x_i} \ln (1 - x_i) \right] \qquad [kJ / mol]$$

where

b_c is the concentration exergy

R is the universal gas constant (kJ/(mol·K))

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[7] Note that the water flow should be expressed in the adequate units.

[8] htttp://www.exergoecology.com

T_0 the ambient temperature in K

x_i is the molar concentration of substance i in the mixture in mol/mol

Non-fuel minerals are physically valued by means of their scarcity in nature and energy costs associated with extraction. This can be assessed through exergy replacement costs, defined as the exergy required by prevailing technologies to return a resource from the dispersed state, to the physical and chemical conditions in which it was first delivered by an ecosystem. The calculation of exergy replacement cost is done by means of multiplying the concentration exergy by a factor called unit exergy replacement cost (k_c), which accounts for the irreversibility of real processes with respect to reversible processes:

$$b_c^* = k_c \cdot b_c$$

where

b_c^* is the exergy replacement cost in kJ/mol

k_c is the unit exergy replacement cost (dimensionless)

Exergy replacement cost of some minerals are shown in the following table (note that for practical purposes, units are here expressed in MJ/kg instead of kJ/mol). Abundant and easy to mine minerals in the crust have low exergy replacement cost, as opposed to minerals scarce and difficult to extract.

Table 2 — Exergy Replacement Cost of some minerals[9]

Mineral	$b_c^* \left[MJ / kg \right]$
Copper	292
Fluorite	183
Gold	553,250
Gypsum	15
Lime	3
Magnesite	26

The exergy replacement cost will be taken into account when raw materials from natural resources come into play.[10]

Flow exergy could be taken into account if raw materials were introduced to the process with different conditions of the environmental ones (for instance, higher temperature).

So, exergy related to raw materials is obtained by means of the sum of chemical exergy and exergy replacement cost:

$$B_{raw\ material} = MW \cdot (b_{ch} + b_c^*) \cdot \dot{m}_{raw\ material} \qquad \left[kW \right]$$

where

[9] bc* of some minerals according to Valero and Valero [11]

[10] The detailed methodology and a comprehensive list of exergy replacement costs (bc*) of substances can be found in Valero, Valero and Domínguez [10]

$B_{raw\ material}$ is the exergy from raw materials

MW is the molecular weight of the given compound in mol/kg

b_{ch} is the chemical exergy in kJ/mol

b_c^* is the exergy replacement cost in kJ/mol

$\dot{m}_{raw\ material}$ is the mass flow rate in kg/s

4.4.2 Complementary indicators

In addition to the headline indicators suggested above, practitioners following these guidelines may complement their study with a cradle-to-gate analysis based on Life Cycle Assessment (LCA). The headline indicators are representative of the onsite resource efficiency of the process but offer only a partial view of the upstream impacts associated with the process under study. By using an LCA approach (defined in ISO 14040 and ISO 14044), a holistic view of resource efficiency is possible.

Recommended LCIA (Life-Cycle Impact Assessment) indicators are described in the ILCD Handbook [4] which are detailed guidelines complementary to the LCA ISO standards.

4.4.3 Key Performance Attributes

KPAs are variables that are used to restrict the optimization space. The **KPAs** may cover the following aspects of the process:

— Production costs (e.g. €/tonne of product);

— Production rates (e.g. tonne of product/year);

— Quality and reliability (e.g. steam quality or steam dryness, particle size distribution, density);

— Safety (e.g. production rate of corrosive flows).

These KPAs will set the overall framework for all process optimization and improvement actions. In other words, any valid set of Process Parameters suggested by the system, see Figure 4, must be within the restricted region so the characteristics mentioned above are not impacted by the new settings.

4.4.4 Process Parameters

A Process Parameter (PP) provides information of a property that impacts the process. Although not all of them are necessarily monitored on a plant, they generally are. Any PP can be, somehow, related with the resource utilization and all of them can be considered when applying the proposed methodology. But in order to reduce the number of PP to be considered by the optimization process, a sensibility analysis is conducted, selecting only those with major influence on the defined KRIs (See 4.4.5). For instance, a process temperature or sub-system pressure could be critical for quality or safety but will not have the same impact in terms of resource consumption, not satisfying the threshold the sensitivity analysis sets in comparison with other PPs under consideration.

4.4.5 Critical Process Parameters

There are some parameters with a major influence on the defined KRIs. These are the so-called Critical Process Parameters (CPPs).

The CPPs can be defined as the parameters directly related to the KRIs of a process that has a more relevant influence on it, i.e.: KRI = f (CPP1, CPP2 … CPPn). In principle, the CPPs should be the minimum (or nearly the minimum) set of variables that allow for the modelling of a complex process regarding the KRI.

Depending on the sector that the methodology is applied in, it may occur that many process parameters appear, thereby increasing the application complexity.

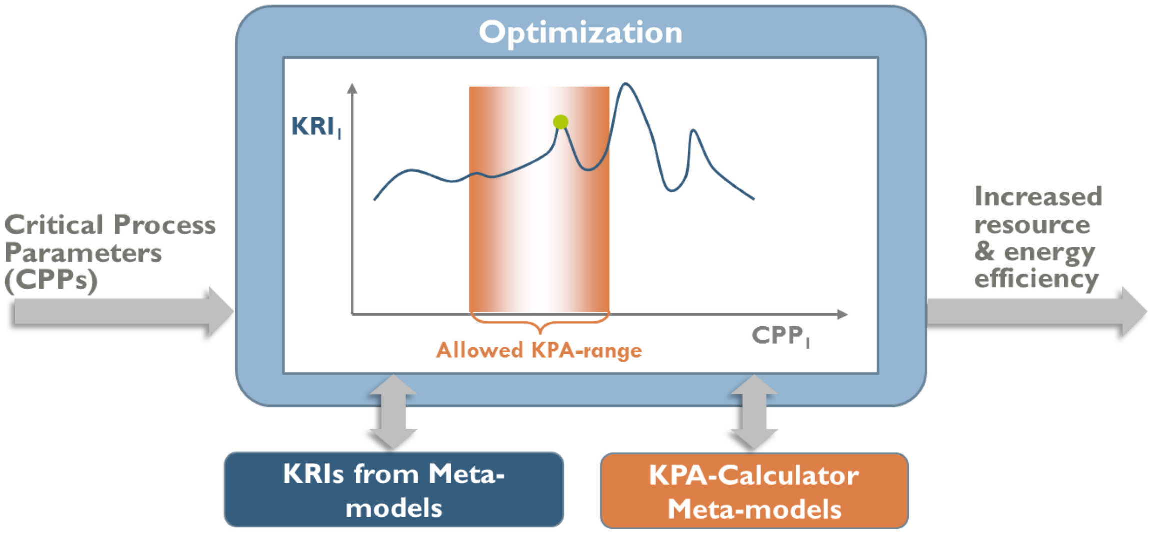

Figure 4 — Allowed KPA range, KRI and CPP axis

For the identification of the CPPs, several methodologies and approaches are applicable which can be based upon recorded process data or process modelling. In any of these approaches, the most impacting parameters have to be identified which can be done e.g. by sensitivity analysis or similar methods.

Once identified, and as the final part of the proposed methodology, a set of optimized CPPs is supplied suggesting more efficient operating parameters with respect to the KRIs and taking into account the constraints given by the KPAs.

4.5 Benchmark using KRIs

4.5.1 general

The term “benchmarking” can refer to a wide variety of concepts. In the context of this CWA, “benchmarking” refers to developing and using metrics to compare resource intensity of industrial facilities and processes.

4.5.2 Benchmarking

Benchmarking provides guidance on what figures we expect to see reported for the majority of businesses in the different industry sectors. Industry benchmarks have been developed to help companies and enterprises to assess their business performance by comparing their business with others (internally and externally) in the same industry sector. Although the benchmarks are primarily used to do comparisons within the same sector, it can also be used to identify best practices across sectors where common process units are used.

When facilities / business are benchmarked using a consistent methodology, it is possible to identify best practices as well as opportunities for improvements across industry sectors. This can be valuable because it increases the availability of industrial efficiency data in a way that businesses and stakeholders can more effectively identify and implement improvements to increase productivity and competitiveness. Benchmarks will provide companies and enterprises with a better picture of their competitive position and will allow them to take more informed decisions for future strategies, investments, initiatives, actions, etc.

A resource use benchmark is a type of industry benchmark. These benchmarks provide key resources indicators (KRI's) ratios relevant for a given industry to identify if the business performance:

- is similar to other businesses within the given industry
- falls within or outside the industry benchmark range for the industry
- differs from the industry benchmark range and why this may be.

Since a benchmark is a reference that allows comparisons to be made, this comparison is typically set in ranges that are chosen in such a manner that most businesses in an industry are within or close to the agreed benchmark range.

The bands are split into four quartiles based on number of participants in the benchmarking study for each industry:

- Top / First Quartile: 0 to 25 %
- Second Quartile: 25 % to 50 %
- Third Quartile: 50 % to 75 %
- Bottom / Last Quartile: 75 % to 100 %

Two of the central pillars of a benchmark are that it allows for a fair comparison of facilities regardless of their size, and that it is applicable to a wide range of facilities. This is achieved by ensuring that only a single benchmarking methodology is required.

Last but not least, by using benchmarking data policymakers can set a voluntary or mandatory performance target, for example to achieve efficiency gains or requirements.

4.5.3 Benchmarking Methodologies Issues and Recommendations

There are several factors influencing the success of the implementation of a benchmarking program aside from the benchmarking methodology itself.

This is shown in the following bullets.

- **Common definitions**

  The availability of common definitions, including which parameters or indicators will be covered if a benchmark is being used, and clear standards as to which industrial sectors and facilities are covered under which terms.

- **Reliable data measurement and verification systems**

  The availability of reliable and consistent data measurement and verification systems to ensure confidence in parameters and indicators.

- **Committed contributions**

  The contribution of considerable efforts by all stakeholders, including industrial representatives.

SMART principles are primarily relevant for mandatory or voluntary comparison methodologies. Targets set based on benchmarks should be SMART:

- **Specific**

The target must explicitly specify which KRI is to be achieved.

- **Measurable**

  The target must allow for regular measurement of how much progress facilities are making in order to ensure it is encouraging action.

- **Appropriate**

  Targets must be relevant to the overall aims and objectives of a broader policy.

- **Realistic**

  The target must be achievable within the compliance period which involves a careful balance. Targets must push operators to make efficiency investments beyond business-as-usual but must not be so strict that they force facilities to leave the jurisdiction or simply ignore the targets as unachievable.

- **Timed**

  Targets must have a set timeframe and should be set in the short or medium term to promote early action.

As an example, a table is included below to show how benchmarking can be applied in the framework of the KRI's previously defined in the document.

Table 3 — How benchmarking can be applied

TYPE	BENCHMARKED KRI	COMPARISONS ENABLED
Allowance Allocation	KRI1, KRI2, KRI3, etc…	Facilities that produce the same product can be compared to each other
Mandatory performance standard	KRI1, KRI2, KRI3, etc…	Facilities within a regulated sector can be compared to each other
Voluntary, single-sector	KRI1, KRI2, KRI3, etc…	Facilities can compare themselves to the sector average
Voluntary, multi-sector	KRI1, KRI2, KRI3, etc…	Facilities can compare themselves to others in the sector

In addition to the types of benchmarking mentioned above, a facility can also compare its current performance to its historical performance as a tool for continuous improvement.

Annex A
(informative)

Example of use of the methodology

A.1 General

An example of how the defined KRIs can be used within an industry has been developed. The methodology is applied to a fertilizer production process. KRIs have been calculated from the following plant configuration.

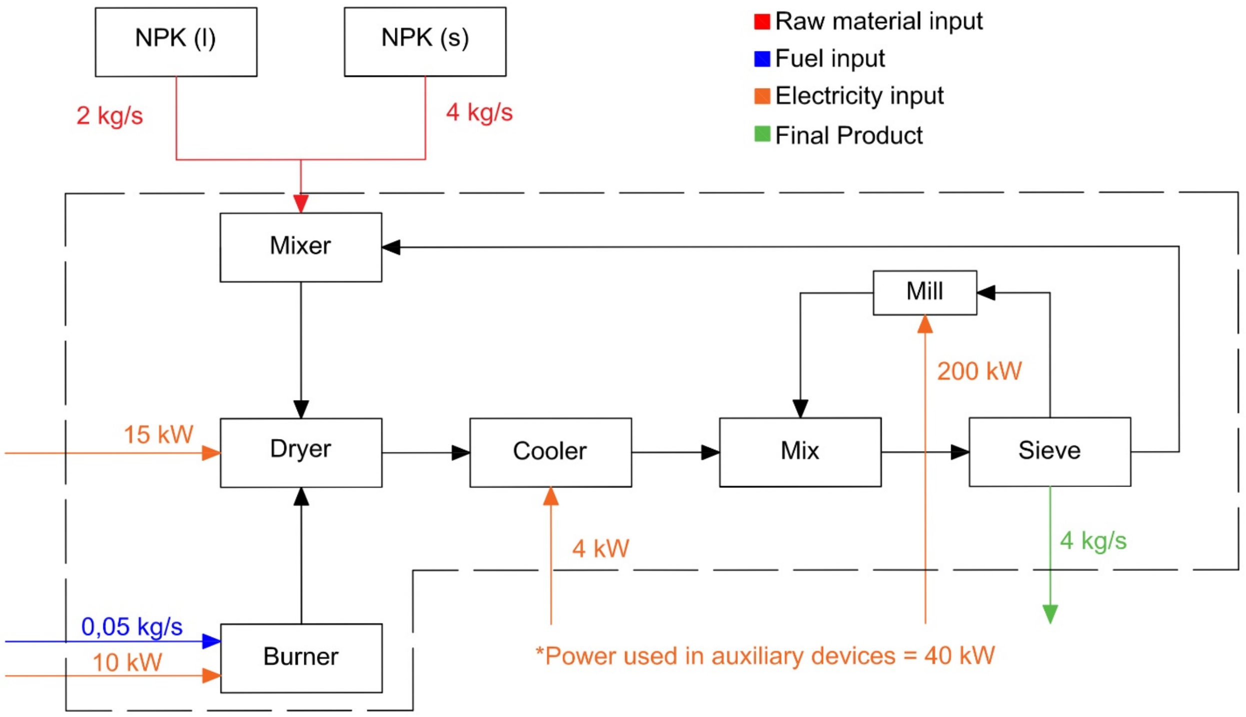

Figure A.1 — Overview over the system's boundary

The system's boundary is outlined through the dotted line and hence inputs and outputs are those entering or leaving the box. KRIs are calculated by means of the value of these inputs and outputs.

The Output Unit (OU) is 4 kg/s of product (NPK fertilizer).

In the following, the five Key Resource Indicators defined in this CWA are calculated using the example.

A.2 Unit Material Cost indicator (UMC)

This indicator assesses the raw material consumption of the process. The raw material inputs are solid and liquid NPK fertilizer. Therefore, the UMC indicator of this plant can be calculated through the quantity of raw materials introduced to the process.

$$UMC = \frac{\dot{m}_{NPK,in,l} + \dot{m}_{NPK,in,s}}{\dot{m}_{NPK,out}} = 1,5\,\frac{kg\ raw\ materials}{kg\ NPK\ produced}$$

With:

$$\dot{m}_{NPK,in,l} = 2\,kg\,/\,s$$

$$\dot{m}_{NPK,in,s} = 4\,kg\,/\,s$$

$$\dot{m}_{NPK,out} = 4\,kg\,/\,s$$

A.3 Direct Primary Energy Consumption indicator (DPEC)

The energy inputs of the plant are electrical energy (EE) and natural gas (NG). For electricity consumption, the auxiliary devices also need to be considered. The Conversion Factor considered for converting electricity into primary energy consumption is associated to an average value for EU-28.

$$DPEC = \frac{CF \cdot EE + \dot{m}_{NG} \cdot HHV_{NG}}{\dot{m}_{NPK,out}} = 694,5\,\frac{kJ}{kg\ NPK\ produced}$$

With

CF = 2,5 kW/kW (for EU-28[11])

$$EE = 269\,kW$$

$$\dot{m}_{NG} = 0,05\,kg\,/\,s$$

$$HHV_{NG} = 42110\,kJ\,/\,kg$$

A.4 Gross Water Use indicator (GWU)

This indicator takes into account the water introduced externally. In this process, water, in the liquid form of the fertilizer, is used as raw material. It is the water content of the raw materials, so it is obtained by multiplying the raw material flow by its humidity (ω).

$$GWU = \frac{\dfrac{\dot{m}_{NPK,in,l} \cdot \omega_l}{\rho_{water}}}{\dot{m}_{NPK,out}} = 0,0005\,m^3\,/\,kg$$

$$\omega_l = 99\%$$

$$\rho_{water} = 1000 \times 10^{-3}\ \mathrm{kg/m^3}$$

[11] EU legislation applies a Primary Energy Factor of 2.5 when calculating the energy efficiency of nearly all ‘electricity using’ products. [7]

A.5 Net Water Use indicator (NWU)

The net water used in the process is evaluated with this indicator. The difference between the water introduced and the water that leaves with the final product will be the numerator of the indicator.

$$NWU = \frac{\dfrac{\dot{m}_{NPK,in,l} \cdot \omega_l - \dot{m}_{NPK,out} \cdot \omega_{NPK,out}}{\rho_{water}}}{\dot{m}_{NPK,out}} = 0,00047\, m^3\ /\ kg$$

$$\omega_{NPK,out} = 2\ \%$$

A.6 Resource Exergy Indicator (REI)

A.6.1 General

Exergy allows to assess different types of flows with the same units. Accordingly, it is possible to evaluate with one indicator the electricity consumption, fuel consumption, water and raw material use of the fertilizer plant.

$$REI = \frac{B_{energy} + B_{water} + B_{raw\ material}}{OU} = 1437\ kJ\ /\ kg$$

The calculation of each exergy component is explained below.

A.6.2 Exergy from energy flows

The exergy related to electricity consumption is equivalent to its energy value as seen in Section 4.4.1.6.1.

$$B_{power} = 269\ kW$$

Chemical exergy of fossil fuels equals to the high heat value of the fuel.

$$B_{Fuel} = \dot{m}_{NG} \cdot HHV_{NG} = 2105,5\ kW$$

$$HHV_{NG} = 42,110\ kJ\ /\ kg$$

Therefore, exergy related to energy sources is:

$$B_{energy} = 2.5 \cdot B_{power} + B_{fuels} = 2778\ kW$$

A.6.3 Exergy from water flows

Water flows enter and leave the system’s boundary at the same temperature and pressure conditions as the ambient, so:

$$B_{water} = 0\ kW$$

The chemical exergy component of water is calculated within the raw material’s exergy.

A.6.4 Exergy from material flows

The exergy of the fertilizer used as raw material has two components, its chemical exergy and its exergy replacement cost. In this case, flow exergy associated to raw materials is zero because they are introduced at environmental conditions. The chemical exergy of the NPK fertilizer ($B_{ch,_{NPK}}$) has been obtained from the exergoecology portal[12].

$$b_{ch,_{NPK}} = 368\,kJ\,/\,kg$$

$$b_{ch,H_2O} = 42\,kJ\,/\,kg$$

$$B_{ch,NPK,in,l} = \omega_l \cdot \dot{m}_{NPKin,l} \cdot b_{ch,H_2O} + \left(1-\omega_l\right) \cdot \dot{m}_{NPK,in,l} \cdot b_{ch,NPK} = 91\,kW$$

$$B_{ch,NPK,in,s} = \dot{m}_{NPK,in,s} \cdot B_{ch,NPK} = 1472\,kW$$

Exergy Replacement Cost can be calculated by means of the methodology found in Valero and Valero [9]. For instance, if the raw materials come from phosphate rock:

$$b^*_{c,NPK} = k_c \cdot b_{c,i} = 350\,kJ\,/\,kg$$

$$B^*_{c,NPK,in,l} = \left(1-\omega_l\right) \cdot \dot{m}_{NPK,in,l} \cdot b^*_{c,NPK} = 7\,kW$$

$$B^*_{c,NPK,in,s} = \dot{m}_{NPK,in,s} \cdot b^*_{c,NPK} = 1400\,kW$$

Therefore, the exergy of the material input can be calculated by means of the sum of chemical exergy and exergy replacement costs of the materials.

$$B_{raw\ material} = B_{ch,NPK,in,l} + B_{ch,NPK,in,s} + B^*_{c,NPK,in,l} + B^*_{c,NPK,in,s} = 2970\,kW$$

A.7 Example of use of KPAs

An example of how KPAs can be used within an industry has been developed following the same example used for the KRIs above. Due to the ad hoc nature of the KPAs, these will have to be defined according to the analysed facilities.

Three different representative KPAs have been defined in the following example, one legislative, one economical and one technical:

Composition of the gases from the burner: Due to legislative restrictions, the composition of the hot gases generated in the burner should not trespass the allowed limits. Hourly Emission Limit Values for NO_2 and CO has been limited to 40 and 10 µg/m^3 respectively. According to this restriction, the operation of the burner should be adjusted in order to accomplish with this restriction.

Monetary Unit Cost of the product: The production cost of final products is usually one of the most important restrictions for scheduling production operations. The manufacturing cost of final marketable product, NKP in this case, is limited to 11 €/kg of NKP. This value could be calculated by accounting the natural gas and power consumed, their monetary cost and the mass flow rate of the market product.

Temperature of the gases at the exit of the dryer: One of the main issues that can be found during the treatment of exhaust gases is the rust effect due to low exhaust temperature. In order to avoid this, a minimum exhaust temperature for gases is set at 358 K.

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[12] www.exergoecology.com

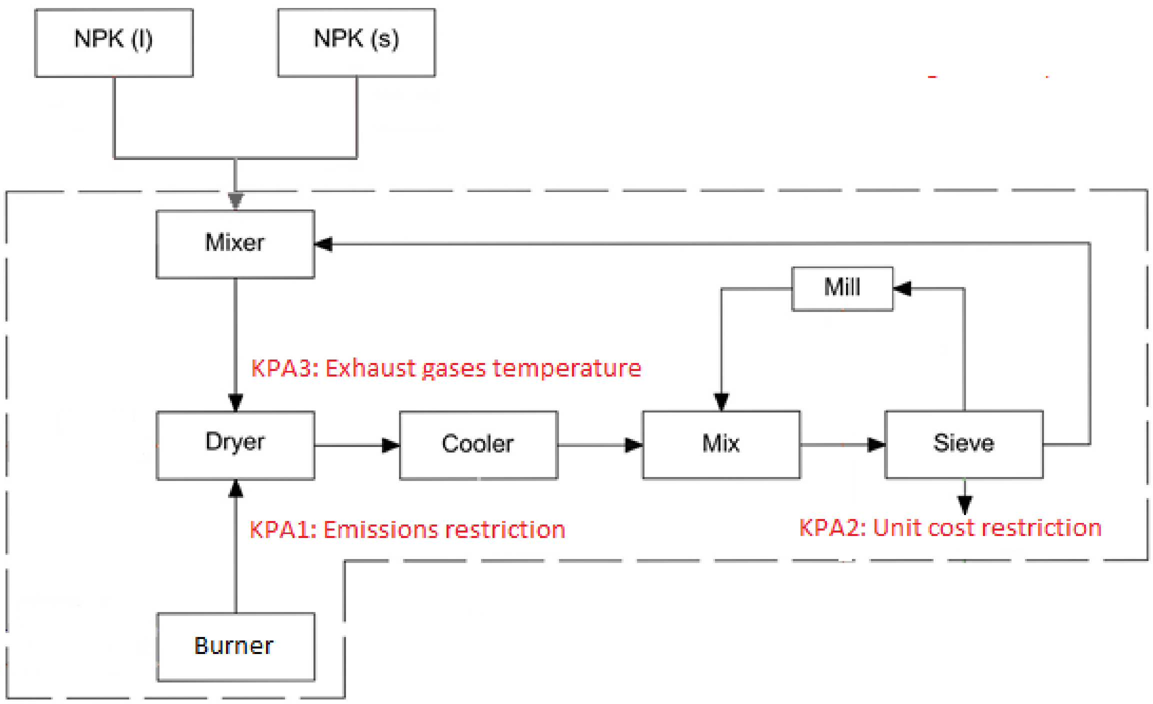

Figure A.2 — Example

A.8 Example of use of CPPs

An example of how the defined CPPs can be used within an industry has been developed following the same example used for the KRIs above. Due to the ad hoc nature of the CPPs, these will have to be defined according to the analysed facilities. Additionally, the relation between CPPs and KPAs should be also previously obtained.

Two different representative CPPs have been defined in the following example:

Volumetric flow of natural gas in the burner: The modification of this parameter will have a relevant impact on the temperature of the exhaust gases and the emissions.

Volumetric flow of NKP liquid: The amount of liquid fertilizer will present an important influence on the recirculation ratio, increasing the monetary cost of the market product due to the decrease in the production ratio in case the amount of water is higher than required.

A.9 Following steps

Once the KRIs, KPAs and CPPs have been calculated or identified and the relationship between them clarified, the next step is the resetting the CPPs in the way that new KRI values oriented to a decrease in the resources consumption or the increase of the productivity are obtained. This CPP modification will provide a new set of operational variables that should consider the KPAs' limits.

Due to the definition of four different KRIs based on the raw material, energy and water consumption, four different optimum CPPs could be obtained and, consequently, four sets of operational variables. In this case, the most relevant, more expensive or scarcer resources should be prioritized by optimizing their associated KRI. The advantage of using the exergy KRI as the optimization parameter is that resources are already prioritized according to their exergy content (i.e. physical value) and therefore a unique set of operational variables will be obtained. The optimization of CPPs will require calculus and mathematical specific techniques that should be developed by means of commercial or ad hoc software for each different industry.

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