Exergy-based performance indicators for industrial practice†

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Abstract

Key performance indicators (KPIs) are powerful tools that industries can use not only to monitor their activities but also to highlight their unexploited potential. Energy-based KPIs are nowadays mostly used to evaluate industrial process performances. However, these indicators might present some limitations and might give misleading results in some circumstances. An example is represented by industrial processes that make use of different energy forms (e.g. electricity and heat) and of different material inputs, and are therefore difficult to compare in terms of energy. A further example can be found in the Carnot engine that, despite being ideal, can have quite low energy efficiency (e.g. the energy efficiency of a Carnot engine working between 700 K and 300 K is 57%), suggesting that its performance can be improved.

The use of exergy-based KPIs allows us to overcome many of the limitations of energy-based indicators. The exergy efficiency of Carnot engines is 100%, clearly indicating that the system cannot be further improved. Moreover, the use of specific exergy consumption instead of specific energy consumption to monitor the performance of a process allows one to take into account possible differences in quality of material and energy streams.

In the present work, exergy-based KPIs for industrial use are reviewed. The paper outlines advantages and limitations of the reviewed indicators, with the scope of promoting their use in industry. A systematic use of exergy-based KPIs not only gives a meaningful representation of process performances in terms of resource use, but it can also direct efforts to improve the processes.

In order to better understand their meaning under different circumstances, the revised indicators are applied to three industrial processes.

Keywords: Key Performance Indicators, energy efficiency, exergy

1. Introduction

A key performance indicator (KPI) is defined as a piece of information that can be measured at different moments of time in order to monitor the performance of a system [1]. Because of systems' complexity, KPIs are often not perfect measures and their interpretation might be challenging. However, they are important tools to track the quality and evolution of systems. Since KPIs are often used to direct decision making processes, the selection of relevant and representative indicators is fundamental.

The increasing attention to energy savings has created the need to integrate traditional economic-based performance indicators with KPIs that can account for resource and energy use of processes. In many countries, industry is one of the largest energy users (e.g. in 2013, the industry sector accounted for 25% of the final energy consumption

†Dedicated to the memory of Professor Jan Szargut who pioneered the field.

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Nomenclature

M	mass, kg
$\dot{E}$	exergy flow rate, MW
$\dot{W}$	power, MW
e	specific exergy use, J/kg / J/J_{el} / MJ/Sm^3o.e.
k	exergy replacement cost, -
y	exergy destruction ratio, -
E	exergy, MJ
IP	improving potential, MW
RAI	relative avoided irreversibility, -

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	Best Available Technology
CExC	Cumulative Exergy Consumption
EEA	Extended Exergy Analysis
KPI	Key Performance Indicator
LCA	Life Cycle Assessment

Greek letters

α	renewability parameter, -
δ	efficiency defect, -
ϵ	exergy efficiency, -
η_{II}	second law efficiency, -
π	process maturity indicator, -
ζ	environmental compatibility indicator, -

Subscripts

1	state 1
$1-2$	from state 1 to state 2
2	state 2
$abat$	abatement
c	consumed
d	destruction
ex	exergy
ext	external
id	ideal
in	inlet
int	internal
k	process component k
kg	kilogram
out	outlet
p	produced
$prod$	product
ref	reference
$renew$	renewable
$task$	task
tot	total
tr	transiting
w	waste

Superscripts

min	minimum

of the European Union [2]). Thus, the assessment of the energy efficiency of industries, both as a single and as a sector, has become increasingly more important. Nowadays, the KPIs that are most used with this purpose are those based on energy analysis, such as energy efficiency or specific energy consumption per unit of product [3].

However, the use of energy-based performance indicators has shown to have some drawbacks in many cases. An example is the simultaneous evaluation of energy and material use. Energy and material resources are typically measured in different units. This makes it difficult to compare processes that have different energy and material use [4].
Another drawback becomes evident when energy-based indicators are used to evaluate different forms of energy, such as electricity and low temperature heat. Indeed, while the energy in 1 kWh of electricity is quantitatively the same as the energy in 1 kWh of heat at 30°C, their quality and, thus, the use that can be made out of them is very different [5].
Exergy is a measure of the maximum work that can be produced from a certain amount of energy or material [6]. To base performance indicators on exergy is an alternative that allows us to overcome many of the limitations of energy-based KPIs [4]. First of all, it makes it possible to account for losses in quality of resources, and to meaningfully compare different types of energy, as well as to compare energy with material resources. Moreover, by using exergy-based indicators, it is possible to assess how far an industrial process is from ideality and, thus, to determine its potential of improvement.
Exergy-based performance indicators do not take economic considerations into account. This is not necessarily a limitation, as it makes exergy-based indicators independent of time-dependent factors such as resource prices and policies.
While exergy-based KPIs have been widely used in academic settings, they have not been systematically adopted in industry yet. The main reason behind this is that many of the potential users of such indicators are unfamiliar with exergy analysis [7]. However, some attempts to introduce exergy concepts into common practice have been done. In the public sector, a first example can be found in Switzerland, where in 2001 in the state of Geneva, an article was introduced that made it compulsory to apply exergy analysis for evaluation of new large building projects [8]. Moreover, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established a technical group named Exergy Analysis for Sustainable Buildings, to promote the use of exergy concepts for the assessment of energy use in buildings. In 2015, Science Europe released an opinion paper to reach out to policy makers [9]. In the document, they discussed the need to move from energy accounting to exergy accounting. The purpose of this effort was to support a transition that would lead to the measurement of both quantity and quality of energy, as well as to the assessment of exergy destruction in processes.
The work in this paper is part of a broader project, whose aim is to improve energy efficiency in Norwegian industries beyond state-of-the-art [10]. A first step towards the achievement of such a goal is to establish a metric that can be used not only as a post-design tool to assess and compare performances of different industrial processes, but also as a tool that can guide the design phase.
To the best of the authors' knowledge, a comprehensive work that systematically gathers and discusses different exergy-based performance indicators cannot be found in the literature. Exergy efficiency is the exergy-based parameter that has been discussed the most. Indeed, several definitions of this indicator have been proposed, generating the need to find a unique exergy efficiency definition that could be applied uniformly [11–16]. Cornelissen [14] showed that results and conclusions obtained with different exergy efficiency definitions might be very different.
However, exergy efficiency is only one of the exergy-based KPIs that can be used in an industrial analysis. Exergy efficiency was used together with the exergy renewability indicator and the environmental compatibility parameter to evaluate the performances of ethanol production routes [17], gas-fired combined cycle power plants [18], and paper production and recycling [19]. The improvement potential of the Turkish industrial sector was estimated together with its exergy efficiency [20]. Voldsund et al. [21] evaluated the performance of offshore oil and gas processing using not only different definitions of exergy efficiency, but also different parameters for specific exergy use and destruction.
Exergy analysis and exergy-based KPIs have also been applied to systems other than industrial ones. In the literature, works can be found where exergy analysis is applied to entire sectors [20, 22–24] or to the whole society of different countries [25–29]. Exergy analysis has also been used to assess the exergy consumption of the Earth [30], as well as Earth exergy resources in terms of both fuel [31] and non-fuel resources [32].
Traditionally, exergy analysis is applied to the energy and material streams. However, with the application of exergy analysis to more complex systems, large efforts have been

done to extend the analysis to systematically include non-energetic externalities such as human labour, capital costs, and environmental remediation costs [33, 34]. These efforts have lead to the concept of Extended Exergy Analysis (EEA) [33], which has also been further extended to include ecosystem products and services [35].

However, in order to define and limit the scope of this work, we will restrict the analysis to performance indicators related to thermodynamic energy and material flows only.

The scope of this work is to review exergy-based performance parameters and to highlight their significance in the assessment of performance of different industrial systems. Moreover, we shall illustrate the meaning of their results using three different industrial processes as examples.

2. Exergy analysis

Exergy is measured in the same unit as energy. However, exergy and energy are fundamentally different.

Energy analysis is related to the first law of thermodynamics, which states that energy (and mass) are conserved at any time. Energy performance indicators used in industry are mostly based on energy analysis. However, these parameters do not allow us to take into account that energy in different forms has different quality and different ability to perform work. This is well known in industry, where for instance waste heat at low temperature does not find application, while high temperature waste heat can be utilized.

The term 'exergy' was first used by Rant [36] in 1956 to refer to the part of energy that is available to perform mechanical work (the terms 'available work' and 'availability' have also been used equivalently to 'exergy' [37]). Differently from energy analysis, exergy analysis is based not only on the first thermodynamic law, but also on the second one. The second law of thermodynamics states that entropy is produced in any real process, and, therefore, useful work is lost. This means that exergy is not conserved, and some exergy loss occurs in any real process. By establishing an exergy balance on the process, the destruction of exergy can be determined. Exergy losses can be distinguished between internal and external. Internal exergy destruction is due to irreversibility within the system boundary and it is caused by phenomena such as heat transfer over finite temperature differences, friction, and irreversible mixing [38]. External exergy destruction takes place at the boundary of the system, when waste flows are discharged and mixed irreversibly with the environment [38].

In an industrial analysis, to consider exergy instead of energy allows us to account for the quality of different types of energy used in the process, and to establish how well the potential of resources is exploited. Moreover, differently from energy-based indicators, exergy-based indicators can indicate if a potential to improve a process exists. An example can be made to explain this: the Carnot engine is ideal, but its energy efficiency when operating between the temperatures of 700 K and 300 K is 57% [39]. Thus, the use of the energy efficiency is, to some extent, misleading, as it suggests that a large margin to improve the system exists, while the system is already ideal and therefore cannot be improved. On the other hand, the exergy efficiency of the Carnot engine is always 100%, giving a clear indication that the system cannot be further improved. Since performance parameters are used to direct efforts to improve processes, it is important to choose indicators that can point at achievable goals.

2.1. Exergy balance

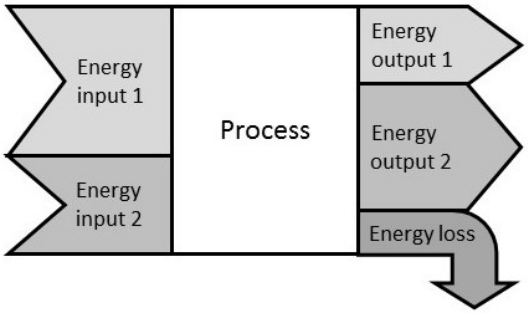
For a process in a steady state, the exergy balance is:

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_{d} = \dot{E}_{out} + \dot{E}_{d,int} + \dot{E}_{d,ext} \qquad (1)$$

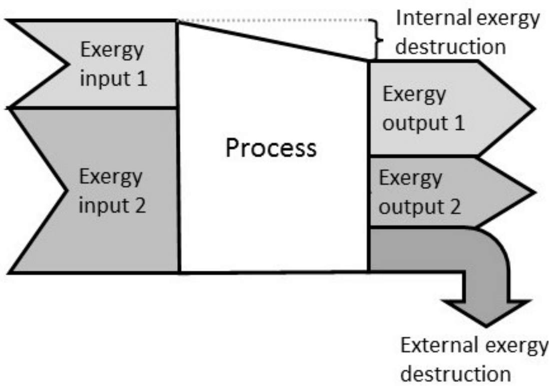
where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the sums of the exergy flows entering and leaving the system respectively, and $\dot{E}_{d}$ is the total exergy destroyed in the process. Exergy destruction can be further distinguished into internal exergy destruction due to irreversibilities within the system boundaries ($\dot{E}_{d,int}$) and external exergy destruction taking place as waste streams mix with the outdoor environment ($\dot{E}_{d,ext}$).

2.2. Sankey and Grassmann diagrams

The use of Sankey diagrams to visualize energy analysis results is quite established. In Sankey diagrams, energy flows entering and leaving a steady state process are graphically represented by arrows, whose width is proportional to the magnitude of the energy flow (Fig. 1(a)). According to the first law of thermodynamics, energy is conserved. Thus, the total width of the arrows entering



(a) Sankey diagram.



(b) Grassmann diagram.

Figure 1: Example of Sankey diagram (a) and Grassmann diagram (b) for a fictitious process.

the system is equal to that of the arrows leaving the process.

The exergy-based equivalent of Sankey diagram is the Grassmann diagram, which is used to visualize the results of exergy analysis. In this case, the arrow widths are proportional to the exergy flow magnitude (Fig. 1(b)). Due to irreversibilities, exergy is destroyed in a process. Thus, the overall width of the arrows leaving the system is always smaller than that of those entering the process. The difference between them represents the exergy destruction due to internal irreversibility ($\dot{E}_{d,int}$). The exergy that is lost due to the discharge of waste streams into the environment ($\dot{E}_{d,ext}$) is visualized by a external exergy destruction arrow.

Grassmann diagrams give an immediate idea of how much of the original exergy input is lost, both through irreversibility or with waste streams.

However, when large fractions of exergy inputs transit the process without undergoing any transformation, the representation of exergy losses with Grassmann diagrams is difficult, if total exergy flows are used. This is typical of processes where the products have large chemical exergy (e.g. fuel), as we will see in Section 6.1.

3. Exergy-based performance indicators

3.1. Exergy efficiency

Many definitions of exergy efficiency can be found in the literature, defined according to different needs and objectives. A series of works from the 1950s and 1960s made a first effort to distinguish and discuss the different kinds of efficiencies [11–13, 40]. The exergy efficiencies can be divided into three main groups [14, 41], which are presented in Sections 3.1.1-3.1.3.

3.1.1. Total exergy efficiency

For a system in a steady state, the total exergy efficiency is defined as the ratio of all exergy flows leaving the system, $\dot{E}_{out}$, to the exergy flows entering it, $\dot{E}_{in}$:

$$\epsilon_{tot} = \frac{\dot{E}_{out}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_d}{\dot{E}_{in}} \tag{2}$$

The last equivalence is obtained by substituting Eq. 1 into Eq. 2. This indicator is also called input-output efficiency by some authors [15, 42]. Since it considers all outputs and inputs regardless of whether they are useful or paid for, ϵ_{tot} can be regarded as the efficiency having the most thermodynamic significance [43].

Equation 2 has an alternative version. In the alternative version, the external exergy destruction, $\dot{E}_{d,ext}$ is not counted as exergy dissipation, but as a process output. Then, the total exergy efficiency takes the form:

$$\epsilon_{tot} = \frac{\dot{E}_{out} + \dot{E}_{d,ext}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_{d,int}}{\dot{E}_{in}} \tag{3}$$

In some situations, it is necessary to take the exergy of the system into account. This is the case when systems are not in a steady state. The total efficiency of the system between state 1 and state 2 should then be defined as:

$$\epsilon_{tot} = \frac{E_2 + E_{out,1-2}}{E_1 + E_{in,1-2}} \tag{4}$$

where E_1 and E_2 are the exergy of the system at state 1 and state 2, and $E_{out,1-2}$ and $E_{in,1-2}$ are the total amounts of exergy leaving and entering the system in the considered time interval. When the system is in a steady state, E_1 and E_2 are the same. However, they can vary significantly in a transient system.

The total exergy efficiency has been widely used, as its definition is unambiguous and it can be applied to any well defined system. Examples of use of the total exergy efficiency for evaluation of industrial processes include applications to renewable and non-renewable power plants [44], production of petrochemical and oleochemical based alcohols [44], hydrogen production [45], paper production and recycling [19], industrial chlor-alkali processes [46], pyrometallurgical processes [47], offshore oil and gas processing [16, 21]. This indicator is most meaningful when one needs to determine the overall efficiency of a system where most of the exergy flows entering the system undergo some kind of transformation, or where no particular output flow is in focus. On the other hand, if one is interested in only some particular output flows, or not all exergy flows undergo transformations, the total exergy efficiency might give misleading results [14]. Moreover, in such cases, ϵ_{tot} shows to be not very sensitive to changes in the system.

3.1.2. Task exergy efficiency

The task efficiency, which is also called the rational efficiency or consumed-produced efficiency, can broadly be defined as the ratio of the useful exergy produced by the process, $\dot{E}_p$, to the exergy that is consumed to perform the process, $\dot{E}_c$ [5]:

$$\epsilon_{task} = \frac{\dot{E}_p}{\dot{E}_c} \tag{5}$$

The exergy produced and consumed by the process is defined differently by different authors. Marmolejo-Correa and Gundersen [15] identified four different definitions proposed by different authors. Moreover, some room for interpretation exists also within the same definition of produced and consumed exergy. In spite of their definitions, $\dot{E}_p$ and $\dot{E}_c$ should in principle include all the exergy variations in the process, so that the exergy balance (Eq. 1) can be rewritten as:

$$\dot{E}_c = \dot{E}_p + \dot{E}_d \tag{6}$$

Even though the task efficiency is easy to apply and can give sometimes a more sensitive measure of the process efficiency than the total efficiency does, its definition is not unique and it leaves some room for interpretation. Moreover, the task efficiency cannot be defined for systems where useful outputs cannot be expressed in terms of exergy, such as systems that are dissipative by design or whose function is to exchange heat with the environment (e.g. cooling towers) [38].

The task efficiency has been defined and applied to different industrial processes, such as thermal power plants [5, 48], air separation [14], heat storage systems [49], oil and gas platforms [16, 21, 50, 51], and silicon production [52, 53].

3.1.3. Exergy efficiency disregarding transiting exergy

The efficiency disregarding transiting exergy is similar to the total efficiency, but it subtracts the exergy that does not undergo any transformation, $\dot{E}_{tr}$, from the exergy flows entering and leaving the system [54]:

$$\epsilon_{tr} = \frac{\dot{E}_{out} - \dot{E}_{tr}}{\dot{E}_{in} - \dot{E}_{tr}} \tag{7}$$

A detailed description on how to determine the transiting exergy of a process has been provided by Brodyansky et al. [54]. Similarly to the task exergy efficiency, ϵ_{tr} is more sensitive to changes in system operation than the total exergy efficiency. However, even though its definition is unambiguous and, therefore, not open for interpretation, it might be quite complex to determine [14]. It has been applied to steam methane reforming [55], air separation unit [14], and various manufacturing processes [56].

The exergy efficiency disregarding transit exergy and the total exergy efficiency coincide when all exergy flows undergo transformations. The use of this kind of efficiency is particularly useful to assess the efficiency of industrial processes where the transit exergy represents a large fraction of the exergy inputs. Many such examples can be found in the oil and gas processing industry. For instance, in the liquefied natural gas processing plant of Snøhvit, Norway, the transit exergy was found to represent 93.8 % of the total inlet exergy [57].

3.2. Component exergy destruction

Industrial processes are usually complex systems, that involve different sub-processes and components. When available data allow for it, it might be useful to carry out exergy analysis for the different components that make up the overall process. The exergy efficiencies presented in Sections 3.1.1-3.1.3 can also be applied to single components. An additional indicator that can give an indication on the performance of different process components is the component exergy destruction ratio [5]:

$$y_{d,k} = \frac{\dot{E}_{d,k}}{\dot{E}_d} \tag{8}$$

where $y_{d,k}$ and $\dot{E}_{d,k}$ are the exergy destruction ratio and the exergy destruction of the component k. This parameter indicates how different parts of systems contribute to decrease the overall efficiency. Thus, it can point at the sub-systems where possibilities for improvement are greater and on which efforts should be focused. The component exergy destruction ratio has been calculated for the components of systems such as upstream petroleum plants [58], thermal power plants [5], and refrigeration cycles [59].

3.3. *Specific exergy-based indicators*

An indicator frequently used in industry is the energy used for production of one unit of product. This parameter is usually referred to as specific energy use. Similarly, it is possible to define a specific exergy use. If the product is measured in kilograms, the specific exergy use per kilogram of product can be defined as:

$$e_{kg} = \frac{E_c}{M_{prod}} \tag{9}$$

where E_c is the exergy consumed to produce the mass of product M_{prod}. Equivalently, such a parameter can be defined per unit volume or per unit of product. When the process includes all the steps necessary to transform the raw materials into the final product, then the indicator accounts for the exergy that is consumed during the whole production cycle, and it takes the name of Cumulative Exergy Consumption (CExC) [60].
When this indicator is used to compare products from different production plants and the quality of the products is not the same, a comparison with such an indicator might not be fair. In order to partially account for differences in product quality, the specific exergy use can be expressed in terms of exergy consumption per unit exergy of products:

$$e_{ex} = \frac{E_c}{E_{prod}} \tag{10}$$

where E_{prod} is the exergy of products.
While the specific exergy use can be useful to compare processes, it does not give a direct indication of the exergy destroyed by the process. The specific exergy use can, thus, be coupled with the specific exergy destruction:

$$e_{d,kg} = \frac{E_d}{M_{prod}} \tag{11}$$

Also in this case, the indicator can be expressed in terms of exergy destruction per unit of exergy of products:

$$e_{d,ext} = \frac{E_d}{E_{prod}} \tag{12}$$

3.4. *Environmental exergy-based indicators*

One of the fields where exergy analysis has found application is industrial ecology. Industrial ecology is defined as the study of material and energy flows in industrial activities and of the impact they have on the environment [61]. Ayres et al. [62] suggested exergy as the most appropriate indicator for both resource and waste accounting.
When materials and energy entering a process are not renewable, the industrial process impacts on the availability of resources. Thus, it might be relevant to distinguish between renewable and non-renewable resources used by systems. The renewability parameter has been defined by Dewulf et al. [17] as:

$$\alpha = \frac{\dot{E}_{in,renew}}{\dot{E}_{in}} \tag{13}$$

where $\dot{E}_{in,renew}$ is the sum of input exergy flows supplied from renewable resources. This type of inputs does not contribute to the depletion of resources. In an ideal process ($\alpha = 1$), the only inputs are renewable exergy flows. This indicator has been applied to different industrial processes, such as ethanol and polyethylene synthesis through different production routes [17, 44], electricity production from renewable and non-renewable resources [17, 18, 44], biofuel production [63], petrochemical and oleochemical based alcohol production [44], paper production and recycling [19], hydrogen production [45]. Even though it appears easy to calculate, the renewability parameter might be difficult to evaluate when non-raw materials enter the process. In such a case, it is necessary to trace input materials back to the primary resources necessary to produce them. Even though it does not relate input flows to output ones, this indicator is particularly useful to add information on the nature of process inputs, and their impact on the depletion of natural resources. Moreover, it is very useful when alternatives that exploit renewable resources are to be compared with non-renewable based solutions. Indeed, due to the typically low exergy density, the exergy efficiency of nowadays technologies that exploit renewable exergy sources is most of the times low in comparison to that of processes that use non-renewable resources. An example can be found in electricity production, where for instance the use of exergy efficiency alone to evaluate solutions that exploit fossil fuels versus solutions exploiting solar cells might favor the non-renewable solution [17]. While their exergy efficiency might be low, processes using renewable exergy resources do not contribute to resource depletion [64].

An indicator that has been introduced to better assess the degree of depletion of non-renewable resource is the exergy replacement cost [65]:

$$k = \frac{\dot{E}_{in,BAT}}{\dot{E}_{in}} \tag{14}$$

where $\dot{E}_{in,BAT}$ is the exergy needed to produce and concentrate the used resources with nowadays best available technologies (BAT). The exergy of a resource (i.e. exergy of the process inputs) can be defined as the amount of work necessary to produce it starting from components present in the reference environment. However, exergy represents the thermodynamic minimum necessary work, which can be very far from values that can be achieved in reality. An example is represented by mineral resources, which would require much more work than the theoretical one, if they were to be produced and concentrated with nowadays available technologies [65]. For this reason, the exergy replacement cost is calculated as the ratio of the exergy required to replace the used resource using the current best available technologies and the actual exergy of it. This indicator has been calculated for many different resources. A summary of the exergy replacement costs of world mineral reserves can be found in Ref. [66].

Exergy is not only a metric for energy and material inputs in an industrial process, but also for waste outputs. For this reason, it has been argued that exergy can be used as a measure of environmental impact of industrial activities [67–70]. Some authors suggested that when exergy-based indicators are used to asses environmental impact, an absolute reference state should not be adopted, since the impact of waste streams depends on the environmental sink into which wastes are disposed [70]. A way to quantify process environmental impact is through the environmental compatibility indicator [17]:

$$\zeta = \frac{\dot{E}_{in}}{\dot{E}_{in} + \dot{E}_{abat}} \tag{15}$$

where $\dot{E}_{abat}$ is the sum of the exergy flows necessary for the abatement of process emissions and wastes. In an ideal case ($\zeta = 1$), the process emits only heat. The environmental compatibility is however subject to some degree of arbitrariness, since one can consider different levels of abatement. The highest level of abatement is represented by closure of the resource cycle [19]. This parameter has been calculated for gas-fired combined cycle power plants [18], paper production and recycling industry [19].

The evaluation of the environmental cradle to grave consequences of a product by life cycle assessment (LCA) has become a quite established technique. LCA can also be evaluated in terms of exergy, by carrying out the exergy analysis of a complete product life cycle [71].

Due to the importance of the assessment of environmental impact of industrial activities, exergy-based KPIs are not the only indicators that have been defined with this purpose [72]. However, to review indicators that are not defined in terms of exergy is beyond the scope of the present work.

3.5. *Other exergy-based performance indicators*

A concept that is useful to employ in industry is the improvement potential [73]:

$$IP = (1 - \epsilon) \cdot \left(\dot{E}_{in} - \dot{E}_{out}\right) = (1 - \epsilon) \cdot \dot{E}_d \tag{16}$$

The indicator gives an idea of the potential exergy savings that can be obtained by improving the process. The exergy destruction of the process, $\dot{E}_d$, represents the exergy that in principle could be saved if the process was ideal. However, real processes can never reach the ideal limit. Indeed, processes need to take place in finite time, and thus, some exergy destruction is unavoidable. The factor $1 - \epsilon$ (between zero and 1) in Eq. 16 is used to take this into account. The lower the efficiency, the larger the $\dot{E}_d$ fraction that could potentially be recovered. On the other hand, when the exergy efficiency is already close to unity, most of the process exergy destruction is most likely unavoidable.

The improvement potential has been evaluated for the United Kingdom energy sector [22], as well as for the Turkish industrial sector [20] and cement sector [74].

Even though it expresses only the order of magnitude of the exergy destruction that could be avoided, and not an exact measure of it, the improvement potential has the advantage of being an absolute number, as opposed to the many exergy-based KPIs that are dimensionless ratios.

A similar kind of approach has been adopted by other authors, which have tried to distinguished between avoidable and unavoidable exergy destruction in different ways. Tsatsaronis and Park [75] proposed to evaluate the unavoidable exergy destruction as the exergy destruction obtained when the exergy efficiency of the process is the maximum achievable with today's technology. Avoidable and unavoidable exergy destruction have been calculated according to this method for different processes, among which cogeneration systems [75], combined cycle power plants [76], fluidized bed coal combustors [77], and heat recovery steam generators [77].

A second approach defines the avoidable exergy destruction by comparing the process $\dot{E}_d$ to the exergy that would be destroyed if the process was optimally controlled so that its entropy production (or, equivalently, exergy destruction) was minimum, $\dot{E}_d^{min}$ [78] (maintaining the same operational targets). The minimum exergy destruction was calculated for different process units such as heat exchangers [78], distillation columns [79], chemical reactors [80, 81], steam reformers [82], paper drying machines [83], hydrogen production [84], and membrane separation processes [85]. In order to directly compare the current exergy destruction to the minimum possible one, Zvolinschi and Kjelstrup [86] defined the process maturity indicator:

$$\pi = \frac{\dot{E}_d^{min}}{\dot{E}_d} \tag{17}$$

This indicator was estimated for heat exchangers, chemical reactors, distillation columns and paper drying machines [86].

However, a certain degree of arbitrariness is still present in the definition of unavoidable exergy destruction.

The exergy loss of a certain process can also be compared with that of a reference case [87]. In this case, it is possible to define the relative avoided irreversibility:

$$RAI = \frac{\dot{E}_d - \dot{E}_{d,ref}}{\dot{E}_{in,ref}} \tag{18}$$

This parameter has been mainly used to compare alternatives for combined heat and power production [88–90].

An indicator closely related to the exergy efficiency is the efficiency defect, which indicates the fraction of exergy that is lost during a process:

$$\delta = 1 - \epsilon \tag{19}$$

Any of the exergy efficiencies described in Section 3.1 can be implemented in its definition. This indicator is particularly useful to describe systems that have no useful exergy output, such as systems that exchange heat with the environment, that are designed to accelerate a process or that are dissipative by design [38]. Despite the fact that no useful exergy output can be identified in these cases, their operation should nonetheless be carried out with minimum irreversibilities.

In the field of industrial ecology, this indicator is referred to as the depletion number [7].

Even though it is not a proper exergy-based parameter, the second-law efficiency gives a measure of the exergy destroyed in a process. This parameter compares the exergy that is produced (by a work producing process) or consumed (by a work consuming process) with the one that would be produced or consumed by an ideal reversible process operating between the same states [91]. For a work producing process:

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{id}} = 1 - \frac{\dot{E}_d}{\dot{W}_{id}} \tag{20}$$

where $\dot{W}$ is the power produced by the process, while $\dot{W}_{id}$ is the power that would be produced by the equivalent ideal process. Similarly for a work consuming process:

$$\eta_{II} = \frac{\dot{W}_{id}}{\dot{W}} = 1 - \frac{\dot{E}_d}{\dot{W}} \tag{21}$$

where $\dot{W}$ is the power consumed by the process, and $\dot{W}_{id}$ is the power that would be consumed by the equivalent ideal process. Even though the second-law efficiency gives a clear indication of how far a process is from ideal operation, the calculation of the ideal power might not be easy [43]. While relatively straightforward for certain process units, it might be very complex to determine it in complex industrial processes. The second-law efficiency can be easily calculated for systems such as heat pumps [92] and thermodynamic cycles in power plants [93].

4. On the choice of the system boundaries

The choice of system boundaries can considerably influence the results of energy and exergy analyses. The system boundary determines what is considered input, output and transformation occurring within the system. There is no unique way to define system boundaries, and several meaningful choices are usually possible. This problem has been widely discussed in the field of life cycle analysis, where the lack of a standard to draw system boundaries has many times limited the validity of comparative studies [94].

In any case, system boundaries need to be properly defined, as they form the premises of the analysis. Indeed, process streams are identified in accordance with the choice of system boundaries. Since the results of the analysis depend on the choice of the system boundaries, this choice needs always to be stated alongside results.

When the scope of the analysis is to monitor the improvements of the considered industrial process over time, it is important to maintain the system boundaries unchanged, in order for the comparison to be meaningful.

If different industrial processes need to be compared, the selection of system boundaries can favour some processes over others, and some degree of arbitrariness is inevitably present. It is indeed difficult to find equivalent system boundaries for different processes.

When considering alternatives, the choice of system boundaries may influence the rankings of different solutions, and can direct decisions on what process to favor in wrong directions [94]. In such instances, the selection of process boundaries should be such that output streams are as similar as possible.

5. On the choice of the reference ambient conditions

Exergy can be seen as a measure of disequilibrium between a system and its environment. When a system is in equilibrium with the environment, its exergy is zero. However, the conditions of the ambient in terms of temperature, pressure, and chemical potentials are not constant in time, nor uniform across the globe. This fact introduces some challenges in exergy calculations of systems and processes. In order to keep calculations to a reasonable level of complexity, it is necessary to select a set of constant and homogeneous reference ambient conditions. Such a choice is subject to some degree of arbitrariness.

When the considered process is inside an isolated system (i.e. a system that does not interact with the ambient), it is possible to define a reference ambient that is said to be a *restricted dead state*. In this case, the thermodynamic conditions of the restricted dead state are those of the process surroundings within the isolated system.

For open systems, the reference ambient is represented by the outdoor environment, which is said to be an *unrestricted dead state*. In this case, the conditions of the reference state are more difficult to define. Authors in the literature are divided between two approaches [95]. In the first type of approach, a local reference state is defined to best represent the local thermodynamic conditions of the environment at the considered location and time. According to the second approach, a universal dead state should be used, which is the same for any process around the globe.

When one uses a locally defined reference state, the results of exergy analysis are more representative of the real process in combination with its environment. However, the task to locally define a consistent reference state might be challenging, especially when the process includes reacting systems [95].

Many authors have tried to define and propose a universal standard reference environment with fixed reference temperature, pressure and chemical potentials of its components [96, 97]. The adoption of a universal standard reference environment simplifies the analysis, as it takes away the task of defining a consistent reference state. However, the results of the analysis might not be representative of processes located in areas where the ambient conditions are very different from those assumed by the universal standard reference environment.

Two of the universal standard reference environments proposed in the literature are the one by Szargut [96, 98] and the one by Ahrendts [97]. Although in many cases they give comparable results, their definition is based on different principles. One of the principles at the base of Ahrendts's universal reference environment is that the environment should be in equilibrium. The complications of defining such an equilibrium environment are reflected in the large number of attempts made by Ahrendts [99] to define the reference state. His finally proposed reference state has been criticized by different authors. Some of the arguments were that exergy values calculated with this reference state do no match with experimental values [100], and that since the Earth is not in equilibrium, an equilibrium-defined reference state is not relevant [101].

Szargut suggested to base the universal standard reference state on an *Earth similarity condition*, where a reference substance is chosen for every element. The exergy of any other substance may then be determined starting from those of the reference substances, by considering balanced chemical reactions. The reference substances chosen by Szargut are selected based on their abundance and on whether or not they have low Gibbs energy of formation. This universal reference state has also received critiques for different reasons. One of the critiques derives from the fact that chemical exergies of components other than the reference ones might become negative [99]. Thus, the reference state is not entirely consistent.

Despite its shortcoming, the reference state proposed by Szargut has been widely used. A detailed discussion of the different reference states can be found in the work of Szargut et al. [100], where the authors also argue in favor of the need for an international standard for the reference environment.

The choice of reference ambient conditions affects in a different way internal and external exergy destruction. Indeed, the internal exergy destruction is determined by the difference between the exergy of the streams entering the process and the exergy of the streams leaving the process (including those that are discharged into the ambient). When the properties of input streams are characterized by direct measurements, the only parameter of the reference ambient that affects the results of calculations is the assumed ambient temperature. However, if some of the input streams are not properly characterized, and their conditions are assumed to be equal to those of the reference state, the results might be affected by the choice of reference pressure and composition as well. Ertesvåg [102] showed that the chemical exergy of atmospheric gases and gaseous fuels changes due to variations in ambient conditions.

On the other hand, the calculation of external exergy destruction can be strongly influenced by the reference environment choice. For this kind of losses, exergy is lost by irreversible mixing of some output streams with the environment. Thus, external exergy losses are equal to the difference of the exergy of waste streams at the conditions they leave the process and the exergy they would have at the reference state conditions. When the real local ambient conditions are significantly different from those of the assumed reference ambient, calculated external exergy losses might be very different from the actual ones.

Utlu and Hepbasli [103] assessed how the exergy efficiency of different Turkish industrial sectors is influenced by the dead (reference) state temperature. They found that the exergy efficiency of the overall industrial sector increases from 25% to 29% when the reference ambient temperature decreases from 298 K to 273 K. Similar results have been obtained for the exergy efficiency of steam power plant [104], gas turbine cogeneration systems [105], and thermal power plants [106, 107]. Rian and Ertesvåg [57] showed how the exergy efficiency of an offshore liquefied natural gas processing plant benefits from its location in the cold arctic weather, where the outdoor temperature of 277 K has a considerable positive impact on fuel consumption [57].

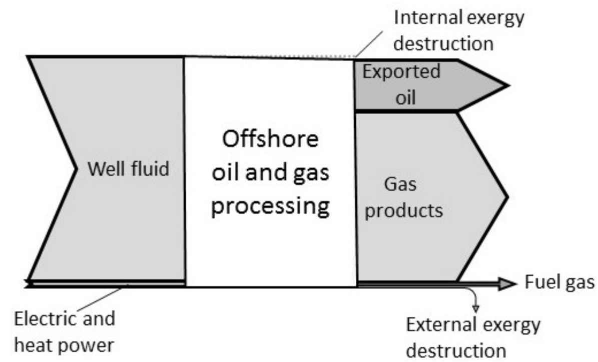
The effect of ambient pressure has been studied for turbofan engines [108, 109], where the exergy efficiency was found to decrease from 66.1% at sea level to 54.2% at 11000 m. The impact of air relative humidity has also been investigated [110, 111].

Since the results of exergy analysis depend on the assumed reference state, this should always be clearly stated.

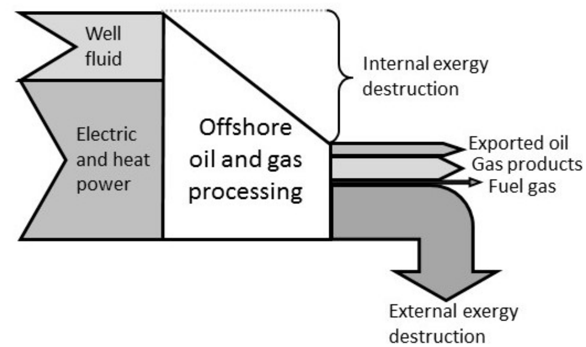
6. Examples of application of exergy-based KPIs to industrial processes

In order to show practical examples of how different exergy-based KPIs can quantify industrial process performances, we now apply the revised parameters to three different case studies.

6.1. Case studies



(a) Grassmann diagram based on total exergy flows.



(b) Grassmann diagram where transiting exergy flows are disregarded.

Figure 2: Grassmann diagram for the oil and gas processing platform, where the total exergy flows are considered (a), and where the transiting exergy flows are omitted from the analysis (b).

To present the exergy analysis of new industrial processes is beyond the scope of this paper. However, numerical insight is valuable when it comes to assess different KPIs for practical use. Since this work is aimed at potential users in industries, the exergy-based KPIs reviewed in the previous sections are applied to three different industrial processes, whose exergy analyses have been already presented in the literature. These are a North Sea oil and gas processing plant [50], a gas-fired combined cycle power plant, where CO_2 is abated through bio-gas conversion [18], and a silicon production process [52]. The selected case studies present characteristics that enable us to highlight the KPIs' advantages and limitations when applied to processes of different nature.

A detailed description of the considered oil and gas processing platform and the related process flowsheets can be found in Ref. [50]. Reservoir products are complex mixtures of different components, where the main fraction is represented by crude oil, natural gas and water. These components need to be first separated and then processed. Thus, in addition to the production manifold, the oil and gas facility includes systems for crude oil treatment, natural gas processing, and water purification.

The fluid from the reservoir is the main exergy input to the process. A second exergy input is represented by the electric power (mainly consumed by compressors) and heat. The other inputs are sea water streams for cooling and for eventual reservoir injections. However, since they are at reference state conditions, the exergy associated with these flows is zero. The electrical power that is needed by the process is provided by an external utility plant. The main outputs of the process are processed oil and natural gas. An additional output is fuel gas, which is sent to the utility plant to be used as fuel in gas turbines.

Figure 4 shows the exergy flows entering and leaving the oil and gas processing platform. Exergy calculations assume a reference temperature and pressure of 278 K and 1.01 bar, while the chemical composition of the reference ambient is that proposed by Szargut [98]. The Grassmann diagram in Fig. 2(a) pictures the total exergy flows involved in the process. Since the main purpose of the plant is to separate the components of well fluids, large amounts of exergy inputs simply transit across the process without undergoing any transformation. Thus, when the Grassmann diagram considers total exergy flows, the internal and external exergy destruction looks almost negligible on a global scale. However, when the transiting exergy is excluded from the analysis (Fig. 2(b)), it becomes evident how the exergy destruction represents over three quarters of the transformed exergy input, and that a big potential for improving the process exists. Circa 50% of the transformed exergy inputs is lost by internal exergy destruction, while approximately 25% is lost due to external exergy destruction. An advantage of differentiating between internal and external exergy destruction is that it allows us to pinpoint what kind of actions should be undertaken to improve the usage of exergy inputs. Indeed, in order to decrease internal exergy losses, process changes

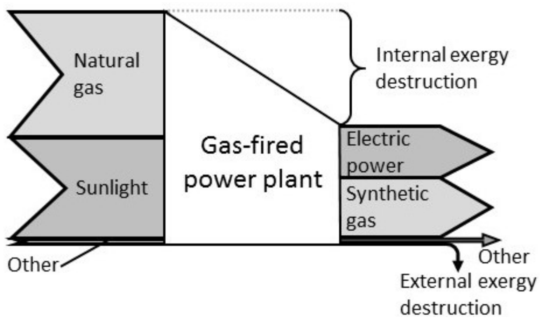
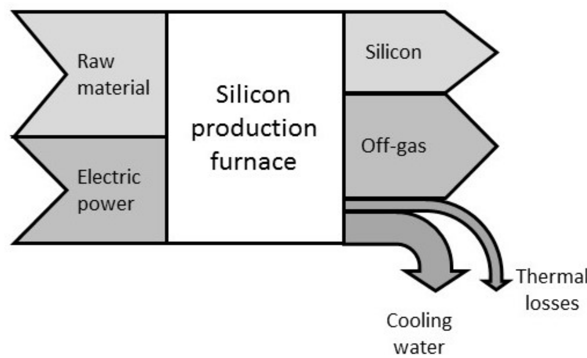
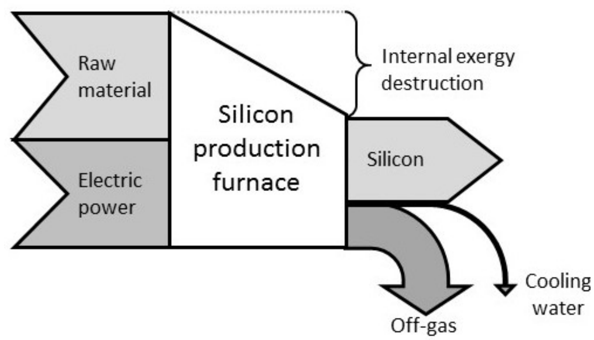


Figure 3: Grassmann diagram for the gas-fired power plant with CO_2 chemical absorption and bio-gas conversion.



(a) Sankey diagram based on energy flows.



(b) Grassmann diagram based on exergy flows.

Figure 4: Sankey and Grassmann diagram for the silicon production process.

are needed. On the other hand, when the exergy destruction is external, large amounts of potentially useful exergy flows are discharged into the ambient. In order to reduce such losses, a possibility is to recover the exergy content of waste streams and utilize it as input to other processes.

The second case study is a gas-fired power plant with CO_2 abatement through bio-gas conversion, described in detail in Ref. [18]. The power plant combusts natural gas as fuel, and it is integrated with an amine absorption process for CO_2 capture. The mono-ethanolamine and carbon necessary to the absorption process are regenerated during the process. Carbon dioxide is finally converted into synthetic gas and fertilizer through photosynthesis and anaerobic digestion, where the main external exergy inputs are sunlight and make-up water. A fraction of the produced electrical power is used to satisfy the internal need for power.

The assumed reference state has same conditions as in the previous example, except for the reference temperature, which is assumed to be 288 K. In this case, the largest part of the exergy fluxes entering the process undergoes some kind of transformation before leaving the system. Figure 3 shows the Grassmann diagram for the considered power plant, where the total exergy flows are considered. Since the transiting exergy flows are very small, it is not possible to visually detect differences between the Grassmann diagram considering total exergy flows (Fig. 3) and the one where transiting exergy is not considered (not reported here).

The last considered case is a process for the production of silicon, which has carefully been described in Ref. [52]. In the process, raw materials (mainly quartz and carbonaceous reduction materials) reacts to produce silicon and large amounts of off-gases and thermal energy. The reaction takes place thanks to the high temperature generated with the use of electric power [52]. The ambient reference temperature for this case study is 298 K, while the other ambient conditions are the same as for the the previous cases.

It is interesting to compare the results of the exergy analysis of the process with those of energy analysis. Figure 4(a) represents the process Sankey diagram, while Fig. 4(b) illustrates the Grassmann diagram. According to the first law of thermodynamics, energy is conserved. Thus, the amount of energy that enters the process in Fig. 4(a) equals the energy that leaves the system. It can be noticed that the off-gases are the largest energy stream

leaving the process, representing circa 45 % of the energy input. The cooling water contains circa 20 % of the energy leaving the system. This suggests that the installation of some measures for the recovery of thermal energy would enable us to recover 65 % of the wasted energy. This would bring the energy efficiency of the process above 90 % (thermal losses amounts to circa 8 % of the energy input).
However, by looking at the Grassmann diagram, we realize that the exergy of the off-gasses and cooling water is only 20 % of the exergy output. Thus, its eventual recovery allows us to bring the exergy efficiency to circa 50 %. This is due to the fact that almost half of the exergy input is destroyed within the process itself, due to internal irreversibilities. Thus, in order to further improve the exergy efficiency and resource use in the process, one would need to modify the process so that internal irreversibilities are reduced.
The low exergy content of the thermal energy in the off-gas and cooling water is due to the fact that their temperature is relatively low (533 K and 306 K respectively). Despite the Sankey diagram gives valuable insights into the energy streams crossing the system, it still considers electric power, material resources, and low temperature heat as equally valuable. The use of the Grassmann diagram allows us to account for the different quality of the various energy forms.

6.2. Exergy-based KPIs

While Grassmann diagrams are useful tools, providing an immediate idea of how the potential of the input resources is utilized, exergy-based KPIs can help gaining a deeper insight on the process performances.
Table 1 shows the exergy efficiencies presented in Section 3.1 calculated for the considered case studies. For the gas-fired combined cycle power plant, the three exergy efficiencies are very similar to each other. This is due to the fact that most of the exergy flows that enter the system undergo thermodynamic transformations. In such a case, it is possible to obtain a meaningful evaluation of the process performance by using any of the exergy efficiencies.
However, the situation is very different for the offshore processing plant, where total exergy efficiency, task exergy efficiencies and exergy efficiency disregarding transiting exergy are very different from each other. This phenomenon is typical of processes where large amounts of exergy cross the system without undergoing any transformation. In the present case, the total exergy efficiency of the offshore plant is approximately equal to one, suggesting that the process is close to ideality. However, it is clear from Fig. 2(b) that a large potential for improvement exists. In the present case, this parameter is not able to properly evaluate the process performances, as it does not signal a need for improvement of the process. Moreover, the parameter is not sensitive to changes, since efforts to enhance the process can result only in very small increments of total exergy efficiency (order of 0.1%).
As mentioned in Section 3.1.2, there is no unique definition for task exergy efficiency. Indeed, authors in the literature have considered different contributions to the produced and consumed exergy terms that enter the definition of task efficiency (Eq. 5). It has been shown that by considering different definitions of such terms, very different values of task efficiency for the same process can be obtained [16]. The three different values for ϵ_{task} reported in Table 1 have been calculated in Ref. [16] by following the approach of three alternative groups of authors. For the silicon furnace, a possible task exergy efficiency has been defined excluding the exergy of the volatiles introduced with the carbonaceous materials from the exergy inputs [53]. Despite the fact that the task efficiency succeeds into highlighting that a good margin to improve the system exists, its non-unique definition leaves room for interpretation and may cause problems when it is necessary to apply it systematically to processes of different nature.
The exergy efficiency disregarding transiting exergy is well defined and it clearly underlines process needs for improvement. However, it requires detailed calculations of the different components of the exergy flows, which might be complex to do.
When actions need to be taken to improve the system, it is useful to have an overview of the fraction of exergy destroyed in every sub-process. In this way, efforts to improve the system can focus on sub-processes with the highest potential for improvement. However, this requires a detailed analysis of the process components. Table 2 shows the component exergy destruction ratio for every sub-process of the offshore processing plant. By looking at the table, it is possible to individuate reinjection trains, production manifold, and recompression train as respon-

Table 1: Exergy efficiencies for the offshore oil and gas processing plant, for the gas-fired power plant with CO_2 chemical absorption and bio-gas conversion, and for the silicon production process.

	Processing plant from Ref. [50]	Power plant from Ref. [18]	Silicon plant from Ref. [52]
ϵ_{tot}	0.995	0.52	0.33
ϵ_{task}	0.13/0.38/0.71	0.51	0.40
ϵ_{tr}	0.18	0.51	0.34
δ = 1-ϵ_{tot}	0.005	0.48	0.67

Table 2: Component exergy destruction ratios for the offshore oil and gas processing plant components.

	Processing plant from Ref. [50]
Internal exergy destruction	
Production manifold	17%
Separation train	2.9%
Export section	0.9%
Recompression train	15%
Reinjection trains	38%
Fuel gas system	1.9%
External exergy destruction	
Flared gases	18%
Discharged water	5.4%

sible for the largest fraction of internal exergy destruction (they cause 38%, 17%, and 15% of the total exergy destruction). Efforts to improve the process should then be focused on these sub-processes. A large part of the total exergy destruction is due to external exergy destruction (circa 23%). When feasible, a way to reduce external irreversibility is to recover the exergy content of waste streams.

Specific indicators such as energy consumption or CO_2 emissions per unit of product are largely employed by industry. As presented in Section 3.3, this kind of indicators can be expressed also in exergy terms. Table 3 shows the most relevant specific exergy-based indicators for the considered processes. As seen in Table 1 the definition of consumed exergy (that is used in Eq. 9) is ambiguous, as it can be identified in different ways. In the calculation of the specific exergy consumption and destruction, we defined the consumed exergy as the difference of the total exergy input and the transiting exergy:

$$E_c = E_{in} - E_{tr} \tag{22}$$

As reported in Table 3, the unit of product is measured in different units for the two process. In oil and gas processing plants, a possible way to quantify the exported products is to use standard cubic meters of oil equivalent (Sm^3o.e.). This allows us to account for the different nature of products. The primary product of the gas-fired power plant is electrical power. Thus, the specific exergy consumption and specific exergy destruction can be expressed per joule of electric power produced. Silicon production can be characterized in terms of exergy consumption per kilogram of produced silicon. The specific exergy consumption of the offshore processing plant, of the gas-fired power plant, and of silicon production are 925 $\frac{\text{MJ}}{\text{Sm}^3\text{o.e.}}$, 4.3 $\frac{\text{J}}{\text{J}_{\text{el}}}$ and 88 $\frac{\text{kJ}}{\text{kg}_{Si}}$ respectively. These parameters can be very useful for monitoring the improvement of a specific process over the years, but also for comparison of industrial processes with similar products. Nowadays, energy consumption per unit of product is the indicator mostly used with this scope. As an example, in the silicon industry, the kilowatt-hours consumed per kilogram of silicon produced is the parameter normally used as benchmark for the process. In the present case, the specific electricity consumption of the process is 11.7 $\text{kWh}_{el}/\text{kg}_{Si}$. However, this parameter allows one to account for the use

Table 3: Specific exergy use and specific exergy destruction for the offshore oil and gas processing plant, for the gas-fired power plant with CO_2 chemical absorption and bio-gas conversion, and for the silicon production process.

	Processing plant from Ref. [50]	Power plant from Ref. [18]	Silicon plant from Ref. [52]
$e_{\mathrm{Sm^3 o.e.}}$ / $e_{\mathrm{J_{el}}}$ / $e_{\mathrm{kg_{Si}}}$	925 $\frac{\mathrm{MJ}}{\mathrm{Sm^3 o.e.}}$	4.3 $\frac{\mathrm{J}}{\mathrm{J_{el}}}$	88 $\frac{\mathrm{kJ}}{\mathrm{kg}_{Si}}$
$e_{\mathrm{d,Sm^3 o.e.}}$/ $e_{\mathrm{d,J_{el}}}$/ $e_{\mathrm{d,kg_{Si}}}$	757 $\frac{\mathrm{MJ}}{\mathrm{Sm^3 o.e.}}$	2.1 $\frac{\mathrm{J}}{\mathrm{J_{el}}}$	60 $\frac{\mathrm{kJ}}{\mathrm{kg}_{Si}}$
e_{ex}	5.5	2.0	3.0
$e_{\mathrm{d,ext}}$	4.5	1.0	2.0

of electric power only, while other energy inputs are not considered. Moreover, possible differences in input material quality are neglected. This represents a limitation, especially when comparing different processes. For instance, the specific energy consumption of the considered oil and gas processing plant is 667 MJ/Sm^3 o.e.. However, the same parameter for another processing platform was found to be 20 MJ/Sm^3 o.e. only (Platform B in Reference [21]). Such a difference in specific energy consumption is mainly due to a difference in input material streams, rather than to a difference in performances of the two platforms. Indeed, the most of the energy demand of a processing plant is due to compression power. Since the input well streams in the second platform have much higher pressure than those in the first platform, the need for compression power and, thus, the energy use of the process are much smaller [21].

Since the specific exergy consumption is able to account for differences in energy and material inputs, to consider the corresponding exergy-based KPI might allow for a more fare comparison of different processes.

The specific exergy consumption measures the amount of exergy that is necessary to produce one unit of product, but it does not indicate how much of the input exergy is wasted or what the margins for improvement are. By comparing this parameter to the specific exergy destruction, it is possible to understand how well exergy inputs are utilized, and how much of it could be saved.

When products are several and different in nature (e.g. the offshore platform produces not only oil to be exported but also fuel for turbines and gas for injections, as well as the gas-fired power plant produces synthetic gas and fertilizers in addition to electric power), it can be advantageous to express the specific exergy use and specific exergy destruction in terms of unit exergy of products (e_{ex} and $e_{d,ext}$). Indeed, these parameters allow us to account for all different products in the same units. We define the exergy of products (at the denominator of Eq. 10 and Eq. 12) as:

$$E_{prod} = E_{out} - E_{tr} \tag{23}$$

In an ideal case, the specific exergy consumption, e_{ex}, is 1, while the specific exergy destruction, e_d is 0. These parameters as well as the exergy efficiency disregarding transiting exergy could be used in principle to compare the performances of the three processes, as they evaluate the total use of resources. However, in practice, the efficiency of different processes is influenced by many factors, such as location (e.g. offshore processes are subject to additional constraints due to limited areas and volumes) or progress in the different technologies required by the process (e.g. newly emerged technologies are usually less efficient than the well established ones).

Among the technologies whose technological limits are low are those that utilize renewable resources with low exergy density, such as sunlight or tidal power. However, since they exploit renewable exergy, they have low impact on the availability of resources. Thus, in many cases, they should be favoured over alternatives that exploit non-renewable resources, even though global exergy efficiencies might be lower. A parameter that is useful in this sense is the renewability parameter, α. Table 4 shows that while the renewability parameter is zero for the offshore oil and gas processing plant, circa 43% of the exergy input in the gas-fired power plant is renewable. Moreover, thanks to the CO_2 abatement through bio-gas conversion, the environmental compatibility indicator of

Table 4: Other exergy-based KPIs for the offshore oil and gas processing plant, for the gas-fired power plant with CO_2 chemical absorption and bio-gas conversion, and for the silicon production process.

	Processing plant from Ref. [50]	Power plant from Ref. [18]	Silicon plant from Ref. [52]
α	0.00	0.43	0.44
IP	23 MW	420 MW	43 MW

the power plant is close to unity (ζ = 0.95 [18]).

Since the silicon production process makes use of electric power from hydroelectric source, its renewability parameter is quite large (0.44). However, similar plants in other locations might make use of electric power produced by different energy sources, and thus can have lower renewability parameter.

The improvement potential is a useful concept for industries as it expresses the possible exergy savings in power units, thus as an absolute number. For this reason, the parameter can be easily related to savings in monetary terms. Table 4 shows that the improvement potential is very large for all considered industrial processes. In particular, the improving potential of the gas-fired plant is one order of magnitude higher than that of the other processes. This is mainly due to the fact that the absolute exergy destruction is larger in the gas-fired power plant.

7. Summary

Many different exergy-based KPIs can be found in the literature, with characteristics that make them suitable for different purposes. Prior to the selection of indicators comes the selection of an appropriate basis for the analysis. Figure 5 illustrates the steps that one can follow to choose exergy-based KPIs. As a first step, the system, its constraints, and the boundaries that separate it from the environment should be properly defined. This allows one to uniquely determine the system input and output exergy streams.

Second, a reference state that is representative for the considered process should be chosen. Indeed, conditions assumed by standard reference states might be very different from the actual ones, and might lead to improper results.

Next, an important characteristic of the process should be evaluated. When most of exergy inputs are transformed during the process, exergy analysis can be carried out considering total exergy streams. However, if the untransformed exergy is a large fraction of the exergy input, then the transiting exergy should be properly calculated, and subtracted from the exergy streams. Even though this procedure might complicate calculations, it allows for a more meaningful representation of process performances. This is typically necessary when material streams entering and leaving the system have high chemical exergy (e.g. fuels) and do not undergo chemical transformations.

The exergy-based KPIs to be used in a specific case should be then chosen according to the process characteristics and scope of the analysis. Table 5 presents a summary of the parameters reviewed in this work. Advantages and limitations of the listed KPIs are indicated to provide a better overview of the different parameters, and to help readers in the selection of KPIs appropriate for their case.

8. Conclusions

In this work, we have reviewed the exergy-based key performance indicators (KPIs) that can be found in the literature, in order to highlight their significance in the assessment of performances of different industrial systems. The final scope is to promote their use in industry. Indeed, while energy-based KPIs are most used in the industrial sector, some of their limitations can be overcome by replacing them with exergy-based KPIs.

Grassmann diagrams are useful tools that give an immediate idea of the fraction of exergy input that is lost due to internal irreversibilities, and of the fraction lost due to the discharge of waste flows into the ambient. When a large part of exergy input crosses a process without undergoing transformations, Grassmann diagrams in terms of total exergy flows do not give a proper process representation. In

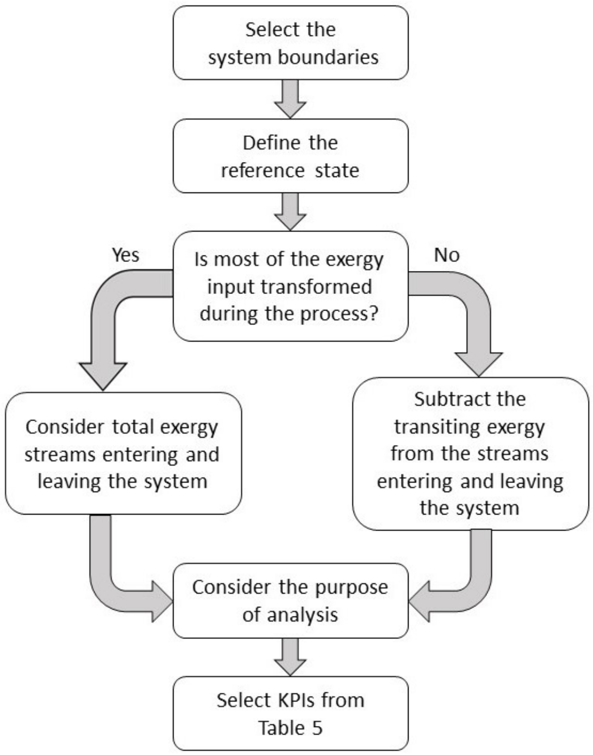


Figure 5: Advised steps for the selection of KPIs for a specific case.

such cases, it is best to exclude the transiting exergy from the analysis.

Several types of exergy efficiency can be found in the literature. Despite being easy to calculate and unambiguous, the total exergy efficiency is not representative of processes whit large transiting exergy. In general, the exergy efficiency that disregards the transiting exergy gives a more meaningful evaluation of process performances, but it might be complex to calculate. The task efficiency has the fundamental disadvantage of not being uniquely defined and of leaving room for interpretation.
The specific exergy use is a parameter that resembles indicators well known in industries, such as specific energy use or specific CO_2 emissions. Even though it is useful to monitor process performances over time or to compare similar processes, this parameter does not give an idea of the exergy that is wasted in a process, unless it is coupled with the specific exergy destruction.
Exergy-based KPIs can also be defined to quantify resource depletion and environmental impact of industrial activities. The renewability parameter allows us to determine what fraction of process inputs derives from renewable resources, while the exergy replacement cost assesses the exergy expense necessary to replace the resources consumed by industrial processes. Environmental impact can be expressed in exergy terms through the environmental compatibility indicator, or it can be assessed by carrying out the exergy analysis of a complete life cycle of products. While it gives important insights into the process nature, environmental exergy-based KPIs might be complex to calculate or they could depend on assumptions, such as those on the state of the best available technologies or on the definition of remediation costs.
Other indicators such as improvement potential, process maturity indicator, or relative avoided irreversibility can give an idea of the possible exergy savings that would result from the process improvement.
In order to obtain meaningful exergy-based KPIs, the boundaries between system and environment should be well defined and properly stated, alongside with the thermodynamic properties of the reference state.
Despite the fact that exergy analysis and exergy-based indicators are nowadays mature concepts, their main limitation is due to the fact that their application is still mostly limited to academic settings. Indeed, the performance indicators used in the industry sector are only based on energy. For this reason, future efforts should be directed towards the promotion of exergy concepts outside academia. A systematic use of exergy-based KPIs in sectors like industry does not only give a better representation of process performances in terms of resource use, but it can also meaningfully direct efforts to improve processes.

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Table 5: Exergy-based KPIs.

		Definition	Advantages	Disadvantages
Efficiency				
ϵ_{tot}	(Eq. 2)	$\frac{\dot{E}_{out}}{\dot{E}_{in}}$	unambiguous definition, simple, applicable to any system	not meaningful or sensible to changes when transit exergy is large
ϵ_{task}	(Eq. 5)	$\frac{\dot{E}_p}{\dot{E}_c}$	sensitive to changes, simple, can be tailored for the specific system	does not have a universal definition, leaves room for interpretation
ϵ_{tr}	(Eq. 7)	$\frac{\dot{E}_{out}-\dot{E}_{tr}}{\dot{E}_{in}-\dot{E}_{tr}}$	unambiguous definition, sensitive to changes	might be complex to calculate
Component exergy destruction				
$y_{d,k}$	(Eq. 8)	$\frac{\dot{E}_{d,k}}{\dot{E}_d}$	useful to point at components with larger improvement potential	requires detailed knowledge of process components
Specific KPIs				
e_{kg}	(Eq. 9)	$\frac{E_c}{M_{prod}}$	intuitive, simple, useful to establish a benchmark	unsuitable when processes have several products, cannot show how far processes are from ideality
e_{ex}	(Eq. 10)	$\frac{E_c}{E_{prod}}$	can be used when products are several and of different nature	cannot show how far processes are from ideality
$e_{d,kg}$	(Eq. 11)	$\frac{E_d}{M_{prod}}$	shows how far a process is from ideality, if coupled with e_{kg}	unsuitable when products are several
$e_{d,ext}$	(Eq. 12)	$\frac{E_d}{E_{prod}}$	shows how far a process is from ideality, if coupled with e_{ex}	should be coupled with e_{ex}
Environmental exergy-based KPIs				
α	(Eq. 13)	$\frac{\dot{E}_{in,renew}}{\dot{E}_{in}}$	favours the use of renewable sources (α=1 when all inputs are renewable)	it can be complex to trace input materials back to their primary resources
k	(Eq. 14)	$\frac{\dot{E}_{in,BAT}}{\dot{E}_{in}}$	assesses resource depletion accounting for technological limitations	dependent on current technological limitations
ζ	(Eq. 15)	$\frac{\dot{E}_{in}}{\dot{E}_{in}+\dot{E}_{abat}}$	accounts for impact of process waste by taking abatement exergy costs into account	abatement exergy costs are not uniquely defined
Other KPIs				
IP	(Eq. 16)	$(1-\epsilon)\cdot\dot{E}_d$	expresses the process improvement potential in power unit	gives only an indication of the improving potential rather than an accurate calculation of it
π	(Eq. 17)	$\frac{\dot{E}_d^{min}}{\dot{E}_d}$	expresses the potential to reduce exergy losses under some given constraints	depends on constraints assumed on the process
RAI	(Eq. 18)	$\frac{\dot{E}_d-\dot{E}_{d,ref}}{\dot{E}_{in,ref}}$	good to compare possible alternatives to a reference case	does not allow the comparison of different processes
δ	(Eq. 19)	$1-\epsilon$	suitable to describe the performances of dissipative processes	has the same limitations as the ϵ used in its definition
η_{II}	(Eqs. 20-21)	$\frac{\dot{W}}{\dot{W}_{id}}$ or $\frac{\dot{W}_{id}}{\dot{W}}$	unambiguous definition, measures how far a process is from ideality	can be complex to calculate