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Previous editions
- (This is the first edition)

Amendments
-
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1. Introduction

Energy efficiency and energy management are major efforts in production plants today and for many processing plants electricity, fuel gas and steam are major cost drivers. Many standards and recommendations exist (e.g. [1] and [2]) that help plant and production site managers to understand and to report their energy consumption and to optimize their processes. Today’s Energy Performance Indicators (EnPIs) support plant operations but are often used to report in hindsight.

Figure 1 shows the relationship of this recommendation with other national and international standards. The analysis of this diagram shows a need for the standardization of real-time resource efficiency indicators. Both, resource efficiency in general and resource efficiency indicators as well as reporting in real time have not yet been covered well in the standards. The dark grey fields on the bottom right in Figure 1 show the scope of the REIs defined in this recommendation.

<table>
<thead>
<tr>
<th>Manufacturing Industry</th>
<th>Retrospective</th>
<th>Real-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>ISO 50001</td>
<td>ISO 14040-44</td>
</tr>
<tr>
<td></td>
<td>ISO 20140</td>
<td>ISO 14045</td>
</tr>
<tr>
<td></td>
<td>ISO Guide 118</td>
<td>ISO 14051</td>
</tr>
<tr>
<td></td>
<td>IEC Guide 119</td>
<td>ISO 22400</td>
</tr>
<tr>
<td></td>
<td>IEC TR 62837</td>
<td>WD ISO 14052</td>
</tr>
<tr>
<td></td>
<td>VDI 4800</td>
<td>VDI 4800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process Industry</th>
<th>Retrospective</th>
<th>Real-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>ISO 50001</td>
<td>ISO 22400</td>
</tr>
<tr>
<td></td>
<td>ISO Guide 118</td>
<td>IEC Guide 118</td>
</tr>
<tr>
<td></td>
<td>IEC Guide 119</td>
<td>IEC TR 62837</td>
</tr>
<tr>
<td>Material Efficiency</td>
<td>VDI 4800</td>
<td>VDI 4800</td>
</tr>
</tbody>
</table>

Legend:
ISO 14040-44: Environmental management – Life Cycle Assessment
ISO 14045: Environmental management – Eco efficiency assessment of product systems
ISO 14051: Environmental management – Material flow cost accounting
WD ISO 14052: Environmental management – Material flow cost accounting
ISO 20140: Automation systems and integration – Evaluating energy efficiency and other factors of manufacturing systems
ISO 22400: Automation systems and integration – Key performance indicators for manufacturing operations management
ISO 50001: Energy Management System
IEC Guide 118: Energy Efficiency aspects inclusion in electrotechnical standards
IEC Guide 119: Preparation of energy efficiency publications
IEC TR 62837: Energy Efficiency through Automation Systems
VDI 4800: Resourcecoefficient (German VDI Recommendation – Resource Efficiency)
VDMA 66412: MES Kennzahlen (German VDMA Recommendation – MES Performance Indicator)

Figure 1: Relationship of this recommendation with other standards

In this recommendation the implementation of Resource Efficiency Indicators (REIs) is proposed whereby resources are material and energy and their combination, and they also cover environmental impacts such as waste and emissions. They are suitable for real-time monitoring and optimization of industrial production sites such that the effect of technical improvements and of operational policies can be measured and actions can be derived for (real-time) plant performance improvements.

According to a NAMUR non-representative survey, plant managers see potential in more measurements and better, possibly real-time Performance Indicators (PI) that need to cover the energy and raw materials used.

2. Purpose

The purpose of this recommendation is to provide guidelines using Resource Efficiency Indicators (REIs) that specify standardized energy and material use as well as the environmental impact of production within a specified technical system boundary and especially for operational (not only retrospective) use. The results can be used to find the resource optimal operating point. The recommendation can be considered an extension of NA 140 [3] and in line with NE 145 [4] and NE 147 [5].
In Section 6 the recommendation provides a general description of energy and material efficiency evaluation and puts the recommended indicators into context.

Section 7 defines the guiding principles for REI development and the necessary definition of a baseline for reporting. Individual reporting for different hierarchical levels (operator, plant manager) is described and suggestions for the correct implementation and visualization are given.

3. Scope of Application

This NAMUR recommendation allows solution providers to develop methods to implement and to visualize Resource Efficiency Indicators (REIs) beneficial to the operation of plants in the processing industry, chemical and biochemical industry and integrated production sites. It provides different aspects of the implementation in plants according to the specific REI.

Some of the REIs are generic for all plants of a production complex; some are specific for selected plants. In section 8, which is the core of this recommendation, the different aspects of the implementation are given. A methodology to select and evaluate REIs for the desired purpose is given. Production complexes consist of interconnected and interdependent plants. The recommendation provides general principles how to aggregate REIs hierarchically and how to calculate the contribution of each plant and influencing factors to the aggregated REI.

Section 9 illustrates how the REI reporting can be implemented. REI reporting has to be incorporated in DCS, PIMS and MES, displaying REIs in real time serves as advisory and decision support. In automatic control (e.g. model predictive control and real-time optimization), REIs can be used as the objective that drives the process towards improved resource efficiency.

The recommendation is non-exhaustive concerning possible REIs and readers are encouraged to find and define their own indicators in accordance with the guiding principles. The typical target group are processing industry, chemical and biochemical industry and integrated production sites.

4. Normative References

No references

5. Terms and Definitions

5.1. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC</td>
<td>Advanced Process Control</td>
</tr>
<tr>
<td>BAP</td>
<td>Best Achievable Practise</td>
</tr>
<tr>
<td>BDP</td>
<td>Best Demonstrated Practice</td>
</tr>
<tr>
<td>DCS</td>
<td>Distributed Control System</td>
</tr>
<tr>
<td>DR</td>
<td>Data Reconciliation</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
</tr>
<tr>
<td>EFA</td>
<td>Energy Flow Analysis</td>
</tr>
<tr>
<td>GRI</td>
<td>Global Reporting Initiative</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>EnPI</td>
<td>Energy Performance Indicator</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>JRC</td>
<td>Joint Research Centre</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>MES</td>
<td>Manufacturing Execution System</td>
</tr>
<tr>
<td>MFA</td>
<td>Material Flow Analysis</td>
</tr>
<tr>
<td>MORE</td>
<td>Abbreviation of the project: Real-time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants</td>
</tr>
</tbody>
</table>
5.2. Terminology for plant hierarchy
In this recommendation the following terms for the enterprise and plant hierarchy based on IEC 62264-1 [6]
are used:
1. Enterprise
2. Site
3. Area
4. Plant
5. Plant Section
6. Equipment
7. Control Module
The term "plant section" is generally used to refer to all of the above in general.

6. Real-Time Resource Efficiency and its Application to Processing Plants

6.1. General
Depending on the intended field of application the interpretation of the term “Resource Efficiency” differs. A
clear understanding of these terms is necessary.

6.2. Resource efficiency
As yet, there is no standardized definition for the term “resource efficiency”. The European Commission de-
fines resource efficiency in the following way:
“Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising im-
pacts on the environment. It allows us to create more with less and to deliver greater value with less input.”
In a recent paper, resource efficiency for the process industry was defined more specifically as
"a multi-dimensional entity that includes the environmental load and the efficiency of the utilization of material
and energy in the production of the desired products. Other resources as e.g. manpower, production capacity,
and capital are not included in the discussion [...].”[7]
Using this definition and this recommendation, plant personnel can evaluate the resource efficiency of produc-
tion processes and visualize if the current resource efficiency corresponds to the best demonstrated practice
and potentially optimize it.
6.3. REIs as (Key) Performance Indicators

A (key) performance indicator (KPI) is a type of performance measurement that evaluates the success of an activity. Often KPI relate a measurement to another, resulting in relative measures. They are called efficiency when they are given per plant section of input and intensity, when they are given per plant section of product output. [7]

In the recent literature, the following definition is given:

“KPIs represent a set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization.” [8]

Meaningful KPI have to fulfil certain criteria [9] some of which are also true for the REIs in this recommendation:

1. The direction of movement must be consistent with the change in actual performance.
2. The magnitude of movement must be consistent with the magnitude of change in actual performance.
3. The information provided by the KPI results from action by the operator and a change in the KPI can be influenced by action of the operator.
4. It should be possible to automate the KPI calculation and visualize it for online display and reporting.

For different purposes a number of KPIs exist, often using different names for very similar measures. The term KPI is generally widely used but preferred in financial applications. The KPI used in energy management systems (ISO 50001) are called Energy Performance Indicators (EnPI). Here, in order to differentiate the indicators from the others, the term Resource Efficiency Indicator (REI) is used. Resources in this case are primarily material and energy and their combination, but also cover environmental impacts such as waste and emissions. Despite the term "efficiency" REIs can also be defined as intensities.

The Resource Efficiency Indicators in this recommendation can be used for real-time monitoring and optimization of resource efficiency in processing plants as well as for reporting, extensible to Life Cycle Analysis.

Resource Efficiency Indicators (REIs) are intended to measure the efficiency of the usage of material and energy for industrial production sites such that the effect of technical improvements and of operational policies can be measured and actions can be derived for (real-time) plant performance improvements.

Resource efficiency indicators are classified into three categories (Figure 2):

1. **Energy**: This is based on an energy flow analysis (EFA). Indicators from this group measure how much energy is consumed for the production of one plant section of product.
2. **Material**: This is based on a material flow analysis (MFA). Indicators from this group measure the amounts of raw materials consumed for the production of one plant section of product.
3. **Environmental**: Here, the REI measures the environmental impact of the production process, e.g. by measuring greenhouse gas emission equivalents per ton of product.

![Figure 2: Categories of resource efficiency indicators](image)

For some indicators the classes may overlap.

Resource efficiency is a multi-dimensional entity (because multiple resources are usually needed to produce a product or several products simultaneously), whereas economic efficiency can be measured by one single figure and in one single plant section, money. The consumption of different resources and the environmental impact can be integrated into one figure by weighting the streams in comparable plant sections. If these plant sections are financial (prices or costs), the single figure comprising the weighted separate resources will fluctuate with price or cost fluctuation losing its physical meaning. If the weights are chosen on physical grounds, for example the calorific value or the energy that is required to produce a certain carrier of secondary energy, such an integration can help describe resource efficiency using a single figure. Wherever possible, physical
plant sections should be preferred to make resource efficiency transparent and to reduce the influence of external factors.

6.4. Real-time REIs and real-time challenges

Resource Efficiency monitoring is extended to “real time” in this recommendation. Depending on the intended field of application the interpretation of the term “real time” differs. A clear understanding is necessary.

A measurement, analysis or optimization technology in the sense of this recommendation is considered “real time” if

1. The time delay and the sampling time of the entire analysis procedure – measurements and data processing – are sufficiently short compared to relevant process dynamics. [10]

2. The time resolution is similar to the typical frequency of changes of manipulated variables. [7]

Due to the presence of disturbances and fluctuations in all production processes, resource efficiency indicators have to be averaged over sensibly chosen intervals to avoid that their values are dominated by stochastic influences. The averaging must not be longer than the periods over which the manipulated variables are kept constant to include effect of the operational policies.

Real-time REIs are significantly different from REIs or KPIs for historic analysis because they allow online monitoring and fast intervention to improve resource efficiency. Indicators that help steer the real operations of the plants towards improved resource efficiency must be computed in real time from the data collected in the process monitoring and control systems. Real-time data must be processed to account for measurement errors and dynamic effects to assure that the material balances are satisfied, otherwise no reliable information is obtained.

Providing REIs in real time poses a number of challenges for measurement, data collection and visualization such as missing information, short calculation time and missing data. When REIs need to be averaged or aggregated, wrong temporal or spatial aggregation must be avoided.

Real-time REIs are defined based on instantaneous values at a specific time point but usually filtering and averaging over a suitable period of time is necessary to reduce fluctuations and noise effects. The choice of the sampling and averaging periods is plant dependent. The choice of the temporal aggregation interval is crucial. The interval should be short so that the indicators can be used to make operational decisions.

A very typical challenge for real-time REI calculation is quality measurements that occur at different sampling intervals. The typical practical solution to this problem is to use zero order hold of the latest measurement leading to a possibly incorrect real-time REI. A typical second problem is incorrect averaging over time to filter REIs. The average of a typical REI with time is not the average of its last few values. In contrast, the REI calculation must be based on the average of the last measurements used.

It is beyond this recommendation to provide solutions for these challenges but the reader should be aware that they exist.

6.5. Improvement of economic plant performance

The indicators defined by this recommendation can be used to show economic performance. Many of the indicators employ a concept called “resource currency”. It is possible to replace these weighting factors by average or current real prices in order to visualize economic performance and justify investments.

7. Requirements for Real-Time REIs

7.1. Defining principles

For real-time resource efficiency indicators, the following eight principles are recommended (cf. [11], [23], [25], [22]):

1. Gate-to-gate approach

As the entity of interest is an area, plant or plant section, the boundary of the analysis is the limit of the respective entity as only this can be influenced in real time (“area fence approach”).

2. Indicating technical performance independent of market fluctuations

The flows of material and energy are not to be related to real-time economic indicators, technical performance is separated from the economic performance.
3. **Based on material and energy flow analysis**

The resource efficiency indicators are based on the physical flows and conversion of raw materials and energy to products and flows into the environment as objective characteristics of a production process. The identification of important streams for the material and energy flow analysis has to be done individually for each case.

4. **Resource and output specific with a potential for meaningful aggregation**

Within the sensibly chosen system boundaries, the indicators need to be directionally correct, i.e. improvements of the indicators demonstrate better process performance. All net flows of raw materials, energy, and products that cross the boundaries of the system under consideration have to be determined without aggregation. An exemplary list of streams and conversions is shown in Table 1.

**Table 1: Aspects to be considered during the definition of REIs on the basis of MFA and EFA**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Conversions/Mixing/Splitting</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>Chemical reactions (mass)</td>
<td>Products</td>
</tr>
<tr>
<td>Energies by source</td>
<td>Heat of reaction (energy ↔ mass)</td>
<td>By-products</td>
</tr>
<tr>
<td>Other: water, air</td>
<td>Combustion (energy ↔ mass)</td>
<td>Waste (liquid/solid/gas)</td>
</tr>
<tr>
<td></td>
<td>Stream splits, mixing (Imperfect) separations</td>
<td>Heat/Energy (losses)</td>
</tr>
</tbody>
</table>

Based on the material and energy flow analysis, process specific REIs should be defined with respect to the resources and the products:

\[
\text{REI}_{\text{RPS}} = \frac{\text{Resource Input}}{\text{Product Output}}
\]

Such a resource and product specific (RPS) REI by itself does not show whether the process is operated well. It has to be compared with historical or model data to evaluate the plant resource efficiency change. This data can be a baseline or – for optimal operation – the Best Demonstrated Practice (s. Section 7.2):

\[
\text{REI}_{\text{norm}} = \frac{\text{REI}_{\text{RPS}}}{\text{REI}_{\text{RPS,baseline}}} \quad \text{or} \quad \Delta \text{REI}_{\text{OIP}} = \text{REI}_{\text{RPS}} - \text{REI}_{\text{RPS,baseline}}
\]

This ratio or distance can be expressed as a percentage or in absolutes, for example a number of physical plant sections. A challenge in the application of such an analysis to chemical production complexes is the tree-like nature of the complex. Aggregation over product streams, plant hierarchy and tagged comparable plant sections is desirable.

5. **Considering storage effects**

To realize “real-time” capability, the choice of the temporal aggregation interval is crucial. The interval has to be short enough to derive operational decisions. Ideally a hold-up change (e.g. the level change in a surge tank or distillation column bottom) is considered in the consumption or production figures. Long-term effects such as catalyst degradation or fouling must either be used in the calculation period or be defined in a suitable manner.

6. **Including environmental impact**

The impact on the environment must be taken into account separately to measure the ecological performance. Emission of pollutants to air, water and soil can be used as separate indicators. For these separate indicators the other rules apply in the same manner but they should not be combined. In case multiple factors are evaluated, an overall environmental impact can be obtained by introducing a weighted sum, according to the individual impact, e.g., by using the global warming potential or CO₂ equivalents. [12]

7. **Hierarchy of indicators – from the whole production site to a single apparatus**

Production processes are interconnected and the production resources are typically organized hierarchically as shown in Figure 3. An REI for an individual equipment may be misleading because resource utilization can be shifted to other plants by different local operational policies. Generic resource efficiency indicators must be defined on a scale where the net effect on the resource efficiency can be measured through a bottom-up aggregation. The generic nature of these general indicators enables an aggregation for products, plants or complete production sites. Specific, often local, indicators for a specific piece of equipment that are equipment or
plant specific but cannot be aggregated can be introduced. Care must be taken to avoid false signals leading to attempts to improve the specific indicators at the expense of a worse overall performance.

Figure 3: Strategic level reflected by (generally aggregatable) generic indicators and plant specific indicators used on operational level

8. Extensible to life-cycle analysis

Applying the REIs might result in a trade-off between environmental impacts (e.g. the overall carbon footprint) and plant operations. This cannot be influenced by staff in real time (see principle 1). For reporting and assessment purposes, the REIs defined in this recommendation can be extended to a Life Cycle Assessment using the aggregation scheme and the evaluation of the feed streams with the relevant REIs as a weighting value. [13], [14]

7.2. Definition of the employed baseline

7.2.1. General

In this recommendation, Baseline is a defined state of the plant averaged over a specified period of time dependent on external factors.

This baseline can be the average of cleaned processed production data over a representative time period in stationary operation. The Best Demonstrated Practice (BDP) is defined as the desired state of the plant based on historical data. In case of batch production this BDP is normally the golden batch. The term Best Achievable Practice (BAP) is used if the optimal plant operation can be derived from a process model that is sophisticated enough to be used for extrapolation.

As this recommendation aims at achieving a more resource efficient plant state and historical data is typically available – in contrast to a process model – the derivations are performed for the BDP. If a plant model is available, the BAP can be used – the mathematics remain unchanged. If the plant can achieve the BAP, BDP and BAP should converge to the same value in the long run.

Two different types of factors which impact the baseline have to be distinguished:

- Influenceable factors that can be manipulated by the management or the operators and
- Non-influenceable factors that are independent from the decision maker.

Sometimes a differentiation is not easily possible. Examples for the factors are given in Table 2.
Table 2: Influenceable and non-influenceable factors on plant performance

<table>
<thead>
<tr>
<th>Influenceable</th>
<th>Non-influenceable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating point</td>
<td>Weather</td>
</tr>
<tr>
<td>e.g. Reflux ratio of a distillation column</td>
<td>Feedstock composition</td>
</tr>
<tr>
<td>Valve position</td>
<td>Feedstock quality</td>
</tr>
<tr>
<td>Operating procedures</td>
<td>Product mix</td>
</tr>
<tr>
<td>Day of week, weekend, shift</td>
<td>Plant Load</td>
</tr>
<tr>
<td></td>
<td>Cooling water temperature</td>
</tr>
<tr>
<td></td>
<td>Time and intensity of the last cleaning of the plant</td>
</tr>
<tr>
<td></td>
<td>Catalyst age</td>
</tr>
<tr>
<td></td>
<td>Heat exchanger fouling</td>
</tr>
<tr>
<td></td>
<td>Equipment age</td>
</tr>
</tbody>
</table>

If the concept of the recommendation is followed and these factors are removed, the resulting indicators fulfil section 4.4.3 “Energy Review” of the international standard ISO 50001:2011. [1]

Plant personnel can only change the plant performance by changing the factors they can influence. As such, the non-influenceable factors should be visualized by a changing baseline according to the factor, but not as room for improvement. Different people in a hierarchy have different capabilities of influencing a plant and thus their personal baseline might have different influenceable and non-influenceable factors. Table 3 illustrates this concept.

Table 3: Influencing factors dependent on plant hierarchy

<table>
<thead>
<tr>
<th>Organizational Plant Hierarchy</th>
<th>Degree of Freedom (influenceable)</th>
<th>Included in Baseline Function (non-influenceable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Management</td>
<td>Product mix/volume</td>
<td>External Influences, e.g. weather</td>
</tr>
<tr>
<td></td>
<td>Production plan(s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant loads</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Job/utility allocation(s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Process parameters</td>
<td></td>
</tr>
<tr>
<td>Plant Management</td>
<td>Production plan</td>
<td>External Influences</td>
</tr>
<tr>
<td></td>
<td>Job/utility allocation</td>
<td>Product mix/volume</td>
</tr>
<tr>
<td></td>
<td>Process parameters</td>
<td>Plant load</td>
</tr>
<tr>
<td>Plant Operator</td>
<td>Job/utility allocation</td>
<td>External Influences</td>
</tr>
<tr>
<td></td>
<td>Process parameters</td>
<td>Product mix/volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Production plan</td>
</tr>
</tbody>
</table>

A simplified representation of BDP baselines for the operators and for plant management is shown in Figure 4.
Figure 4: Different BDP baselines for different groups

7.2.2. Baseline and BDP function calculation

The user is free to implement a method of their choice for baseline and BDP curve identification. Here, a method of data classification is recommended as well as using quantile statistics to be robust against outliers. The following method can be used to identify either an average baseline or a BDP curve:

1. Define the REI under consideration.
2. Define the non-influenceable factors.
3. Remove outliers in all dimensional directions of the data, e.g. by using the 5- to 95-percentile. Three dimensions could be the non-influenceable factors “outside temperature”, “plant load” and the modelled factor “energy consumed per plant section of product”.
4. Divide the data into intervals according to the non-influenceable factors. In the above example this would be the outside temperature and the load. A starting point can be to split the data range into 10 equidistant intervals. For the baseline, use the median of the function data in each interval, for the BDP use the median of the best 10% of the values, where the percentage is a tuning factor of the method. The resulting data points are the set of representatives for the baseline regression.
5. Perform a regression of the representatives using a polynomial or any other function. The representatives of the intervals can be weighted using the standard deviation around the selected representative, when a fixed number of equidistant intervals is used.
6. If representatives are outliers in the regression, as shown abstractly in Figure 5, a method for outlier removal should be applied.
7.2.3. Using Baseline and BDP

The calculated baseline or BDP represents the average and best operation case under specific non-influenceable circumstances. The deviation of plant operation from the baseline indicates that the plant is operated differently; a deviation from the BDP shows the potential improvement in process performance by a change in operation.

If the aim of REI monitoring is to show the improvement potential in real time, reporting the distance from the BDP and the contribution of plants or equipment to this distance is recommended to allow plant operations to make the right changes to optimize operation. Figure 6 shows as the lower curve a varying BDP and the current operation as the upper curve. For the operator, it can be seen that both plant sections, reaction and distillation are not operated in the best demonstrated way.

Comparing current plant operation with an average baseline can be equally important. If the REI and REI monitoring are used for a management system and for reporting, comparing against an average baseline is a good choice to identify that process performance was improved and where it was improved.

8. Aspects of the Implementation of Real-Time REIs in Processing Plants

8.1. General

Successful implementation and usage of the real-time REIs is based on the following major points:

1. Selection of suitable REIs
2. Collection of the needed measurements
3. Defining a sensible plant structure
4. Implementation in a suitable software package
8.2. Typical REIs

This recommendation provides the concept and the tools to work with REIs. A selection of typical REIs that can be used easily for continuous (Table 4) and batch processes (Table 5) is provided.

Table 4: Examples of generic indicators for continuous processes

<table>
<thead>
<tr>
<th>Indicator Name</th>
<th>Catch Phrase</th>
<th>Formula</th>
<th>Measurements needed</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy required (ER)</td>
<td>Specific Energy Consumption</td>
<td>$ER = \frac{\sum_{i=1}^{n_E} C_E E_i}{\sum_{j=1}^{n_m} m_p,j}$</td>
<td>All energy inputs and outputs and all product streams</td>
<td>Can be separated into different energy types</td>
</tr>
<tr>
<td>Raw Material required</td>
<td>Specific Raw Material Consumption</td>
<td>$MR_i = \frac{m_{R,i}}{\sum_{j=1}^{n_m} m_p,j}$</td>
<td>The relevant raw material inputs and all product streams</td>
<td></td>
</tr>
<tr>
<td>Utilities required</td>
<td>Utilities/Raw Material required per plant section of product (air, water, DI-water)</td>
<td>$MR_i = \frac{U_i}{\sum_{j=1}^{n_m} m_p,j}$</td>
<td>The relevant utility and all product streams</td>
<td></td>
</tr>
<tr>
<td>Material Yield</td>
<td>Overall process yield based on mass flow, also &quot;mass conversion&quot;</td>
<td>$MY = \frac{\sum_{i=1}^{n_m} m_{R,i}}{\sum_{i=1}^{n_R} R_i}$</td>
<td>All raw material inputs and all product streams</td>
<td>Possibly also streams such as air must be considered, when the molecules end in the product</td>
</tr>
<tr>
<td>Overall resource yield</td>
<td>Overall process yield based on weighted flows</td>
<td>$ORY = \frac{\sum_{i=1}^{n_E} C_E m_{R,i} m_p,j + \sum_{i=1}^{n_R} C_E m_{E,i} E_{in}}{\sum_{i=1}^{n_R} C_E m_{R,i} R_i + \sum_{i=1}^{n_R} C_E m_{E,i} E_{in}}$</td>
<td>All energy inputs and outputs, all raw material inputs and all product streams</td>
<td>Depends very strongly on the chosen weighting which must be consistent</td>
</tr>
<tr>
<td>Overall Efficiency based on Resource Currency</td>
<td>Energy streams of a different nature are weighted by a resource currency added and provided production specific.</td>
<td>$OEEC = \frac{\sum_{i=1}^{n_E} C_E m_{R,i} U_j m_{j,k} - \sum_{i=1}^{n_R} C_E m_{E,i} E_{in}}{\sum_{i=1}^{n_R} C_E m_{R,i} R_i + \sum_{i=1}^{n_R} C_E m_{E,i} E_{in}}$</td>
<td>All energy inputs and outputs, all raw material inputs and all product streams, all utility streams</td>
<td></td>
</tr>
<tr>
<td>Waste</td>
<td>Mass of waste type per plant section of product</td>
<td>$W = \frac{\sum_{i=1}^{n_w} m_{W,i}}{\sum_{i=1}^{n_w} m_{W,i}}$</td>
<td>The relevant waste stream and all product streams</td>
<td></td>
</tr>
<tr>
<td>Overall weighted waste</td>
<td>Sum of waste weighted with &quot;waste currency&quot; per plant section of product</td>
<td>$OWNW = \frac{\sum_{i=1}^{n_w} m_{W,i} C_{W,i}}{\sum_{i=1}^{n_w} m_{W,i}}$</td>
<td>All waste streams and all product streams</td>
<td></td>
</tr>
</tbody>
</table>

For the formulae in the table, the following symbols are used:

- $E_i$ as energy inflows or outflows of type $i$ for an RMU,
- $m_{P,j}$ as mass of produced product of type $j$ for an RMU,
- $U_i$ as utility inflows or outflows of type $i$ for an RMU,
- $m_{R,j}$ as raw material import as of type $i$ for an RMU,
- $C_{L,i}$ as relevant weight of stream type $l$ (material or energy) ("Resource Currency") of Type $i$,
- $m_{W,i}$ as waste import or export of type $i$ for an RMU
- $C_{W,i}$ as relevant weight of waste stream ("Waste Currency") of type $i$. 


### Table 5: Examples of generic indicators for batch processes

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Abbreviation</th>
<th>Formula</th>
<th>Hierarchy level</th>
<th>Efficiency factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall resource efficiency</td>
<td>ORE&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Case-specific</td>
<td>Plant level</td>
<td>Case-specific</td>
</tr>
<tr>
<td>Total material efficiency</td>
<td>TME</td>
<td>( \frac{\sum m_p}{\sum m_{k,feed}} )</td>
<td>Batch level</td>
<td>Material</td>
</tr>
<tr>
<td>Material input</td>
<td>MI&lt;sub&gt;k&lt;/sub&gt;</td>
<td>( \frac{m_{k,in}}{m_p} )</td>
<td>Batch level</td>
<td>Material</td>
</tr>
<tr>
<td>Material efficiency</td>
<td>ME&lt;sub&gt;k&lt;/sub&gt;</td>
<td>( \frac{\sum m_{p,stoic,k}}{m_{k,in}} )</td>
<td>Batch level</td>
<td>Material</td>
</tr>
<tr>
<td>Material efficiency with recycle</td>
<td>ME&lt;sub&gt;recycle,k&lt;/sub&gt;</td>
<td>( \frac{\sum m_{p,stoic,k}}{m_{k,in} + (m_{k,recycle,in} - m_{k,recycle,out})} )</td>
<td>Batch level</td>
<td>Material</td>
</tr>
<tr>
<td>Total energy efficiency</td>
<td>TEE</td>
<td>( \left( \frac{1}{CEE} + \frac{1}{HEE} + \frac{1}{EEE} \right)^{-3} )</td>
<td>Batch level</td>
<td>Energy</td>
</tr>
<tr>
<td>Heat product</td>
<td>HP</td>
<td>( \frac{\sum_j Q_{gen,j}}{m_p} )</td>
<td>Batch level</td>
<td>Energy</td>
</tr>
<tr>
<td>Electrical energy efficiency</td>
<td>EEE</td>
<td>( \frac{\sum_j E_{el,used,j} - \sum_j W_{gen,j}}{m_p} )</td>
<td>Batch level</td>
<td>Energy</td>
</tr>
<tr>
<td>Cooling energy efficiency</td>
<td>CEE</td>
<td>( \frac{\sum_m W_{m,cool}}{m_p} )</td>
<td>Batch level</td>
<td>Energy</td>
</tr>
<tr>
<td>Heating Energy efficiency</td>
<td>HEE</td>
<td>( \sum_j Q_{kJ, j} - \sum_j Q_{gen,j} )</td>
<td>Batch level</td>
<td>Energy</td>
</tr>
<tr>
<td>Total waste production</td>
<td>TWP</td>
<td>( \frac{\sum_j m_{j,waste}}{m_p} )</td>
<td>Batch level</td>
<td>Environmental</td>
</tr>
<tr>
<td>Water usage</td>
<td>WU</td>
<td>( \frac{m_{water,in}}{m_p} )</td>
<td>Batch level</td>
<td>Environmental</td>
</tr>
<tr>
<td>Waste production</td>
<td>WP&lt;sub&gt;j&lt;/sub&gt;</td>
<td>( \frac{m_{j,waste}}{m_{product}} )</td>
<td>Batch level</td>
<td>Environmental</td>
</tr>
<tr>
<td>Total reaction efficiency</td>
<td>TRE</td>
<td>( \sum_k \frac{m_{p,react,k}}{m_{k,feed}} )</td>
<td>Phase level</td>
<td>Reaction</td>
</tr>
<tr>
<td>Reaction efficiency</td>
<td>RE&lt;sub&gt;k&lt;/sub&gt;</td>
<td>( \frac{\sum_p m_{p,react,k}}{m_{k,feed}} )</td>
<td>Phase level</td>
<td>Reaction</td>
</tr>
<tr>
<td>Separation yield</td>
<td>SY</td>
<td>( \frac{m_{C, resid} + m_{P, resid}}{m_{C,feed} + m_{P, resid,max}} ) s.t. ( m_{P, resid} \leq m_{P, resid,max} )</td>
<td>Phase level</td>
<td>Material</td>
</tr>
<tr>
<td>Purification energy efficiency</td>
<td>PEE</td>
<td>( \frac{\sum_j Q_{kJ,j} + \sum_j W_{el,j} + \sum_j W_{cool,j}}{m_p} )</td>
<td>Phase level</td>
<td>Energy</td>
</tr>
</tbody>
</table>
For the formulae in the table, the following symbols are used:

- $m_p$: mass of product in specification
- $m_{k,\text{in}}$: mass intake for resource $k$
- $m_{p,\text{preac.k}}$: stoichiometric mass equivalent of raw material $k$ in the formation of product $p$
- $m_{k,\text{recycle.in}}$: mass intake of raw material $k$ from recycle
- $m_{k,\text{recycle.out}}$: mass extraction from batch to recycle for raw material $k$
- $m_{W,j}$: mass of waste $j$
- $m_{k,\text{feed}}$: mass of raw material fed to reaction or purification stage of raw material $k$
- $m_{\text{water.in}}$: mass of consumed water
- $m_{C,\text{resid}}$: residual mass of valuable component $C$ in a batch evaporation (desired)
- $m_{W,\text{resid}}$: residual water content after batch evaporation
- $m_{W,\text{resid,max}}$: maximal permitted residual water content after batch evaporation
- $Q_{\text{gen,i}}$: generated heat $i$
- $Q_{\text{H,i}}$: heat consumption $i$
- $W_{\text{el,i}}$: electrical energy consumption $i$
- $W_{\text{gen,j}}$: generated electrical energy $j$
- $W_{\text{cool,m}}$: electrical energy consumed to supply cooling duty $m$

An exhaustive list of REIs can be found in the results of the EU-Project MORE\(^1\). This list can be explored according to the desired process and resource visualization as well as using a keyword search. For each REI, a standard information sheet exists. An example of such a sheet from the database is shown in Figure 7.

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\(^1\) [http://more.bci.tu-dortmund.de](http://more.bci.tu-dortmund.de) (accessed 11.4.2017)
8.3. Identifying and evaluating sensible REIs

A list of possible indicators, developed with respect to the explanatory notes given in Section 7, should be compiled using an iterative process and evaluated according to the following procedure:

1. **Preselection**

Select a set of promising indicators from the list of generic indicators. While a low number of indicators eases a subsequent comparison, a small number might not be able to cover all aspects of resource efficiency. It is essential to have a measurement concept for defining REIs (see below).

2. **Evaluation I**

The first evaluation must be based on a formal method with the aim to confirm or reduce the number of REIs that will be tried in practice. In this step it is important to check the basic facts. The MORE-RACER method provides such an approach. [11]

3. **Implementation**

The pre-selected indicators are then implemented and tested with real process data. An offline realization gives a feeling for the results and has the advantage of a low initial effort. An online implementation will immediately show the influence of operational decisions on the REI.

4. **Evaluation II**

The implementation is followed by a second evaluation using the same questions. The experience with the real process data will substantiate, and to some extend correct, the first evaluation.
5. Summary

In the last step all tested REIs are compared. All relevant aspects of resource efficiency should be covered by the indicators. If this is not the case, the compiled list of candidates should be screened again, keeping the shortcomings of the current trial set in mind (thus go to step 1 again).

The five point loop above is a classic implementation of a continuous improvement cycle as used in many international management system standards.

8.4. Measurement plan

8.4.1. General requirement of a measurement plan

In order to evaluate REIs correctly, a measurement plan is required. The measurement plan must show the path from the measurements used for the REI to the visualization of the REI. The measurement plan should contain the following specifications:

- Purpose of the used measurements – in this recommendation it is the desired REI
- Physical measurements used to reach the measurement purpose
- If measurements are missing they need to be replaced by adequate estimates or new measurements if economically viable. Two adequate estimation methods are data reconciliation [15] with parameter estimation or state estimation.
- The path of the measurements to the REI, including the electrical path through archives where required
- The measurement uncertainty
- Maintenance and calibration plan of the used measurement

It is recommended to structure this information and display it in diagrammatic form. This allows for an easy understanding and error propagation calculation. A good way to do this is a flowsheet that is described in the next subsection.


8.4.2. Flowsheet for Resource Efficiency Indicators

In order to understand the REI measurement, calculation and aggregation process within a production environment, existing norms offer “effect models” or flow sheets to provide insight and to analyse different areas of data acquisition and the entities participating in producing and providing this data to the REI calculation system [16]. This recommendation will not provide effect models for all REIs.

Figure 8 provides an example for the REI “material yield” for practical development of these models and for further enhancement by the reader. The model shows the hierarchical organization of the production under consideration together with the production plant and its sections. The organizational entities as well as the plants provide different data for calculation of the indicator that is aggregated to the final measure.

The example as depicted below offers key insight into the data aggregation process and the plants included in the required activities. As such, it delivers important options for error and failure detection and resolution in the data acquisition process.
8.5. Aggregation and contribution calculation

8.5.1. General

The evaluation of production processes by the use of indicators is commonplace. Besides financial KPIs, energy performance indicator (EnPI) according to ISO 50001 or environmental and safety indicators are widely spread in the process industry. Mostly, these indicators can be applied to any production plant and thus can be denoted as generic indicators. In addition, specific indicators are often used on a plant, section or equipment level. These are not appropriate for all production plants. Examples are reactor yields or the use of utilities for specific equipment.

Generic indicators are crucial to evaluate the process performance of an aggregated conglomerate of different types of plants. Only generic indicators allow the comparison of different plants through a consistent evaluation framework.

8.5.2. General considerations

Production complexes consist of interconnected and interdependent plants. Typical balancing volumes for physically based REIs are processing plants and adjacent auxiliary plants that are organized in sites, areas, plants, sections, and equipment. The principles of the “Equipment hierarchy” defined in IEC 62264-1 [6] are considered. These plant sections are called “Resource Managed Plant sections (RMU)”. The concepts introduced in this section are specified for continuous production processes but can also be applied to batch or batch-continuous production processes. When applying the concepts to batch, dynamic models with respect to the batch times of the production steps are necessary or the evaluation period has to be increased (interval time ≥ batch time) to avoid incomprehensive or misleading results during a batch. In Section 10 examples of the application for both, continuous and batch processes are presented.
8.5.3. Resource Managed Plant sections

The hierarchy in Figure 3 can be described using balancing volumes. According to the normative standard IEC/TR 62837 [17], where system boundaries are represented as so-called “Energy Managed Plant sections” (EMU), the balancing volume boundaries are called “Resource Managed Plant sections” (RMU) (see Figure 9). They can represent internal plants or other sensible sections. Based on the site or plant specific resource flow model, REI calculations can be done and it is possible to automatically generate suitable displays to visualize REIs using dashboards.

Each RMU can consist of several embedded RMUs. In this case, the above general principles are valid for all RMUs on their relevant hierarchical level.

![Figure 9: The concept of resource managed plant sections (RMU)](image)

REIs can either be defined to assess the efficiency of a RMU or a product stream. For the RMU based view REIs express the efficiency of the transformation from inputs to outputs regardless of the efficiency of the consumed intermediates and raw materials. For the product based view, each stream has an REI attached that provides information needed to calculate the REI of the target product. The product based view allows for a gate-to-gate analysis and can be extended to a life cycle analysis of products with additional upstream and downstream information.

8.5.4. Generic aggregation concept for REIs

This section provides general principles how to aggregate REIs and how to calculate the contribution of each plant section to the aggregated REIs. To consistently aggregate REIs the following aspects are important:

- The hierarchy structure must be guided by the physical site structure, disregarding the organizational structure.
- The hierarchy is used to automatically aggregate the generic REI from the lowest defined hierarchy level upward. This is called a “bottom-up” approach and requires all plant sections to be fully defined, i.e. the mass and energy balance for the defined plant sections or sections on the lowest level must be closed for all significant process streams.
- If the definition of the REI on different hierarchical layers is inconsistent, they cannot be aggregated automatically.
- Additionally, plants can be individually grouped and REI aggregation and contribution calculations can be conducted for generic indicators (Integrated MFA/EFA). Plants of one type or all plants of one business plant section can be analysed.
- REIs can only be aggregated if they are calculated on the basis of the same data collection and potentially data reconciliation approach, whereby all aggregated data must follow the same time model (e.g. minute, hour or production shift, cf. ISO 22400-2 [16])
8.5.5. Bottom-Up aggregation concept for generic indicators

A lumped indicator over the entire site complex does not provide information regarding the performance of single production steps and the possible root cause of a performance deviation. A consequent use of the bottom-up approach and a propagation of low level information to the next levels provides these missing links. Closing the mass and energy balance for all relevant flows on the lowest aggregation level is mandatory to achieve meaningful results on higher levels. Since for most production plants, this is difficult on an equipment level due to missing measurements, the plant section level is recommended. An example for a possible aggregation structure is given in Figure 3.

The evaluation of the performance on a plant section level allows a deeper insight into the process. The BDP and baseline can be calculated on each RMU on the lowest level. The parallel aggregation of performance and BDP results in conclusive findings on higher levels without any additional effort.

Applying the calculation method of Section 6 for a generic REI

\[
\text{REI} = \frac{\text{Resource Input}}{\text{Product Output}} = \frac{\sum_{i=1}^{n} R_i}{\sum_{j=1}^{m} P_{j,\text{out}}}
\]

assuming a closed mass and energy balance, using an aggregation concept of this REI on the lowest level leads to the same result as calculating the REI directly on the highest level:

\[
\text{REI} = \frac{\sum_{i=1}^{n} R_i}{\sum_{j=1}^{m} P_{j,\text{out}}} = \frac{\sum_{k=1}^{p} \text{REI}_k P_k}{\sum_{j=1}^{m} P_{j,\text{out}}}
\]

where \(\text{REI}_k\) denotes the REI of the plant section \(k\) and \(P_k\) the total product flow from plant section \(k\). These product streams either can be either product streams of the aggregated plant section, thus included in the flows leaving the balancing domain \(P_{j,\text{out}}\) or be an intermediate product to be processed in one of the other plant sections. According to this concept, the BDP (cf. Section 7.2) can be aggregated by

\[
\text{BDP} = \frac{\sum_{k=1}^{p} \text{BDP}_k P_k}{\sum_{j=1}^{m} P_{j,\text{out}}}
\]

where \(\text{BDP}_k\) denotes the best achievable practise of plant section \(k\).

As a consequence, applying this concept to each aggregation level leads to consistent results respecting the individual characteristic for each lowest level plant section. Comparing the performance on higher levels with the aggregated BDP is providing more significant results than comparing to an arbitrarily defined high level BDP.

8.5.6. Limitations of the concept

The initial evaluation of each RMU on the lowest level is performed based on energy and mass flow analysis. Thereby, the resource flows might be weighted by currencies as previously introduced to account for a diverse significance. The REI evolved from this analysis contains resource information without a distinction of different sources. Given the example in Figure 10 and neglecting weighting factors, the REIs of RMU1 and RMU2 are computed by

\[
\text{REI}_i = \frac{R_i}{P_i} \quad \forall \ i \in \{1,2\}
\]

The aggregated REI is computed by:

\[
\text{REI} = \frac{\text{REI}_1 P_1 + \text{REI}_2 P_2}{P_{1,\text{out}} + P_{2,\text{out}}}
\]

This calculation is correct for the left hand side of Figure 10 but for the right hand side, the use of product \(P_1\) as resource flow \(R_2\) results in incorrect results since the resource flow \(R_2\) is accounted for twice: Firstly, for its production by the use of \(R_1\) and secondly by \(\text{REI}_2\):

\[
\text{REI} = \frac{\text{REI}_1 P_1 + \text{REI}_2 P_2}{P_{2,\text{out}}} = \frac{R_1 + R_2}{P_{2,\text{out}}} \neq \frac{R_1}{P_{2,\text{out}}}
\]

To avoid this aggregation problem, internal product streams which were used to evaluate the performance of the low level RMUs have to be subtracted, resulting in:
In the given example, $P_1 = R_2$ since no weighting factor was introduced for $R_2$. The resource flow $R_2$ has to be subtracted rather than product flow $P_1$ since the initial evaluation of REI$_2$ and BDP$_2$ might be based on assumptions regarding a resource weight, resulting in the possible conflict $P_1 \neq R_2$.

For integrated processes with weighting factors for resource flows, the above aggregation concept has to be extended:

$$\text{REI} = \frac{\sum_{i=1}^{n} P_i}{\sum_{j=1}^{m} P_j} = \frac{\sum_{k=1}^{P} \text{REI}_k P_k - R C_k P_{k, \text{int}}}{\sum_{j=1}^{m} P_j}, \quad \text{with} \quad R C_k = \frac{\sum_{j=1}^{m} P_j}{\sum_{j=1}^{m} P_j},$$

$$\text{BDP} = \frac{\sum_{k=1}^{P} \text{BDP}_k P_k - R C_k P_{k, \text{int}}}{\sum_{j=1}^{m} P_j}, \quad \text{without} \quad \sum_{j=1}^{m} P_j$$

where $P_{k, \text{int}}$ denotes an intermediate product flow and $R C_k$ the weighting factor for plant section $k$. Thereby the weighting factor corresponds to the value used for the initial evaluation of the subsequent process plant sections. A similar approach is necessary when dealing with energy flows from different sources.

**Figure 10: Exemplary abstract process**

Tanks and batch processes pose another challenge for aggregating REIs. A real-time REI for these streams with the same definition as for continuous processes is not sufficient. Integration of tanks and batch processes can be achieved by integrating the resource inputs and product outputs of a process over time to obtain a useful figure for all downstream processes. In batch cases, the batch time determines a time lag between the first usage of resources and the evaluation of the product. This leads to inconsistent data regarding the currently measured use of resources and the production rate. The aggregation concept can only be applied for reporting intervals higher than the batch time. Nevertheless, the individual evaluation of lower levels (such as plant sections or equipment) remains unharmed by this restriction.

8.5.7. Specific vs. generic indicators

Besides the generic aggregation based on a predefined hierarchy, the aggregation of different plants or pieces of equipment might be interesting, e.g. all compressors of a site. The above concept allows the aggregation of plant sections of different plants by creating a new balancing domain.

Specific indicators which may only apply to plant sections of a certain type, e.g. distillation columns or reactors, can be aggregated automatically throughout one production. If the generic aggregation concept was applied to these plant sections, an additional evaluation is not necessary. This reduces the computation effort and leads to consistent indicators even for specific equipment aggregations.

The restrictions to batch processes and tanks mentioned remain for specific indicators and balancing volumes.

8.5.8. REIs along the site or plant hierarchy – contribution calculation

Figure 3 shows a typical site and plant hierarchy. Resource efficiency indicators are typically calculated on a site and plant level, sometimes also in a section level. Generic indicators on higher level, if a proper EFA/MFA approach is used, result from aggregated lower level performance evaluations. Measurements placed at the balancing boundary can then be used to confirm the aggregation and to detect errors in the lower level measurements. Data-reconciliation techniques are recommended for this purpose.

Contribution analysis is a method that draws the attention of the operator to the strongest influences of a significant REI change and allocates them to the respective lower level process plant section. Thus, the operator is able to quickly identify the root cause of inefficient production states and interfere with a short reaction time.

Assuming the REI are the result of a function of measurements, the following method can be used:

1. Identify relevant influence factors on the process performance and BDP
2. Identify a performance model with respect to all relevant influence factors
3. Calculate the current performance and compare it with the BDP
4. Identify the root-cause of performance deviations

The first and second step is part of Section 7.2. The third step compares the current performance of each RMU with an estimated BDP:

\[ \Delta \text{REI}_i = \text{REI}_i(x_c) - \text{BDP}_i(x_p) \]

where \( x_c \) denotes the current state vector and \( x_p \) the planned state vector. Evaluating this term at comparison state similar to current state, \( \Delta \text{REI}_i \) expresses the performance loss based on a sub-optimal operation.

Evaluating this performance gap for each lower level plant section and aggregating the results, the total performance deviation is given by

\[ \Delta \text{REI}_{OIP} = \sum_{i=1}^{n} \Delta \text{REI}_i \frac{P_i}{\sum_{j=1}^{m} P_{j,ext}}, \]

where \( C_i = \frac{\Delta \text{REI}_i P_i}{\sum_{j=1}^{m} P_{j,ext}} \)

By evaluating the \( C_i \) values, the contribution and root-cause to the total REI deviation can be determined. The influence of noisy measurements can be handled by using data treatment techniques and error propagation to identify the correlation to the indicators.

Besides the evaluation of the performance gap, the user may be interested in the impact of a change in one of the BDP influence factors. As long as the influence factors are independent in the BDP model, the contribution can be computed directly by evaluating the deviations in the BDP curve.

\[ \Delta \text{BDP}_i(Ax) = \text{BDP}_i(x_c) - \text{BDP}_i(x_E) = \sum_{k=1}^{n} \Delta \text{BDP}_{ik} = \Delta \text{BDP}_p \]

where \( \Delta \text{BDP}_{ik} \) denotes the deviation in \( \text{BDP}_i \) based on a deviation in influence factor \( k \). \( \Delta \text{BDP}_p \) is the total BDP deviation based on changes in BDP influence factors. The contribution can be calculated analogously:

\[ C_{ik} = \frac{\Delta \text{BDP}_{ik} P_i}{\sum_{j=1}^{m} P_{j,ext}} \]

More complicated are influence factors which have a non-linear impact on the process performance. One obvious representative is the plant load. Due to the non-linearity of the problem, the allocation of contributions to the flow rate changes is difficult. One approach to tackle this problem is the exploitation of the total differential for the BDP and a subsequent mathematical transformation which makes the linearized and the lumped solution consistent. It can be shown [18], that the REIs change induced by a change of the product mix of the production complex \( \Delta \text{BDP}_L \) is given by

\[ \Delta \text{BDP}_L = \sum_j \frac{\text{BDP}_{j,RC}^P}{\sum_k P_{k,ext}^C} \Delta P_{j,int} + \sum_j \frac{\text{BDP}_{j,RC}^P}{\sum_k P_{k,ext}^C} \Delta P_{j,ext} \]

where the first term represents BDP changes induced by a change in internal product flows and the second term a change in external product flows.

The evaluation method results in three different types of contribution: One is the representation of deviations based on internal or external product flow changes at a constant BDP for all plant sections \( \Delta \text{BDP}_L \), one is the contribution of BDP influence factors on the performance at the current product flow mixture \( \Delta \text{BDP}_p \) and the third is the performance gap which represents the distance from the current operation to the BDP at the current operation point \( \Delta \text{REI}_{OIP} \). Consequently, the REI of an aggregated production complex \( \Delta \text{REI}_C \) is given by

\[ \text{REI}_C = \frac{\sum_i R_i}{\sum_k P_{k,ext}} = \text{BDP}_p + \Delta \text{BDP}_L + \Delta \text{BDP}_p + \Delta \text{REI}_{OIP} \]

where \( \text{BDP}_p \) denotes the planned BDP and \( \text{REI}_C \) the current REI. Further information on the mathematical representation and the application of the concept can be found in [18].
9. Practical Implementation and Minimal Automation and Software Requirements

9.1. Implementation path

Implementation of REI monitoring can be performed step-by-step. This section provides a recommended implementation path for the practitioner. Additional guidelines for implementation providing information beyond automation can be found in the guidebook published by the MORE project [19].

Step 1: Identification of sensible REIs

After familiarization with the principles for REIs, listed in Section 7.1, a team of experts selects a set of potential REIs using the methods from section 8.3. Evaluation should be carried out for all identified potential REIs involving experts from the plant, operational personnel, energy experts and environmental experts.

Step 2: Measurement plan

In this step the available and missing measurements for calculating the identified REIs are identified. Based on this identification, a measurement plan as described in section 8.4 is set up. The accuracy of the measurements, the sampling frequency and the availability in the automation systems are important factors. Missing measurements and the possible application of filtering and data reconciliation have to be evaluated.

Step 3: Stationarity

The computation of real-time resource efficiency indicators will often involve time-varying data, while, in principle, valid resource efficiency indicators for continuous plants require a steady state. Such a plant-wide steady state hardly ever exists. This needs to be dealt with using sensible temporal aggregation or dynamic data reconciliation (state estimation) if necessary. If such an approach is not possible, the user of the REIs needs to be made aware, when the displayed value is not reliable using charts of indicator development. The dynamic behaviour of batch applications require advanced considerations that are outlined in section 10.2.

Step 4: Baseline and BDP definition

Baselines and BDP need to be calculated for each identified REI in each lowest level of aggregation as described in section 7.2.2. This part will take considerable time and judgement and needs to be performed accurately as it forms the basis of real-time improvement of plant operation. The baseline needs to be adjusted once the BDP or the plant itself has been improved.

Step 5: Calculation and aggregation of REIs

According the desired level of information and the considered plant hierarchy, the REIs are calculated for the lowest possible plant sections in the hierarchy. These plant sections must fully describe the higher level for the aggregation to work. The methods in Section 8.5 must be used to calculate the REIs of the lowest plant sections and to aggregate the REIs to the next levels. The concept automatically provides the contributions of the lower levels to the upper levels and the contribution of the identified factors (cf. Section 7.2).

Step 6: Visualization

In a final step that is not included in this recommendation, the results must be visualized in the most efficient way to limit the additional cognitive load for the user. Examples for visualization concepts can be found in the literature [7], [21] and in deliverable 1.4 of the MORE project [20].

9.2. Practical concerns for REIs in automation systems

According to the normative standard IEC 62264-1 [6], production-oriented IT systems are classified into four different functional levels. REI data should be considered at all these system levels. The system oriented view to these four levels should not to be mistaken with the site or plant hierarchy which was specified to describe the aggregation levels (s. section 7.1). In this recommendation it is generally assumed that relevant process data is available on all levels.

The levels differ in functions and typical time frames. In addition, each functional level targets specific user groups:

Level 1: Sensors and Actuators

Based on modern communication technologies and “intelligent devices” basic REIs or at least basic parameters to calculate REIs in upper plant levels can be calculated directly on level 1. REIs of level 1 would repre-
sent e.g., efficiency factors of the equipment itself. An example of such information is the knowledge of the operating point of a pump. Using internal sensors and embedded logic control, the pump system can calculate the current and the most efficiency operating point.

**Level 2: DCS, PLC**

The material and energy efficiency of chemical production processes is strongly influenced by the control algorithms and operational decisions that are made on level 2 during daily production. Real-time REIs as a base for decision support or as an input parameter for open loop or closed loop control strategies (e.g., model predictive controller) and also for optimization methods can be used to immediately increase the resource efficiency of process plants.

**Level 3: PIMS, MES**

Couplings due to stoichiometry, heat integration and recycle streams cause a high degree of integration between different plants and plant sections. The consequences are causal relationships and trade-offs beyond the performance of a single plant section that are not always obvious to the operators and to the control strategies on level 2. For instance, a locally optimized plant section in plant “A” can cause a high energy demand of plant “B” due to heat integration and can subsequently result in a sub-optimal state of the overall production site. Therefore IT-systems of level 3 (e.g., MES, PIMS) can be used to visualize REIs to a broader group of users and to coordinate several plant control strategies. PIMS and MES can offer a suitable basis to calculate REIs base lines which may change dynamically with the current plant or operating mode. They can also be used as a data platform to calculate REIs or at least to offer historical or real-time data which can be read by external systems in order to calculate and visualize REIs.

**Level 4: ERP, SCM**

Enterprise Resource Planning and Supply Chain Management Systems will be used to provide plant scheduling methods and material management features. In most plants of the process industries, the resource efficiency of the production depends critically on discrete decisions on the use of equipment, shutdowns, product changeovers and cleaning or regeneration of equipment. Using systems on level 4 these discrete decisions can be considered in plant-wide dynamic optimization and plant or site wide scheduling and control solutions. Based on the detection of anomalies fast re-scheduling and re-optimization can be triggered.

The leading systems for real-time REI calculations are PIMS, MES and ERP systems. Each real-time REI can also be used for recording and for historical analysis usable in reports. If REIs will be used in historical analysis it is important, that not time-averaged REI data but raw data will be used for calculations.

For more complex and holistic resource efficiency applications such as site wide approaches it is indispensible that the resource flow structure be modelled to give all data a clear and unambiguous context. A resource flow model should describe amongst others:

- the different categories and types of resource flows
- the target and source RMU of the resource flows and
- a set of properties of each resource flow or RMU including master data, calculation methods, URIs to specify the data source of measurements and also constraints which can be used for balancing or data reconciliation.

A system to implement such an information model can be used as an Add-On to common PIMS or MES solutions.

### 10. Examples

**10.1. Generic continuous integrated chemical production site**

The application of the above introduced principles and approaches is exemplarily applied to an integrated production site with common energy and product networks (cf. Figure 11).
The site to be modelled consists of five plants (A1-A5). All plants produce at least one product (black flows). The products are either used in other production plants or sold to the market outside the balancing domain. The plants consume from different resources (R1, R2) or energy sources (E1-E5, ENet). In the following, the EnPI of the complex is used as top level indicator to evaluate the process performance. The balance for the production complex is indicated with the dashed frame which covers principle 1 from Section 7.1.

The EnPI divides the energy consumption by the production of the plants which leave the balancing domain. This indicator relates to physical flows. Thus, the indicator is independent from market conditions and fulfils principle 2 and 3 from Section 7.1. The fourth principle is covered by the definition of the model.

Storage effects are not considered in the demonstration case. Since the lowest abstraction level is the section level, principle 7 holds. The BDP of the plants is assumed to be constant which means there are no relevant factors influencing the individual process performance. The possible impact of influence factors on the performance is shown in Section 10.3.

The aggregated EnPI can be computed as introduced in Section 8.5, the deviation of the performance from the BDP according to Section 8.5.8. The production plant A1 adapts the production rate by firstly increasing the energy demand and afterwards increase the product flow P1 which leaves the balancing domain. Afterwards production plant A2 increases its energy demand and then increases the production rate P2. This process change is visualized in Figure 12. As the energy demand increases prior the production rate adaption, the transition results in a performance loss for plant A1. After the transition, the energy intensity deteriorates to its previous level. The performance arc for plant A2 is similar and timely shifted. The assumption, that a performance loss in one of the plants induces a performance loss for the aggregated complex is obvious. The likely assumption that the improvement of the performance of the plants to the previous level results in a performance of the complex on the prior level in this case is wrong, as Figure 14 visualizes. As the production out of the balancing domain are part of the denominator and the enumerator, the influence on the aggregated indicator can either point up- or downwards based on the individual performances of the plants and the current product mix. Therefore, the parallel computation of BDP and performance for an aggregated complex is helpful to unravel performance evolution under changing process conditions. Applying the aggregation concept to the indicators in Figure 14, the deviation in the performance after the transition can be interpreted as a result of a different product mix from first to last time step since the EnPI has approximately the same distance from the baseline. Nevertheless, this representation contains only information about the complex as a whole, the root-cause of the deviation during the transitions is not visible. Therefore, the contribution analysis introduced in section 8.5 can be applied (cf. Figure 15). The analysis clearly identifies plants A1 and A2 as the root-cause for the performance deviations. The other plants contribute slightly to the performance loss. In this exemplary case, a dynamic production adaption was evaluated which is likely to be accompanied with performance loss-
es compared to stationary operation which in many cases is known and accepted. However, this concept also identifies performance losses in stationary processes where an improvement by plant personnel intervention is realisable.

Figure 12: Energy and production rate of P1 and P2 over time

Figure 13: Energy performance and corresponding baselines for A1 and A2 over time
Figure 14: EnPI and Baseline for the production complex

Figure 15: Performance deviation contribution of the plants

10.2. Sugar plant

10.2.1. Introduction

The considered factory produces food grade sugar from the juice of sugar beets by evaporation and crystallization (see Figure 16 below).[7], [21], [24]

In the first section the fresh juice passes through a cascade of three evaporators and is continuously concentrated by the removal of excess water. Subsequently, the concentrated juice is transferred into the melter, where it is blended with recycle streams that are also rich in sugar content. The melter is a continuously stirred vessel that blends the materials to feed them back into the batch-wise operated crystallizers. The suspended crystals from all crystallizer plant sections are collected and either recycled to the melter or converted to the product stream (sugar). Within the recovery section the waste molasses stream is necessary to purge the system, deteriorating the material efficiency.

The only relevant ingoing energy stream is the external steam supply to the evaporator section. The crystallizers are heated with excess steam, from the evaporator section, that consists of the evaporated water from the
juice. Steam that is not directly used will be vented. The energy integration from effect to effect is possible be-
cause of the increasing vacuum from effect to effect, making the separation less and less energy demanding.

Figure 16: Flowsheet of a production facility for food grade sugar from sugar beets (juice).

The environmental performance of the process is influenced by the water consumption and the amount of
waste material produced. In this process, water is used to wash the sugar crystals during the centrifugation
step of the crystallizer section as well as in the recovery section. The only waste stream is the waste molas-
ses.

10.2.2. Resource efficiency evaluation of the plant

The first step of the analysis is to identify the influences that have an effect on the resource efficiency:

- This process does not involve any chemical reaction. Thus, the performance of the crystallization pro-
  cess and the subsequent centrifugation is the main influence on the material efficiency. Generally, the
  material efficiency improves if more sugar from the raw material ends up in the product stream instead of
  the waste molasses.

- The energy efficiency of the plant is directly affected by the consumption of fresh steam in the evaporator
  section. Due to the energy integration between the evaporator section and the crystallizers the efficiency of
  the processing within the other stages also effects the necessary intake of fresh steam, i.e. a good separation
  yield towards the product stream within the crystallizer section reduces the recycle streams and thus the amount
  of material that needs to be reprocessed. This effectively reduces the energy demand. Furthermore, the set-
  point for sugar concentration after the first stage can be used to shift evaporation load from the evaporators
  to the crystallizers.

- The environmental performance of this process depends on the water usage and the production of waste. Thus, a small waste stream and low water intake per product is beneficial.
The relevant indicators describing all aspects of the resource efficiency are listed below. The energy efficiency of the heating processes is measured with the $\text{HEE}_{\text{evaporator}}$ for the evaporation section and $\text{HEE}_{\text{crystallizer},i}$ for all crystallizer $i$. 

$$\text{HEE}_{\text{evaporator}} = \frac{m_{\text{sugar}}}{Q_{\text{H,steam}} - (\sum_{i} Q_{\text{generated},1,i} + Q_{\text{generated},2,i})} \quad \forall \ i = 1,2,3$$

$$\text{HEE}_{\text{crystallizer},i} = \frac{m_{\text{sugar}}}{Q_{\text{generated},1,i} + Q_{\text{generated},2,i}} \quad \forall \ i = 1,2,3$$

Energy is introduced into the process at the evaporator section as steam $Q_{\text{H,steam}}$. The heating of the crystallizers is supplied with excess heat from the evaporator section ($Q_{\text{generated},1}$ and $Q_{\text{generated},2}$). 

$$\text{CEE}_{\text{evaporator}} = \frac{m_{\text{sugar}}}{W_{\text{cool,condenser}}}$$

$$\text{CEE}_{\text{crystallizer},i} = \frac{m_{\text{sugar}}}{W_{\text{cool,condenser},i}} \quad \forall \ i = 1,2,3$$

Contributions to the cooling energy efficiency are considered at the condenser of the evaporator section ($\text{CEE}_{\text{evaporator}}$) and at each of the crystallizers ($\text{CEE}_{\text{crystallizer},i}$) to condense the steam produced during the crystallization process.

$$\text{ME}_{\text{sugar}} = \text{MI}_{\text{sugar}} = \frac{m_{\text{in,sugar}}}{m_{\text{product,sugar}}}$$

Despite the fact that no reaction occurs, the material efficiency $\text{ME}_{\text{sugar}}$ relates the sugar in the juice that is fed to the process to the amount solid sugar crystals exported from the crystallizer section.

$$\text{WU} = \frac{m_{\text{water,in}}}{m_{\text{sugar}}}$$

The water usage indicator WU captures the amount of water used by the process in the centrifuge of the crystallizer section and in the recovery section. The waste production indicator $\text{WP}_{\text{molasse}}$ that relates the amount of product that is lost in waste streams to the total sugar input. WU and $\text{WP}_{\text{molasse}}$ capture the environmental impact of the process.

$$\text{WP}_{\text{molasse}} = \frac{m_{\text{waste,molasse}}}{m_{\text{sugar}}}$$

10.2.3. Dynamic system behaviour and storage effects

The continuously operated evaporation section is energetically integrated with the crystallizers in the crystallization section, which are operated batch-wise. This results in an ongoing dynamic behaviour of the evaporation section. In order to describe the resource efficiency of this section, it is necessary to evaluate the time...
constant of the considered section. If it is adequately short, the entire section can be regarded as one RMU without the need to analyse the efficiency of each effect individually. Thus, the corresponding efficiencies can be calculated from the inputs and outputs of the section by averaging the measurements over periods that are longer than the systems time constant.

In order to adequately describe the resource efficiency of the key production step within the batch-wise operated crystallizers it is necessary to model the buffer tanks between the crystallizers and the rest of the plant. This is realized by introducing a pseudo state “resource load” per mass of product contained within the buffer.

![Diagram of Buffer Tank]

**Figure 18: Buffer tank between batch-wise and continuously operated plant sections**

The calculation of the dynamic resource load is based on the total mass balance (Eq. 32) and mass balance of the product (Eq. 33). The influx of material \( \dot{m}_n \) from batch \( n \) is calculated from the total mass of the batch and the estimated or measured transfer time. The mass fraction \( \omega_n \) must be known for each batch, either from measurements or a model based estimation.

\[
\frac{dm}{dt} = (\sum_n \dot{m}_n) - \dot{m}_{out} \quad (32)
\]

\[
\frac{dmp}{dt} = (\sum_n \dot{m}_n \omega_n) - \dot{m}_{out} \frac{m_p}{m} \quad (33)
\]

The resource consumption that is “carried” by an element of product material is introduced as an additional state variable. The differential equation for a product specific resource utilization \( r_k \) can then be derived from the balance for the resource consumption state \( m_{cons} \) that reflects the upstream consumption of a resource \( k \):

\[
\frac{dm_{cons}}{dt} = \frac{d(mp_r k)}{dt} = r_k \frac{dm_p}{dt} + m_p \frac{dr_k}{dt} \quad (34)
\]

Substitution of Equation (33) into (34) and solving for \( dr_k/dt \) yields Equation (35).

\[
\frac{dr_k}{dt} = \sum_n \frac{m_n \omega_n}{m_p} (r_{k,in,n} - r_k) \quad (35)
\]

The inlet flowrates \( \dot{m}_n \) are assumed to be constant and are defined by total amount \( m_n \) and the arrival times \( t_{start,n} \) and \( t_{end,n} \) (see Equation (36)).

\[
\dot{m}_n(t) = \begin{cases} 
0, & t < t_{start,n} \\
\frac{m_n}{(t_{end,n} - t_{start,n})}, & t_{start,n} \leq t \leq t_{end,n} \\
0, & t > t_{end,n} 
\end{cases} \quad (36)
\]

The multiplication of the current resource load with the outgoing stream of product yields the amount of consumed resource per product that can be used to calculate the efficiency of the stream.

In case of the transition from a continuous section into batch operation, the total resource consumption associated with the new batch \( n \) can be computed by the integral shown in Equation (37).

\[
r_{k,n} = \int_{t_{start,n}}^{t_{end,n}} \dot{m}_{p,out}(t) \ r_k(t) \ dt \quad (37)
\]

Thus, the product specific resource utilization \( r_k \) is described for all (intermediate-)product streams and can be used to calculate REIs for all RMU of interest.
10.3. Acrylonitrile plant INEOS

Resource efficiency indicators and the presented concepts were applied to the acrylonitrile plants at INEOS in Köln. The plants consume Ammonia and Propylene as major feedstock and produce Acrylonitrile. Ambient air is compressed and utilized in the reactors. A chain of distillation columns purifies the product afterwards. The reaction is exothermal, thus in the reactor section steam is produced which is subsequently utilized as power supply in the turbines or as heat source for the distillation part of the plants. The steam production usually overshoots the demand and steam is exported to the steam grid of the site. A principle sketch in Figure 19 visualizes the dependencies of the plants. Feedstock flows are indicated in green, energy flows on 5bar and 30bar in red, intermediate products in orange and product flows in black. Process plant sections are indicated as black boxes, networks and tanks as circles. The different balancing domains are indicated with dashed and dotted boxes.

![Figure 19: Sketch of the two AN plants of INEOS in Köln and different balancing domains](image)

The energy performance, the product yield and the utility consumption were identified as the relevant indicators to evaluate the process performance. Whereas product yield and utility consumption have a fixed target value, the energy performance of the processes significantly fluctuates with the setup of air compressors in operation and the load of the two plants. Since both plants exchange intermediate product flows prior the distillation parts, a fragmentation of the plants in reaction, distillation and air compressor parts is necessary.

The flow rate of the air compressors is not controllable and the number of compressors in operation is determined by the air demand of the plants. Thus, there is no operational energy saving potential for the compressors and the BDP is assumed to reflect the current operation point.

As a consequence, only the BDP models for the reaction and distillation parts of the plants are identified following the proposed approach in Section 7.2. The results of the BDP identification for one distillation section are visualized in Figure 20.
Figure 20: BDP identification of the EnPI of an AN distillation part

Based on these results, the aggregation and contribution analysis from Section 8.5 were implemented in an integrated deployment platform (cf. Section 9). This platform is connected to the site PIMS which allows calculations with real-time and historical data. The results are visualized on a dashboard which is site-wide available within the INEOS Köln intranet. One view regarding the energy performance is given in Figure 21.

Figure 21: Energy performance dashboard for one AN plant

11. Literature


