TECHNOLOGY • RESEARCH HIGHLIGHTS • VISIONS • SCIENCE

290

Successful Resource Efficiency Indicators for process industries

Step-by-step guidebook

Marjukka Kujanpää | Juha Hakala | Tiina Pajula | Benedikt Beisheim | Stefan Krämer | Daniel Ackerschott | Marc Kalliski | Sebastian Engell | Udo Enste | José L. Pitarch

VTT

VTT TECHNOLOGY 290

Successful Resource Efficiency Indicators for process industries

Step-by-step guidebook

Marjukka Kujanpää, Juha Hakala & Tiina Pajula

VTT Technical Research Centre of Finland Ltd

Benedikt Beisheim & Stefan Krämer

INEOS Köln GmbH

Daniel Ackerschott, Marc Kalliski & Sebastian Engell

Technische Universität Dortmund

Udo Enste

Leikon GmbH

José L. Pitarch

Universidad de Valladolid

RESOURCE EFFICIENCY FOR EUROPE

The MORE Project is supported by the European Commission under the FP7 programme (contract 604068).

ISBN 978-951-38-8517-5 (URL: http://www.vttresearch.com/impact/publications)

VTT Technology 290

ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8517-5

JULKAISIJA – UTGIVARE – PUBLISHER

Teknologian tutkimuskeskus VTT Oy
PL 1000 (Tekniikantie 4 A, Espoo)
02044 VTT
Puh. 020 722 111, faksi 020 722 7001

Teknologiska forskningscentralen VTT Ab
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland Ltd
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

Preface

This guidebook is generated by the EU-funded R&D project “Real-time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants” (MORE). The report summarizes the best practice for REI identification and implementation based on the lessons learned during the project. The authors would like to thank all partners of the MORE project for their input and valuable contributions when preparing the concept for a successful selection process of REIs.

Contents

Appendices

List of figures

List of tables

Glossary

APC	Advanced Process Control
BAP	Best Achievable Practise
BDP	Best Demonstrated Practice
DCS	Distributed Control System
DR	Data Reconciliation
DSS	Decision Support System
EFA	Energy Flow Analysis
EnPI	Energy Performance Indicator
ERP	Enterprise Resource Planning
GRI	Global Reporting Initiative
ISO	International Organisation for Standardization
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MES	Manufacturing Execution System
MFA	Mass Flow Analysis
MORE	Abbreviation of the project: Real-time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants
OECD	Organisation for Economic Cooperation and Development
PEF	Product Environmental Footprint
PI	Performance Indicator
PIMS	Process Industry Modelling System
PLC	Programmable Logic Controller

RACER	Evaluation tool for Relevant, Accepted, Credible, Easy and Robust
REI	Resource Efficiency Indicator
RMU	Resource Managed Unit
RTO	Real Time Optimisation
SCM	Supply Chain Management
URI	Uniform Resource Identifier
WBCSD	World Business Council for Sustainable Development

1. Introduction

The EU-funded R&D project “Real-time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants” (MORE) defined principles for the definition of real-time Resource Efficiency Indicators (REIs) and proposed a number of indicators for integrated chemical plants that can be efficiently used to steer daily operations. The defined indicators are computed based on the processing of real-time data available from monitoring and control systems, including innovative analytical measurements. As the MORE project is focused on large integrated chemical and petrochemical plants with many interconnected units, the real-time REIs and decision support tools have been developed specifically for this domain. The REIs and decision support tools were implemented in four industrial use cases from different sectors of the chemical industry, from oil refining to the batch production of fine chemicals. The full range of options for the use of REIs from monitoring to improving resource efficiency by model-based, real-time optimization was realized and has yielded encouraging results. In addition to addressing the chemical industry, the ambition of the MORE project is to transfer real-time resource efficiency indicators to different sectors of the process industry. This transfer has been investigated in two different case studies, for the sugar industry and for the pulp and paper industry and the indicators were demonstrated to be sufficiently general and flexible.

The guidebook is structured into two main chapters, first providing an introduction to the methodology of real-time REIs, followed by step-by-step procedure for practical application. The methodology chapter provides the most relevant information about resource efficiency, the definition and implementation of real-time resource efficiency indicators, and other aspects that are related to the implementation of REI calculations. The chapter “Step-by-step procedure to develop real-time REIs” provides step-by-step instructions for defining and implementing real-time or near real-time resource efficiency indicators for the process industry. The appendices contain additional information about principles for defining REIs and details about a RACER evaluation tool that can be used to assess the quality of selected REIs for any given application, and further information.

Sites, plants and processes in the process industries are quite diverse, and therefore their different needs must be addressed for a variety of readiness levels resulting in different decision routes. Thus, this guidebook can only present the generic aspects of the definition, calculation, visualization and use of REIs for decision support and real-time optimization (RTO).

Table 1 presents the motivation for plant personnel to start monitoring the resource efficiency indicators to monitor their process in real-time.

Table 1. Why, How and Who of defining and using real-time resource efficiency indicators (REIs)

Why?	To gain better knowledge **of the process, its inputs and outputs, its interconnections with other processes and its resource efficiency, leading to improvements in energy and resource efficiency**
	To engage operators to find and valorise resource efficiency improvement potential
	To improve resource efficiency through ➔ better yields ➔ decreased raw material and energy consumption ➔ reaching environmental targets ➔ decreased waste, waste water, emissions to air
How?	By selecting resource-intensive processes with potential for improvements
	By defining REIs that can be used to steer processes towards more resource efficient operation
	By implementing and utilizing REIs that are useful for monitoring and decision support
Who?	Management, together with operators, technical experts and possibly external advisors

2. Methodology

2.1 Resource efficiency

There is no standardised definition for the term “resource efficiency”. The European Commission defines resource efficiency in the following way (European Commission 2016):

“Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input.”

In this guidebook this political definition is refined into a technical definition:

"Resource Efficiency’ is a multidimensional 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 such as e.g. manpower, production capacity, land use, and capital are not included” (Kalliski & Engell 2016).

2.2 Resource efficiency indicators (REIs) as (key) performance indicators[1]

A (key) performance indicator (KPI) is a type of performance measurement that evaluates the success of an activity. Often KPI relate inputs and outputs and are either intensities, when stated as inputs per unit of product output (Fitz-Gibbon 1990), or efficiencies which are the reciprocals of intensities (Parmenter 2010):

“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.”

For different purposes a number of KPIs exist, often using different names for very similar measures. The KPIs used in energy management systems (ISO 50001) are called Energy Performance Indicators (EnPI). Here, in order to differentiate the indicators from others, the term Resource Efficiency Indicator

[1] This section also appears in the NAMUR Recommendation 162 “Resource Efficiency Indicators for monitoring and improving resource efficiency in processing plants” (NAMUR 2017)

(REI) is used. Resources in this case are primarily materials and energy and their combination, but the MORE indicators also cover environmental impacts such as waste and emissions. REIs can be defined as efficiencies or as intensities.

2.3 MORE principles for defining REI

The MORE resource efficiency indicators are based on eight principles. It is important to take these principles into account when starting to identify REI to ensure real-time capability and that the indicators reflect the technical performance as a result of the plant operation.

- **Gate-to-gate approach**
  As the entity of interest is a production site, a plant or a process unit, the boundary of the analysis is the limit of the respective entity, as only this can be influenced in real-time.

- **Indicating technical performance independently 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.

- **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.

- **Resource and output specific potential for meaningful aggregation**
  Within the 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 must be determined without aggregation.

  Based on a material and energy flow analysis, process specific REIs should be defined with respect to the resources and the products. The indicators can either be defined as intensities or efficiencies depending on the user preference. The definition of resource intensity is shown below. This version of the indicator simplifies the aggregation over different contributions due to having the same basis (product output). The corresponding indicator defined as efficiency is obtained by inverting the intensity indicator.

  $$REI_{RPS} = \frac{Resource\ Input}{Product\ Output}$$

  Such a resource and product specific (RPS) REI by itself does not indicate whether the process is operated well. It must be compared with a reference value obtained from historical or model data to evaluate the plant resource efficiency change:

$$REI_{norm} = \frac{REI_{RPS}}{REI_{RPS,best\ case}}$$

- **Considering storage effects**
  To realise “real-time” REI calculations, the choice of the temporal aggregation interval is crucial. The interval should be short enough to allow the derivation of operational decisions. Ideally a hold-up change is considered in the consumption or production figures. Long-term effects such as catalyst degradation or fouling must be defined in a suitable manner.

- **Include environmental impact**
  The impact on the environment must be taken into account separately in order to measure the ecological performance. Emission of pollutants to air, water and soil can be used as separate indicators.

- **Hierarchy of indicators – from the whole production site to a single apparatus**
  Production processes are interconnected. Analysing an individual apparatus may be misleading because resource utilization can be shifted to other units 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.

- **Extensible to life-cycle analysis**
  For reporting and assessment purposes, an extension to a Life Cycle Assessment should be possible using the aggregation scheme and adding a relevant weighting value to feed streams.

2.4 MORE Real-time Resource Efficiency Indicators

REIs in this guidebook can be used for real-time monitoring and optimization of resource efficiency in processing plants as well as for reporting, and they are extendable to Life Cycle Assessment. Depending on the intended use of the indicators, the interpretation of the term “real-time” differs. Loosely speaking, real-time means often and timely enough for the actions that are based on the indicators. Due to the presence of disturbances and fluctuations in all production processes, resource efficiency indicators must be averaged over sensibly chosen intervals in order to avoid their values being dominated by stochastic influences. In order to properly reflect the effects of the operational policies, the averaging should generally not be longer than the periods over which the manipulated variables are kept constant.

Real-time REIs are significantly different from REIs or KPIs for historic analysis, because they allow online monitoring and rapid intervention to improve resource efficiency. Providing REIs in real-time poses a number of challenges for measurement, data collection and visualisation, such as missing information, missing data or incorrect measurements.

In the MORE project a measurement, analysis, an REI or an optimization technology 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 (Minnich et al. 2016).

2. The time resolution is similar to the typical frequency of changes in manipulated variables (Kalliski & Engell 2016).

Resource efficiency indicators must be averaged over sensibly chosen intervals in order to avoid domination of their values by stochastic influences. In order to include effect of the operational policies, the averaging must not be longer than the periods over which the major manipulated variables are kept constant.

Resource efficiency indicators are classified into three categories (**Figure 1**):

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 unit 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 unit 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.

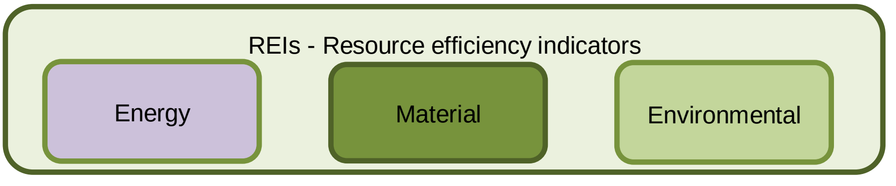

Figure 1. Categories of resource efficiency indicators.

For some indicators the classes may overlap. The categories “Energy” and “Material” are based on energy and material flow analyses, the category “Environmental” is measuring environmental loads, such as greenhouse gas equivalents or water usage.

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 unit, money. The consumption of different resources and the environmental impact can be integrated into one figure by weighting the streams in comparable units. If these units 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 energy that is required to produce a certain carrier of energy, such an integration can help describe resource efficiency using a single figure. Wherever possible, physical units should be preferred to make resource efficiency transparent and to reduce the influence of external factors.

In most cases, a more resource-efficient operation is also economically advantageous, but it is possible that the two objectives conflict because of the cost of measures for the improvement of the resource efficiency or external financial incentives. From the resource efficiency perspective, for example, the minimization of all waste streams is desirable, but this can be associated with high costs, resulting in sub-optimal production from the economic point of view. In such possibly conflicting cases, REIs and economic performance indicators should be considered and reported separately, and analysed e.g. in the form of a Pareto curve or Pareto surface.

The REI approach is different for continuous and batch processes, the main difference being the non-stationary character of the indicators in the batch case.

2.5 Generic and specific indicators

Resource efficiency indicators can be divided into generic and specific indicators. Generic indicators can be applied to every plant and can be aggregated bottom up, whereas specific indicators measure unit specific effects and provide more detailed information on key production steps such as reaction and purification steps that strongly influence the efficiency of the plant. Such specific indicators can e.g. be the energy required for the purification of a mass unit of product or the selectivity of a reactor.

Generic resource efficiency indicators are indicators which are applicable to each unit of the evaluated production complex and are suitable for aggregation. The generic nature of these general indicators enables consistent reporting for each production unit on the lowest hierarchical layer as well as a homogeneous aggregation to measure the resource efficiency with respect to final products, or the performance of large units or complete production sites. A typical example of a generic indicator is the energy performance indicator (EnPI) according to ISO 50001 which measures how much energy is used per ton of product. Generic indicators are crucial to evaluate the process performance of an aggregated complex of different types of production units, but are also suitable for monitoring and comparing individual production units. Generic indicators can be used for the comparison of different units in a consistent evaluation framework.

In many cases, equipment specific REIs, and REIs which can be used to identify the performance of key production steps, are required. Specific indicators cannot always be aggregated. Care must be taken to avoid false signals leading to attempts to improve the specific indicators at the expense of poorer overall performance. Specific indicators provide additional information to identify the causes of less efficient production. Figure 2 presents the plant hierarchy with generic and specific indicators. Table 2 provides examples of generic resource efficiency indicators, defined for continuous processes in steady sate.

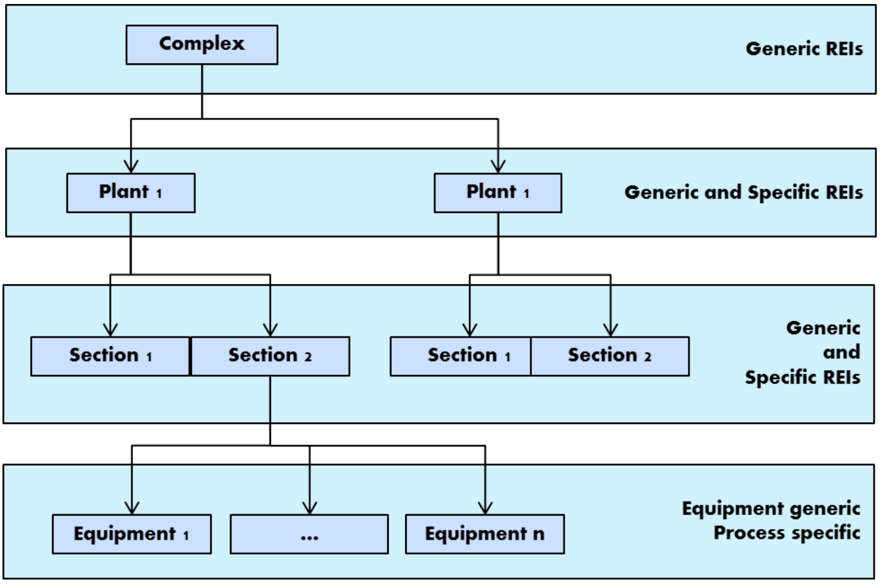

Figure 2. Plant hierarchy with indicators, only generic indicators can be aggregated.

2.6 Examples of MORE REIs

Lists of typical generic REIs that can be used for continuous and batch processes can be found in **Table 2** and in **Table 3**. A comprehensive listing of the indicators that were defined in the MORE project is given in Appendix B. The indicators are mostly given in the form of intensities.

Table 2. Overview of REIs defined for continuous processes.

Indicator Name	Catch Phrase	Formula	Measurements needed	Comment
Energy required (ER)	Specific Energy Consumption	$REI_{ER,A,k} = \frac{\sum_{i=1}^{n_E} E_{i,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	All energy inputs and outputs and all product streams	Can be separated into different energy types
Raw Material required	Specific Raw Material Consumption	$REI_{R,i,k} = \frac{R_{i,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	The relevant raw material inputs and all product streams	
Utilities required	Utilities/Raw Material required per unit of product (air, water, DI-water)	$REI_{U,i,k} = \frac{U_{i,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	The relevant utility and all product streams	
Material Yield	Overall process yield based on mass flow	$REI_{Y,k} = \frac{\sum_{j=1}^{n_P} m_{P,j,k}}{\sum_{j=1}^{n_P} R_{j,k}}$	All raw material inputs and all product streams	Possibly streams such as air must also be considered, if the molecules end up in the product
Overall resource yield	Overall process yield based on weighted flows	$REI_{RY,k} = \frac{\sum_{j=1}^{n_P} C_{P,j} m_{P,j,k} + \sum_{i=1}^{n_E} C_{E,i} E_{i,out,k}}{\sum_{j=1}^{n_R} C_{R,j} R_{j,k} + \sum_{i=1}^{n_E} C_{E,i} E_{i,in,k}}$	All energy inputs and outputs, all raw material inputs and all product streams	Depends on the chosen weighting which must be consistent
Overall Efficiency based on Energy Currency	Energy streams of different nature are weighted by an energy currency which accounts for the different value or exergy of the energy streams, e.g. electrical power has a higher value compared to steam	$REI_{ORE,k} = \frac{\sum_{j=1}^{n_U} C_{U,j} U_{j,in,k} - \sum_{j=1}^{n_U} C_{U,j} U_{j,out,k}}{\sum_{j=1}^{n_P} m_{P,j,k}} + \frac{\sum_{j=1}^{n_R} C_{R,j} R_{j,k} - \sum_{j \in N_{p,out}}^{n_p} C_{P,j} m_{P,j,k}}{\sum_{j=1}^{n_P} m_{P,j,k}} + \frac{\sum_{i=1}^{n_E} C_{E,i} E_{i,in,k} - \sum_{i=1}^{n_E} C_{E,i} E_{i,out,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	All energy inputs and outputs, all raw material inputs and all product streams, all utility streams	
Waste	Mass of waste type per unit of product	$REI_{W,i,k} = \frac{W_{i,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	The relevant waste stream and all product streams	
Overall weighted waste	Sum of waste weighted with "waste "currency" per unit of product	$REI_{OWE,k} = \frac{\sum_{i=1}^{n_W} W_{i,k} C_{W,i,k}}{\sum_{j=1}^{n_P} m_{P,j,k}}$	All waste streams and all product streams	

For the formulae in the table, the following symbols are used:
$REI_{X,A,k}$ as Indicator X from plant *k* or an RMU
$E_{i,k}$ as energy inflows or outflows of type *i* at the gate of Plant *k* or an RMU
$m_{P,j}$ as mass of produced product of type *j* at the gate of Plant *k* or an RMU
$U_{i,k}$ as utility inflows or outflows of type *i* at the gate of Plant *k* or an RMU
$R_{i,k}$ as raw material import as of type *i* at the gate of Plant *k* or an RMU
$C_{l,i}$ as relevant weight of stream type *l* (material or energy) ("Energy Currency") of Type *i*
$W_{i,k}$ as waste import or export of type *i* at the gate of Plant *k* or an RMU
$C_{W,i}$ as relevant weight of waste stream ("Waste Currency") of type *i*

Table 3. Overview of REIs defined for batch processes.

Indicator	Abbreviation	Formula	Hierarchy level	Efficiency factor
Overall resource efficiency	ORE_i	Case-specific	Plant level	Case-specific
Total material efficiency	TME	$\frac{m_{product}}{\sum_k m_{in,k}}$	Batch level	Material
Specific material input	MI_k	$\frac{m_{in,k}}{m_{product}}$	Batch level	Material
Material efficiency with recycle	$ME_{recycle,k}$	$\frac{\sum_p m_{k,stoic,p}}{m_{in,k} + (m_{in,recycle,k} - m_{out,recycle,k})}$	Batch level	Material
Heat product	HP	$\frac{\sum_i Q_{generated,i}}{m_{product}}$	Batch level	Energy
Electrical energy efficiency	EEE	$\frac{m_{product}}{\sum_i W_{el,i} - \sum_j W_{generated,j}}$	Batch level	Energy
Cooling energy efficiency	CEE	$\frac{m_{product}}{\sum_m W_{cool,m}}$	Batch level	Energy
Heating Energy efficiency	HEE	$\frac{m_{product}}{\sum_i Q_{H,i} - \sum_j Q_{generated,j}}$	Batch level	Energy
Total waste production	TWP	$\frac{\sum_j m_{waste,j}}{m_{product}}$	Batch level	Environmental
Water usage	WU	$\frac{m_{water,in}}{m_{product}}$	Batch level	Environmental

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

$m_{product}$	mass of product in specification
$m_{in,k}$	mass intake for resource k
$m_{k,stoic,p}$	stoichiometric mass equivalent of raw material k in the formation of product p (detailed explanation in Appendix 2)
$m_{in,recycle,k}$	mass intake of raw material k from recycle
$m_{out,recycle,k}$	mass extraction from batch to recycle for raw material k
$m_{waste,j}$	mass of waste j
$m_{feed,k}$	mass of raw material fed to reaction or purification stage of raw material k
$m_{water,in}$	mass of consumed water
$m_{resid,C}$	residual mass of valuable component C in a batch evaporation (desired)
$m_{resid,W}$	residual water content after batch evaporation
$m_{max,resid,W}$	maximal permitted residual water content after batch evaporation
$Q_{generated,i}$	generated heat I
$Q_{H,i}$	heat consumption I
$W_{el,i}$	electrical energy consumption I
$W_{generated,j}$	generated electrical energy j
$W_{cool,m}$	electrical energy consumed to supply cooling duty m

2.7 Baseline calculation

2.7.1 Influencing factors and representation of decision makers

Resource efficiency indicators should help identify whether or not the current operation is good with respect to resource efficiency. Hence their absolute value is often not as important as the comparison to a reference point which is called baseline in the following text.

We define *Baseline* as the performance of the plant averaged over a specified period of time. Typically the average of production data over a representative period in stationary operation is used. The value of the baseline usually depends on the mix of products in the period considered, the raw materials used, the operation regime (e.g. load levels) and external influences, e.g. outside temperature. Therefore the baselines should, if possible, be differentiated with respect to the main factors that are externally set and cannot be influenced during operation.

The *Best Demonstrated Practice* (BDP) is an important baseline. It is defined as the best observed operation based on historic data. In case of batch production, the BDP is also called a golden batch. As mentioned above, dependencies of the BDP on the product mix, load levels, raw materials and other influences are often observed.

A term *Best Achievable Practise* (BAP) is used if the baseline is an optimum that is computed from an analysis of the limits of the process performance. In such a theoretical analysis, also the influence of external factors can be considered.

The external factors that influence the baseline, the BDP and the BAP, can be separated into influenceable and non-influenceable factors. Examples of such factors are presented in **Table 4**. If the baseline is not adapted dependent on the key non-influenceable factors, comparing different operation points becomes very difficult.

Table 4. Some influenceable and non-influenceable factors in chemical plants.

Influenceable	**Non-influenceable**
Operating point	Weather
e.g. reflux ratio of a distillation column	Cooling water temperature
Operating procedures	
Influenceability depends on decisions made internally or externally	
Product mix	
Plant load	
Feedstock composition	
Feedstock quality	
Time and intensity of the last cleaning of the plant	
Catalyst age	
Heat exchanger fouling	
Equipment age	

The effect of the non-influenceable factors can be visualised by a time-varying baseline or BDP corresponding to the external conditions. Different people in a hierarchy have different decision authorities and influence on a plant and thus their baselines may reflect different influenceable and non-influenceable factors. Table 5 illustrates this idea. As an example, the operators cannot normally improve plant operations by buying better or different feed stock, but the site manager might be able to make such decisions.

Table 5. Different management levels have different influenceable and non-influenceable factors.

Plant Hierarchy	**Degree of Freedom (influenceable)**	**Included in Baseline Function (non-influenceable)**
Site Management	**Degree of Freedom (influenceable)**	**Included in BDP Function (non-influenceable)**
Plant Management	Product mix/volume Production plan(s) Plant loads Employee/utility allocation(s) Process parameters	External Influences, e.g. weather
Plant Operator	Production plan Employee/utility allocation Process parameters Feedstock composition	External Influences Product mix/volume Plant load

A simplified representation of BDP baselines for the operators and for plant management is shown in **Figure 3**.

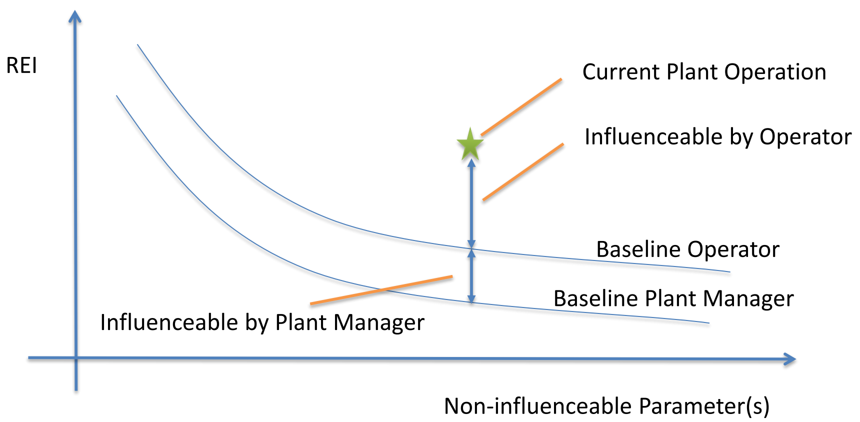

Figure 3. Different BDP baselines for different groups.

The effort for baseline generation increases with an increasing number of non-influenceable parameters. In most cases, a combination of historical data and a simplified or data driven process model will be used to develop a sufficiently accurate representation of the influences that determine the baseline. By reassessing the BDP periodically, previously not encountered operation points can be included and the data from situations that had already occurred can be reassessed so that the best operation is included. If resource consumption increases significantly in certain situations such as partial load or very cold weather, a detailed analysis of the cause, possibly including experimental operations out of the comfort zone, is necessary, especially if the situation is expected to occur more frequently in the future. A reassessment is necessary if the plant or the operation changed significantly due to new installations or other production procedures, e.g. changes of products or product specifications.

The procedure of normalizing the indicators to a BDP has an additional benefit: If the relevant external factors are removed from the indicators, the resulting indicators fulfil section 4.4.3 of the international standard ISO 50001 (2011) on energy management systems and the requirements set by the international standard ISO 50006 (2016).

2.8 Identifying and evaluating the best REIs for your plant

2.8.1 Selecting and defining the plant or unit

The selection of the plant or unit should be based on the contribution of the plant or unit to the overall resource consumption (raw materials, chemicals, utilities) of the plant or site and on the anticipated potential for improvements. We call the section of the plant that is considered for measuring and monitoring its resource efficiency a “Resource Managed Unit” (RMU). It is advantageous if the RMU is well equipped with measurements; at least all flow rates of the streams that enter and leave the RMU and their temperatures need to be known. Real-time or near real-time concentration measurements are usually needed if the material efficiency is of interest.

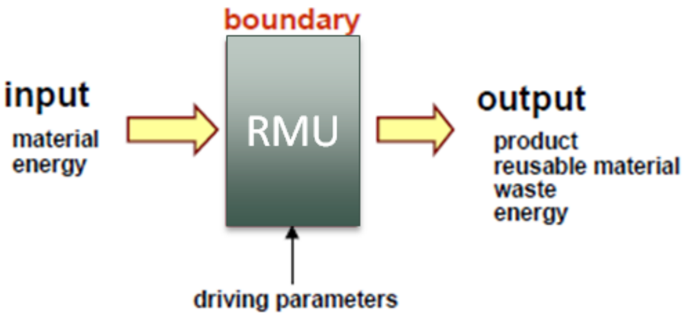

Figure 4. Resource Managed Unit (RMU).

To select the RMUs, it is recommended to organize a workshop with experts from different areas and backgrounds, involving plant managers, operational personnel, energy efficiency experts and environmental experts. External facilitators can be involved for organizing workshops to guarantee fresh viewpoints not to be limited to the normal routines of the plant. A facilitator can also bring external resource efficiency experts into the discussions.

It is necessary to help the external party gain an insight into the plant or unit and into the expectations of the representatives of the company, and to develop a common understanding of the processes under evaluation and of the targets of the REI definition and computation.

2.8.2 Selection of potential REIs

After RMUs and the consumed resources of interest have been selected and defined, the relevant resource efficiency indicators must be identified.

If an indicator is proposed which is not included in the comprehensive list of MORE indicators, a detailed discussion should confirm the suitability of the indicator according to the MORE principles set for the REI (see Section 2.3). Indicators should be relevant, significant and measurable. In addition, the operators or managers should be able to steer the processes based on the information provided by the indicators.

2.8.3 Evaluation using the RACER evaluation tool

An evaluation of all the identified potential REIs, involving experts from the plant, operational personnel, energy experts and environmental experts, is necessary to reduce the number of proposed indicators to an appropriate (as small as possible) set of indicators that covers all major aspects, materials and environmental loads.

In MORE, a specific RACER evaluation approach for REIs was developed that can be utilised to analyse the expected performance of the indicators (Kalliski et al. 2015). RACER is a structured evaluation approach for methods and indicators that is used by the European Commission (2005) and has shown its usefulness e.g. in the EIPOT project (Wiedmann et al. 2009). The abbreviation RACER stands for Relevant, Accepted, Credible, Easy, and Robust.

Suitable indicators should have good or at least acceptable scores in all dimensions, with special emphasis on the acceptance by plant personnel. Based on the scores and on detailed discussions, the best suited indicators can be selected.

2.8.4 Measurement plan and data reconciliation

In order to compute an REI reliably and correctly, a measurement plan is required. The measurement plan must show the path from the primary measurements that are used for the REI calculation to the visualisation of the REI. The measurement plan should contain the following information:

- Aim of the use of the measurements – here it is computation of the REI
- Necessary physical measurements to be carried out either to directly measure or calculate the quantity of interest
- If measurements are missing they need to be replaced by adequate estimates or new measurements if this is economically viable. Two possible estimation methods are data reconciliation with parameter estimation or state estimation (see e.g. Romagnoli & Sanchez 2000).
- The path of the measurements to the REI, including the electrical path and data processing from sensors to data bases
- The measurement uncertainty and the sensitivity of the indicator to the measurement errors
- Maintenance and calibration plan of the measurement systems used.

It is recommended to structure this information and to display it in diagrammatic form. This enables a joint understanding and a calculation of the error propagation and uncertainty intervals of the indicators. NAMUR Recommendations NE145 (NAMUR 2016b) and NE147 (NAMUR 2015) provide additional valuable information on measurement plans, measurement errors and error propagation.

2.9 Aggregation and contribution analysis

Information on resource efficiency can be used for different purposes by different actors on different levels of the plant hierarchy. Thus REIs can be computed on different aggregation levels and be averaged over different periods of time, from short term (real-time) to longer term periods. If information is aggregated, care must be taken that the basic data is computed following the same principles and over similar averaging periods. Also the uncertainties of the indicators should be provided and taken into account in the aggregation. It is recommended to aggregate the data from the lowest hierarchical layer where it is available up to the site level.

Typical balancing volumes for REI calculations are processing plants or units of plants and connected auxiliary plants that are organized in units, sub-plants, plants, complexes and sites. The terminology of the “Equipment hierarchy” defined in IEC 62264 (2013) (Enterprise, Site, Area, Process Cell, Process Unit, Equipment Module, Control Module) should be applied. All these entities are called “Resource Managed Units (RMU)” in this guidebook.

2.9.1 Consistent REI aggregation

- The structure of the RMU hierarchy must correspond to the physical site structure, disregarding the organizational structure.
- The RMU hierarchy should be used to automatically aggregate the generic REIs from the lowest defined hierarchy level upwards. This is called a “bottom-up” approach and requires the REIs of all sub-units to be defined, e.g. the relevant mass and energy balances for the defined units/sections on the lowest level must be closed.
- If REIs are different on different hierarchical layers, they cannot be aggregated automatically.
- Additionally, plants can be grouped and REI aggregation and contribution calculations can be conducted for generic indicators (Integrated MFA/EFA), for example if all plants of one type or all plants of one business unit are analysed.
- REIs can only be aggregated if they were calculated at similar points in time or periods of time. The REIs that were computed from nonlinear formulae must be handled with care because, e.g. the average of an REI may differ from the sum of the resource inputs divided by the product outputs. In such cases, the REI must be re-evaluated by using the individual contributions to the REI.

2.9.2 Bottom-up approach – contribution analysis

In many chemical plants or sites, indicators are in use that are aggregated, for example the energy used per ton of product for a whole plant or site. Such highly aggregated indicators do not provide information on the performance of the subunits and on the possible root causes of a deviation of the performance from its usual value.

To analyse the contributions and the root causes, a bottom-up contribution analysis should be performed. If deviations from the expected performance occur on the lowest hierarchical level, their effect is invisible in each higher level. In order to analyse what caused a reduced – or improved – resource efficiency, the individual contributions must be decomposed. A necessary condition to propagate the resource efficiency to the next higher level is that the mass and energy balances are closed on each level. Otherwise, comparing evaluations of the different levels leads to inconsistent results. Since for most production plants, closing the mass and energy balance on the equipment level is difficult, a sub-unit level is recommended as the starting point of aggregation.

An REI on a higher level can be calculated from the REIs of the units on the next lower level and the values of the product streams by:

$$REI = \frac{\sum_k REI_k (P_{k,int} + P_{k,ext})}{\sum_k P_{k,ext}}$$

where REI_k denotes the REI of sub-unit k, $P_{k,int}$ the product flow from k which is utilized within the balance domain and $P_{k,ext}$ the product flow of k that leaves the domain. The summation is performed over all units and products of the lower level. If BDP curves (cf. Sec. 2.7) are available for the lower level, the deviation of the performance of the upper level from the BDP can be computed directly based on the same information:

$$\Delta REI = \frac{\sum_k (REI_k - BDP_k)(P_{k,int} + P_{k,ext})}{\sum_k P_{k,ext}}$$

The contribution C_j of each sub-unit j to the total deviation thus is:

$$C_j = \frac{(REI_j - BDP_j)(P_{j,int} + P_{j,ext})}{\sum_k P_{k,ext}}$$

The results can be visualized for operators or plant managers with bar charts that help to quickly point to the root-cause of a deviation of the performance. No additional BDP curves are then necessary on higher levels.

In addition to identification of the root-cause of a deviation at the current operation point, exploitation of the above aggregation structure provides an insight into changes of the performance that are due to other circumstances, e.g. choice of feedstock, product mix or ambient conditions which are included in the BDP models of the sub-units.

2.10 Decision support

There are several options for utilizing the developed resource efficiency indicators, ranging from the computation and visualisation of the indicators to real-time optimisation on the basis of fundamental or data-based models.

Visualising the REIs relative to suitably chosen baselines helps the management to detect deficiencies and potentials for improvements and guides the operators in their work. REIs can be used for decision support based on different models and technologies. The most promising but also the most demanding way to utilize REIs is real-time optimization (RTO) in combination with advanced control.

2.10.1 Visualization of REI for real-time monitoring

Resource efficiency is a multi-dimensional concept that should be represented by a set of indicators describing the energy efficiency, the material efficiency and the environmental performance for different products on multiple levels in the plant hierarchy. Representing a number of indicators simultaneously requires efficient dashboard concepts with visualization elements that are best suited to highlight the indicators and are easily comprehended with little effort for interpretation. We propose to use a dashboard concept that gives an overview of the resource efficiency at first glance and subsequently breaks down the contributions to enable the user to conduct a root cause analysis. The structure of the interface and the graphical elements that are used in the interface and their design (e.g. colour coding) are important to achieve acceptance by the operators and to influence their decisions by visualization of the resource efficiency indicators.

Figure 5 shows a dashboard concept for a sugar plant case study including a control panel for navigation through the plant hierarchy, with efficiency indicator bars for the three plant sections indicating the resource efficiency of each section (upper-left). Upon user interaction, the different plant sections can be activated, which triggers an update in the historical trends (lower-left) and the detail view (upper-right) for the selected sub-section- and resource-specific REIs. The lower-right field provides supplementary information about the indicators.

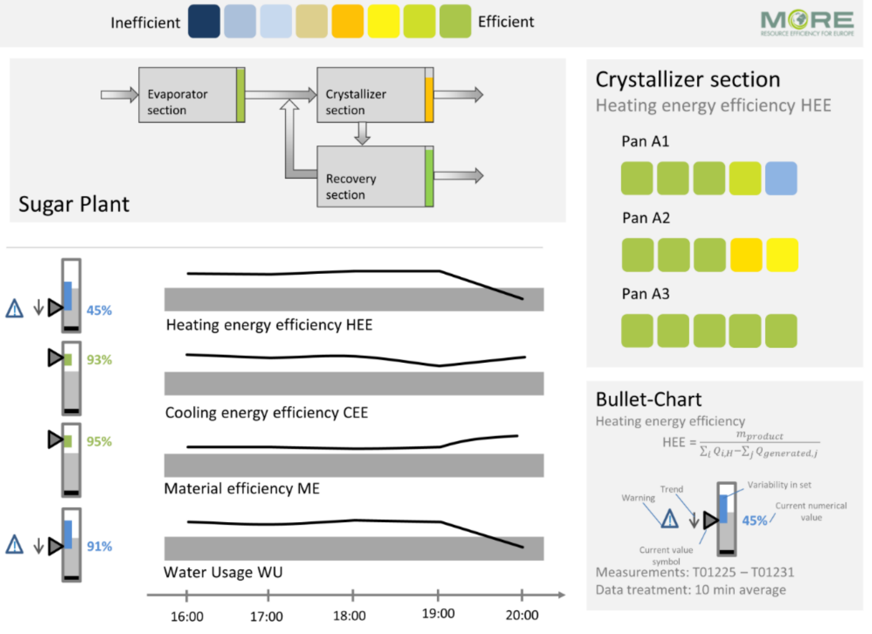

Figure 5. Dashboard concept for a sugar plant.

For the example shown in Figure 5, the user can identify a sub-optimal performance of Pans A1 and A2 in the crystallizer section. Upon user interaction, the visualization is updated for sub-sections further down the plant hierarchy in order to identify the root cause of the inefficiency. Based on this information the operators can, if possible, counteract the effects and bring the production back to the desired operating conditions.

More information on the media elements used to display REI information is available in MORE (2015a) where also guidance is given to the user to identify the most appropriate concepts and visualization elements for a given plant.

2.10.2 What-if analysis

The term “what-if analysis” refers to a scenario-based operator advisory system. The idea is to analyse the resource efficiency and the economic performance of different operation scenarios based on user-specified conditions, e.g. operational policies or external influences (MORE 2015b). Questions that are answered by the scenario analysis are for example: What happens to the efficiency when the throughput is increased? Is it favourable to lower the temperature of cooling water? Should the demand for products be shifted from plant A to plant B?

Figure 6 shows the sequence chart of a what-if analysis. Such operator support system should not only simulate and display the results but also assist the user to define and evaluate the cases that will be investigated. On the one hand, the process of a what-if analysis must therefore be guided, on the other hand, a high degree of flexibility is needed.

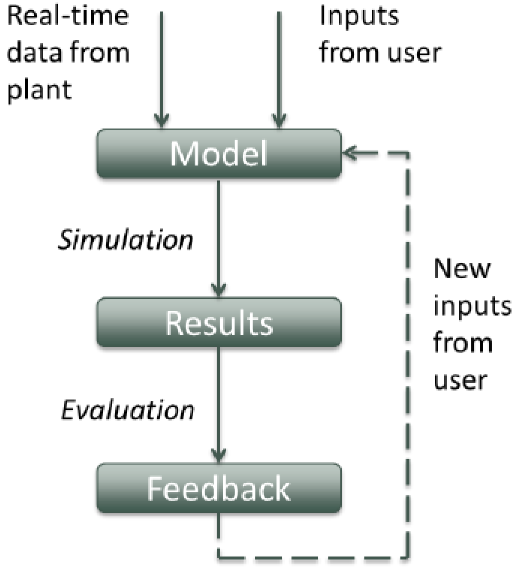

Figure 6. Process of What-if analysis.

2.10.3 Use of REI in optimisation and advanced process control

The REI described above captures three contributions to resource efficiency:

1. Material efficiency
2. Energy efficiency, and
3. Environmental performance.

Multi-criterial optimisation is required if different resource efficiency indicators are considered simultaneously without a predefined weighting. Multi-criterial optimization computes a so-called Pareto front or Pareto set, which is the set of solutions where no criterion can be improved without worsening another one. Then a solution must be chosen on the Pareto front, which is usually a management decision. Management decisions can also be to assign weighting factors of the different contributions. Once the contributions are weighted they can be combined into a single objective function and the trade-off is handled by the weighting. Typically, prices or costs will be used as weights (Ackerschott et al 2016). The resulting objective functions can be used in offline or real-time optimization schemes or the process can be driven to the optimum by model predictive control (Engell 2007).

Figure 7 provides a qualitative classification of the different options for making use of the REI, sorting them according to the benefits that can be expected. Additionally to the benefit, the estimated effort that is required to implement the solutions is plotted. Both benefits and efforts are scaled to the maximum benefit and the maximum effort needed for the realization.

Significant benefits can already be realized by real-time reporting and decision support by displaying the distance from the best demonstrated practice and showing what the differences result from.

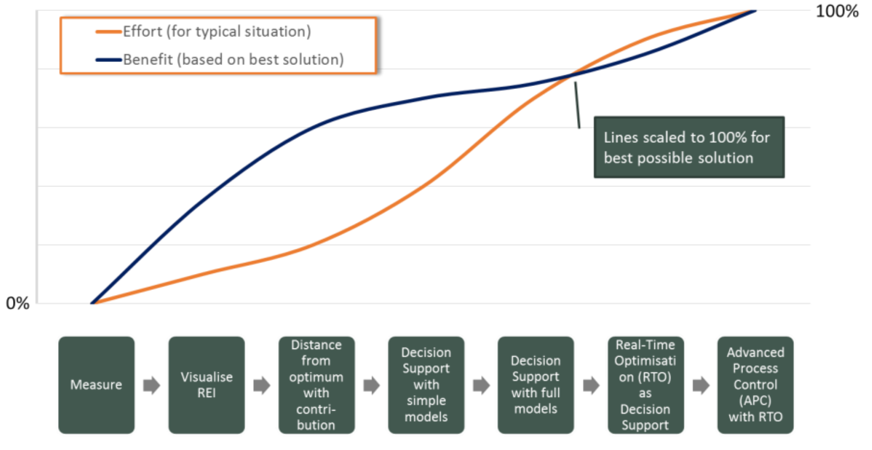

Figure 7. Qualitative plot of efforts and benefits for different levels of utilization of REI.

The benefits that can be expected from the introduction and the utilization of real-time REIs are multifold: knowledge will increase, personnel will be more interested in resource efficiency, direct and indirect emissions will be decreased, and cost savings through improved yields and decreased raw material and energy consumption can be realised.

3. Step-by-step procedure to develop real-time REIs

This step-by-step procedure has been developed to support the European process industry in the identification and selection of relevant real-time REIs for use in plant operations. The step-by-step procedure helps the user to identify and to implement real-time or near real-time resource efficiency indicators that are suitable to monitor plant operations and to guide the managers and operators towards improved resource efficiency.

Before starting the REIs definition and implementation process, it is recommended to go through the following questions, and to set a goal and internal targets for the REIs implementation. This can be done in a workshop or in a meeting involving key managers. Furthermore, it is recommended to engage the plant operators from the early stage of the project onwards in order to ensure their acceptance of the implementation of new indicators. The questions to be asked in the meetings could be, for example, the following:

1) Which are the driving factors to start developing and implementing (real time) REIs?
2) Who are the relevant parties that need to be engaged in the REIs implementation process?
3) What resources (e.g. time, money) are available for REIs implementation? (strongly connected to targeted savings in resources; connected to question 5)
4) What is the expected outcome of the REIs implementation?
5) What are the criteria for a successful REIs implementation (e.g. company level energy saving targets)?

The step-by-step procedure consists of 12 steps that guide through the REIs definition and implementation process. The steps that are discussed below in detail can be regarded as an indicative checklist to guide the REIs definition and implementation process. The actual steps and the level of detail depend of the case in question. The REIs implementation process is divided into three different parts:

1. Definition of the process under consideration,
2. Selection of REIs, and
3. Implementation and use of the selected REIs.

The structure of the process of the definition and implementation of an REIs is shown in Figure 8.

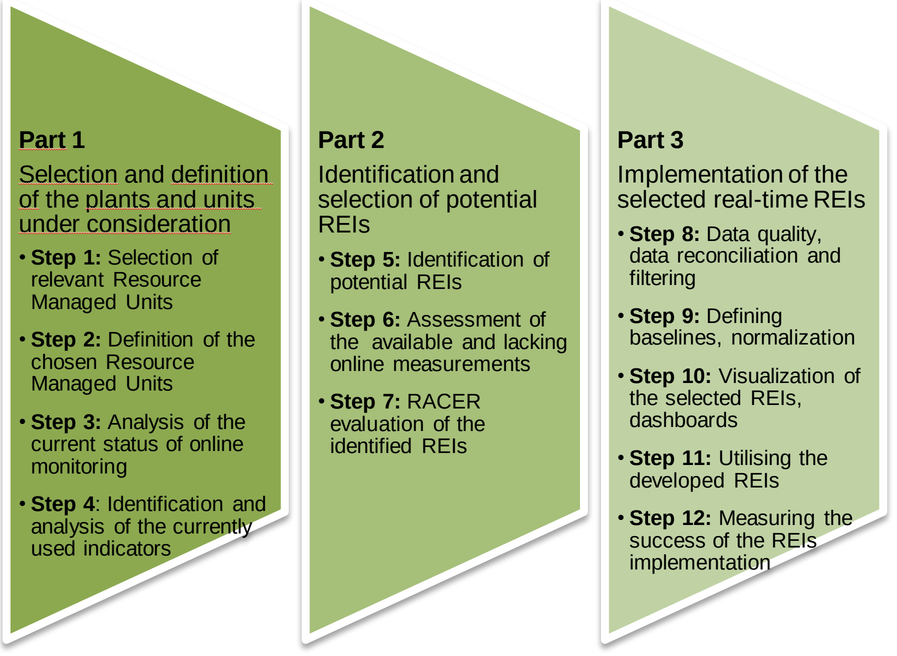

Figure 8. Structure of the step-by-step procedure.

To support the REIs definition and implementation process, a flowchart is visualized in Figure 9. The flowchart helps users to follow the different steps that are introduced in this guidebook. The flowchart guides the progress and indicates the relation between different steps, their order and the decision making points. After each decision making point (answer is yes or no), there exists a path to the next decision making point, or to the prompt to carry out the next task.

It should be noted that the flowchart and the procedure that we describe here in general do not provide specific instructions on all actions that need to be taken to implement real time REIs. Rather, the aim is to give guidance on a general level and to provide a path that the users should follow in the implementation of real time REIs.

For the site-wide approach (between steps 9 and 10) and for aggregating the REIs, more information is available in Section 3.4.

It is recommended that this guidebook is read carefully before starting the REIs definition and implementation process. This improves the effectiveness of the REIs implementation.

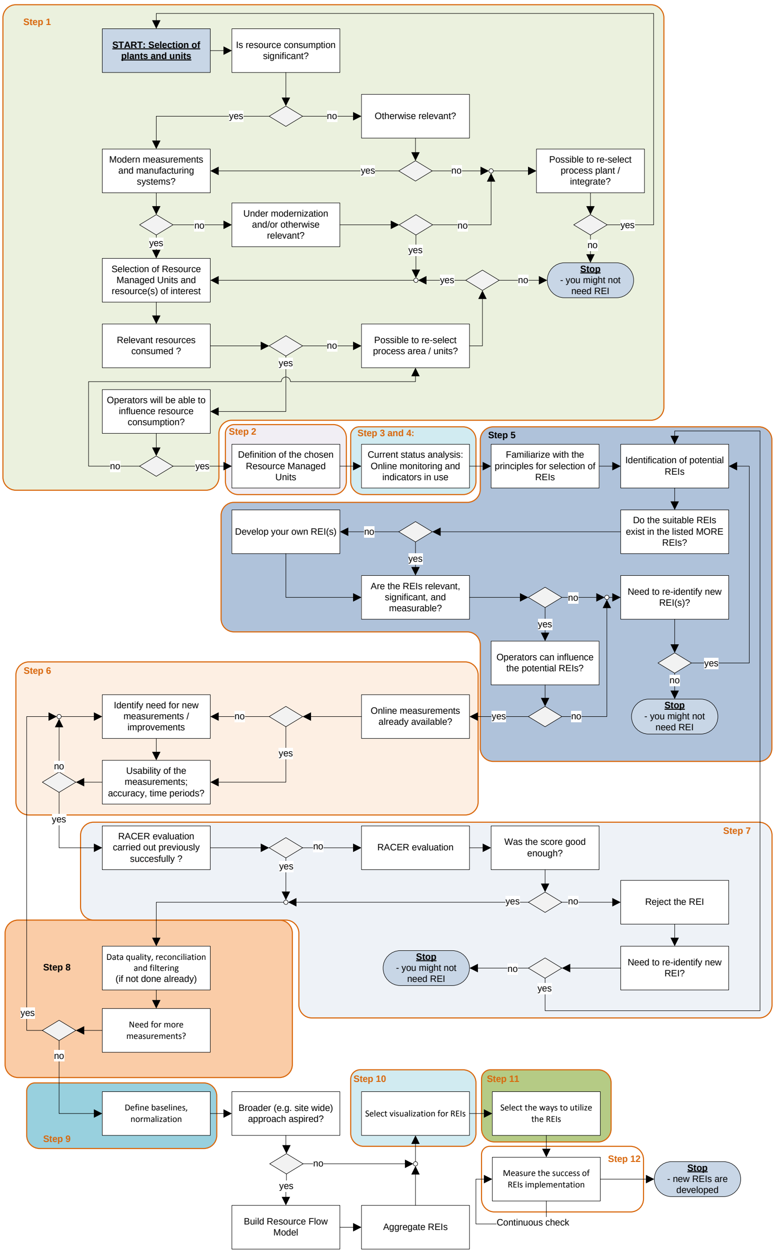

Figure 9. Decision tree for the identification and selection of REIs.

Figure 10 provides an overview of the REIs generation process. The basis for the generation of indicators are energy flow analysis (EFA) and material flow analysis (MFA). The difference between generic and specific indicators was explained in Section 2.5 which also explains and gives guidance on the identification, evaluation and selection of potential indicators. Several MORE REIs may be applicable (see Appendix 2), or new plant specific indicators may be needed. The characterization of the baseline, or the best demonstrated practice (BDP) is required to evaluate the current operation point. The analysis of the contribution of different influencing factors to the REI helps to derive possible actions to improve the process performance.

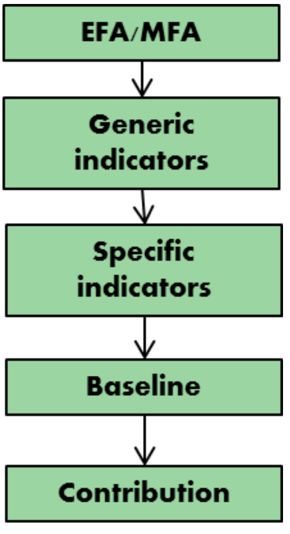

Figure 10. Flow chart of the generation and selection of REIs.

3.1 Part 1: Selection and definition of the plants and units under consideration

The first step is to decide the site, plants and units for which the implementation of resource efficiency indicators is relevant. The first three steps presented below support the selection and definition of the plants and units that are monitored by real-time REIs.

3.1.1 Step 1: Selection of relevant Resource Managed Units

First, the relevant site, complex or plant should be selected at the company level by the company management. This upper level selection will be followed by a sub-selection of process areas or units, unless the focus remains on the whole processing plant or complex. The selected plants or units are called Resource Managed Units (RMUs).

A good tool for carrying out the selection process is to organize a workshop to which various experts are invited. Involving an external facilitator for organizing the workshop may be beneficial, providing fresh viewpoints from outside the normal routines of the plant. The facilitator should also bring external resource efficiency expertise to the discussions.

In case of having an external party facilitating the workshop, or the work in general, an insight into the process plant and into the expectations of the company representatives needs to be provided in order to enable a shared understanding of the processes under evaluation and of the targets of the plant management.

The following action points and questions can be used for selecting the relevant process plants and units.

Selection of the site, plants and units:

- Commit company management and plant managers in the selection process.
- Identify the site and process plants where significant resource consumption (raw materials, chemicals, electricity, heat, water) takes place and where a potential for improvements is recognized.
- Specify the resource(s) of interest.
- Select the relevant plants or units in agreement with the company management and plant managers.
- Is the plant equipped with modern measurement and manufacturing execution or control systems or is it currently or in the near future under modernization? This will enhance the possibilities of applying new REIs.
    - Otherwise, appoint resources for consolidating or installing measurements and monitoring systems, where required. Measurement data will be needed for material and energy flow analysis (MFA & EFA) and for REI calculations. The minimum requirement for the monitoring systems is that it is able to compute and to visualize the (near) real-time REIs.

Selection of the Resource Managed Units:

- Commit a group of experts (plant managers, operational personnel, energy and environmental experts) to do the selection of RMUs in teamwork in order to ensure a comprehensive perspective. This is also needed when the whole site is in the focus.
- Identify the processes or units where a significant consumption of resources takes place and where there is potential for improvement. All relevant plants and units should be discussed thoroughly.
- Define the resource(s) of interest.
- Do the operators or automation system have the possibility to influence the resource consumption of the RMU in question? This is vital to be able to improve the performance from the resource consumption point of view.

- Select relevant plants or - units in agreement with the plant personnel. The acceptance of the plant personnel is necessary from the beginning of the introduction process.

Step 1	
Target:	Selecting the relevant Resource Managed Units
Action:	Commitment of different experts (plant responsible, operational personnel, energy and environmental experts) Selection of the relevant site or plant with potential for improvement Specification the resource(s) of interest Selection of the Resource Managed Units

3.1.2 Step 2: Definition of the chosen Resource Managed Units

When a relevant site and plants or units have been selected and the resource(s) of interest have been specified, the next step is to define these Resource Managed Units in more detail. The concept of RMU is visualized in **Figure 4**.

Aspects that are recommended to be included in the definition of RMU are:

- Schematic diagram of the RMU
- Flows of raw or intermediate materials and energy inputs into the relevant units
- Flows of products, by-products and intermediate products, and waste and recycle streams
- Consumption and production of utilities (e.g. steam, electricity, water)
- Material flow analysis (MFA)
- Energy flow analysis (EFA) (if relevant).

The definition step is a prerequisite for being able to define and select resource efficiency indicators (REIs) in the next step.

Step 2	
Target:	Definition of the Resource Managed Units
Action:	Preparation of materials: Process flow charts Raw and intermediate materials and energy inputs Streams of products, by-products and intermediate products, and recycle streams Emissions and waste outputs Material flow analysis Energy flow analysis

3.1.3 Step 3: Analysis of the current status of online monitoring

Process control and online monitoring systems and tools may set limitations on implementing a new potential real-time REIs. There might be needs to make improvements to these systems and tools before being able to implement new REIs, incurring costs.

The following questions can be used in checking the current status of online monitoring and process control systems and tools, and the needs to upgrade them:

- Existing online monitoring and process control systems
  i. State of the current tools and systems? Are these suitable for adding new online REIs (calculation and monitoring) and for adding new measurements that are possibly needed for the calculation of REIs?
  ii. What kind of limitations do the currently used systems and tools have?
- Are energy or resource efficiency indicators currently monitored? How?
- Indicate the needs to improve the online monitoring and process control systems and tools, if any, for new REIs implementation, based on the answers to the above questions.

Step 3	
Target:	Analysis of the current monitoring and control systems, their potential and limitations, and of the needs to upgrade them
Actions:	List the current monitoring and control systems and tools Evaluate the possibilities for adding the calculation and visualization of REIs for the current systems Indicate the needs for upgrades Make an action plans for updating the existing systems and tools, if needed

3.1.4 Step 4: Identification and analysis of the currently used indicators

This step clarifies how the resource efficiency is currently monitored and managed, analyses the currently used indicators, evaluating whether they can be used as a basis for the definition of real-time REIs.

The following questions can be used in identifying the current status of the resource efficiency monitoring and in the analysis of the currently used indicators:

- How is resource efficiency currently monitored?
  i. For this purpose, what flows of energy and materials are measured and how often?
- How is resource efficiency currently managed?
  i. What actions are taken to improve resource efficiency?
- What are the currently applied indicators?
  i. List the applied indicators
  ii. Current measurement frequencies of the applied indicators?

iii. Are the applied indicators suitable for real-time calculation and usage?
iv. Who follows the evolution of the indicators?
v. What are they compared to?

- What information do the currently applied indicators provide?
  i. How is this information used?
  ii. Did this information lead to resource efficiency improvements?
  iii. Are there needs for new indicators?
- Can the currently applied indicators be used as a basis for the definition of real-time REIs?

Step 4	
Target:	Analysis of the currently used resource efficiency indicators
Actions:	Evaluate the current monitoring of resource efficiency List the currently used indicators Evaluate the suitability of the currently used indicators for real-time calculation and use List the indicators which can be used as a basis for the definition of real-time REIs

3.2 Part 2: Identification and selection of potential REIs

These steps have the goal to identify the relevant real-time resource efficiency indicators (REIs) and to select a subset of these for online calculation and monitoring.

It is strongly recommended to organize a workshop with relevant experts, and preferably organized by an external party. It is recommended to include a separate session in the workshop to familiarize everybody with the eight MORE principles for real-time REIs definition and implementation (see Section 2 and Appendix 1) and with the REIs that have been developed in the MORE project (see Appendix 2).

3.2.1 Step 5: Identification of potential REIs

In order to have useful indicators, actions by the operators or by the control system should have a potential to cause notable changes in the values of the indicators. Otherwise the indicators are not relevant.

The following hints and questions should guide the identification of potential REIs:

- Involve all interested and required experts in the process of identifying potential REIs (e.g. plant management, operators, energy and environmental experts).
- Familiarize the team with the principles of the definition of REI that were developed in the MORE project (Appendix 1).
- Brainstorm open-mindedly about a set of possible indicators:

  - Focusing on the selected resources and process units
  - Keeping in mind that the indicator should be relevant and measurable
  - Recognising that operators need to be able to steer processes online based on the information provided by the indicator
  - All ideas are welcome, even if the proposed indicator does not pass the later evaluation, or if there may be better suited ones!
- Is there relevant online data missing for the calculation of the REIs? Could process models be utilized to fill in the gaps?
- Cross check the suggested REIs with those developed in the MORE project (Appendix 2).
  - If the REIs suggested or a variant of it is not listed, check whether the indicator is defined based on the MORE principles.
- Document and list the identified indicators for the subsequent evaluation and selection process.

Step 5	
Target:	Identification of potential REIs for the selected RMUs
Action:	Involvement of experts of the focus area Open-minded brainstorming of several potential REIs Cross-validation with the REIs developed in the MORE project Documentation of the identified REIs

3.2.2 Step 6: Assessment of the available and lacking online measurements

An important part of the work is to identify and to evaluate the online measurements that are already available, and to identify the ones that are lacking for calculating the identified REIs.

The sensitivity of the indicators with respect to the measurements is an important aspect which must be analysed. It determines whether the available measurements have to be improved, filtered or reconciled and what are the requirements for the accuracy and reproducibility of new measurements.

It is recommended to consider the following aspects in Step 6:

- What measurements are needed for calculating the identified REIs?
  - Accuracy and frequency requirements?
    - The measurement must be sufficiently accurate, which is determined by the sensitivity of the indicator.
    - Time periods between current measurements (e.g. 1 sec, 1 minute, 1 hour or 1 week) suitable for REI calculation?
- What online measurements are currently available for calculating the identified REIs?
  - Review the information that is available from Step 3
  - Is the accuracy of the current online measurements sufficient for calculation of the REI?

- What measurements are lacking for calculation of the identified REIs?
    - Specification of the lacking measurements (accuracy, frequency, etc.)?
    - Estimation of the costs associated with the installation of the required measurements at the required frequency and accuracy.

Step 6	
Target:	Evaluation of whether the available measurements are sufficient and what new measurements are needed
Action:	Sensitivity of the identified REIs with respect to the measurements Specification of the measurements needed for the identified REIs Availability of measurement data, its accuracy and frequency Analysis of the needs for new measurements (accuracy, frequency)

3.2.3 Step 7: RACER evaluation of the identified REIs

The MORE RACER evaluation framework has been developed to analyse the identified REIs in the main categories of Relevant, Accepted, Credible, Easy and Robust, and to provide a basis for the selection of the REIs. The framework does not necessarily deliver one or few best indicator(s), but rather points out the strengths and weaknesses of the indicators under consideration. **Table 6** illustrates the evaluation of the indicators by means of an example. This spreadsheet elucidates the point-system used in the MORE RACER methodology by supporting notes on the sub-criteria, giving assistance to choose an appropriate score for each criterion. **Figure 11** illustrates how the results of the RACER evaluation can be visualized as radar charts.

Scores of two points represent the level of fully achieved, one point the level of partially achieved, and zero points the level of not achieved. Some sub-categories under the main categories (Relevant, Accepted, Credible, Easy and Robust) are treated as indispensable so that zero in one sub category leads to score of zero in the main category.

The MORE RACER evaluation, its principles and the meanings of the main categories (by the definition and explanation of related sub-criteria) are described in more detail in Appendix D. See also (Kalliski et al. 2015).

<u>The following hints and questions provide guidance for the RACER evaluation:</u>

- Are all the relevant experts involved? Involve them (plant responsible, operational personnel, energy and environmental experts) to carry out the RACER evaluation as a teamwork or individually.
- How likely is it that a given indicator will lead to improvements? Carrying out the RACER evaluation for the identified indicators includes a score for their expected success (see the example in **Table 6**).
- Was the RACER evaluation carried out by several experts independently? Compare the results and scores in the experts group, and organize a stratification or at least mutual understanding of the scores.

- Which indicators are scoring well? Do they have acceptance by the operational staff? Do they meet plant specific criteria? If yes, it is possible to select these indicators and to move on to the implementation stage.

Step 7	
Target:	Selection of REIs for the implementation stage
Action:	Involvement of relevant experts Carrying out the RACER evaluation for the identified REIs Selection of REIs that are scoring well for the implementation stage: Good or acceptable scoring in all levels. Acceptance by the plant operators

Table 6. Evaluation example of the main category ‘Relevant’. Three scores are defined, corresponding to the level of success (fully, partially or not achieved) for each of the four sub-categories. The evaluators can pick only one answer for each of the sub-categories. Crucial sub-criteria are marked red, an REI is only appropriate if none of these criteria scores zero.

Relevant			Category average	0,75
Sub-category	Goal related	Suitable for time horizon considered (seconds / hours / campaigns)	Influenced by the actions of the operators	Transferability to other plants
Fully achieved (2 points)	*Indicator reflects resource efficiency directly* ○	*Indicator is meaningful for time periods of interest* ◉	*Can be influenced directly* ○	*General definition; easy to transfer* ○
Partially achieved (1 point)	*Indicator reflects resource efficiency indirectly* ◉	*Use for short term analysis questionable (e.g. windowing effects or holdups not considered)* ○	*Possible influence but not obvious* ○	*Tranferable with adaptations* ○
Not achieved (0 points)	*Indicator is not related to resource efficiency* ○	*Not meaningful on short time scales* ○	*No influence* ◉	*Very specific definition; not transferable* ◉
Comments				
Points	1	2	0	0

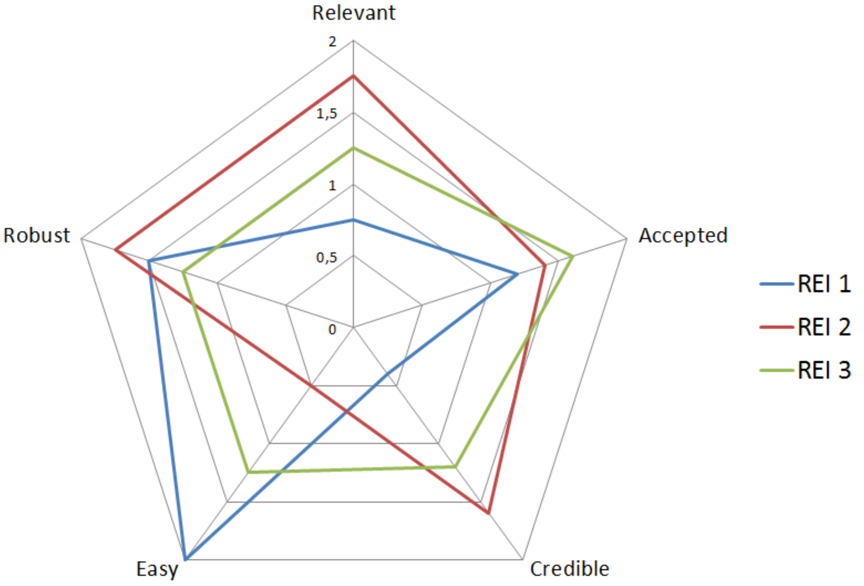

Figure 11. RACER evaluation of REIs. The average values per main category are visualized in radar charts to provide an overview (Kalliski et al. 2015, MORE 2014a).

3.3 Part 3: Implementation of the selected real-time REIs

This stage of the step-by-step procedure comprises the filtering and reconciliation of the data which is used for computing the REIs in order to reduce the effect of measurement errors, for the definition of baselines so that the current values can be compared to average or optimal ones and for the appropriate visualization of the REIs.

There are several options for utilizing the developed REIs beyond visualisation, e.g. by model-based decision support for the operators or for real-time optimization. These are discussed in step 11. Finally, the success of the implementation of the REIs and of their use must be evaluated, with the success criteria as the driving factors that were identified in the beginning of the REIs selection and implementation, in particular the improvements of resource efficiency that were achieved. Based on the outcome, the set of indicators may have to be enlarged or reduced. The evaluation of the success should be repeated periodically, as it may turn out that in daily practice, only some indicators are used or additional information would be helpful. Decisions on investments for measurements may also be revised.

3.3.1 Step 8: Data quality, data reconciliation and filtering

An important aspect in the definition and computation of real-time resource efficiency indicators is to deal with rapid (compared to the relevant time scale) fluctuations of the measurements and measurement errors.

In principle, the computation of valid resource efficiency indicators requires that the plant is in steady state and that the data is consistent with physics, in particular that the mass and energy balances are satisfied. However, a plant-wide steady state is only rarely observed, as disturbances act on the plants and they undergo changes of the operating points to which they react with significant time constants and delays.

Therefore time-averaging and often also dynamic data reconciliation are needed and should be taken into account already in the definition of the real-time resource efficiency indicators.

When applied correctly, data reconciliation leads to estimated values of the measured quantities that fulfil the mass and energy balances. Attention must be paid to the fact that some sensors may exhibit gross errors. To reduce sensitivity to these errors, the cost function for data reconciliation must be chosen properly, e.g. as the Fair Function (Huber 2014). Then from the reconciled data it can also be inferred which instruments have gross errors and should be re-calibrated or replaced, and whether additional measurements would provide benefits (Krämer & Engell 2017).

Data reconciliation can also provide estimates of the variance of the reconciled process variables that can be used to compute the confidence intervals of the REI based on the sensitivities of the indicators with respect to the measurements.

It must be noted, however, that data reconciliation using models beyond the usual satisfaction of mass balances requires considerable effort in process modelling and realization of the estimation scheme, and so it should only be applied when needed. A comprehensive description can be found in Taylor and del Pilar (2013) and Bagajewicz and Jiang (2000).

Step 8	
Target:	Decide whether data reconciliation is required Realize the computation of reconciled data Identify faulty measurements and evaluate the benefit of introducing new measurements
Action:	Evaluation of the available process models Estimation of the required effort for data reconciliation Application of mass balance-based data reconciliation and potentially full data reconciliation Identification of measurements with gross errors Improvement of measurements with gross errors Estimation of the benefit of installing additional measurements or better sensors

3.3.2 Step 9: Defining baselines, normalization

The definition of baselines is needed in order to be able to compare the current operation point with the selected baseline to get information on how well the process is performing based on the REI value. A baseline can also be used to validate the success of the improvement of the operation of the plant or unit.

The reference baseline for resource and product specific REI can be based on Best Demonstrated Practice (BDP), on historical data (simple baseline), or on theoretical optimum (see Section 2).

$$REI_{norm} = \frac{REI}{REI_{best\ case}}$$

The reference should be adapted to important non-controllable influences, e.g. the product quality, the plant load or the outside temperature. If the baseline that was computed based on the best historical data is reproducibly improved, the reference level should be adapted.

The following method can be used to identify either a baseline (historical data) 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. If the non-influenceable factors are e.g. outside temperature and load and the modelled factor is the energy consumed per unit of product, these are the three dimensions.
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. This data is 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. Weighting is not recommended when algorithms for interval calculation are used, as they select the intervals according to data clusters.
6. If representatives are outliers in the regression, as shown abstractly in **Figure 12**, a method for outlier removal should be applied.

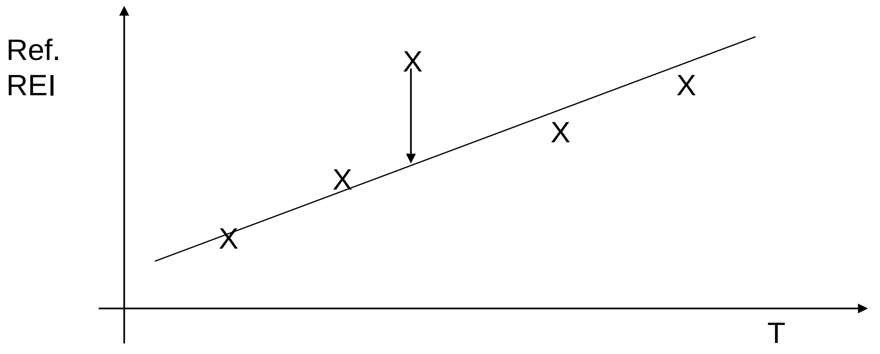

Figure 12. REI baseline characterization based on measurement data.

Step 9	
Target:	Defining the baselines of the REIs
Action:	Chose the baselines of interest: Best demonstrated practice, historical data or theoretical optimum Compute the chosen baselines from historic data or by a theoretical analysis

3.3.3 Step 10: Visualization of the selected REIs, dashboards

The content and the density of information in a visualization element should be limited to a minimum which still serves the intended purpose. This includes aspects such as background colouring, background pictures and unnecessary grids and borders. These rules were introduced as the concept of “data-ink ratio” by Tufte (2001), stipulating reduction of the use of non-data ink.

A comprehensive overview is given in Table 7. If the considered method fully meets one of the requirements listed on the left, then this is indicated by a “+” sign in the corresponding field of the matrix. A “○” sign is used if the criterion is partially met and the field is left blank if the form of presentation is not suitable for the requirement. The selection criteria for visualization elements in Table 7 help to select appropriate elements to create efficient dashboard solutions.

The visualization elements must then be combined to dashboards that are easy to use but allow the user to dig deeper into the available information. An example was shown in Section 2.10.

Table 7. Overview of visualization elements.

	Plant structure diagram	Sunburst diagram	Sankey diagram	Radar plots	Aggregated tiles	Bullet charts	Stacked bars	Stacked area plots	Sparklines	Trajectory plot w. trust region	Difference charts
Plant overview	+	+	+	+	○						
Qualitative	○	+	+	+	+				+		+
Quantitative		○	+			+	+	+		+	○
Batch data			+	+	+	+	+			+	
Continuous process data			+		○	+	○	+	+	○	+
Trends				○	○	○	+	+	+	+	+
Many indicators (>5)		○	○		+	+			+		
Indicator history				○	○	○	+	+	○		○
Fluctuating data						+	+		+		+
Absolute	+	+	+	+	+	+	+	+		+	+
Relative	+	+		+	+	+	+	+		+	+

Step 10	
Target:	Identify the most suitable visualization elements for the selected indicators
Action:	Assess the selected set of indicators with respect to the number of indicators, the type of process and the process structure Based on the analysis, select the appropriate visualization elements from the supplied matrix

3.3.4 Step 11: Utilising the developed REIs

After implementing the REIs and their visualization, there are many options for how to utilize this information:

- Operators can use the provided information to improve resource efficiency, either based on their knowledge of the process and the results of their actions or by using model-based decision support.

- Plant managers can use the REIs to monitor the quality of the operation of the plant and to detect problems early on. This may trigger investigations of possible changes in the plant or in the operating policies.
- REIs provide a tool to compare the resource efficiency of the process to similar plants and to draw conclusions about possible improvements.
- REIs can be used as optimization criteria in process optimization, possibly in a multi-criteria optimization in which several indicators and the economic performance are taken into account.
- Issues that are suddenly appearing which may harm operation (such as sensor damage, blocked actuators or leaks) can be quickly detected and located by operators from variations in the monitored REIs. Operators may take quick decisions to resolve or at least to palliate the problems.

For example, fouling or wearing is time dependent and the selected REIs may be sensible to such changes of the state of the plant. Necessary actions involve cleaning or changing worn-out parts. The optimal point in time for maintenance can be determined by single or multi-criteria optimization including resource efficiency measures (REIs) and economic indicators (Kalliski et al. 2017).

Step 11	
Target:	Utilization of the developed REIs
Action:	Real-time computing REIs from measurements and REIs visualizations help to detect problems and sub-optimal operation. Can provide hints where to take corrective actions. What-if REI analysis: test different alternatives in simulation to compare the results with actual REI values. Definition of objective functions for optimization based on REIs and economic criteria, subject to model constraints, providing better operation points or operational policies. Use of the above information to make right decisions about plant upgrades and future process modifications.

3.3.5 Step 12: Measuring the success of the REIs implementation

The implementation of REIs requires the staff involved, external support and possibly investments in new equipment (e.g. new measurements or monitoring systems). The expected benefits should be clarified for all parties involved from the management to the operational level. Different stakeholders measure success in different ways; management is interested in numbers, whereas operators value well-functioning tools and control systems that reduce their workload.

The questions below can be used to measure the success of the implementation of REI calculations, visualization and decision support based on REIs. The success criteria should be clearly defined in the beginning of the project (see the questions presented at the beginning of this section). The first set of questions measures the success immediately after the implementation of the REIs and the second set is intended for continuous, long-term evaluation.

After the first implementation of REIs calculations, visualizations and decision support:

- What were the driving factors for implementing real time REIs?
- Was the engagement of the relevant parties successful?
- Are the indicators informative for plant operators and plant managers?
- To what extent has the implementation of REIs changed and improved the operation, management and decision processes at the plant and company levels?
- Did the resources (e.g. time, money) consumed justify the potential expected savings?
- Were indirect benefits obtained, e.g. better understanding of the plant and its constraints, hints for technical improvements obtained?
- Can the REIs be transferred to other plants? Can the investment into dashboards, reconciliation algorithms etc. be leveraged at other plants?

Periodic evaluation of the success of the implementation of REI calculations, visualizations and decision support based on REIs:

- Are the driving factors for implementing the REIs still valid?
- Are there new aspects when comparing to original driving factors?
- Are there other parties that should be engaged in the implementation or REIs?
- Is the baseline set still valid or is there a need to revise it (e.g. due to improved historical data)?
- Were the criteria for a successful implementation met?
- To what extent has energy and resource efficiency improved since introduction of the REIs? How much of this improvement can be attributed to the availability of the REIs and the associated support tools?
- To what extent did use of the REIs increase economic performance at the plant and company levels?
- To what extent did use of the REIs improve environmental performance at the plant and company levels?

It is recommended to evaluate the impacts of implementing REI calculations, visualizations and decision support using a wider perspective and including possible impacts elsewhere on the site and upstream and downstream in the value chain. Impacts can be measured at the operational level, company level and sectoral level. The assessment can be conducted through interviews, questionnaires, collecting actual data of economic and environmental flows and using Life Cycle Assessment (LCA) and other relevant tools to evaluate improvements achieved in the overall performance (SAMT 2016).

Further information on the case study evaluations and impact assessment can be found in MORE (2017a and 2017b).

Step 12	
Target:	Measure the success of the implementation of the calculation, visualization and use of real-time REIs
Action:	Relevant questions as listed above Impact assessment: Questionnaires, interviews, LCA, balance sheets, statistics

3.4 Efficient implementation of REIs on a larger scale

3.4.1 Motivation

The computation of REIs from measurements is not very complicated, provided that the necessary measurements are available and are sufficiently accurate. The computations can be implemented in state-of-the art SCADA or MES or PIMS systems. However, the one-by-one implementation of each individual calculation for each unit considered is time-consuming and the maintenance of these computations when changes are made to the instrumentation or to the IT systems is problematic. An implementation based upon an information model of the plant or site can reduce the effort considerably in the long run.

The goal of such an information model is to provide a process-oriented context to the data sources in order to combine the data with additional information based on the structural information. The knowledge of the material and energy flow network of a site or plant is of special importance and relevance. Besides the amount and the direction of flows including internal recycles, information about flow categories, compositions of flows and possibly additional characteristics are required. In addition, the following issues have to be linked to the flow and their properties data: generic calculation algorithms, characteristic constraints and also material or energy type specific master data (e.g. standard enthalpies). The knowledge that a specific measurement represents a flow of the product X, which flows between the plant unit 1 and the plant unit 2 and has product characteristics which depend on a specific property of the a flow downstream is missing.

If such information is available, it can be used for automated balancing and data reconciliation.

In order to use structural information online for REI calculations as well as for retrospective material and energy efficiency analysis, the streams in a plant should be described in a formal manner by a resource flow information model. Based on this information model, a company can describe the energy and material flows of a site in an intuitive but nonetheless formal manner so that all the information which is needed for real-time energy or material performance calculations is merged and related to a structured holistic knowledge base. This knowledge base can also be used to calculate missing measurement data or to provide online plausibility checks based upon material or energy balance equations.

Such a modelling framework, as developed in MORE, acts as a central data and calculation hub, which attaches to the data semantic information and the necessary context. REIs can then be aggregated automatically using aggregation rules based on the plant hierarchy that is described by the resource flow model.

A generic aggregation approach to compute REIs by a bottom-up method is described in Section 2.9 and in Kalliski et al. (2016). Exploiting the information on the structure of the plant, the contribution of each subunit to the REI of the aggregated unit becomes transparent. This helps to quickly identify the source of the deviation from the expected behaviour.

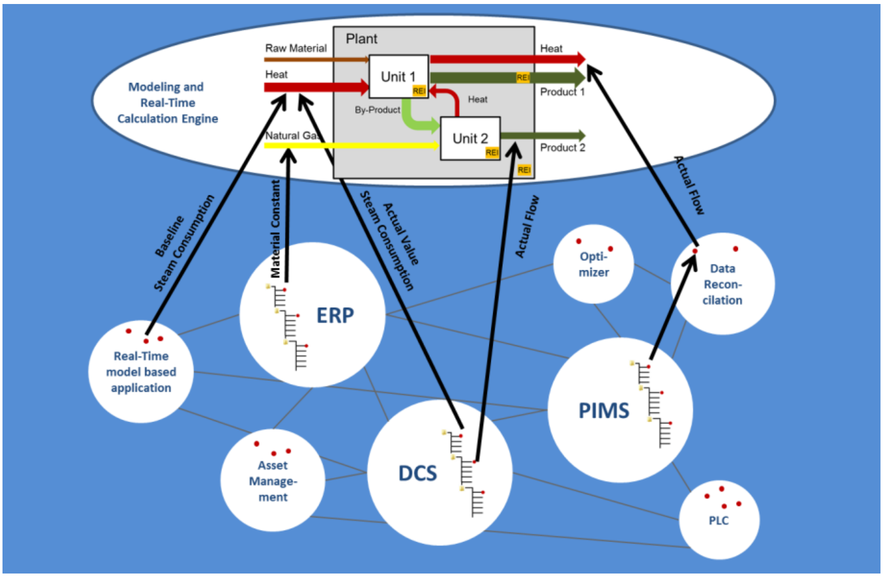

Figure 13. Use of a resource flow model of a site to link data points in heterogeneous data sources to data elements of the data model.

3.4.2 Building a resource flow model

In the first step a company specific Type Model must be designed (see Figure 14). The user must define what kinds of plants and plant units, what types of resource flows and what types of substances exist at the site. In addition, the user can decide what kind of properties and calculation methods should be designed on a type level. All properties and calculation methods which are specified on a type level are valid for all instances which will be derived from a specific type element. Furthermore, an organisational hierarchy should be specified in order to define balance volumes that correspond to the organizational structure and suitable REI aggregation functions.

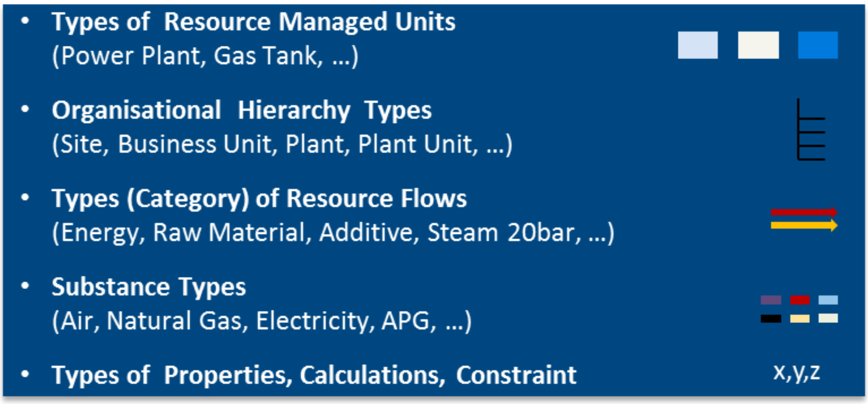

Figure 14. Step 1 – Specifying a Type Model.

In the second step the Type Model is used to define a site or plant specific instance of a generic resource flow model. The resource flow model is typically structured hierarchically and provides an overview of the network of interconnected resource flows and their properties.

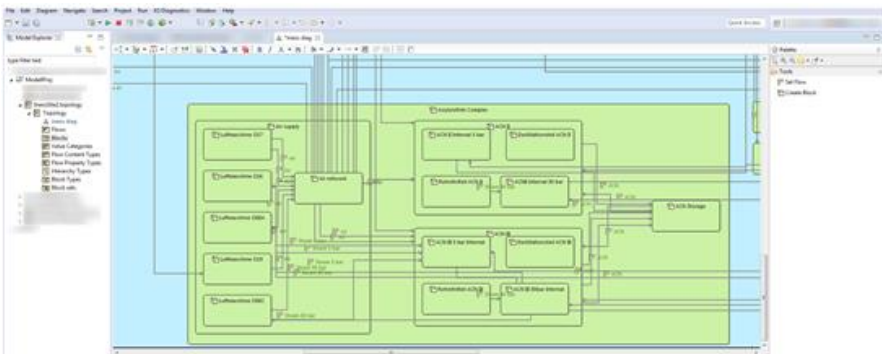

Figure 15. Step 2 – Modelling a site- or plant-specific resource flow structure.

In the third step, specific properties can be linked to the units and flows. For example a property which represents a measurement point can be linked to an external data point of a connected Plant Information Management System (PIMS).

In the final step, the visualization of the calculated results in an application-specific user interface is defined. These can be REI dashboards or decision support tools that include interactive interface elements for the users.

A tool to define and implement such an information model can be used as an add-on to Plant Information Management Systems (PIMS) or Manufacturing Execution Solutions (MES). Such a tool was developed in MORE by the partner LeiKon.

3.5 Overcoming potential obstacles and challenges in the definition and the implementation of REIs

Different challenges may arise during the definition and implementation of real-time REIs, for example technical problems with online measurements, workforce availability, lack of sufficient resources to cover costs, personnel not being motivated or management not being committed. **Table 8** lists some challenges that can occur and outlines potential approaches to overcome them.

Table 8. How to overcome the most typical problems and challenges in REI definition and implementation.

Problem/issue/challenge	Solution
Motivation of managers and operators to contribute to the definition and the implementation of REIs	Involving all affected parties from the beginning; discussions, meetings, workshops
Insufficient financial resources	Use of a stage-gate approach, performing a pre-study first. Provide realistic cost estimates. Approval of the cost by senior management. Timely and honest information about problems with costs and deadlines. Obtaining approval of modified budgets and timelines if necessary.
Lack of qualified personnel for realization of the REIs computation and visualization is not available as planned.	Extend the timeline. Use external resources. Increase staff.
Reluctant acceptance of new dashboards	Involve operators in dashboard design. Training in the use of the dashboards. Consider using flexible development/ software tools at the beginning in order to be able to adjust the design later, using the same data.
No full utilization of new real time REI	Repeated training and evaluation, implementation of optimisation algorithms offline or online on a suitable platform.
REIs are not sensitive to the actions of the operators or otherwise unsuitable.	Analysis of whether the considered indicator of resource efficiency can be influenced at all. The REI need to be modified or developed further.
The plant or the products or the mode of operation are modified.	Check whether REIs and baselines need to be adapted. Perform adaptation as soon as sufficient data is available. Decision support and optimization tools must also be adapted.
Insufficient quality of the measurements	Installation of new measurement devices. Re-calibration of existing measurements. Data reconciliation.
Lack of redundancy for data	Add new sensors at suitable locations to

Problem/issue/challenge	Solution
reconciliation with the current set of sensors	measure more quantities.
Software tools and algorithms for REI computation and visualization have to be updated repeatedly.	Use tools to structure the information about the plant structure, flows and REIs that are easy to use. Make sure that software is well documented.
Regulative or legislative challenges, e.g. claims that REIs are used to compare the performance of the operators.	Transparency of the project goals and implementation. Negotiations with authorities and representatives of the workforce.
Realized savings do not match the estimated potential.	Investigate the computations and the reasons for the inefficiency. Check whether all contributions to resource efficiency are captured with the developed and implemented REIs (e.g. production logistics, significant streams across system boundaries not included).
Implemented REIs are not monitored/ used by the operating staff	Include the evaluation of the indicators regularly in staff meetings, require inclusion of REIs in documentations and reports.
REIs not used by higher management	Provide indicators relative to baselines (c.f. Section 2.3), aggregate indicators, explain the meaning of the indicators.

4. Concluding remarks

Existing Key Performance Indicators (KPIs) can rarely support daily decision making processes in plant operations. With real-time Resource Efficiency Indicators (REIs) the effect of technical improvements and operational policies can be measured and actions can be derived for real-time or near real-time plant performance improvements.

This step-by-step guidebook has been developed to support the European process industry in gaining better knowledge of the production processes, leading to improvements in resource efficiency. The step-by-step procedure helps the user to identify and implement real-time or near real-time resource efficiency indicators suitable for monitoring plant operations and guiding managers and operators towards improved resource efficiency.

Sites, plants and processes in the process industries are quite diverse, and therefore different needs exist with a variety of readiness levels resulting in different utilization levels and routes in the selection and implementation process of new real-time REIs. Thus, this guidebook focuses on the generic aspects of the definition, calculation, visualization and use of REIs for decision support and real-time optimization (RTO).

References

Ackerschott, D., Beisheim, B., Krämer, S. & Engell, S. 2016. Industrial Application of Multi-criterial Decision Support to improve the Resource Efficiency. Cyber-Physical & Human-Systems CPHS 2016, Col 49, Issue 32, pp. 124–128.

Bagajewicz, M.J. & Jiang, Q. 2000. Comparison of steady state and integral dynamic data reconciliation, Computers & Chemical Engineering, Vol 24, Issue 11, pp. 2367–2383, ISSN 0098-1354.

Barker, M. and Rawtani, J. Practical Batch Process Management, Oxford: Elsevier, 2005, pp. 1-2.

Engell, S. 2007. Feedback Control for Optimal Process Operation, Journal of Process Control 17, 203–219.

European Commission. 2005. Impact assessment guidelines SEC (2005) 791.

European Commission. 2016. Resource Efficiency. http://ec.europa.eu/environment/resource_efficiency/ [Cited 30.8.2016]

Fitz-Gibbon, C. T. 1990, Performance indicators, BERA Dialogues (2), ISBN 978-1-85359-092-4.

Huber, P. 2014. Robust statistics, in: M. Lovric (Ed.), International Encyclopedia of Statistical Science, Springer Berlin Heidelberg, pp. 1248–1251.

IEC 62264:2013. Enterprise-control system integration.

ISO 50001:2011. Energy management systems -- Requirements with guidance for use.

ISO 50006:2016. Energy management systems. Measuring energy performance using energy baselines (EnB) and energy performance indicators (EnPI). General principles and guidance.

Kalliski, M. & Engell, S. 2016. Real-time resource efficiency indicators for monitoring and optimization of batch-processing plants. The Canadian Journal of Chemical Engineering. DOI: 10.1002/cjce.22717.

Kalliski, M., Beisheim, B., Krahe, D., Enste, U., Krämer, S. & Engell, S. 2016. Real-time resource efficiency Indicators - Material and energy efficient plant operation. atp- Automatisierungstechnische Praxis 01/2016.

Kalliski, M., Krahé, D., Beisheim, B., Krämer, S. & Engell, S. 2015. Resource efficiency indicators for real-time monitoring and optimization of integrated chemical production plants. Computer Aided Chemical Engineering 37, 1949–1954. ISBN 978-0-444-63429-0. http://dx.doi.org/10.1016/B978-0-444-63576-1.50019-4.

Kalliski, M., Voglauer, B., Seyfriedsberger, G., Röder T. & Engell, S. 2017. Resource efficient operation of an evaporator network in the viscose fiber production. Accepted for European Symposium on Computer-Aided Process Engineering 27, Barcelona, 2017.

Krämer, S. & Engell, S. (Eds.) 2017. Monitoring and Improvement of the Resource Efficiency of Processing Plants, book to be published Wiley-VCH, Weinheim, Germany in Summer 2017.

Lutter, S. & Giljum, S. 2005. Development of RACER Evaluation Framework. ERA-NET SKEP Project EIPOT.

Minnich, C., Hardy, S. & Krämer, S. 2016. Stopping the babylonian confusion: An updated nomenclature for process analyzers in PAT applications. Chemie Ingenieur Technik, 88 (6), 694–697, doi: 10.1002/cite.201500188.

MORE EU project. 2017a. D5.2 Report of conclusions about the use of REIs and the DSS to improve efficiency in the selected sites. Project deliverable.

MORE EU project. 2017b. D6.7 Impact assessment. Project deliverable.

MORE EU project. 2015a. D1.4 Visualization concept for multi-dimensional resource efficiency indicators. Project deliverable. http://www.more-nmp.eu/wp-content/uploads/2015/02/MORE-D1.4-Visualisation-concept-for-multi-dimensional-REIs1.pdf.

MORE EU project. 2015b. D3.1 Tool for What-If Analysis. Project deliverable. http://www.more-nmp.eu/wp-content/uploads/2015/05/MORE-D3.1-Tool-for-what-if-analysis.pdf.

MORE EU project. 2014a. D1.2 Set of real-time resource efficiency indicators for continuously operated integrated plants. Project deliverable. http://www.more-nmp.eu/wp-content/uploads/2016/02/D1.2_Set-of-real-time-REIs-for-continuously-operated-integrated-plants_public.pdf.

MORE EU project. 2014b. D1.3 Set of real-time resource efficiency indicators for batch processing plants. Project deliverable. http://www.more-nmp.eu/wp-content/uploads/2014/11/MORE-D1.3-Set-of-real-time-resource-efficiency-indicators-for-batch-processing-plants.pdf.

NAMUR 2017. Resource Efficiency Indicators for monitoring and improving resource efficiency in processing plants. NAMUR Recommendation NE 162. Planned Edition 2017.

NAMUR 2016b. Uniform Description of the Error of Measurement of Field Devices. NAMUR Recommendation NE 145. Edition 2016.

NAMUR 2015. Energy accounting Measurements in Chemical Parks. NAMUR Recommendation NE 147. Edition 2015.

Parmenter, D. 2010. Key performance indicators: Developing, implementing, and using winning KPIs, second edition (2nd ed.). Hoboken: John Wiley & Sons.

Romagnoli, J. & Sánchez, M.C. 2000. Data processing and reconciliation for chemical process operations. Academic Press.

SAMT. 2016. Best practice solutions: Methods for sustainability assessment within the process industries. SAMT - Sustainability assessment methods and tools to support decision making in process industries, EU-SPIRE 2015-2016. VTT. http://www.spire2030.eu/samt-

Taylor, J.H. & del Pilar, R. 2013. Nonlinear dynamic data reconciliation: In-depth case study, *2013 IEEE International Conference on Control Applications (CCA)*, Hyderabad, pp. 746–753.

Tufte, E.R. 2001 The Visual Display of Quantitative Information, Cheshire: Graphics Press.

Wiedmann, T., Wilting, H., Lutter, S., Palm, V., Giljum, S., Wadeskog, A. & Nijdam, D. 2009. Development of a methodology for the assessment of global environmental impacts of traded goods and services. SKEP ERA-NET Project EIPOT.

Appendix A: Principles of the real-time measurement of resource efficiency

Below, the eight principles of real-time REI definition and implementation are listed and explained in more detail.

- **Gate-to-gate approach**
  As the entity of interest is a production site, a plant or a process unit, the boundary of the analysis is the limit of the corresponding entity. The procurement of more environmentally friendly raw materials, or distribution to more or less sustainably operating customers is a business decision and is not influenced by the decisions of plant operators or plant managers. Thus, upstream and downstream contributions, e.g. to the carbon footprint, are initially not considered in the definition of real-time REI for chemical plants. Nevertheless, aggregation and extension to a life cycle assessment is possible and intended.

- **Indicating technical performance independently of market fluctuations**
  In the primary indicators, the flows of material and energy are not to be related to economic indicators such as the sales value of the products or the costs of resources. As a result, the technical performance is separated from the economic performance. If the economic value of streams is known, material and energy flow indicators can be converted to economically meaningful numbers, adding an influence of market conditions through price fluctuations of resources and products. The possibility of a trade-off between resource efficiency and economic performance was discussed in Chapter 2.4 and should be approached, if necessary, by providing the information transparently, e.g. by the computation of Pareto fronts, in order to allow strategic decisions resolve the conflict.

- **Based on material and energy flow analysis**
  The resource efficiency indicators are based on physical flows and the conversion of raw materials and energy to products and flows into the environment, which are objective characteristics of a production process independent of the extrinsic, possibly volatile economic conditions. The identification of important streams for the material and energy flow analysis must be made individually for each case. It must capture all relevant inputs, outputs and environmental impacts. Ideally, the material and energy balances are completely closed. If the same input material can be converted into either the product or the by-products, or serve as a source of energy, an integrated energy and material flow analysis must be performed. Different sources of energy can be aggregated using suitable units, e.g. total energy.

- **Resource and output specific with a potential for meaningful aggregation**
  Firstly, the system boundaries for computation of the primary REI must be defined. The size of the elements considered should be such that the indicators are unambiguous, i.e. that it is clear that improvements of the indicators demonstrate better process performance and are not possibly outweighed by negative effects on subsequent or previous steps (in the case of recycles) within a production process. Therefore the entities considered should be larger units with input and output streams that lead to a specified product, not individual pieces of equipment. If indicators for subunits are required, they must be comparable and it must be possible to aggregate them to the indicator of the whole unit. Only in this way can the influence of the subunit on the total and on a parallel unit be visualised.

  Secondly, all net flows of raw materials, energy, and products that cross the boundaries of the system under consideration must be determined. Each resource should be measured individually, without aggregation at this stage. In the next step, the specific flows and conversions inside the system limits are analysed in order to link the inputs to the outputs. An example of a list of streams and conversions that should be considered is shown in **Table 9**.

Table 9. Aspects to be considered during the definition of REI on the basis of MFA and EFA.

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

On the basis of the material and energy flow analysis, process specific REIs should be defined with respect to the resources and the products. The indicators can either be defined as intensities or efficiencies depending on the user preference. A definition based on resource intensity is shown below. This version of the indicator simplifies the aggregation over different contributions due to its use of the same basis (product output). The corresponding indicator defined as an efficiency is obtained by inverting the intensity indicator.

$$REI_{RPS} = \frac{Resource\ Input}{Product\ Output}$$

REIs that provide a physical number provide physical information. Such a resource- and product-specific (RPS) REI by itself does not indicate directly whether the process is operated well but it will, if compared with historical data, show plant resource efficiency changes. If optimal operation is desired, a reference case obtained from a theoretical analysis (based on a model) or from the best demonstrated practice (based on historical data) is the baseline to compare with. The best demonstrated practice may vary with external factors such as ambient conditions or plant load.

$$REI_{norm} = \frac{REI_{RPS}}{REI_{RPS,best\ case}}$$

A challenge in the application of such an analysis to chemical production complexes is the tree-like nature of the complex. Different products and products of different specifications (e.g. purities) are produced from an often lower number of resources and the specification of the products may determine the required resource input to a great extent. This will result in very different levels of physical resource efficiency figures and also in different best demonstrated cases. As such, different products should be treated differently. Nonetheless, for site- or plant-wide decisions, aggregation over product streams could be desirable. The degree of aggregation over products or resources, especially if it is used as a deviation from the best demonstrated practice, must be determined case-by-case.

- **Considering storage effects**
  In the definition of real-time REI the choice of the temporal aggregation interval is crucial. On the one hand, the interval should be short so that the indicators can be used to take operational decisions. On the other hand, storage effects should not be allowed to lead to incorrect indications. If material or energy is stored in the unit for a period of time and the amount stored varies, the indicators must either be computed over periods of time during which the storage effects can be neglected or, preferably, the hold-up change must be considered in the consumption or production figures. In addition, long-term effects such as catalyst degradation or fouling must either be used in the calculation period or be defined as a state for best demonstrated practice in a suitable manner.

- **Include environmental impact**
  The impact on the environment must be taken into account separately in order to measure the ecological performance. A full EFA and MFA will include energy losses and pollutant streams. Emission of pollutants to air, water and soil as well as the generation of solid waste per unit of product can be used as separate indicators. It must be considered for each case whether different categories are needed depending on the impact and the use of the waste streams. Amount of waste per product manufactured may have to be differentiated according to waste that is incinerated (and generates or consumes energy), re-used, e.g. as construction material, or

deposited. Defining an indicator for the amount of emissions and waste is the basis for evaluation of environmental impacts.

- **Hierarchy of indicators – from the whole production site to a single apparatus**
  If the various pieces of equipment of a process are interconnected in a complex fashion as shown in **Figure 16**, an REI for an individual apparatus may be misleading, because resource utilization can be shifted to other units by different local operational policies. Therefore the generic resource efficiency indicators must be defined on a scale on which the net effect on the resource efficiency can be measured in a meaningful way. In order to improve the overall resource efficiency which is monitored by the generic REI, specific indicators can be introduced on the operational level. Local REIs with direct meaning and relevance for the operators are useful and important in daily operations. In their definition, care must be taken to avoid false signals which lead to attempts to improve the local indicators at the expense of poorer overall performance. Transparent aggregation and contribution calculation is required in order to avoid this problem.

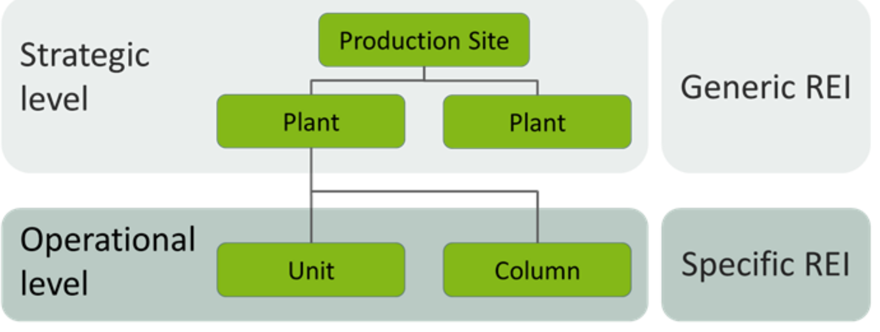

Figure 16. Strategic level can utilize generic indicators, and specific indicators are used on an operational level.

- **Extensible to life-cycle analysis**
  For the operational decisions in a processing plant, upstream or downstream influences may or may not be meaningful. The origin of oils from natural resources may, for example, influence the carbon footprint of the final product, but this cannot be influenced either by the technology of the plant or by its operation. The use of more environmentally friendly raw materials may even reduce the resource efficiency of the production unit, because of a higher energy input needed in purification steps. On the other hand, the carbon footprint may influence decisions on the use of renewable vs. fossil sources of energy. By initially performing the analysis on a detailed level (i.e. specifying electric energy or natural gas rather than just the consolidated consumption of energy), it is possible to consider such

external effects by relating the streams of mass and energy to environmental indicators such as the amount of CO_2 produced per unit of the resource. For reporting and assessment purposes, the REIs defined and used in MORE can be extended to a Life Cycle Assessment (e.g. CO_2-footprint) by weighting the different streams with the upstream impacts.

Appendix B: Resource efficiency indicators (REIs)

The indicator database compiled consists of 16 main indicators that are listed below in the form of indicator set-cards compiling the most important information. Furthermore, 41 derived indicators are briefly listed underneath. The database with the complete information about all indicators can be accessed online, including a process analysis feature to identify the correct indicators for your process: http://more.bci.tu-dortmund.de.

Name (Abbreviation):	Energy required (ER)	ID: IN001
Formula:		$ER = \frac{\sum_i E_i}{m_p}$
Efficiency category:		Energy
Direction of improvement (Type):		Lower (intensity)
Measurements required:	E_i: energy amount from source i m_p: product mass i: energy sources	
Description:	Energy required per unit of product	
	Energy Performance Indicator according to ISO 50001	

Name (Abbreviation):	Utilities/Raw Material required (MR)	ID: IN003
Formula:		$MR = \frac{U}{m_p}$
Efficiency category:		Material
Direction of improvement (Type):		Lower (intensity)
Measurements required:	U: required utility m_p: product mass	
Description:	Utilities/Raw Material required per unit of product (air, water, DI-water)	

Name (Abbreviation):	Unconverted Raw Material (URM)	ID: IN005
Formula:		$URM = \frac{\sum_i m_{R,i,in} - m_{R,i,converted}}{\sum_i m_{R,i,in}}$
Efficiency category:		Material
Direction of improvement (Type):		Higher (efficiency)
Measurements required:	i: reactants $m_{R,i,in}$: reactant mass of species i introduced to the process $m_{R,i,converted}$: converted reactant mass of species i	
Description:	Material losses in the process	

Name (Abbreviation):	Material Yield (MY)	ID:	IN006
Formula:		$MY = \frac{\sum_j m_{P,j,out}}{\sum_i m_{R,i,in}}$	
Efficiency category:		Material	
Direction of improvement (Type):		Higher (efficiency)	
Measurements required:	i: reactants j: products $m_{R,i,in}$: reactant mass of species i introduced to the process $m_{P,j,out}$: product output of product j		
Description:	Overall process yield based on mass flow, also "mass conversion"		

Name (Abbreviation):	Overall Resource Yield (ORY)	ID:	IN007
Formula:		$ORY = \frac{\sum_j C_{P,j} m_{P,j,out} + \sum_t C_{E,t} E_{t,out}}{\sum_i C_{R,i} m_{R,i,in} + \sum_t C_{E,t} E_{t,in}}$	
Efficiency category:		Material/Energy	
Direction of improvement (Type):		Higher (efficiency)	
Measurements required:	i: reactants j: products t: weighting factor $E_{t,in/out}$: energy amount of type t introduced/created $m_{R,i,in}$: reactant mass of species i introduced to the process $m_{P,j,out}$: product output of product j		
Description:	Overall process yield based on weighted flows		

Name (Abbreviation):	Specific Product Loss (SPL)	ID:	IN008
Formula:		$SPL = \frac{\sum_j m_{P,loss,j}}{\sum_j m_{P,j,out}}$	
Efficiency category:		Material	
Direction of improvement (Type):		Lower (intensity)	
Measurements required:	j: products $m_{P,j,out}$: product output of product j $m_{P,loss,j}$: losses of product j		
Description:	Loss of valuable product specific to the amount of product produced		

Name (Abbreviation):	Overall Weighted Waste (OWW)	ID: IN011
Formula:		$OWW = \frac{\sum_i C_i m_{W,i}}{m_p}$
Efficiency category:		Material
Direction of improvement (Type):		Lower (intensity)
Measurements required:	i: waste type C: weighting factor $m_{W,i}$: waste mass of species i m_p: product mass	
Description:	Waste based on waste "currency" per unit of product	

Name (Abbreviation):	Specific Catalyst loss (SCL)	ID: IN016
Formula:		$SPL = \frac{m_{cat,loss}}{m_p}$
Efficiency category:		Material
Direction of improvement (Type):		Lower (intensity)
Measurements required:	m_p: product mass $m_{cat,loss}$: mass of catalyst lost	
Description:	Process performance with respect to catalyst losses	

Name (Abbreviation):	Overall Efficiency based on Energy Currency (OEEC)	ID: IN025
Formula:	$OEEC = \frac{\sum_i (EC_i m_{i,in}) - \sum_j (EC_j m_{j,out}) + E_{el} EC_{el} + Q_{Steam} EC_{Steam}}{m_p}$	
Efficiency category:	Material/Energy	
Direction of improvement (Type):	Lower (intensity)	
Measurements required:	i: waste type EC: weighting factor Energy currency $m_{i,in}$: mass of ingoing species i $m_{i,iout}$: mass of outgoing species i m_p: product mass	
Description:	Energy streams of different nature are weighted by an energy currency which accounts for the different value of the energy streams (e.g. electrical power has a higher value compared to steam (exergy)).	

Name (Abbreviation):	Overall Operation Efficiency based on Utility Currency (OEUC)	ID: IN026
Formula:	$OEUC = \frac{\sum_i (UC_i M_i) + \sum_{t=0}^{t_{op}} (E_{el}(t) * UC_{el} + \sum_{i=1}^{ns} UC_i * Q_i(t))}{t_{op}}$	
Efficiency category:	Material/Energy	
Direction of improvement (Type):	Lower (intensity)	
Measurements required:	M_i: fixed utilities required to start Q_i: utility streams UC: weighting factor utility currency E_{el}: electrical energy ns: number of utility streams t_{op}: total operation time	
Description:	Total use of utilities of different nature (streams, catalysers, cleaning products, etc.) per unit of time, which are weighted by utility currency, accounting for their different costs.	

Name (Abbreviation):	Component Material Efficiency (ME)	ID: IN033
Formula:	$ME = \frac{\sum_p m_{p,stoic,k}}{m_{k,in}}$	
Efficiency category:	Material	
Direction of improvement (Type):	Higher (efficiency)	
Measurements required:	$m_{p,stoic,k}$: stoichiometric mass equivalent of the reactant k incorporated into the product material (formula given at the end of this appendix) $m_{k,in}$: mass of reactant k introduced	
Description:	stoichiometric mass equivalent of raw material k in product p per mass of k introduced	

Name (Abbreviation):	Component Material Input (MI)	ID: IN034
Formula:	$MI = \frac{m_{k,in}}{m_p}$	
Efficiency category:	Material	
Direction of improvement (Type):	Higher (efficiency)	
Measurements required:	m_p: product mass $m_{k,in}$: mass of reactant k introduced	
Description:	mass of raw material k introduced per mass of product obtained	

Name (Abbreviation):	Overall Resource Efficiency (ORE)	ID: IN035
Formula:		$ORE_j = \frac{\sum_i m_{p,i}}{r_j}$
Efficiency category:		Material or Energy
Direction of improvement (Type):		Lower (intensity)
Measurements required:	$m_{p,i}$: mass of product i r_j: resource used of resource entity j	
Description:	Sequence-dependent resource consumption and other overhead efficiency	

Name (Abbreviation):	Separation Yield (SY)	ID: IN038
Formula:		$SY = \frac{m_{C,resid} + m_{W,resid}}{m_{C,feed} + m_{W,resid,max}}$ with $m_{W,resid} \leq m_{W,resid,max}$
Efficiency category:		Material
Direction of improvement (Type):		Higher (efficiency)
Measurements required:	$m_{C,resid}$: mass of valuable component C in the product $m_{W,resid}$: mass of water in the product $m_{C,feed}$: mass of valuable component C fed to the separation unit $m_{W,resid,max}$: maximum of residual water allowed in product formulation	
Description:	Mass of valuable component C plus water obtained from purification per theoretical maximum.	

Name (Abbreviation):	Gaseous Emissions (GE)	ID: IN044
Formula:		$GE = \frac{\sum_i m_{i,ge}}{m_p}$
Efficiency category:		Material
Direction of improvement (Type):		Lower (intensity)
Measurements required:	$m_{i,ge}$: mass or volume of gaseous emissions of type i m_p: product mass	
Description:	Sum of gas emission per unit of product	

Name (Abbreviation):	Global warming potential (GWP)	ID: IN056
Formula:		$GWP_{tot} = \sum_i C_{GWP,i}\, m_i$
Efficiency category:		Environmental
Direction of improvement (Type):		Lower
Measurements required:	m_i: mass of emission i $C_{GWP,i}$: GWP weight for material i	
Description:	Mass of CO_2 equivalent (eq) for selected functional unit	

Derived Indicators:

ID	Abbreviation	Indicator	Parent indicator
IN002	REE	Relative Energy Efficiency	IN001
IN004	RME	Relative Utility/Raw Material Efficiency	IN003
IN009	SRL	Specific Resource Loss	IN007
IN010	W	Waste	IN011
IN012	TOC	Total Organic Carbon	IN011
IN013	VOC	Volatile Organic Compounds	IN011
IN014	S	Selectivity	IN033
IN015	C	Conversion	IN005
IN017	CHPE	CHP Efficiency	IN007
IN018	OPPE	Overall Power Plant Efficiency	IN007
IN019	FE	Furnace Efficiency	IN007
IN020	LFG	Loss to Flare Gas	IN007
IN021	RLFG	Resource Loss to Flare Gas	IN007
IN022	FEL	Flare Energy Loss	IN007
IN023	PLFG	Product loss to Flare Gas	IN007
IN024	OEE	Overall Enthalpy Efficiency	IN025
IN027	CTE	Cooling Tower Efficiency	IN007
IN028	CEE	Cooling Energy Efficiency	IN031
IN029	EEE	Electrical Energy Efficiency	IN031
IN030	HEE	Heating Energy Efficiency	IN031
IN031	TEE	Total Energy Efficiency	IN024
IN032	HP	Heat Product	IN025
IN036	PEE	Purification Energy Efficiency	IN031
IN037	RE	Reactant Efficiency	IN006
IN039	TME	Total Material Efficiency	IN007
IN040	TRE	Total Reactant Efficiency	IN037
IN041	WP	Waste Production	IN010
IN042	TWP	Total Waste Production	IN041
IN043	WU	Water Usage	IN007

ID	Abbreviation	Indicator	Parent indicator
IN045	BP	By-Products	IN007
IN046	MWV	Materials used by weight or volume **G4-EN1**	IN006
IN047	ECO	Energy consumption within the organization **G4-EN3**	IN007
IN048	EI	Energy intensity **G4-EN5**	IN007
IN049	TW	Total water withdrawal by source **G4-EN8**	IN003
IN050	TWW	Total weight of waste by type and disposal method **G4-EN23**	IN010
IN051	TMC	Total material consumption	IN007
IN052	TEC	Total energy consumption	IN006
IN053	TMO	Total material output	IN007
IN054	TEO	Total energy output	IN006
IN055	PO	Processed output	IN007
IN057	FPE	Finished products efficiency performance	IN007

$m_{k,stoic,p}$ is the mass of reactant k that is incorporated into valuable product and $m_{in,k}$ is the mass of substance k fed to the batch. The material efficiency improves with the selectivity of the reaction ($\sum_p m_{k,stoic,p}$ increases) and the minimization of material losses ($m_{in,k}$ decreases). For an arbitrary reaction according to Equation (A2-1), $m_{k,stoic,p}$ is calculated by Equation (A2-3). The required coefficients $\nu_{k,p}$ are obtained by decomposition into the ideal net formation reactions of the products, see Equation (A2-2),

$$\underbrace{\sum_i \nu_k R_k}_{reactants} \rightarrow \underbrace{\sum_p \nu_p P_p}_{products} + \underbrace{\sum_t \nu_t W_t}_{waste} \quad \text{(A2-1)}$$

$$\sum_k \nu_{k,j} R_k \rightarrow \nu_p P_p \quad \forall\, p \text{ with } \nu_k = \sum_p \nu_{k,p} \quad \text{(A2-2)}$$

$$m_{k,stoic,p} = n_{k,stoic,p} M_k = n_p \frac{|\nu_{k,p}|}{\nu_p} M_k = m_p \frac{|\nu_{k,p}|}{\nu_p} \frac{M_k}{M_p} \;\forall\, k, p \quad \text{(A2-3)}$$

Here, M_k and M_p are the molecular weights and $\nu_{k,p}$ and ν_p are the stoichiometric coefficients. In cases in which the raw material is converted into multiple products or into an additional undesired side product, the atom efficiency is taken into account.

Appendix C: Batch and continuous processes

Industrial process is a generic term describing equipment and procedures that chemically, physically or mechanically transform raw materials in order to obtain products. In general, industrial processes can be categorized either as discrete, continuous, batch and semi-batch or mixed processes (Barker and Rawtani 2005). The following table gives definitions for each of the process types.

Table 10. Definitions for discrete, continuous and batch processes.

Process type	Definition
Discrete processes	Each part or product undergoes a sequence of operations that are performed by machines, a combination of machines, assembly lines and the like. The products can be uniform over longer periods of time, be produced in product batches or be individual items with specific features. Discrete processes are typically found in the manufacturing industry.
Continuous processes	Streams of material enter, flow through, and leave the processing equipment continuously. For longer periods of time, the processing conditions vary only slightly around predefined operating points, or are adapted slowly to compensate for drifts in the process. Usually there is a significant amount of back-mixing or of material recycling within the process, to increase the overall material and energy efficiency of the process. This leads to the fact that it cannot be said precisely from which raw material and under what conditions a certain amount of product has been produced. Continuous plants can be operated in campaigns during which the raw materials and the products remain essentially constant, whereas in between the campaigns the raw materials and/or the processing conditions are changed so that different products (usually the same product with different grades, as in the high-volume production of polymers) are generated.
Batch and semi-batch processes	Batch processes convert defined and discrete amounts of materials into products with the desired properties. During the production the materials undergo a series of steps that take place in the same piece of equipment or in different pieces of equipment. In the latter case, transfer operations between the processing steps are performed. Each step of the production procedures is a dynamic process that starts from a certain condition (state) of the material in the batch and ends with a different state of the material. Typical steps are heating, reaction, mixing, cooling, and separations that are performed in batch mode. Within one piece of equipment, the transformations occur gradually over time but the location of the material does not change. In fed-batch (or semi-batch) processes, some of the material is added gradually to the batch, e.g. to reduce the amount of

Process type	Definition
	heat produced during a reaction or to facilitate mixing. From the point of view of the dynamics of the individual processing step, semi- or fed-batch processes are different from batch processes and have more degrees of freedom (the feed rates), but if the batch is only considered before and after a processing step, there is no difference between pure batch and semi-batch operation.
Mixed processes	Some production processes consist of continuously operated units and of units operated in batch mode, according to the easiest and/or most economical way to perform the different production steps. Between continuous processes and batch units, storage tanks are needed. One continuous process may feed several batch production lines and several batch lines may feed further continuous processing lines. Such a setting can be beneficial e.g. when the reaction stage is difficult to perform continuously but the throughput is high enough for continuous purification steps, or conversely because the downstream operations can only be performed in batch mode.

When defining resource efficiency indicators for processes and plants, a distinction must be made between continuous and batch processes. Many products of the chemical industry, as well as e.g. of the food industry and pharmaceuticals, are produced in batch mode in which the transformations are applied to a well-defined, discrete amount of material. For such processes, tailored real-time resource efficiency indicators are needed. For continuous plants, many currently used resource efficiency indicators make sense and can be used in steering the operation of the plant.

Real-Time Resource Efficiency Indicators for continuously operated integrated plants

The mass and energy flow indicators can depend strongly on the specification of the product, in particular on its purity and other properties, e.g. colour, because meeting tighter specifications requires a higher input of energy and of some material, e.g. for bleaching. Therefore product always means product with specific properties. In multiproduct plants the indicators are given on a product reference basis. They commonly refer to the main product or a group of desired products.

Detailed descriptions and explanations for developed indicators, MFA and EFA analyses, primary energy usage, total thermodynamic energy content and energy currency are publicly available in MORE [2014a].

Real-Time Resource Efficiency Indicators for batch processes

Batch processes, due to their transient nature and the logistic aspects involved, require special attention in the definition of resource efficiency indicators. Indicators must be defined per batch and monitored along the trajectory of the batch (i.e. the sequence of production steps) and compared to a standard ("golden batch") for the same amount and type of product.

In the definition of real-time resource indicators for batch processes, two aspects are crucial. Firstly, the feeds of material and energy into a batch process vary over time, but only the total consumption of resources for each batch produced matters, not the instantaneous consumption. Secondly, the integrity of the individual batches facilitates the monitoring of the resource efficiency of batch production. The "natural" discretization of time for batch production is the production period of each batch.

Detailed descriptions for developed indicators and explanations and helpful figures for understanding the batch process indicators are publicly available in MORE (2014b).

Appendix D: The MORE-RACER REI evaluation methodology

In MORE the modified RACER structured evaluation approach is utilised to analyse the performance of resource efficiency indicators qualitatively and quantitatively. The framework proposed here will usually not deliver a single best indicator, but illustrates differences between several indicators and provides a basis for an informed selection of REIs (Kalliski et al. 2015).

MORE-RACER is based upon the RACER methodology proposed by the European Commission (2005) which has shown its usefulness e.g. in the EIPOT project (Wiedmann et al. 2009).

MORE-RACER is a specialization of the RACER approach which was developed specifically to evaluate resource efficiency indicators that are computed in real-time and can provide guidance for the daily operations of a plant or a single unit of a process.

Relevant

- **Goal-related**
  The indicator must be related to resource efficiency and reflect changes in performance with respect to resource efficiency.
- **Suitable for the time horizon considered**
  The indicator is suitable for real-time monitoring. The time scale considered is from minutes to campaigns in which one specific raw material is processed. Variations of resource efficiency over time (e.g. day or night, summer or winter) should be reflected appropriately.
- **Influenced by the actions of the operators**
  Decisions and actions applied by the operators have an influence on the REI so that it can be used to optimize the resource efficiency of the plant or unit.
- **Transferable to other industries**
  Since MORE aims standardization, the REI should be applicable to as many industrial sectors and companies as possible. Indicators should be defined in a general way, avoiding unit- or process-specific references.

Accepted

The proposed indicator should be accepted by:

- **Stakeholders (e.g. higher management)**
  Stakeholder acceptance is helpful for realization of resource efficiency monitoring and optimization projects. The REI should be suitable for reporting and strategic decision making.
- **Plant managers**
  Meaningful reflection of the overall process state and transparency of the indicator increases the acceptance by the plant managers.

- **Plant operators**
  Unambiguous and transparent REI support acceptance by the operators.
- **Academia**
  Concepts and indicators that are accepted by academia are more likely to be the subject of teaching, further research and hence further improvement.
- **Public**
  The evaluated resource efficiency indicator can be communicated to the customers or to the general public in order to prove a resource-efficient and environmentally friendly production.

Credible

- **Consistency in direction and magnitude**
  Changes in the value of the REI occur when the actual performance in terms of resource efficiency shifts. The direction of the movement is the same for the REI and for the real performance and ideally the relationship is linear.
  Unambiguous information provided by an indicator is clear and can be related to decision making without the need for extensive explanations.
- **Transparency of data collection and data treatment**
  It is explicitly stated how the data should be collected/measured and which pre-treatments (filtering, averaging) can be applied.
- **Avoidance of double accounting**
  The REI does not describe the same phenomenon as an already utilized REI. Computation of the REI does not count an influence twice.
- **Clear documentation of assumptions and limitations**
  Assumptions that are made and limitations of the indicator (e.g. it is only appropriate in a specific range) are pointed out.

Easy

- **Technical feasibility**
  Hard- and software to measure, calculate and display the REI is available or can easily be installed. It is technically feasible to realize an appropriate sampling rate and measurement delay for the considered time horizon.
- **Data availability**
  Measurements of the required data exist and historical data is also available as a reference. Otherwise the installation of the measurements must be feasible and the cost for this must be taken into account.
- **Automatically compiled, displayed and reported**
  It is feasible to implement an automatic processing of the measured data, such that the indicator can be computed and displayed in real-time to give feedback on the current resource efficiency. Furthermore, batch, campaign and/or monthly reports can be compiled to provide impact assessments.
- **Predictive models can be derived**

Predictive cause-effect models are able to represent the response of the indicators for a plant, plant section or unit to the actions of the operator at the required level of detail. These models are either existent or can be derived with moderate effort.

Robust

- **Theoretical background**
  The theory behind the definition of the indicator is valid without gaps or questionable assumptions.
- **Data quality**
  The accuracy and reproducibility of the (processed) measurements are sufficient to avoid significant fluctuations in the indicator due to measurement errors.
- **Reliability**
  The necessary measurements are reliable and continuously available.
- **System boundaries, energy and mass balances**
  Balances of the system in terms of energy and material can be closed, based upon a clear definition of the system boundary. There is no missing information on important streams.

The evaluation is performed in two ways. A grading system for all main and sub-criteria presented in this framework is utilized which enables the users to perform an approximate screening of the proposed REIs. The range is between 0 and 2 points, where 0 means “criterion not fulfilled”, 1 point represents “partially fulfilled” and 2 points means “completely fulfilled” (Lutter & Giljum 2008). In addition, keywords can be used to annotate the score.

Series title and number

VTT Technology 290

Title	**Successful Resource Efficiency Indicators for process industries** Step-by-step guidebook
Author(s)	Marjukka Kujanpää, Juha Hakala, Tiina Pajula, Benedikt Beisheim, Stefan Krämer, Daniel Ackerschott, Marc Kalliski, Sebastian Engell, Udo Enste & José L. Pitarch
Abstract	Indicators for the resource consumption and environmental impacts of products and production processes in process industries have been developed and are increasingly used for many purposes. Most companies monitor their energetic and material efficiency and report Key Performance Indicators (KPI), normally in retrospect over extended periods of time (e.g. per business year). KPI reflect the choice of raw materials, the plant technology used and the operational performance without distinguishing between the different influences. As such, they cannot support decision-making processes in daily plant operations. With real-time Resource Efficiency Indicators (REIs), the effect of technical improvements and of operational policies can be measured and actions can be derived for real-time or near real-time plant performance improvements. This step-by-step guidebook will support the European process industry in identification and selection of relevant REIs from the operational point of view. The methodology consists of twelve steps for selecting and defining the process units for consideration, identifying and selecting REIs, and implementing and evaluating them. The guidebook provides a technical introduction to the methods that should be used and a detailed step-by-step procedure that can be followed to successfully implement the core ideas of real-time resource efficiency monitoring and improvement. For reference, additional technical details are provided in the appendices.
ISBN, ISSN, URN	ISBN 978-951-38-8517-5 (URL: http://www.vttresearch.com/impact/publications) ISSN-L 2242-1211 ISSN 2242-122X (Online) http://urn.fi/URN:ISBN:978-951-38-8517-5
Date	February 2017
Language	English
Pages	57 p. + app. 18 p.
Name of the project	Real-time Monitoring and Optimization of Resource Efficiency in integrated Processing Plants (MORE)
Commissioned by	European Commission
Keywords	guidebook, resource efficiency, REI, resource efficiency indicators, efficiency analysis, real-time, process industry, decision support
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111

VTT TECHNOLOGY 290 Successful Resource Efficiency...

Successful Resource Efficiency Indicators for process industries

Step-by-step guidebook

Indicators for the resource consumption and environmental impacts of products and production processes in process industries have been developed and are increasingly used for many purposes. Most companies monitor their energetic and material efficiency and report Key Performance Indicators (KPI), normally in retrospect over extended periods of time (e.g. per business year). KPI reflect the choice of raw materials, the plant technology used and the operational performance without distinguishing between the different influences. As such, they cannot support decision-making processes in daily plant operations. With real-time Resource Efficiency Indicators (REIs), the effect of technical improvements and of operational policies can be measured and actions can be derived for real-time or near real-time plant performance improvements.

This step-by-step guidebook will support the European process industry in identification and selection of relevant REIs from the operational point of view. The methodology consists of twelve steps for selecting and defining the process units for consideration, identifying and selecting REIs, and implementing and evaluating them. The guidebook provides a technical introduction to the methods that should be used and a detailed step-by-step procedure that can be followed to successfully implement the core ideas of real-time resource efficiency monitoring and improvement. For reference, additional technical details are provided in the appendices.

ISBN 978-951-38-8517-5 (URL: http://www.vttresearch.com/impact/publications)
ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8517-5