Real-time Resource Efficiency Indicators
Resource efficiency

- The **resource efficiency** of chemical plants is influenced by:
  - Plant design
  - **External influences** (e.g. weather, feedstock quality,...)
  - **Operation** and maintenance

- **Goal of the EU Project MORE:**

  Efficiency improvement by **better operation**
  based on **RTREI** and decision support

**KPI**
- Retrospective
- For reporting

**RTREI**
- Real-time
- For Optimization
Screening of available indicators

- Many existing standards and proposals
- Indicators are for large-scale analysis, e.g. of the economy of a complete country
- Intention often is to reduce to one or very few indicators, e.g. land use, CO₂ footprint
- Not directly useful for steering plant operations
Principle: MORE from less!

- Indicators measure the input of resources per unit of valuable outputs (products) over a (short) period of time.

  $$REI = \frac{Resource\ Input}{Product\ Output}$$

- **Resources**: Materials, electricity, fresh water, ....
- **Outputs**: Products with specified properties.
- Indicators initially should be **specific**: Specific consumption of energy in case of the use of raw material A for the product with specification Y.
Material and energy flow analysis

- Site fence (or plant boundary) defines the system boundary

- All inputs and outputs must be considered
- Alternative use / conversion must be taken into account
- Split of resources between products must be determined

Raw material

Natural gas

Heat

Unit 1

Unit 2

Product 1

Product 2

Heat

Heat

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Specific RTREI

- Resource input per product output

\[ REI_{RPS} = \frac{\text{Resource input}}{\text{Product output}} \]

RPS = Resource and product specific

- In order to be useful for plant operators, RTREI should be related to a baseline

\[ REI_{\text{norm}} = \frac{REI_{RPS}}{REI_{RPS,\text{Referenz}}} \]

- Baseline:
  - Historical data – best observed operations
  - Model-based optimization
  - Thermodynamic or stoichiometric limits
Environmental load

• Must also be included – separate indicators
• Many possible indicators
  – Use of fresh water
  – Polluted water of different categories
  – Gaseous emissions (greenhouse gases)
  – Harmful emissions
  – Solid waste of different categories
• Relevance depends on the location
<table>
<thead>
<tr>
<th>Output REI</th>
<th>Formula</th>
<th>Explication</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Main products</td>
<td>$\frac{m_{product}[t]}{m_{product_max}[t]}$</td>
<td>Overall asset effectiveness</td>
</tr>
<tr>
<td>2.2. By-products</td>
<td>$\Delta \frac{m_{component}[t]}{m_{product}[t]}$</td>
<td>Difference to target value</td>
</tr>
<tr>
<td>2.3. Energy delivered</td>
<td>$\frac{m_{delivered_energy}[kWh\ or\ t]}{m_{product}[t]}$</td>
<td></td>
</tr>
<tr>
<td>2.4. Water discharge</td>
<td>$\frac{V_{waste\ water}[m^3]}{m_{product}[t]}$ and/or $\frac{m_{TOC}[mg]}{V_{waste\ water}[m^3]}$</td>
<td>Waste water quantity to the sewerage network; TOC = total organic carbon</td>
</tr>
<tr>
<td>2.5. Emissions to air</td>
<td>$\frac{m_{VOC}[mg]}{V_{gas\ emission}[m^3]}$ and/or $\frac{m_{NOx\ or\ SO2}[mg]}{V_{gas\ emission}[m^3]}$</td>
<td>VOC = volatile organic carbon</td>
</tr>
<tr>
<td>2.6. Solid waste</td>
<td>$\frac{m_{waste}[t]}{m_{product}[t]}$</td>
<td>Waste has to be specified (Recovered, recycled, disposed)</td>
</tr>
</tbody>
</table>
Combined mass and energy flow analysis

- Raw materials can be converted or used as a source of energy (e.g. by exothermic side reactions)
- Introduction of the “Total Energy Consumption”

\[
REI = \frac{\sum_{i=1}^{n_{Steam}} m_{S,i} + W_{el} + m_{FG} H_{FG}^U + \sum_{j=1}^{n_R} \Delta H_j^R}{m_p}
\]

- Accounts for the flows of energy due to the heat of reaction of the main reaction and the reaction to by-product
- Influence of operation on performance increases as catalyst selectivity is taken into account
Dynamic effects

• When REI are computed over short periods of time, storage effects may distort them.

• If large recycle streams are present, feedback effects occur on a long time scale.

• Remedies:
  – Choose integration period long enough
  – Include storage terms (accumulation/depletion) into the computation

• Long-term effects must be included in some cases
  – Deactivation of a catalyst dependent on the mode of operation
Primary and secondary RTREI

- Primary RTREIs for monitoring, optimization, reporting and decision making on the plant level
- Secondary RTREIs for use in day to day operations of individual units
Secondary indicators

• Measure the efficiency of units or of pieces of equipment
  – E.g. steam consumption per ton of material processed
  – Local view, may not always be correct from a global perspective ("shift of burden")

• Helpful for operators and managers to assess and improve the daily operations

• Only comparable under similar conditions
Clear focus on resource efficiency

- Resource efficiency indicators should not be mixed with economic performance indicators
- Economic performance can be indicated in addition to explore trade-offs
  - Pareto front indicates the trade-off
- The choice of the operating point is a management decision
Extension to LCA

• Extension to life-cycle assessment and CO$_2$-footprint possible by including additional (upstream) information

• But: RTREI should guide managers and operators
  → should be independent of external factors and decisions
  → should be normalized for different conditions (baseline)
RTREI for batch and mixed plants

- Individual batches
  - Homogeneous product
  - Allocation of resources to this batch

- Overall production
  - Plant logistics
    - Scheduling performance
    - Bottlenecks
  - Slow dynamics
    - Catalyst degradation
    - Fouling

![Diagram of RTREI for batch and mixed plants]

Legend:
- A1
- A2
- B
- C
- Waiting
RTREI for individual batches

Electrical energy efficiency
\[ EEE = \frac{\sum_i W_{i,el}}{m_{product}} \]

Heating energy efficiency
\[ HEE = \frac{\sum_j Q_{j,H}}{m_{product}} \]

Cooling energy efficiency
\[ CEE = \frac{\sum_m W_{m,cool}}{m_{product}} \]

Heat product
\[ HP = \frac{Q_{gen}}{m_{product}} \]

Material efficiency
\[ ME_k = \frac{m_{k,in}}{\sum_p m_{p,eq,k}} \]

Total material efficiency
\[ TME = \frac{\sum_k m_{k,in}}{m_{product}} \]

Waste production
\[ WP_j = \frac{m_{j,waste}}{m_{product}} \]

Total waste production
\[ TWP = \frac{\sum_j m_{j,waste}}{m_{product}} \]

Total energy efficiency
\[ TEE = \frac{\sum_i W_{i,el} + \sum_j Q_{j,H} + \sum_m W_{m,cool}}{m_{product}} \]

Material efficiency
\[ TME = \frac{m_{k,in}}{\sum_p m_{p,eq,k}} \]

Total waste production
\[ TWP = \frac{\sum_j m_{j,waste}}{m_{product}} \]

Water Usage
\[ WU = \frac{m_{water,in}}{m_{product}} \]

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Treatment of recycles

- Recycles in batch productions
  - The amount of recycled material may vary
  - The input is adjusted accordingly
  - These variations should not influence the efficiency of the batch

- Material input must be corrected for RTREI calculation
  - Example: Material efficiency

\[
ME_{k,\text{recycle}} = \frac{m_{k,\text{in}} + (m_{k,\text{recycle,in}} - m_{k,\text{recycle,out}})}{\sum_p m_{p,eq,k}}
\]
Merging batches

- Parallel batches in different units are merged to the final product batch

- Calculation of resource efficiency indicators
  - Considered as a single batch
  - Calculation as for the single batch case
  - Same set of indicators
Splitting batches

• Homogeneous splitting

\[ \alpha_i = \frac{m_i}{m_{in}} \text{ with } \sum_i \alpha_i = 1 \]

→ Weighting of all consumed resources
→ REI for both product batches

• Splitting by separation

\[ \beta_i = \frac{m_{pi}}{m_{p1} + m_{p2}} \text{ with } \sum_i \beta_i = 1. \]

→ Consumed energy is weighted by factor 
\[ W_{el,i} = W_{el,in} \cdot \beta_i \]
Transitions batch ↔ continuous

\[ m \equiv \text{total mass in CSTR} \]
\[ m_p \equiv \text{product mass in CSTR} \]
\[ r_i \equiv \text{resource consumption per product (upstream)} \]

**Model equations**

\[
\frac{dm}{dt} = \dot{m}_1 + \dot{m}_2 - \dot{m}_{out}
\]

\[
\frac{dm_p}{dt} = \dot{m}_1 w_1 + \dot{m}_2 w_2 - \dot{m}_{out} \frac{m_p}{m}
\]

\[
\frac{dr_i}{dt} = \frac{\dot{m}_1 w_1}{m_p} (r_{i,in,1} - r_i) + \frac{\dot{m}_2 w_2}{m_p} (r_{i,in,2} - r_i)
\]

with

\[
\dot{m}_1(t) = \begin{cases} 
0, & t < t_1 \\
m_1 / (t_2 - t_1), & t_1 \leq t \leq t_2 \\
0, & t > t_2 
\end{cases}
\]

\[
\dot{m}_2(t) = \begin{cases} 
0, & t < t_3 \\
m_2 / (t_4 - t_3), & t_3 \leq t \leq t_4 \\
0, & t > t_4 
\end{cases}
\]
Transitions batch ↔ continuous

\[ m \equiv \text{total mass in CSTR} \]
\[ m_p \equiv \text{product mass in CSTR} \]
\[ r_i \equiv \text{resource consumption per product (upstream)} \]
REI for overall batch plant

• Resource consumption that cannot be attributed to a single batch
  – Catalyst exchange
  – Recycle purification
  – Cleaning resource consumption
  – Effect of production scheduling

Overall resource efficiency

\[ ORE_i = \frac{m_i}{m_{\text{product,total}}} \]

• Statistical analysis of the individual batch RTREI on a medium time horizon (> weeks)
  – Discover effects of plant logistics (bottlenecks)
  – Evaluate scheduling performance
Sugar Plant

Evaporator section

Crystallizer section

Recovery section

Inefficient

Efficient

Heating energy efficiency HEE

Cooling energy efficiency CEE

Material efficiency ME

Water Usage WU

Bullet-Chart

Heating energy efficiency

\[ \text{HEE} = \frac{\sum Q_{LH}}{m_{\text{product}}} \]

Measurements: T01225 – T01231

Data treatment: 10 min average

Crystallizer section

Total energy efficiency TEE

Pan A1

Pan A2

Pan A3

Warning

Trend

Variability in set

Current numerical value

Current value symbol

Trend

Warning

Inefficient

Efficient
Summary: Definition of RTREIs

• First step: Primary Resource Efficiency Indicators
• Material and energy flow analysis is the core
• Site fence defines the system boundary
• Environmental load (emissions/waste) should be considered separately
• Refinement to secondary (tactical) indicators
• Trade-off with economic criteria not to be mixed with REIs
• Aggregation of indicators and addition of information on the incoming streams \( \rightarrow \) cradle-to-grave analysis

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Thank you for your attention