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Energy and Resource Efficiency in the Process Industries

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1.1 Introduction

Climate change, reduced access to fresh water, loss of biodiversity and pollution are possible downsides of industrial production. Among the different sectors of industrial production, the sector of the chemical and process industry has a relatively large impact on resources and on the environment as most production units in this sector use natural, often non-renewable resources directly or via their supply chains. One main goal of current environmental policies is to slow down global warming by decreasing CO_2 emissions. The most significant measure in this direction is to switch to renewable resources in the generation of electric power, heating of buildings and industrial production. When the source of raw materials cannot be changed in the short or medium term, an important intermediate step is to increase the overall resource efficiency, in power generation as well as in industrial production.

Energy efficiency has been a prominent topic of public discussion, scientific research and engineering; it is covered in many books and publications as well as by legislation. *Resource efficiency* has been on the research agenda for a while; and although many large companies have started to embrace the concept of resource efficiency [1–5], it is not as visible as energy efficiency to the general public. For this reason, the countries of the European Union recently started extensive studies (e.g. "Resource efficiency as a challenge for the basic chemical industry in Germany" [6]) and research and innovation projects and support actions within FP7 and Horizon 2020 on a European level or ProGress I and II in Germany. Still, resource efficiency remains less clear as an overall concept supporting the efficient utilization of resources, as it is not as easily grasped as the concept of energy efficiency which concerns one single physical variable and leads to one indicator. Resources, in contrast, encompass a large spectrum of inputs that are used in production, including many resources that people do not think of immediately, such as fresh water, natural gas as a raw material for chemicals, precious metals, land use or biodiversity.

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This chapter intends to provide an understanding of what is meant by resources and resource efficiency specifically in relation to the chemical and process industry. It summarizes the major measures towards a more resource-efficient process industry and relates them to the subsequent chapters of the book.

In many industries, energy such as heat and electrical power can be treated separately from raw materials; raw materials are converted into products using energy. The general term resources is not even used in those industries, or raw materials and indirect indicators such as land use are treated as resources, but energy is not included. In the process industry, especially the chemical industry, energy and raw materials need to be treated together as resources; the focus on energy alone is not enough. While many production processes in the manufacturing industries, e.g. the automotive industry, shape and assemble pieces of material, processes with chemical reactions convert materials from one to another, convert materials into energy and sometimes also carriers of energy into materials – for example, in the case of ammonia production where natural gas and air are converted to ammonia. The plants often use raw materials that in other industries would be considered as (carriers of) energy such as natural gas or oil.

The process industry, especially the chemical industry combines chemical reactions often with energy-intense separation processes. This is, on the one hand, resource- and energy-intensive; on the other hand, chemical plants convert resources into products with little waste heat and emissions. The overall resource usage is therefore often much higher than in other industries, but much of the resources, especially the carbon, is bound in long-life products. With cost being the main driver, efficient use of resources and waste minimization have been a key concern of the process industry since the first plants were built. Linnhoff developed heat integration before any environmental legislation existed [7]. Nonetheless, further efforts for resource-efficient production are needed for a sustainable industry in the future.

1.2 Energy and Resources

1.2.1 What Do We Mean by Energy and Resources?

Physically, the term energy is well defined. It can appear in a number of different forms such as potential, kinetic, chemical energy and many others. It is fundamental in the domain of thermodynamics, as the first law of thermodynamics states that energy is always conserved and, in contrast to common language, is not consumed but only converted from one form to another. When engineers and plant managers talk about energy, they typically have in mind the energy inputs that they need to operate their plants – normally, steam, electric power, natural gas or other fuels. So the concept is similar to that of exergy, which is the energy that is available to be used for the given purpose and can be utilized and transformed, for example, into mechanical work.

The term *resource* is more broadly defined: "Natural resources are materials and energy in nature that are essential or useful to humans" [8, p. 9].

Resources needed to make products in the process industry can be defined in a more limited manner. In the context of this book, our understanding is:

***Resources* are the environment, land, air and water, and all materials and the energy required to make the desired products.**

Human labour and human creativity without doubt are also precious resources, but when we speak of resource efficiency in this book, we leave this element out of the discussion.

1.2.2 Classification of Energy and Resources

The energy required for process operation can be classified into primary energy and secondary energy. Primary energy is defined as the energy that is directly provided by nature, for example, sun and wind, or contained in materials that are found in nature and that has not been converted into a different form of energy. Primary energy can be subdivided into non-renewable sources such as natural gas, oil or uranium and renewable sources such as solar and wind energy. Secondary energy is not as clearly defined, as it contains all energy that has been transformed from primary energy into a more useful form such as electricity or steam.

The definition of the sources of resources by Miller states that "these resources are often classified as renewable (such as air, water, soil, plants, and wind) or non-renewable (such as copper, oil, and coal)" [8, p. 9]. The concept is similar to that of energy because primary energy is included in this broad definition of resources.

In the process industry, both primary and secondary energy are used to operate plants. Primary energy is normally oil and natural gas, both are fossil resources and non-renewable. Biological gas and biological oils are possible renewable resources, but today they are not available at competitive prices and in competitive quantities. Secondary energy is normally provided as electricity and heat, often in the form of steam, but also as compressed air and others. A choice nowadays often exists to use more or less renewable sources of secondary energy. As it is not possible to differentiate the source of the secondary energy that arrives at the point of use into renewable or non-renewable energy, an energy balance approach is used, where the overall amount of energy that was produced from renewable sources is classed as renewable secondary energy.

The process industry uses many raw materials as feedstock. Just as the energy that is used, the raw materials are part of the overall use of resources. While some processing plants use part of their raw materials from renewable sources such as wood or palm oil, the majority of the plants today still uses resources that are of fossil origin and therefore non-renewable. As customers demand more and more renewable-based ("bio-based") products, a mass balance approach was developed by BASF that, similar to the approach to the energy balance, classifies some products as renewable if the equivalent share of renewable feedstock has been used [9]. This approach is still subject of debates (see, e.g. [10]).

1.3 Energy and Resource Efficiency

According to the International Energy Agency,[1]

> "Energy efficiency is a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input."

Using energy efficiently is important for two reasons. Firstly, the depletion of non-renewable sources poses societal problems in the long run, and, secondly, primary energy is often converted to usable energy through the chemical process of combustion that leads to greenhouse gas emissions.

Resource efficiency considers a broader picture. It means that resources are used in an efficient manner and that more product is produced from fewer resources. The European Union defines resource efficiency in the following way:

> "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."[2]

Increasing the resource efficiency of production processes is part of an overall effort towards securing our current way of life for more people and for future generations. Using resources efficiently covers a broad spectrum. It means that as little resources as possible are used to make a product and as much as possible of the energy and raw material needed is bound in a long-living useful product and not turned into greenhouse gases.

In a recent paper, resource efficiency for the process industry was defined more specifically as

> "a multi-dimensional entity that includes the environmental load and the efficiency of the utilization of material and energy in the production of the desired products. Other resources as e.g. manpower, production capacity, and capital are not included in the discussion [...]." [11]

According to this definition of resource efficiency, one can evaluate the performance of production processes, visualize if the current resource efficiency corresponds at least to the best demonstrated practice and optimize it.

1.4 Evaluation of Energy and Resource Efficiency

The evaluation of resource efficiency can be divided into three categories:

- **Energy**: Measures how much energy is consumed for the production of one unit of product or how much product is obtained for a certain input of energy.

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1 http://www.iea.org/topics/energyefficiency/ – accessed 27.2.2017
2 http://ec.europa.eu/environment/resource:_efficiency/index_en.htm – accessed 27.2.2017

- **Material**: Measures how much of the different types of raw material is consumed for the production of one unit of product or how much of the raw material is converted into the product.
- **Environmental**: Measures the environmental impact of the production process, for example, by measuring greenhouse gas equivalents per ton of product, or the production of waste water or material that has to be deposited.

Resource efficiency is a multi-dimensional quantity because multiple resources are often used to produce a specific product. The consumption of different resources and the environmental impact can be integrated into one figure by weighting the streams in comparable units.

The World Business Council for Sustainable Development (WBCSD) has developed a framework for eco-efficiency indicators [12] that are very general and not directly applicable to specific resources.

Company-specific environmental indicator systems are an important tool in planning, steering and controlling production processes [13]. Current environmental management systems, such as the EU-EMAS Regulation or systems according to ISO 14001 [14], require an explicit commitment for continuous improvement of the environmental performance, but do not suggest indicators. The standard ISO 14051 [15] on Material Flow Cost Accounting is the first standard in the ISO Technical Committee 207 on “Environmental Management” to provide tools to improve resource efficiency in organizations. Eco-efficiency assessment ISO 14045 [16] is an assessment of the environmental performance of a production system in relation to its value. Overall, the mentioned systems for measuring and visualizing resource efficiency are of a general nature and focus on environmental impacts. Performance assessment methods for individual plants or companies are not in use on a broader scale.

The Institute for Environment and Sustainability of the EU Joint Research Centre (JRC) prepared a document on life-cycle-based macro-level monitoring indicators for resources, products and wastes for the EU27 [17]. Its purpose is to support life-cycle-based environmental policies. The goal of calculating the indicators is the quantification and monitoring of actual progress towards a more sustainable development of the European Union.

The Global Reporting Initiative (GRI) proposed a comprehensive Sustainability Reporting Framework (called “The Framework”) that is widely used around the world to achieve greater organizational transparency. The Framework of GRI sets out the Principles and Standard Disclosures that organizations can use to report their economic, environmental and social performance and impacts, that way covering many aspects of sustainability.

Using such systems, most companies internally monitor energy and material efficiency and report environmental key performance indicators (KPIs) of the impact of their production processes on the environment. Typically, the three classes are reported separately and not combined into a single resource efficiency indicator (REI), but are used for sustainability reporting. Sustainability reporting is usually not directly related to specific production processes and done in retrospect, aggregated over long periods of time and over many production units. Therefore, it cannot support the decision-making processes in daily plant operations. Real-time resource efficiency has not yet been used to steer the day-to-day operation of processing plants towards an improved environmental performance or for the systematic exploration of the trade-off between ecological impact and profitability.

1.5 Evaluation of Energy and Resource Efficiency in Real Time

The methods in the previous section provide general concepts for resource and energy efficiency reporting in hindsight. Real-time resource efficiency is the cornerstone of solutions for real-time decision support in daily process operations. Suitable performance indicators that describe resource efficiency in real time are needed in addition to the ones for reporting, and – ideally – they can also be used for reporting.

A suitable definition of real time was identified for resource efficiency in Kalliski and Engell [18] and states, that "the time delay and the sampling time [..] are sufficiently short compared to relevant process dynamics [and] to the typical frequency of changes of manipulated variables".

The concept of real time is also important at the management level. Here, the length of the shortest sampling time will differ substantially from the process time constants and will usually increase further up the hierarchy. For an operator, real time might be measured in minutes or hours; for production planning, real time will be measured in weeks or months. For the definition of REIs that can be used for performance assessment and decision support of production processes in real time, a number of principles have been defined by the MORE project [11, 19, 20] that are valid for resource efficiency reporting as much as for energy performance reporting. A database of indicators developed during the MORE project that can be used for plants in the process industries can be found online[3].

Both the development of suitable indicators and these principles are described in detail in Section 5.2.4.

1.6 The Chemical and Process Industry[4]

1.6.1 Introduction

The process industry is defined as "an industry [...] that is concerned with the processing of bulk resources into other products" [22]. The process industry comprises many industrial sectors, the biggest being chemicals, metals, pulp and paper, cement, food and pharmaceuticals.

Eight main sectors of the European process industry (chemicals, cement, ceramics, engineering, minerals and ore, non-ferrous metals, steel and water)

3 http://more.bci.tu-dortmund.de – accessed 19.3.2017

4 This section is a summary of a similar section in the public deliverable 6.7 "Impact Assessment" of the project MORE [21]. The work of Sophie Vallet Chevillard, Eva Fadil (inno) and Marjukka Kujanpää (VTT) is gratefully acknowledged.

represent 20% of the total European industry in terms of turnover and employment. These sectors comprise more than 450 000 enterprises, have over 6.8 million employees and more than 1600 billion Euro annual turnover.[5] As the chemical industry plays a prominent role in the use of fossil resources and the consumption of energy, we provide a few more details on this sector to highlight the significance of the improvement of the resource efficiency in the process industry.

The chemical industry is an important sector of the process industry: world chemicals turnover was valued at 3232 billion Euro in 2014[6]. The chemical industry in Europe is quite heterogeneous and three main broad product areas can be considered as outputs: base chemicals (including petrochemicals and their polymer derivatives along with basic inorganics), speciality chemicals and consumer products. Base chemicals represented 59.6%, speciality chemicals 27% and consumer products 12.6% of the total EU sales in chemicals in 2014. The speciality chemicals group is the most heterogeneous one with regard to products, production processes, supply chains and business structures.

1.6.2 The Structure of the EU Chemical Industry

The value chain of the chemical industry for the most part starts with crude oil and natural gas. For crude oil, the first step is refining. There are approximately 100 refineries in Europe, providing feedstock to about 80 large chemical sites.

Economies of scale are a major advantage for integrated chemical production sites (the Ludwigshafen site of BASF being the most prominent example in Europe), chemical parks and industrial clusters. “Sites within clusters which comprise groups of separate sites, have tended to enjoy more competitive advantages because of a multiplicity of chemical plants and owners, ranging from feedstock and commodity producers to fine and technologically advanced specialty chemical businesses.” [23] Such clusters are typically formed around a production centre (often a petrochemical site) or close to ports.

The chemical industry is linked to a large number of other industrial sectors. Nearly two-thirds of EU chemicals are supplied to the EU industrial sector. The contribution of the chemical industry to the EU gross domestic product (GDP) is 1.1%, out of the 15% of the total contribution of the European industry.

1.6.3 Energy and Raw Material Use of the Chemical Industry

The chemical industry worldwide accounts for more than 30% of global industrial energy use. This figure is high because a large portion of the feedstock to chemical plants could be used as a carrier of energy in other applications. Naphtha, which is light petrol, is the main feedstock to the petrochemical industry, but it can also be burnt in power plants to produce heat and electricity or in cars to achieve locomotion. This is important because the reduction in the usage of energy for

5 http://ec.europa.eu/research/industrial_technologies/sustainable-process-industry_en.html – accessed 27.02.2017

6 All figures taken from CEFIC facts and figures http://www.cefic.org/Facts-and-Figures/ – accessed 27.02.2017

the industry is often only measured by reducing the energy required to make a product. By combining energy and raw materials to resources, improving the resource efficiency makes production overall more efficient.

According to Eurostat [24], the chemical and petrochemical sector utilizes about 19% of the total input of energy of the industry in Europe. The raw material used in the EU chemical industry mainly comprises refining products (68%), natural gas (21%), renewables (9%) and coal (1%).

For the German chemical industry, Voss [6] and Hassan [25] analyzed a number of facts on the use of carriers of energy that are valid for the chemical industry world-wide:

- The German chemical industry is the second largest energy consumer in Germany. It uses the largest amount of natural gas and the largest amount of electricity of the total natural gas and electricity consumed in Germany.
- Fossil raw materials are used as both raw materials for the chemical processes and as fuel to produce electricity and steam. The cost fraction of energy can be as high as 48% and the cost fraction of raw materials can be as high as 90%. Being energy and material efficient (hence resource efficient) can be a substantial competitive advantage.
- Different carriers of energy are used for different purposes, for example, fuels are converted to process heat and steam, and electricity is used for drives, motors and electrochemical production.
- The chemical value chain is very complex: Typically, integrated and coupled production processes are used to avoid generating streams of materials which are not used further and have to be disposed of as well as to make efficient use of the heat that is produced in some production steps (mostly chemical reactions).
- Generating steam and electricity within a company is common, typically in combined heat and power (CHP) plants that often use off-gases and off-liquids.
- Process heat above 400°C cannot be produced by CHP, and therefore specialized heat generators such as furnaces are required. Excess heat is typically used in other processes. Heat generated in this way has a share of approximately 50% of the total use of thermal energy.
- Recent energy efficiency improvements were typically achieved by reductions in the consumption of steam and fuel, and the utilization of electricity in turn has increased. The availability of electric power from renewable sources at very low prices during some periods will further stimulate this development.

1.7 Recent and Potential Improvements in Energy and Resource Consumption of the Chemical and Process Industries

The International Energy Agency carried out a study [26] that was summarized in [27]. The specific energy consumption (SEC) of the chemical industry per world region was mostly influenced by five important processes (leading to the production of nine chemicals and accounting for half of the sector's energy use including electricity): steam cracking, the production of ammonia, methanol, chlorine (including sodium hydroxide) and soda ash. The total potential for improvements with available technology was, for the example of Germany, calculated to be between 1.5% (top-down calculation) and 12.5% (bottom-up calculation) with the production rate unchanged. The study used a comparison between the current and the best available technology and takes into account that some plants need to be rebuilt. The results of the study indicate that in Germany substantial energy efficiency improvements will not be achieved easily as much work in this direction has already been done.

The greenhouse gas emissions from the European chemical industry have decreased over the past 25 years. This is mainly due to the decrease in nitrous oxide (N_2O) emissions. In 2014, the emissions of greenhouse gases of the European chemical industry totalled 1316 million tonnes of CO_2 equivalents. This corresponds to (only) about 3% of the total European greenhouse gas emissions, which were 44 192 million tons of CO_2 equivalents in the year 2014.

CEFIC showed that the energy performance and the environmental performance of the chemical industry have improved dramatically in the past 25 years (cf. CEFIC Facts and Figures, Figure 7.3, p. 52, 2016[7]). Nonetheless, this process cannot end today; further improvements are required and possible.

1.8 What Can Be Done to Further Improve the Resource Efficiency of the Process Industry?

Resource efficiency improvements are a step-wise procedure. Each step will have a certain impact on the process or on the path taken to make a product. Schächtele and Krämer in 2012 summarized the approach towards energy efficiency improvements in the chemical industry in four action items [28]. These action items are visualized in Figure 1.1 and apply to resource efficiency as well as to energy efficiency. To provide a more holistic view, we suggest an extension to a step-wise procedure and add an additional point:

In Step 1, a plan is made. Step 2 consists of measuring the important process streams and visualizing the result. In Step 3, process operations are improved. In Step 4, the process to make a product is improved, either by changes to the existing process equipment, which includes alternative or better raw materials, or by choosing a completely new chemical route or a new process design. In Step 5, an existing or new process is integrated in industrial symbiosis. We briefly discuss the different steps in the next subsections.

1.8.1 Make a Plan, Set Targets and Validate the Achievements

Before starting one or several technical improvement projects, companies typically set targets or targets are set by legislation or by voluntary commitments of the industry. Generally agreed on paths to define targets and goals in organizations are provided by management systems. The ISO Series 9000, 14000 and

7 Taken from CEFIC facts and figures http://www.cefic.org/Facts-and-Figures/ – accessed 27.02.2017

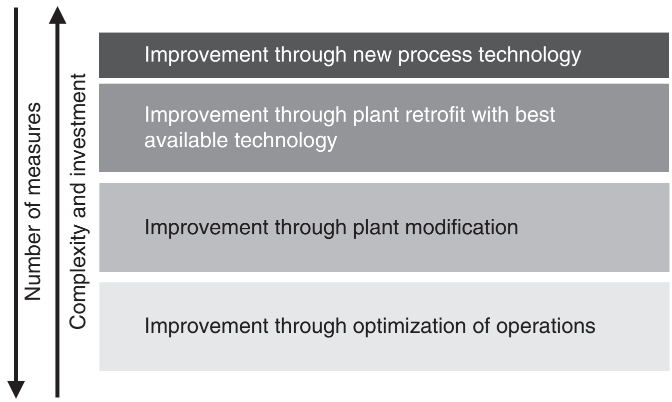

Figure 1.1 Improvement of production in general terms. (Adapted from Schächtele 2012 [28].)

50000 describe management systems for quality management, environmental impact management and energy management in a concise and usable manner and are adopted by many companies.

ISO 50001:2011 [29] and the standards ISO 50002 to 50015 in this family provide guidance on how to implement a goal-oriented energy management system. Practical guides are available, and they provide step-by-step guidance on the implementation of a management system and the necessary methods to choose measures with a high probability of success ([30] and a free guideline in many languages [31]).

As yet, there is no standard aiming at resource efficiency, one of the reasons probably being the multifaceted nature of the terms "resource" and "resource efficiency". The first successful attempt at normative advice on resource efficiency management was provided by the German Association of Engineers e.V. (VDI) in its guideline VDI 4600 [32] and VDI 4800 Part 1 [33]. Currently there are no standardization projects concerned with resource efficiency at the ISO level.

We recommend using the approach of existing management systems to set targets for resource efficiency and to use the underlying plan-do-check-act (PDCA) cycle to achieve the targets and to maintain continuous improvement. For energy, this is well defined and covered in Chapters 2 and 3.

Once a plan and the targets and measures to achieve the targets exist, it is necessary to measure and to visualize the situation before and after the implementation of measures using physically based KPIs (REIs).

1.8.2 Measure and Improve Operations

A phrase that is often quoted is "You can't control what you can't measure". Although this is not always completely true, the issue needs to be taken very seriously. You can only move your process close to the operational constraints that define an optimal operation if you do have the right measurements in place, the measurement results are sufficiently accurate and the data is suitably condensed into indicators and visualized.

In measuring the resource efficiency of production processes, sensing needs to be understood as the need for acquiring reliable information about what is taking place in and around the plant. Measurement systems acquire process data, sensible interpretation turns it into information and as such into “controlled variables” that can be optimized.

Figure 1.2 shows different possibilities to improve process operations with respect to resource efficiency. We believe that establishing a good reporting and visualization system for real-time REIs requires little effort and already results in tangible benefits. Using more advanced methods requires additional effort but also leads to higher benefits. Optimal process operations in the end are only possible with full-scale monitoring, optimization and advanced control solutions. If these are employed in order to improve resource efficiency, they need to use resource efficiency measures in their objective functions.

In Chapter 5, methods for the definition and calculation and visualization of REIs that were developed in the EU co-funded project MORE[8] (Real-Time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants) are discussed. They are the cornerstone of solutions for real-time decision support and optimization to improve the resource efficiency. The required analytical measurements are discussed in Chapter 6, Chapter 7 covers the implementation in IT-systems and the necessary data pre-treatment is described in Chapter 8.

Once a good visualization of resource efficiency has been achieved, the potential for improvements can be realized and targets can be set and their achievement measured. The visualization is often a value in itself as it motivates people to improve their performance.

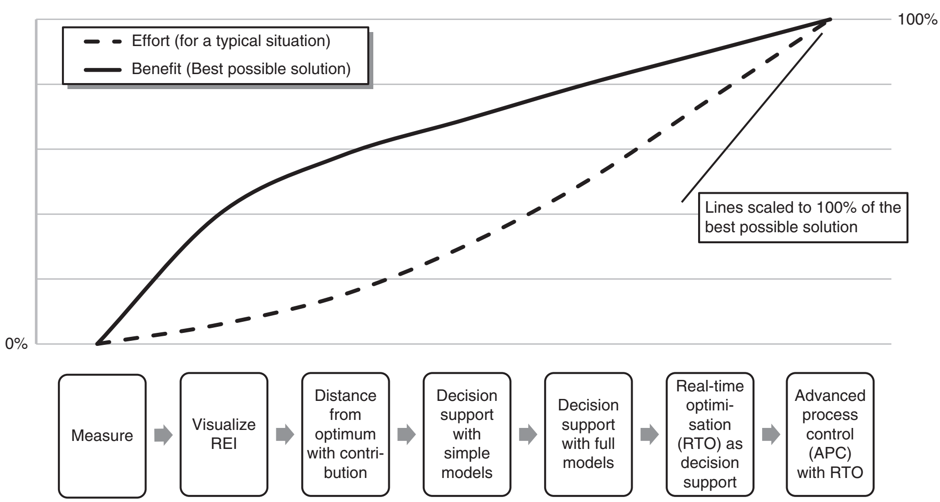

Figure 1.2 Qualitative visualization of the required effort and of the benefit of solutions for the improvement of process operations.

8 The MORE project received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No 604068.

Some improvement in resource efficiency can already be achieved by constant attention of the operators, but resource optimal operation is typically only achieved by model-based advanced automation methods. Advanced decision support, advanced control and online optimization can be used to implement resource efficiency operational policies. These methods are covered in Chapters 9–11.

Some plants can be operated in a flexible manner and achieve resource efficiency improvements on a larger scale, for example in the electrical grid, by managing their energy demand and consuming energy at time when its production has a smaller environmental impact. This "demand side response" is covered in Chapter 12.

Concerning energy efficiency, many of the methods have already been put into practice. Chapter 13 provides a real-life example from a large industrial company showing the improvements made through the successful application of the described principles.

1.8.3 Improve the Process

Applying the decision support technologies described will improve the resource efficiency of a given plant towards its existing technical limit. After this, no further improvement will be possible without changing the process equipment and process configuration. Various possibilities with increasing complexity and capital expenditure exist for such plant upgrades.

The first choice for many companies will be the exchange or retrofit of the equipment in existing processes to improve resource efficiency. Typical examples are de-bottlenecking and heat and mass integration as well as improvements of the utilities system. When the most limiting bottleneck is found and removed, the resource efficiency can increase significantly, but there are limits to the improvement of resource efficiency without changing the structure of the process.

The second possibility therefore is to partly or completely rebuild the plant. Two paths are possible: to build the same plant with new equipment and possibly on a larger scale and thus to benefit from economies of scale, or to build a different plant using the best available technology that will make the same product as before but with a higher efficiency and lower environmental loads.

The final option is to replace the resources that are used in the current process by others, making the overall life cycle far more efficient. An example from the past is the replacement of coal-based chemistry by petrochemistry.

Chapters 14 and 15 cover the synthesis of chemical processes and utilities systems to achieve higher resource efficiency.

Even the best available processes produce some waste and waste heat that is lost if the process is not part of a larger integrated structure. Chapter 16 cover mass and heat integration concepts for plants and sites. At large chemical sites, such an integrated structure ("Verbund") is already in place, but many stand-alone processes still leave room for improvements through integration.

1.8.4 Integrate with Other Industrial Sectors and with the Regional Municipal Environment

Integrating processes and companies with other industrial sectors or public infrastructures by providing, for example, municipal heat can be a further step towards resource efficiency. Industrial symbiosis will be the next important and necessary step to make a step change in resource efficiency. The idea of industrial symbiosis is covered in depth in Chapter 17 which is a result of the Horizon 2020 SPIRE project EPOS [34].

1.8.5 Don't Forget the People

The methods mentioned are all technical, in the words of Chapter 18, "objective" solutions to improve resource efficiency. The human side of the equation constitutes another important element, the "subjective" aspect. As long as plants are not operated fully automatically and equipped with model-based online optimization, operators and managers play a key role in the success of any resource efficiency improvement measure. Also, for the development of new, more resource-efficient processes, creativity and motivation of the engineers involved are crucial. A trustful company culture with the common goal of achieving the best possible resource efficiency is required to develop, implement and maintain any kind of improvement. Human beings act and react in a more complex, subjective and emotional manner than do technical systems. Thus, to achieve a successful implementation of the technical solutions that will improve resource efficiency in the long run, an appropriate company culture is essential. Chapter 18 describes a path towards such a culture, ideally affecting the whole company and inter-company relations.

1.9 Conclusions

This chapter sets the stage for the subsequent discussion of resource efficiency in the chemical and process industry and of measures towards the improvement of resource efficiency in the following chapters.

In the context of this book, ***resources* are the environment, land, air and water, and all materials and the energy required to make the desired products**. Resource efficiency thus means to *make more from less*.

Resource efficiency is not yet as prominent a topic as energy efficiency, as it is multi-facetted and not as easily understood. In the process industry, especially in the resource-intensive base chemicals industry, energy and raw materials need to be treated together as resources – the focus on energy alone is not sufficient. Improvements of energy and resource efficiency and minimization of waste have been at the heart of continuous improvements and revamping in the process industry for a long time, and a standstill in this effort is not possible especially not in Europe where economic and ecologic pressures are high. The following chapters discuss methods and tools that should be applied on a broad scale on the path towards improved resource efficiency.

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