Energy Efficiency Analysis of Crossover Technologies in Industrial Applications

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Abstract—Industry accounts for one-third of global final energy demand. Crossover technologies (e.g. motors, pumps, process heat, and air conditioning) play an important role in improving energy efficiency. These technologies are used in many applications independent of the production branch. Especially electrical power is used by drives, pumps, compressors, and lightning. The paper demonstrates the algorithm of the energy analysis by some selected case studies for typical industrial processes. The energy analysis represents an essential part of energy management systems (EMS). Generally, process control system (PCS) can support EMS. They provide information about the production process, and they organize the maintenance actions. Combining these tools into an integrated process allows the development of an energy critical equipment strategy. Thus, asset and energy management can use the same common data to improve the energy efficiency.

Keywords—Crossover technologies, data management, energy analysis, energy efficiency, process control.

I. Introduction

SUSTAINABLE development worldwide encloses a transformation of the energy systems. The German energy transition is a long-term strategy for the development of a low-carbon energy system that is based on renewable energy and improved energy efficiency [1]. It is driven by four main objectives:

- reduction of CO_2 emissions
- phasing-out nuclear power
- improving energy security through a reduction of fossil-fuel imports
- guaranteeing industrial competitiveness and growth

The transformation process affects not only the power generation but also the demand side in all sectors of the national economy. Energy is consumed in three end-use sectors of buildings (for heating and cooling), transportation, and industry. Connecting these three sectors is described by the term "sector coupling" [2]. It means using renewables in all end-use sectors. This can either be done by using renewables directly (e.g. heat pumps, photovoltaics, solar heating) or by using electricity from renewables in the other sectors. The increasing use of electricity from renewable energy sources will reduce the greenhouse gas emissions. The process of sector coupling also includes the increase of energy efficiency. Energy efficiency means using less energy to provide the same service.

As industry accounts for one-third of global final energy demand, it is necessary to improve the energy efficiency of industrial processes. The structure of the energy consumption in industrial enterprises depends on many factors (e.g. use of primary energy resources, energy intensity of the products, the production process, and installed equipment). There are different energy streams flowing through a plant (Fig. 1). Balances of all streams are necessary to implement energy management functions [3]. In many plants, the energy streams are only measured by a single meter at the source. The energy use of single processes is mostly unknown. Thus, data of the PCS must be used for the energy analysis.

Energy efficiency targets include activities for single processes, as well as strategies for the complete enterprise. In industrial enterprises, crossover technologies play an important role for energy efficiency. They are characterized by a large number of applications independent of the production branch. Typical technologies include motors and drives, pump systems, compressed air, lightning, process heat, and air conditioning systems. Thus, pumps are the largest industrial user of motor-driven electrical energy [4]. Therefore, the analysis of these technologies has a strong impact on the overall energy efficiency.

II. Crossover Technologies

The industrial energy consumption has a heterogeneous character because of the diverse structures in the manufacturing sector. But, there are some common properties concerning technologies that are used in many different processes. We define crossover technologies as energy consuming processes with the following characteristics:

- There is a large number (e.g. millions) of applications in the industry.
- They have a large share of the industrial energy demand.
- They consist of similar basic elements.
- There are common problems concerning sizing, control, efficiency, and maintenance.
- In the most cases, they have an essential optimization potential

We count as crossover technologies: motors and drives, pump systems, process heat, compressed air, lightning, and air conditioning systems. Electrical motors play a dominant role within these technologies. They are used for machine drives such as pumps, compressors, fans, mixers, grinders, and other materials handling or processing equipment, accounting for about 54% of electricity consumption in U.S. manufacturing sector [4].

An energy analysis of a motor and drive system requires attention not only to the basic elements of equipment but to

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the system as a whole. A systems approach analyzes both the supply and demand sides of the system and how they interact. A typical failure occurs when the motor size is larger than necessary. This is often done because of applying "safety factors". An oversized motor will run most the time under inefficient operation condition. Manufacturing systems usually do not operate under constant condition all the time. Motor and drive system loads often vary according to production demands, environmental conditions, and changes in customer

requirements. To optimize system performance, the engineer must configure the system to avoid inefficiencies and energy losses. This can be done by customized sizing and/or by the installation of speed control by means of power electronics. In many cases, oversized and inefficient drives are still used in historically grown industrial enterprises with changing production programs. The exchange of long term running motors by new ones with high efficiency class saves much energy and costs.
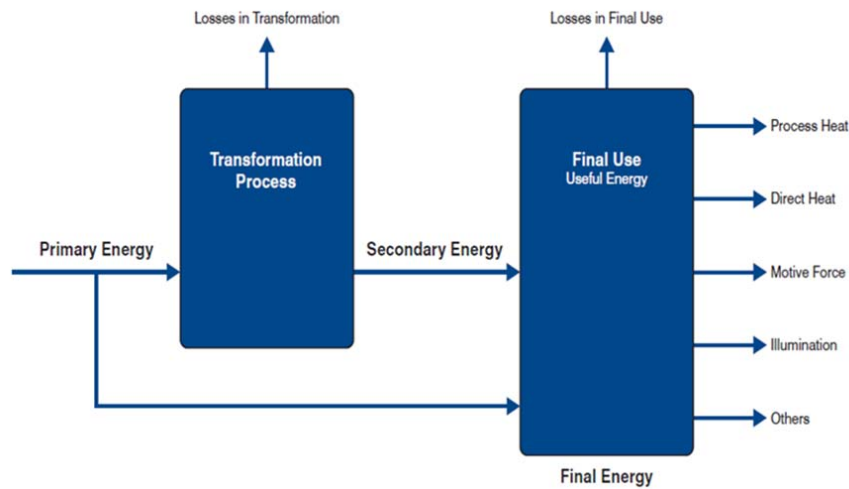

Fig. 1 Energy flow in an industrial plant [3]

Pumping systems represent one of the main crossover technologies in the industry. They account for nearly 20% of the world's electrical energy demand and range from 25 to 50% of the power consumption in industrial enterprises [5]. A pumping system consists of the following main components: pump unit, drive (mainly electric motor), pipe system, instrumentation (valves, fittings), and tanks as storage system. The energy efficiency of a pumping system depends on all components. Thus, the energy demand E of the system is:

$$E = \frac{H \cdot Q \cdot \rho \cdot g}{\eta_p \cdot \eta_m \cdot \eta_d} \quad (1)$$

with H - head, Q - flow rate, ρ - density of the fluid, g - gravity constant, η_p - efficiency rate of the pump, η_m - efficiency rate of the motor, η_d - efficiency rate of the drive. Furthermore, the energy demand is strongly influenced by the resistance of the pipe system. In Section IV, we will describe a methodological approach for the energy analysis of a pumping system.
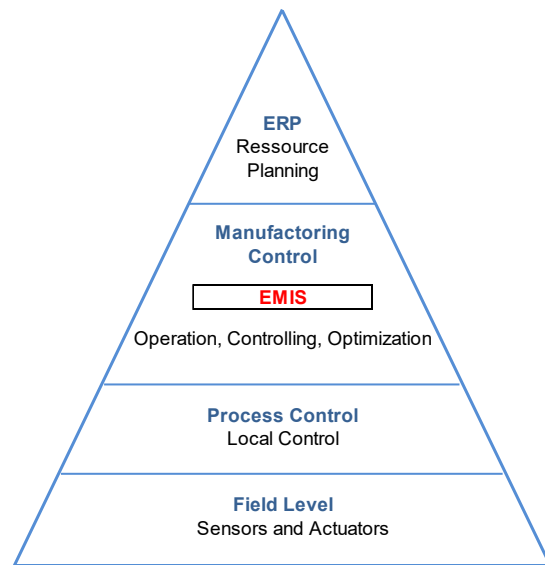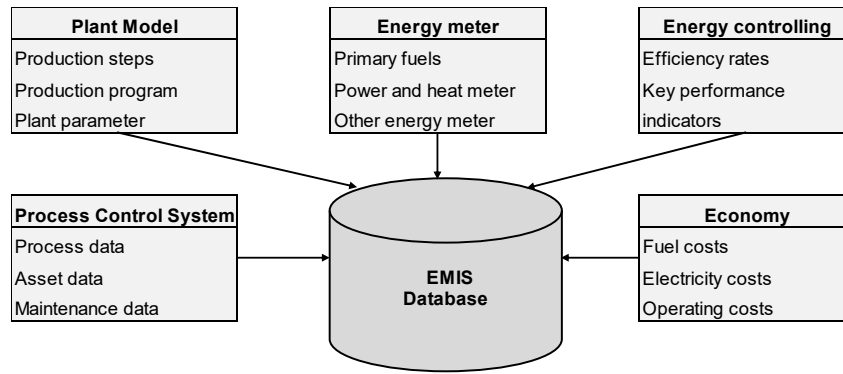

Fig. 2 Industrial automation system

Fig. 3 Energy information system

III. Energy Data Analysis

In many plants, only the main energy streams are measured. The energy use of single processes is mostly unknown. The installation of additional measurement devices (e.g. flowmeters or wireless electric power meters) is one option to get more information about the energy consumption. Otherwise, retrofitting of energy meters into running processes is difficult and in many cases impossible. Alternatively, we can use specific information coming from the automation system, which controls the production process. These data are collected by an energy information system (EMIS). The field level of an automation system realizes the basic control of the manufacturing process. It contains the sensors and actuators that are required to control the production steps [6]. The sensors measure the process parameters (mass flow, temperature, pressure, etc.) and send the signals to the process control level. The actuators receive signals from the control level and perform a function, e.g. they start a pump or close a valve. At the control level, the signals from the sensors in the field are processed, and the commands to the actuators are generated. Generally, these operations are managed by a PCS using a field bus network [7]. Fig. 2 shows the structure of an industrial automation system.

The PCS collects all process data and stores them in a process database. These data can be used to build up an energy information system (Fig. 3). EMIS includes all types of energy streams entering or leaving the system boundary that are influenced by plant operation. Typical classes of energy are:

- electricity
- fossil fuel (fuel gas, fuel oil, natural gas, coke, etc.)
- renewable resources (solar, biomass)
- steam at different pressure levels and hot water
- compressed air

EMIS contains additionally general information about the production processes, costs, and energy controlling indicators. By means of the process data, we can calculate the energy consumption of production units which are not individually measured by a single meter. Thus, we get the power consumption of a pump by using the measured values of the variables in equation (1).

In the industry, a large share of the energy consumption is caused by process heating. But, heat meters are not available in all steps of the production process. In this case, we can use the data collected by the corresponding sensors in field level of PCS to calculate the heat flow:

$$Q = \dot{m} \cdot c_p \cdot \Delta T \qquad (2)$$

where: Q - heat flow, $\dot{m}$ - mass flow, c_p - specific heat capacity of the medium, ΔT - temperature difference between output and input.

The temperature sensors and the flow meter of the PCS provide the basic information needed for the calculation in (2).

IV. Asset and Energy Management

The EMIS represents the basis of an EMS. EMS is defined as a "set of inter-related or interacting elements of a plan which sets an energy efficiency objective and a strategy to achieve that objective" [8]. The PCS provides the main data input. On the other side, additional measurements are needed to describe the energy flow through the production process. Fig. 4 shows the structure and the data flow of EMS including soft- and hardware tools to realize the following functions:

- providing the data of the energy consumption
- supervising the energy situation of the plant
- calculating energy balances
- identifying the main energy consumers
- create key performance indicators
- increasing the energy efficiency of the production process

Generally, PCS includes tools for the asset management. Asset management systems (AMS) observe the performance of the production systems, and organize the maintenance procedure. AMS plan and record the results of maintenance testing, inspection and repair. These may be supplemented by equipment monitoring tools, which measure and evaluate the current equipment performance. Asset measurements play a key role for energy systems (e.g. boiler drum level, compressor surge measurements, vibration monitoring of pumps and compressors, and steam trap monitoring). Generally, the asset measurements have a direct relation to the energy performance of the plant unit. Combining these tools into an integrated process allows the development of an energy controlling system. The plant model is involved as a

part of the EMIS (see Fig. 3). Thus, asset and energy management can use the same common data, and the results of the supervision are sent back to the database of EMIS.
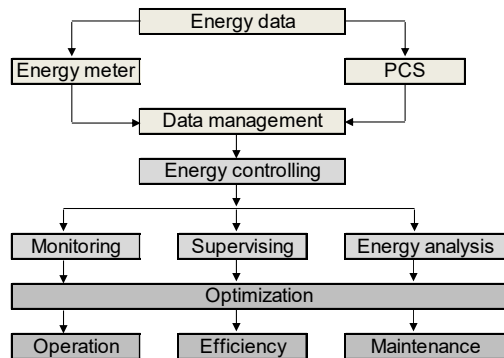

Fig. 4 Energy management system

Corresponding to the architecture of the automation system (see Fig. 2), there are two general possibilities to combine AMS with EMS. As shown in Fig. 4, all energy relevant data are collected by sensors in the field level of the automation system. Additionally, missing measurements will be replaced by calculations using basic data of the PCS. This means that the EMS functions are integrated directly in the field level. The second option represents the installation of a separate EMS software tool integrated in one of the higher levels of the automation pyramid (e.g. control or enterprise level). Both options need an access to an energy information system (EMIS) in combination with data management functions as process data analysis and validation [3].

V. ENERGY EFFICIENCY ANALYSIS

We will demonstrate the methodology of an energy analysis by some case studies for crossover technologies. The energy audit represents the first step of an energy analysis.

A. Energy Audit

An energy audit is defined as a detailed analysis of the energy performance of an energy system. The audit can be applied to a complete organization, but also to a single equipment, system or process. The audit analyzes the energy consumption, and provides measures to improve the energy efficiency. Energy audits identify the main energy consumers, calculate optimization potentials, and they provide recommendations for improvement of energy performance. The audit includes the calculation of financial benefits [9].

Fig. 5 shows the algorithm of an industrial energy audit. The main energy inputs and flows are analyzed following the procedure described in Fig. 4. Then, they are related to the main production lines by calculating energy balances. By the comparison of the energy intensity and the efficiency rates of the different technologies, the main energy consumers are identified. The optimization potentials of the energy saving procedures are calculated. The efficiency calculation provides the information about the amortization of the planned improving procedures. The controlling system supervises the results of the expected energy savings.
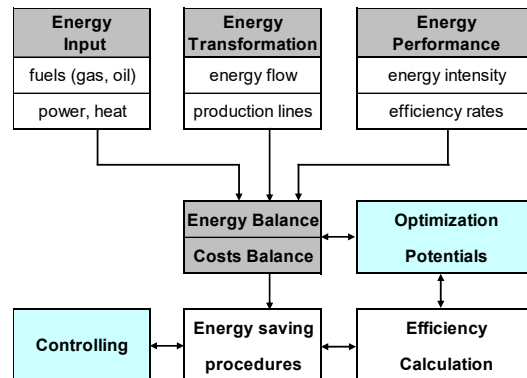

Fig. 5 Energy audit

Energy audits are important elements in the EU energy efficiency strategies. They are mandatory for large companies, but even small to medium-sized enterprises (SME) can benefit. SME can conduct a voluntary energy audit to get tax benefits. Furthermore, they will achieve an overview about the energy performance of the company. Because of the large number of applications, crossover technologies play an important role within the frame of an energy audit.

B. Pumping Systems

Nearly in all industrial enterprises pumping systems are running in the production process. The energy efficiency of a motor driven pumping system mainly depends on the drive, the pump itself, the control system, and the pipe system. The end-use applications define the requirements of the pumping system (e.g. pressure, flow rate). These determine the dimension of the components and their configuration. Of all of the types of pumps, the centrifugal pump is the most commonly used. It has many advantages: simple construction, low relative cost, low maintenance, quiet operation, and reliability. The main causes for inefficient operation of pump systems are:

Pressure is needed to pump the medium (liquid, gas) through the system. This pressure has to be high enough to overcome the resistance of the system, which is also called "head". The friction head is the loss needed to overcome that is caused by the resistance to flow in the pipe system. It is dependent on the dimension and configuration of the system. Furthermore, the flow rate and the physical properties of the medium influence the needed pressure. The total head is the sum of static head and friction head [10].

- The installed components are inherently inefficient at the normal operation conditions.
- More flow is being provided than the systems requires.
- More head is being provided than the system requires.
- The pump is running when not required by the system.
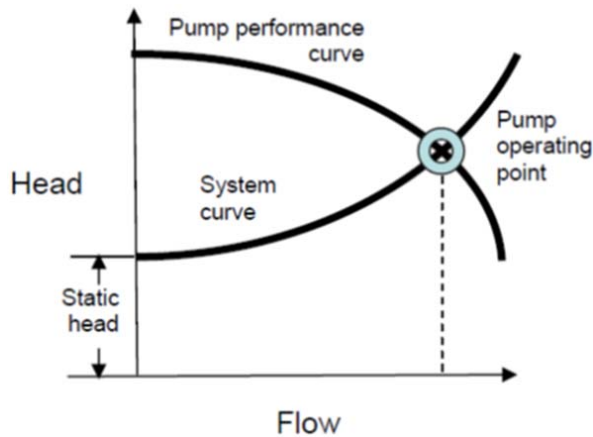- The installed components have degraded in service.

Fig. 6 Performance of a pump [10]

The head and flow rate determine the performance of a pump, which is shown in Fig. 6. It shows a typical curve of a centrifugal pump where the head gradually decreases with increasing flow. With increasing resistance of the pipe system the head will also increase. The pump operating point is determined by the intersection of the system curve and the pump curve. The pump work can be described as a function of the total head and of the mass of the pumped medium in a given time period. The shaft power (P_s) is defined as the power required transferred from the motor to the shaft of the pump. It depends on the efficiency of the pump and can be calculated as:

$$P_S = \frac{h_p}{\eta} \qquad (3)$$

Otherwise, we can calculate the pump efficiency:

$$\eta = \frac{h_p}{P_S} \qquad (4)$$

h_p denotes the hydraulic power, calculated by:

$$h_p = Q \cdot (h_d - h_s) \cdot \rho \cdot g \qquad (5)$$

where: Q - flow rate, h_d - discharge head, h_s - suction head, ρ - density of the fluid, g - gravity constant.

The discharge head h_d describes the vertical distance between the pump centerline and the surface of the liquid in the destination tank, and the suction head h_s results from lifting the liquid relative to the pump center line.

The pump performance parameters (flow rate, head, and power) will change with varying rotating speeds. The equations that explain the relationships between the performance parameters are known as the "Affinity Laws":

For a given pump with a fixed diameter impeller, the capacity will be directly proportional to the speed, the head will be directly proportional to the square of the speed, and the required power will be directly proportional to the cube of the speed.

As can be seen from the above laws, a small reduction in speed will result in a very large reduction in power consumption. Thus, power can be saved by installing flow control systems (e.g. frequency converter). Flow control by speed regulation is always more efficient than by a control valve. This is because valves reduce the flow, but not the energy consumed by pumps.

Improving the energy efficiency of a pumping system also includes the analysis of the pipe network. This can be realized as a part of the asset management (see Section IV). Energy saving will be supported by:

- adequate dimension of the pipe network
- avoid bottlenecks in the network
- minimization of the flow length in the system
- ensure continuous maintenance of the pipe system, valves and other fittings

Because energy consumption accounts for more than half of the total cost of the pump life cycle, the optimization potential of energy efficiency is very high.

C. Process Heating and Cogeneration

Industrial process heating operations are responsible for more than 50% of the total energy demand. There are a wide range of process heating applications, which are to achieve important materials transformations such as heating, drying, curing, phase change, etc. Energy is supplied from a diverse range of sources, and includes a combination of electricity, steam, and fuels such as natural gas, oil, coal, biomass and other renewable resources.

Generally, the PCS can be used to detect optimization potentials (see Section III). There are the following options to save energy in process heating systems:

- optimization of the process temperature
- avoid heat losses
- recovery of output heat of the process
- implementation of heat storage systems
- cogeneration of heat and power in a combined cycle

Cogeneration technologies combine simultaneously the heat and power production within one system [11]. In many industrial processes the power and heat demand coincide in time. Thus, cogeneration technologies are available as backpressure steam turbines, combined gas and steam turbines, and gas motor based CHP units. The cogeneration increases the efficiency of the consumption of the primary fossil fuels, while significantly reducing the emissions of greenhouse gases (GHG) and other pollutants.

Waste heat from the power generation can be used at different temperature levels. In the simplest case, the heat recovery of a gas motor CHP supplies heating of the industrial facilities. Also cooling is possible in combination with an absorption cooling machine. By a district heating network, facilities in the neighborhood of the plant can be supplied.

Fig. 7 shows the sizing of a CHP system consisting of two CHP modules depending on the annual heat demand of a supply system. The heat capacity of the CHP units reaches

30% of the peak heat demand, covering about 60% of the annual heat work. The residual will be supplied by a heat boiler. Thus, we can achieve 5000 to 6000 running operation hours of the cogeneration system achieving high amortization conditions.
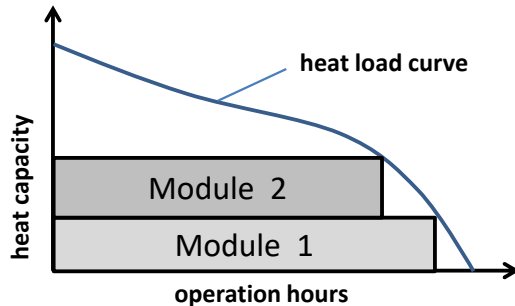

Fig. 7 Heat load curve with CHP modules

VI. CONCLUSION

Crossover technologies are responsible for a large share of the industrial energy consumption. They are characterized by a large number of applications independent of the production branch. The energy analysis of these technologies shows that there are common problems dealing with: low energy efficiency, oversized dimension of the system, lack of control, and maintenance deficits.

Energy audits identify the main energy consumers, calculate optimization potentials, and they provide recommendations for improvement of energy performance. The energy data management represents the basis of an energy audit. Additionally, for the data of the energy meters, specific information is used coming from the PCS. These data are collected by an energy information system.

Asset management plays a key role for energy systems. Generally, the asset measurements have a direct relation to the energy performance of the plant unit. Combining these tools into an integrated process allows the development of an energy controlling system.

The described case studies show that an energy analysis requires attention not only to the basic elements of equipment but to the system as a whole. A systems approach analyzes both the supply and demand sides of the system and how they interact.

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