Chapter 2
Energy Flows in Factories

This chapter introduces the theoretical foundation for the concept to be derived in this book. Initially the factory morphology is explained and all elements of a generic factory system are introduced. Central terms and definitions of energy types and the energy conversion and utilisation are given. The economic aspects of supplied energy flows are put into focus.

2.1 Factory Environment

While striving for energy transparent factories, it becomes vital to give a clear definition of the involved terms respecting the field of application—the factory. Schenk, Wirth et al. define the term *factory* as a place for innovative, creative and efficient value creation of industrial goods (Schenk et al. 2013, p. 7). Whereas Wiendahl et al. define it as the representation of a local concentration of the primary factors of production: personnel, equipment, buildings and materials, and the derived factors knowledge, skills and capital (Wiendahl et al. 2009, p. 33). Manufacturing is made visible and tangible by the factory.

Demands of the manufacturing task are put into specific technical, spatial and temporal categories, conditions, features and quantities. Manufacturing becomes manageable by the human through the factory (Helbing et al. 2010, p. 49). Factory types are generally structured by their techno-organisational and economic aspects (Schenk et al. 2013, p. 51). This point of view is not capable of giving an insight into the actual levels of abstraction. Wiendahl et al. classify the factory types according to the customer perspective into (Wiendahl et al. 2009, pp. 34–36):

- High tech factory (technology driven, innovative products, high process quality)
- Fast reaction factory (time driven, high performance logistics)
- Breathing factory (flexible throughput, cost-effectiveness at varying throughput)
- Customer-individual factory (individuality, high customer integration)
- Variant-flexible factory (diversity, modular product and production structure)
- Low-cost factory (cost-orientation, hard target costing, product focus)

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The listed types are never considered separately, but more as a key-featured mixture of all types. In fact, the factory is subject to constant change. Shortened innovation cycles, profit renewal cycles and market launch cycles force factory planning and operation activities to react with flexible and versatile systems. Nyhuis et al. describe flexibility as the possibility to allow adaption within given boundaries. Whereas mutability is described as the potential to allow a rapid adaption of the organisational and technical structure outside of given boundaries with acceptable investment expenses (Nyhuis et al. 2008, pp. 24–25).

2.1.1 Levels of Abstraction Within a Factory

Westkämper introduces *activity units* (German: Leistungseinheiten) as a self-contained, viable system, which is able to perform a transformation process at any level of abstraction. He describes viable systems as something that manages its own resources and knowledge, executing and steering its processes and that contributes discretely to the value addition (Westkämper 2006, p. 52). These activity units can represent the smallest value adding unit on the lowest level of abstraction of the factory, or it can be aligned horizontally and be integrated into an activity unit on the next higher level of abstraction as shown in Fig. 2.1.

Figure 2.1 is a combined collection of phrasing for the levels of abstraction of manufacturing found in literature. *Factory sites* are the local representations of manufacturing, noticeable by society. They contain all peripheral entity clusters needed to enable manufacturing on site. Such peripheral entity clusters are buildings, technical building services, facilities for social means, health, security and administration as well as organisational services such as facility management, maintenance, tool making as well as security service. Factory sites can incorporate multiple manufacturing segments (Verl et al. 2011, p. 348; Westkämper 2006, p. 55).

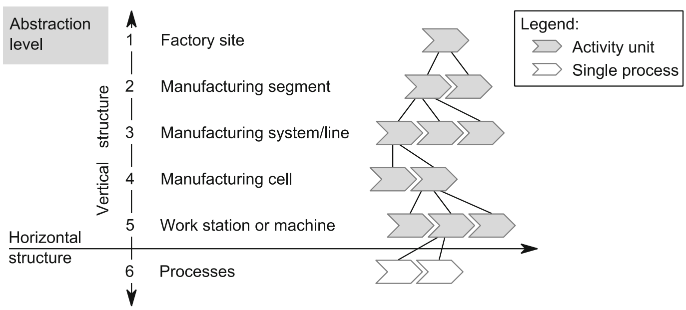


Fig. 2.1 Levels of abstraction of manufacturing, in reference to Westkämper (2006, p. 56), Müller et al. (2009, p. 42), Verl et al. (2011, p. 348)

A *segmentation of manufacturing* or a factory site into self-contained areas of manufacturing activity is used to draw distinct system boundaries from an organisational or management perspective. Physically, the segmentation is carried out by distinguished areas and buildings with operation and administration functions (Westkämper 2006, pp. 56–57; Müller et al. 2009, p. 41).

Manufacturing systems include mechanical production as well as assembly activities with bound supply and disposal systems. Verl et al. also use the term manufacturing line to describe a higher degree of automation and rigidly interlinked machines and work stations with its own transport and storage infrastructure (Verl et al. 2011, p. 348). Moreover, manufacturing systems have their own automated control system. *Manufacturing cell* is the dominating term for a local grouping of machines and work stations operated by a working group.

Work stations are places for manual or semi-automated production execution, which can be understood as the smallest single activity unit. *Processes* are performed manually at work stations or on automated basis operated by humans through machines. Both value adding and non-value adding processes are considered. One differentiates between technical processes (e.g. form turning or tapping) and organisational processes (e.g. procurement of tools or design of a component) (Westkämper 2006, pp. 57–58).

2.1.2 *Functional Structure of a Factory*

The organisational and technical structure can be clustered into generic functions, which can be found in any factory. In Fig. 2.2, these functions are depicted in reference to Helbing et al. (2010, p. 50). Factories provide the technological

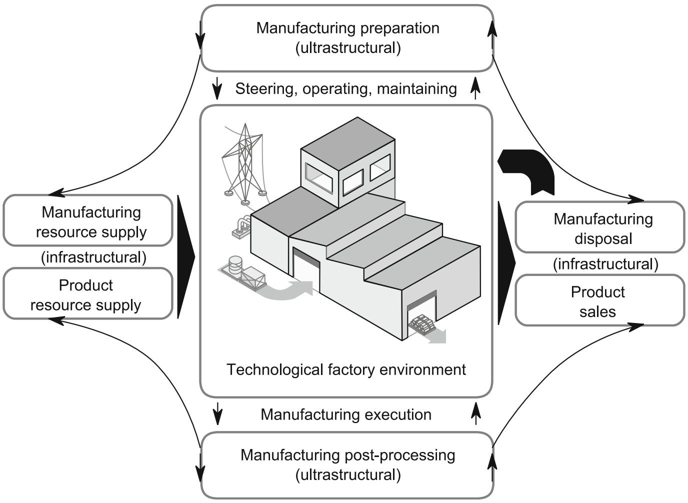


Fig. 2.2 Functions of a factory, in reference to Helbing et al. (2010, p. 50)

environment to realise manufacturing. The manufacturing function requires supporting functions as shown in Fig. 2.2, such as manufacturing preparation and post-processing, the manufacturing resource supply and disposal as well as the steering, operating, maintaining and execution of the manufacturing within the factory.

According to Fig. 2.2, the supporting functions can be clustered into ultrastructural and the infrastructural ones. The ultrastructural factory section consists of sales and procurement, manufacturing preparation, total operational factory sections, functional sections, social care sections, administration sections, business or commercial sections and information provision. Within the ultrastructural sections the inner and outer information flows dominate. Infrastructural sections of a factory consist mainly of supply functions but also of commonly used sections of a factory. The energy as well as the operating resource supply is differentiated into system supply and space supply. Furthermore, it consists of equipment supply, solid waste disposal, operating resource recycling and disposal, energy recovery, infrastructural joints, constructional sections, outside sections, sanitary and shelter sections. Within the infrastructural sections the energy and material related total interdependence dominates (Helbing et al. 2010, p. 51).

The technological environment represented by the factory's core business consists of all stages of manufacturing, material flow, testing and laboratory processes. The material flow can be further diversified into: supply, commissioning, shipping, storage, transport and transfer. Within the technological factory environment, the manufacturing programme, the technology, as well as the product flow, dominate the complex.

A factory provides the proper boundary conditions and environment to produce goods, which themselves meet the demands of the market. Consequently, manufacturing can be described as a transformation process, adding value to raw materials or semi-finished goods (input) by transforming them into goods of higher value or final products (output) for the customer (Westkämper 2006, p. 34). The value adding process takes place in various stages of manufacturing. As depicted by the graph in Fig. 2.3, value addition is a function of time. The duration from order placement to delivery of the goods to the customer is understood as the throughput time (Westkämper 2006, p. 34).

In order to realise the transformation process, various inputs are needed. The inputs are usually called production factors and are not manufactured in-house, but need to be bought from different supply markets (resource, energy, supplier, investment goods, equity, labour and service markets) (Westkämper 2006, pp. 34–35). Besides the functions and value addition processes of a factory, there are actual entities performing the value creation processes and peripheral entities supporting the value creation.

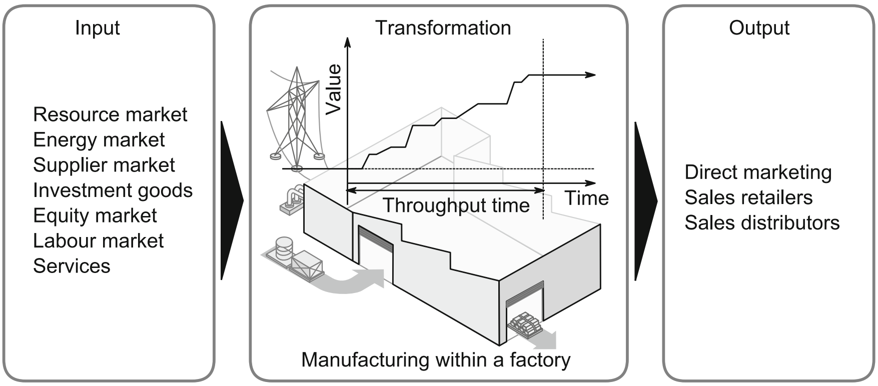


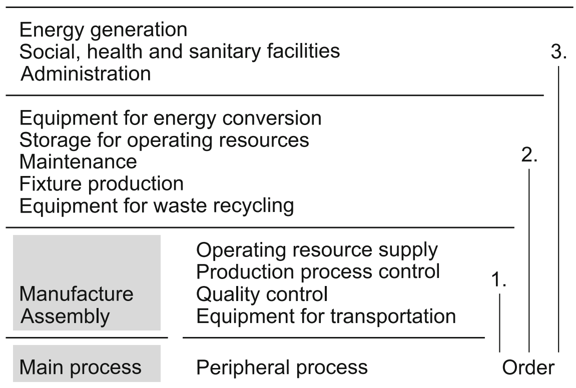
Fig. 2.3 Manufacturing, a value adding transformation process, in reference to Westkämper (2006, p. 34)

2.1.3 Entities of a Factory

Transformation processes, respectively manufacturing equipment and machines, demand human workforce, energy supply, operational resources, information supply as well as transport and disposal of fixtures, raw materials, goods and waste. Some of these supplies for example cannot be immediately provided, but have to be converted or generated first, for provision to the places of demand in the factory. The technical adjacency of these services is classified by Schenk, Wirth et al., introducing the *peripheral order*. Exemplary services and equipment supporting the main process of manufacture and assembly are listed from first to third order in Fig. 2.4.

Schenk et al. describe the 1st peripheral order equipment to be directly dependent on the production programme and main process. Such processes are for example quality control or directly linked transportation processes. The 2nd peripheral order is not dependent on the product programme, but has a direct link or

Fig. 2.4 Peripheral order of supporting processes



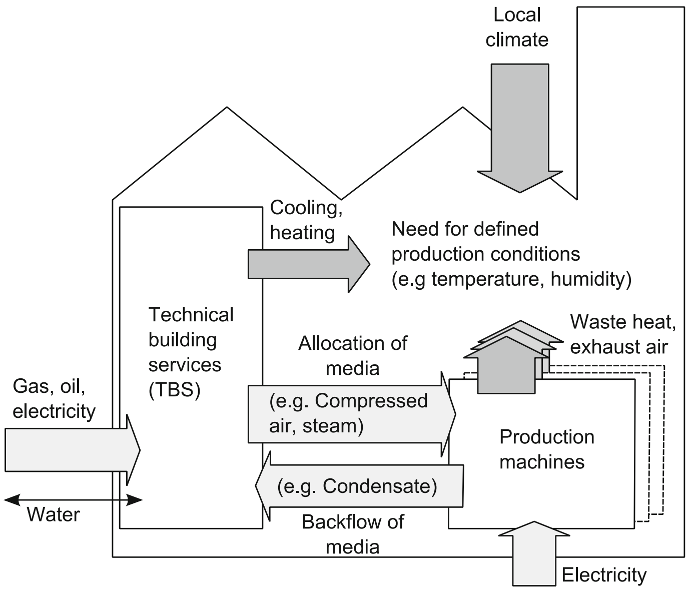


Fig. 2.5 Holistic factory view on the entities and their energetic interconnections (Thiede 2012, p. 39; Hesselbach et al. (2008, p. 625)

involvement into the workflow of the main process. This could be for example maintenance activities or the disposal and treatment of waste flows (e.g. metal chips and coolants) of main processes. The 3rd peripheral order has the furthest adjacency and is fairly independent from the main process. They provide the general working environment and condition for the human workforce or for machines and equipment, for example (Schenk et al. 2013; pp. 135–136).

The more detailed a manufacturing site is examined from different levels of abstraction and different peripheral orders, the more obvious it becomes that the emerging material and information flows as well as the energy flows are not only caused by the main processes of manufacturing, but also by peripherals and external factors. To underline this, Thiede has first introduced along with Hesselbach et al. the holistic definition of the factory elements and has focused on the energetic interconnections between them, as presented in Fig. 2.5 (Thiede 2012, p. 39; Hesselbach et al. 2008, p. 625).

Thiede divides the factory into three major elements: *manufacturing* (consisting of production machines, human workforce coordinated by production planning and control), *technical building services* (e.g. electricity distribution, equipment for compressed air generation, heating and cooling systems as well as steam generation and condensate collection) and the *building shell*.

Machines, technical building services and the building (shell) react upon internal and external energetic loads. Machines demand grid-bound energy flows to perform processes, e.g. from technical building services and themselves generate an internal load within the building by emitting not effectively utilised energy as waste heat. This internal load and the external load induced by the local climate have to be compensated by technical building services, by heating, cooling, filtering and humidifying to establish the required technical and social working conditions for manufacturing. All these services demand energy and are in combination with the manufacturing processes and the internal energy conversion processes responsible for the induced energy flows within a factory

2.2 Energy Flows and Energy Conversion in Factories

Next to material, human and informational resources, energy is one of the most vital elements needed for the manufacturing of goods in factories. Without changes in energy states, no raw material can be extracted or be transported to their destination for further processing. Energy exists in various forms, can be put into discrete units, can be distributed via grids or pipelines and can be purchased at stable quality. Energy has become a matter of availability and demand, which is seemingly rising all over the world, in direct correlation to the growing wealth of industrial nations as shown in Fig. 1.2. Since energy, like any other resource, is not infinite, higher demands result in higher economic value. Tradable energy has to be converted from primary energy sources. These conversion processes result in direct environmental impacts (see Fig. 1.1), which become, due to legislative regulations and subsidies for alternative conversion processes, a growing economic cost factor for tradable energy. Hence, the importance for energy transparency in factories gains more significance.

As the background on energy and energy flows play a central role in this book, a short excursus on the essential definitions of energy and its related terms will be given in reference to the comprehensive fundamentals of thermodynamics presented by Baehr and Kabelac (2009) in their work.

2.2.1 Definition of Energy and Related Terms

Energy is a physical quantity measured in the SI-unit Joule.

$$1\ \mathrm{J} = 1\ \mathrm{J} = 1\ \mathrm{Nm} = 1\ \mathrm{kg\ m^2\ s^{-2}}$$

The units Nm and kg m^2/s^2 are known from mechanics. Mechanical energy is described through kinetic energy E_{kin} and potential energy E_{pot}. Mechanical energy is an extensive state quantity, proportional to mass and dependent on the velocity and the coordinates in space, describing the movement of the system. The energy of a stationary system is called inner energy U and is defined through

$$U := E - E^{\mathrm{kin}} - E^{\mathrm{pot}}.$$

The total energy E of a system is the sum of inner energy, kinetic energy and potential energy. The inner energy is an extensive state quantity; the specific inner energy is dependent on the thermodynamic temperature and the specific volume of a system.

The inner energy can be split into three parts, the thermal, chemical and nuclear inner energy. The thermal inner energy is influenced by temperature and specific volume. Within chemical reactions, the molecular bonding energy is altered. For example, in combustion reactions the chemical inner energy decreases while the thermal inner energy increases. The same phenomenon is valid for nuclear reactions, where nuclear inner energy is converted into thermal inner energy of the fissile material.

The first law of thermodynamics states that the difference of total energy at state 1 (E_1) and at state 2 (E_2) of a system is equal to the difference in quantity of heat (Q_{12}) and work (W_{12}) transferred to (positive sign) and transferred from (negative sign) the system, expressed by the energy balance equation

$$Q_{12} + W_{12} = E_2 - E_1. \tag{2.1}$$

The energy of a closed system is constant. Heat and work are not state quantities but process quantities indicated by the double index 12. As processes are taking place in time, the starting and end states in time τ_1 and τ_2 are introduced. For $\tau_2 - \tau_1 = \Delta\tau \rightarrow 0$, two new time-dependent process quantities are introduced. The heat flow $\dot{Q}$, and the (mechanic or electric) power P, which could also be called work flow $\dot{W}$. The new equation is the power balance equation

$$\dot{Q}(\tau) + P(\tau) = \frac{dE}{d\tau}. \tag{2.2}$$

For transient processes the equation is extended by the energy flow entering and exiting the system boundary. The transported energy consists of its enthalpy H, kinetic and potential energy. The specific enthalpy is dependent on temperature and pressure.

According to their definition, $\dot{Q}$ and P have the SI-unit J/s, which can also be expressed in the more commonly found unit 1 W = 1 W = 1 J/s. For the quantity of energy, the combination of a unit of power and a unit of time, e.g. 1 W s = 1 J is commonly found. Especially for electrical energy, the larger unit

$$1\ \mathrm{kW\ h} = 3600\ \mathrm{kW\ s} = 3.6 \times 10^6\ \mathrm{J} = 3.6\ \mathrm{MJ}$$

is used in technical applications (Baehr and Kabelac 2009, pp. 47–89).

The second law of thermodynamics constitutes that work, mechanical and electrical energy can be fully converted into inner energy and heat. In contrast, inner energy and heat can never be fully converted into work, mechanical or electrical energy. From a power engineering perspective this results in the fact that different energy types are evaluated differently. Therefore, a thermal engine can only convert a share of the heat flowing to a system, into work leaving the system. The other share consists of dissipated heat flows into the environment at the lowest possible temperature. The same is valid for the inner energy, which also cannot be converted in the same manner into work. The determining extensive state quantity for that law is the entropy S. The entropy changes induced through heat and mass flows to and from a system. It increases due to irreversible processes within a system. Entropy can only leave the system boundary in combination with heat flows leaving the system. In technical systems, these heat flows are often addressed as waste heat (Baehr and Kabelac 2009, pp. 95–97; Cleveland and Morris 2009, p. 552).

Moreover, there are two classes of energy. The first is energy being convertible into any other energy type without constraints (due to the second law of thermodynamics). The second is convertible into other energy types only with constraints. The unconstrained convertible energy types are mechanical energy and electrical energy. These types are entropy free and are subsumed under the term *exergy*. In order to convert constrained energy types as inner energy, enthalpy and energy leaving the system as a heat flow into entropy-free exergy, there must be a way to dispose the remaining entropy to a neighbouring system, e.g. the environment. The limiting factor for this is the environmental temperature. The share of energy that is not convertible into exergy is called *anergy*. Hence, every possible energy type follows the equation

$$\text{energy} = \text{exergy} + \text{anergy}.$$

To support the comprehension of the exergy and anergy balance, Fig. 2.6 shows the flow diagram of a thermal heat engine. The heat flow $\dot{Q}$ to the machine at the available temperature T_m consists of two shares, the possible usable exergy $\dot{E}_Q$ limited by the second law of thermodynamics and the non-convertible anergy $\dot{B}_Q$. Depending on the technical design of the machine, the effective work $|P|$ can be converted accompanied by the internal losses $\dot{E}_L$.

Yet another share of energy is lost during the heat conversion process due to the fact that the outside temperature T_0 is not equal to the lowest possible temperature T_E of the environment. Figure 2.6 visualises the possible losses of technical energy conversion processes and the terminology in relation to energy conversion and is at the same time introducing the Sankey diagram,[1] extending the conventional energy view to the split visualisation of exergy and anergy. Sankey diagrams show

[1]This flow chart was named after the Irish engineer Captain Henry Phineas Riall Sankey, who first used this visualisation in a technical context (Sankey 1989).

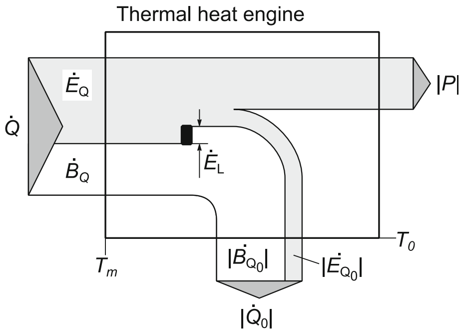


Fig. 2.6 Exergy and anergy flow of a thermal heat engine, in reference to Baehr and Kabelac (2009, p. 173)

quantitative, width-proportional, directed flows of the same physical unit (Baehr and Kabelac 2009, pp. 172–173).

In the context of a factory, the technical relevance of exergy and anergy are evident. Technical processes like heating, cooling, lighting, production of goods, transportation and the transmission of data demand energy—moreover, effective work or electricity, which is exergy. To supply exergy to technical processes in factories, primary energy must be converted (Baehr and Kabelac 2009, pp. 150–158)

2.2.2 Energy Types at the Factory Gate

The conversion of primary energy sources from import, storage or extraction or from renewable sources into final energy, supplied to the factory, is defined as the *energy chain* (Cleveland and Morris 2009, p. 167). Primary energy is the energy embodied in natural resources such as coal, crude oil, sunlight, wind, running rivers, vegetation and uranium, before being processed the first time by human hand. When speaking of the primary energy demand of a nation or a branch of industry, the direct supply, the conversion into actually supplied final energy and the energy needed for conversion, transformation or distribution and storage are accounted in the balance (Cleveland and Morris 2009, p. 402).

Primary energy is converted by the energy sector to final energy by briquetting plants, coking plants, heat plants, combined heat and power plants, refineries, hydro power plants and other conversion processes for geothermal, water, air and solar power.

Final energy is a collective term for all types of energy finally sold to the end customer, e.g. industrial sector (without energy sector), transportation sector, households as well as commerce and services. This is mainly made up of fuel oil, natural gas, electricity, coal, district heating, wood and peat. In reference to RWE, Fig. 2.7 shows in exemplary manner, the energy chain for the German industrial sector with accumulated values for one year in petajoule (Rebhan 2002, p. 1165).

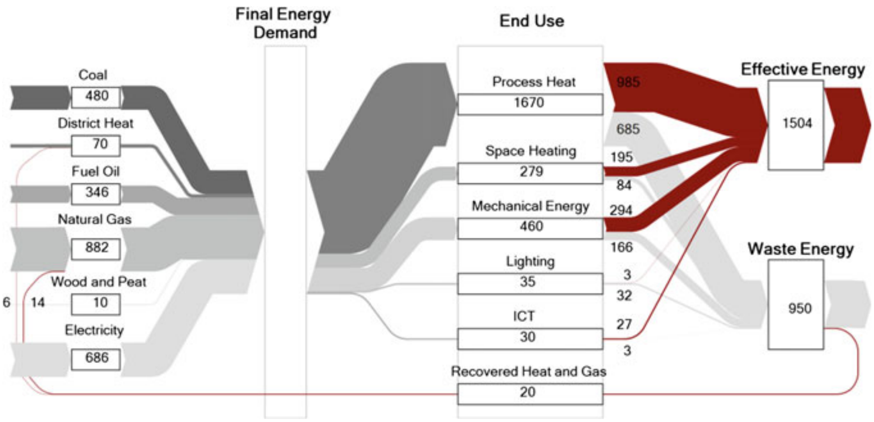


Fig. 2.7 Energy chain of the German industry from final energy types to effectively utilised energy shares in petajoule (Rebhan 2002, p. 1165)

The energy chain shows vividly how the final energy types are utilised within industrial processes (the end use is directly associated with the conversion and utilisation efficiency of the individual end use purpose).

Natural Gas

Natural gas consists of small or short hydrocarbon compounds. Methane is the most common compound, but also other fractions like ethane or propane or even butane and ethene can be found. Natural gas is for most parts extracted from underground natural gas fields, often combined with oil fields. Natural gas is after crude oil and coal, the third most important primary energy in the world. In 2012 the delivery rate was at 3.4×10^{12} m^3 and is expected to remain at a steady level. Natural gas has gross calorific values in the range of 10 up to 14 kWh/kg and a net calorific value about 10 % less of its gross value. In Germany the standardised net calorific value of natural gas is 9.77 kWh/Nm^3. Natural gas is a pipe-bound energy type and can be supplied as final energy via pipe directly to the end user or can be converted as a secondary energy into process, district or space heating and also electricity (Cleveland and Morris 2009, p. 340; Andruleit et al. 2013, pp. 54–103).

Coal

Coal, as well as gas and oil, is a fossil fuel, based on carbon compounds. It was before oil-domination, the most important industrial primary and final energy type. Coal is based on compressed dead prehistoric vegetation. It is denser than peat, contains less water and has a higher calorific value. With increasing calorific value the moisture decreases and the carbon share increases. Due to it having the largest resources globally and having a share of nearly 30 % of the global primary energy sources, coal is still the most relevant energy type. About 41 % of the world's electricity is converted from coal. The main classes of coal are defined by their calorific value: meta-lignite, sub-bituminous coal, bituminous coal and anthracite

(>4.56 MJ/kg), which is traded globally, and ortho-lignite and peat (<4.56 MJ/kg), which is primarily used close to the deposit and converted into electricity. Approximately 18 % of the world's extracted high calorific coal is traded around the globe, of which China, Japan and India have imported about 49.3 %—tendency rising. From 2005 onwards, China was expected to build up the equivalent of the total power grid capacity of the United Kingdom by coal-fired power plant per year, leaving no doubt about the origin of the carbon dioxide emissions of Fig. 1.1 (Andruleit et al. 2013, pp. 27–29; Cleveland and Morris 2009, pp. 94–95; Katzer 2007, p. 63).

Fuel Oil

All fuel oil types have their origin in crude oil, which is a mixture of long-chained hydrocarbons in liquid stage, extracted from underground cavities. With a share of over 33 % of the world's primary energy demand, it is the most important energy type worldwide. Since the beginning of the industrial extraction until the end of 2012 about 44 % of the original reserves[2] of crude oil were already "used up". Today, crude oil is the primary energy type whose depletion is farthermost advanced. Crude oil is differentiated according to the way of extraction into conventional oil (viscosity < 1 g/cm^3), like heavy crude oil, light crude oil and condensate as well as non-conventional oil, like bitumen or shale oil, which are extractable only by means of high technical and controversially discussed efforts. Final energy types (fuel oil derivatives) converted from crude oil are petroleum, gasoline, diesel fuel and kerosene (Andruleit et al. 2013, pp. 20–101; Cleveland and Morris 2009, p. 117, 135, pp. 205–206).

Wood and Peat

Wood and peat as yet another final energy type is accounted for as biomass. Biomass is of comparably low relevance in comparison to fossil fuel, but is outrunning nuclear fuel as a primary energy type. Wood is considered to be a sustainable final energy type with a net calorific value of 2.2–5.3 kWh/kg. Over 70 % of the global wood harvest is used already as a fuel or can be potentially utilised as such—corresponding to 500 million tons of oil equivalent[3] (Andruleit et al. 2013, pp. 13–14; Cleveland and Morris 2009, p. 377, 565).

Electricity

Electricity or electrical energy is the first final energy type which is not just a refined or processed primary energy type, but is a truly converted energy type from one of the above introduced energy types. Electricity can be converted from chemical energy or from other primary energy types such as nuclear fission (nuclear energy) and natural solar (radiation energy from electromagnetic waves), with intermediate energy types such as hydro (potential and kinetic energy) and wind (kinetic energy) as shown in Fig. 2.8. Electrical energy is converted and provided

[2]Original reserves are the cumulated extraction plus the left over reserves. Reserves are, at today's prices and state of the art, economically feasible extractable energy resources.

[3]Tons of oil equivalent = 1 toe = 1.1×10^3 m^3 natural gas = 41.8×10^9 J.

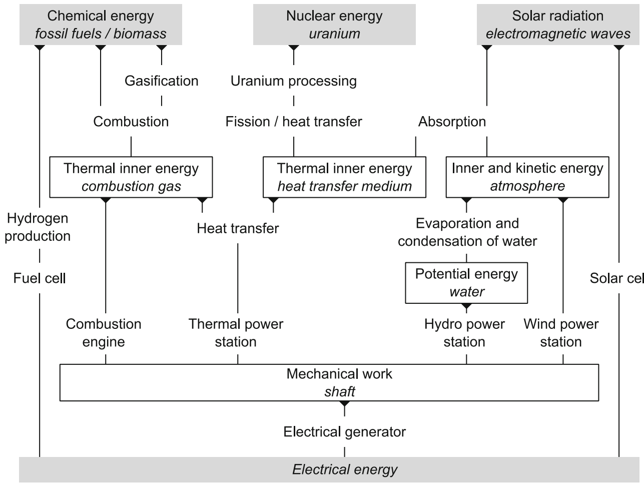


Fig. 2.8 Energy conversion chain of electrical energy (Baehr and Kabelac 2009, p. 530)

by a combination of electrical potential and electrical current over the grid (electric circuit) from "generator" to "consumer". Besides in photoelectric cells and fuel cells, electricity in large scale energy engineering is converted through power plants by combustion (chemical to mechanic), fission (chemical or nuclear to mechanic) or absorption in series with principles to convert inner and kinetic energy of the atmosphere into mechanical work at the shaft of an electric generator. Electric generators provide the electric grid with commonly three-phase electric power with an alternating current of 50 Hz (e.g. Europe, Africa and large parts of Asia) or 60 Hz (most of North and Central America (Rebhan 2002, pp. 16–17; Cleveland and Morris 2009, p. 156, 468).

Electricity is generated in power stations with voltages between 3 and 30 kV and is transformed into the high voltage and the super high voltage grid between 220 and 750 kV to be distributed via aerial lines in integrated networks (of the European Network of Transmission System Operators for Electricity (ENTSO-E) in Europe and the North American Electric Reliability Corporation (NERC) in North America). In cities and large industrial parks, the voltage is transformed by sub-stations into the medium high- and high voltage grid of the public utility (e.g. energy supply company) at 3–150 kV. Within large industrial sites with own transformers or in commercial or residential areas with transformers of the public utility, the voltage is transformed to 0.4–0.66 kV for small "consumers". For Central Europe the low voltage grid is operated at 230/400 V (Crastan and Westermann 2012, pp. 4–12; Daniels 2000, pp. 320–321; Cleveland and Morris 2009, p. 527).

District Heat

District heat is produced at a central location often in combined heat and power plants, heat plants or as recovered heat as a by-product of industrial processes. The heat is transported as steam. In metropolitan areas a growing share of residential houses is heated by district energy. District heat has technical and economic advantages: It makes combined heat and power generation more economic than in decentralised generation, the incineration of difficult energy sources such as coal, waste, sewage sludge or biomass is easier to handle and control in large-scale power plants and the recovery of industrial waste heat becomes possible. The heat is coupled into an insulated two pipe transport network with a feed and a return line. Existing steam systems (>120 °C) are more and more substituted by hot (>120 °C) or warm (≤120 °C) water systems because of the technically challenging condensate return path. The supply at the gate of the customer/consumer is done directly without system separation or, more commonly, indirectly by system separation with a heat exchanger. In industrial applications, district heat is provided in a three pipe system, to provide two temperature levels, one season-dependent (e.g. winter at 130 °C/summer at 70 °C) for space heating and one constantly high temperature level for process heat (Krimmling 2008, pp. 79–81; Daniels 2000, pp. 320–321; Cleveland and Morris 2009, p. 141).

2.2.3 Factory Internal Energy Conversion for End Usage

Manufacturing processes need effective energy to add value in forms of produced goods. However, to enable this ultimate energy conversion within a production machine, multiple factory-internal energy conversion steps have to pass through. This energy chain can be very industry and process specific. Therefore, a flow scheme with generic chains is difficult to provide within a general statement. For instance, Wohinz and Moor have given a factory internal energy chain with a prevalent general scheme for manufacturing companies in Fig. 2.9.

Similar to the big picture flow scheme of Figs. 2.7 and 2.9 indicates that the factory internal technical building services convert final (external) energy types, supplied at the factory gate, into intermediate (internal) energy types or directly into effective energy types, such as

- space heat (inner energy),
- process heat (inner energy),
- process electricity,
- mechanical energy (e.g. compressed air) and
- light (electromagnetic energy),

which is ultimately converted into losses (anergy) and waste (exergy), which can partially be recovered for internal utilisation or sold to external third parties.

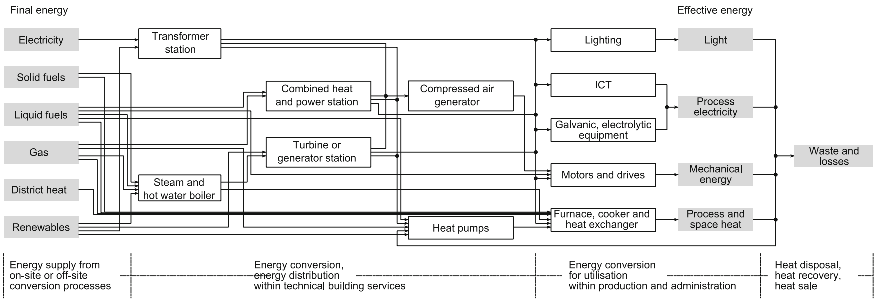


Fig. 2.9 Factory internal energy conversion in reference to Wohinz and Moor (1989, p. 36)

Electricity

Electricity, as the most universal energy type, is considered to be exergy, which can be converted into any of the above named effective energy types. Therefore, electricity can be found as a final energy type at the factory gate, as well as an effective energy type in internal conversion processes. Main conversion processes for electricity found in industrial environments are electrical drives, cooling units, compressed air generators and lighting, as well as information and communication technology (ICT). Typical conversion efficiencies are listed in Table 2.1.

Exemplary manufacturing processes utilising electricity on the spot are arc welding (joining), or electric discharge machining (separating).

Space Heat

Space heat is considered to be inner energy. The inner temperature ϑ_i levels are standardized for individual space types (e.g. for administration rooms, lecture

Table 2.1 Conversion efficiency and coefficients of performance for common internal energy types converted from electricity (Baehr and Kabelac 2009, p. 578; Krimmling et al. 2008, p. 146)

Internal energy type	Conversion efficiency/factor from electricity η_c respectively ε_c	Typical conversion entity/device
Light (electro-magnetic radiation)	0.2	Fluorescent lamp
ICT	0.5–0.95	Switch-mode power supply
Mechanical energy	0.94–0.99	Electric motor
Process cooling energy	0.01–6.33[a]	Electrically driven chiller
Space cooling energy	3.0–8.0	Electrically driven chiller
Space heat	>0.98	Electric radiator
Process heat	>0.97	Continuous-flow water heater

[a]The coefficient of performance depends on the cooling task. Mentioned in this example are the performances for target temperatures ranging from −268 °C to −20 °C at an environmental temperature of 20 °C for reversal processes

rooms and workshops). The needed standardised heat flow is calculated on the basis of the inner and outer standardised temperature ϑ_o, as well as constructional and technical parameters like the envelop surface A and the heat transition coefficient k (also called k-value), as well as the volume flow of outside air $\dot{V}$, the specific heat capacity and the density of air ρ. One basic equation for the standardised heat flow $\dot{Q}_S$, as the sum of the transition heat flow $\dot{Q}_T$ and the ventilation heat flow $\dot{Q}_V$, can be expressed as

$$\dot{Q}_S = \dot{Q}_T + \dot{Q}_V = kA(\vartheta_i - \vartheta_o) + \dot{V}\rho c(\vartheta_i - \vartheta_o). \tag{2.3}$$

Daniels remarks that national and European standards for factory buildings do not consider the effect of inner (e.g. humans, machines and equipment) and solar thermal influences. These two effects are considered as keys for low energy buildings supported by new construction and design concepts (Daniels 2000, pp. 48–53; DIN EN 12831; Milles 2005, pp. 3–9).

Space heat as well as process heat is produced by diverse technical energy conversion processes from final fuels and other energy types (e.g. renewables) with some technical and environmental constraints, according to Table 2.2.

More details on single technical conversion processes extending the content of Table 2.2 will not be presented in this book—moreover, an overview is given.

Table 2.2 Conversion processes for space and process heat production (Daniels 2000, p. 59)

Energy type	Energy conversion	Drawbacks
District heat	Heat exchanger	Condensate (steam)
Steam, hot water, warm water		
Solid fuels	Boiler plant	Storage (bunkering), environmental burden
Fossil fuels, peat, biomass, waste		
Liquid fuels	Boiler plant, combined heat and power plant	Storage (tanks)
Light oil, heavy oil, petrol		
Gaseous fuels	Boiler plant, combined heat and power plant, fuel cells, heat pump	To some extend storage (tanks)
Natural gas, liquid gas, methane gas, biogas		
Electricity	Heat storage boiler, thermal storage heating stove, heat pump	Storage
Geothermal energy	Heat pump	Drilling, regeneration of soil
Environmental energy	Convection	
Air flow, surface water, waste water	Generators, heat exchangers	Fluctuation of availability
Solar energy	Flat, pipe collector, absorber plates, parabolic collectors	Storage, seasonal dependency
Radiation		

Hot and warm water distribution is classified into two pipe, one pipe and single floor systems. The two and one pipe distribution are sub-classified into vertical and horizontal distribution. The materials most often installed are copper, synthetic materials or composites (Daniels 2000, pp. 83–85). Space heat is transferred by heat exchangers, categorised into open heat exchange surfaces (such as flat or profiled plate heaters, radiators, active or passive convectors and radiant ceiling plates) and structure integrated heat exchange surfaces (such as floor heating or wall heating) (Krimmling et al. 2008, pp. 91–95).

Process Heat

The term *process heat* differentiates from the term *space heat* mainly by its purpose of final usage. Whereas space heat aims at establishing an acquired temperature level in enveloped space, process heat aims at providing desired amounts of heat to energy conversion processes of the technical building services (e.g. absorption refrigeration) or directly to manufacturing processes. From a thermodynamic perspective, the better differentiation criterion is the needed temperature level of the heat flow at the desired point of use, as shown in Table 2.3. The higher the temperature level, the higher the possible work to be performed.

For warm and hot water as well as for heat transfer oil the transferable heat flow can be calculated by

$$Q_T = \dot{m} c_p \Delta t.$$

Steam as an energy type allows considerably higher amounts of energy to perform work due to the enthalpy of vaporization.

Cases where heat is provided to the process, not via heat exchangers in cyclic processes, but directly to the process in an open loop, higher temperature levels become possible. At this point the energy carrier becomes part of the chemical reaction. This applies for example to blast furnaces.

Table 2.3 Types of process heat clustered into temperature levels and areas of industrial application (Daniels 2000, p. 66; Schmid 2004, p. 107; Schieferdecker 2006. p. 12–13)

Energy type	Temperature (°C)	Common areas of application
Warm water	60–40	Space heating in buildings
Warm water	<100	Cleaning, dyeing, washing, cooking
Hot water	<190	
Steam	<350	Sterilising, steaming, dyeing, distilling
Heat transfer oil	<400	Cooking
Electricity (capacitive, infrared, inductive, resistance, electric arc)	<3400	Sintering, melting, induction furnace/hardening
Hot air/flue gas	>50	Drying, recovered heat utilisation in heat pumps, absorption refrigerators

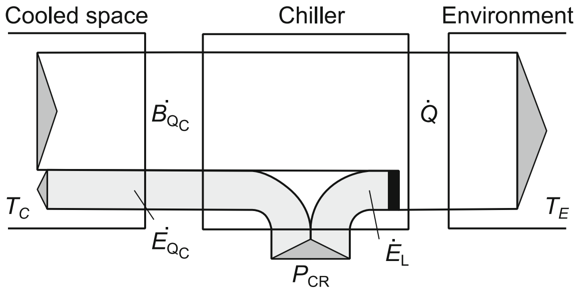


Fig. 2.10 Exergy and anergy flows of a chiller (Baehr and Kabelac 2009, p. 576)

Exergetic efficiency of heating processes and calorific values of heating processes are presented in detail by (Baehr and Kabelac 2009, pp. 581–592).

Cooling processes can be regarded as a special case of process or space heat extraction with heat pumps. The wanted cooling capacity (power) $\dot{Q}_C$ is the extracted anergy flow $\dot{B}_{Q_C}$ from an enveloped cooled space at the wanted lower temperature T_{C} to the surrounding environment at a temperature T_E, as shown in Fig. 2.10. This wanted anergy flow is facilitated by a chiller utilising work P_{CR} to deliver the exergy demand $\dot{E}_{Q_C}$ to the cooled space. Due to irreversibility the exergy losses $\dot{E}_L$ are added to the extracted anergy flow.

The cooling capacity of the chiller $\dot{Q}_C$ is the sum of the extracted anergy flow $\dot{B}_{Q_C}$ and the supplied exergy flow $\dot{E}_{Q_C}$ (both flows have opposite signs). The evaluation of a chilling process shown in Fig. 2.10 is defined by the coefficient of performance

$$\varepsilon_{\mathrm{CR}} := \dot{Q}_C / P_{\mathrm{CR}}. \tag{2.4}$$

The coefficient of performance can be greater than one. The thermodynamically more important exergetic efficiency

$$\zeta_{\mathrm{CR}} := \left|\dot{E}_{Q_C}\right| / P_{\mathrm{CR}} = 1 - \dot{E}_L / P_{\mathrm{CR}} \tag{2.5}$$

can only reach one in the limiting case of reversibility (Baehr and Kabelac 2009, pp. 571–578). Chillers cannot only be driven by mechanical or electrical power but also by a heat flow $\dot{Q}_R$, which could be a recovered heat flow from flue gas or other sources. Thermally driven chillers are technically realised by absorption refrigeration. The coefficient of performance of an absorption refrigeration process is defined by Baehr and Kabelac with reference to Bošnjaković (Baehr and Kabelac 2009, p. 602; Bošnjaković 1960, p. 235).

Mechanical Energy

Mechanical energy has been introduced already in Sect. 2.2.1, but a special focus should be set on one of the most prominent mechanical energy types that is not only regarded as an effective energy type but also as an intermediate, internal energy type—compressed air. Compressed air is converted from electrical energy by either dynamic or displacement compressors in diverse sub-types presented in detail by (Ruppelt 2003, p. 34). Compressed air conversion processes account for approximately 10 % of the total industrial electricity demand within Europe (Ruppelt 2003, pp. 2–3). This statistic highlights the relevancy of this mechanical energy type. For a better comprehension of the efficiency of compressed air conversion some simplifications have to be made. When air is defined as an ideal gas (same gas constant) and the isothermal state change is described by:

$$p_1 V_1 = p_2 V_2. \tag{2.6}$$

The resulting mechanical work W_{12}^V that is necessary to perform the demanded strain work of uniform tension can be derived as (Baehr and Kabelac 2009, p. 60):

$$W_{12}^V = -\int_1^2 p dV = -p_1 V_1 \ln(V_2/V_1). \tag{2.7}$$

The adiabatic and isentropic state change describes a pressure change without any heat flows entering or leaving the system more accurately, but still in an ideal approximation. Both ideal approximations serve Gloor as thermodynamic limits to evaluate the efficiency of compressed air generation processes as depicted in Fig. 2.11.

The diagram shown in Fig. 2.11 indicates conversion intensities in electrical power per volume flow over a range of typical relative pressure levels found in industrial applications. Compressed air has various purposes not only as an energy type but also as an information media. The following types are differentiated (Hirzel and Köpschall 2012, pp. 13–14):

- Supply air (to drive tools and pneumatic machinery and pilot air)
- Active air (to convey or transport substances, media, etc.)

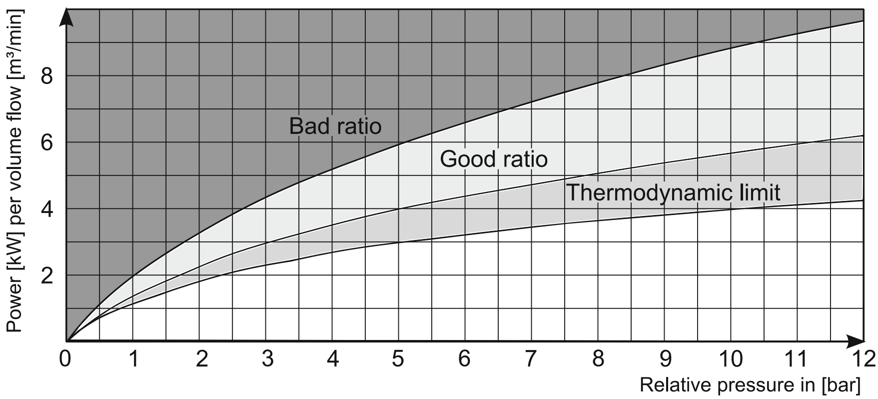


Fig. 2.11 Evaluation of compressor efficiency (Gloor 2000, pp. 1–10)

- Process air (for direct use within processes, e.g. drying and cooling)
- Vacuum air (to create partial vacuum with compressed air)
- Testing air (used for pressure testing and checking).

Process Electricity

Process electricity subsumes the direct utilisation of electrical energy within the desired process to perform the desired value. According to Wohinz and Moor, this includes the direct utilisation within electro-chemical processes such as electrolytic or galvanic equipment, but also for equipment of the technical building services (TBS) such as signalling devices or ICT equipment in general, where electricity is used to process and store information (Wohinz and Moor 1989, p. 33).

Light as an electro-magnetic energy type is considered separately from process electricity, because it is not the direct electric current or voltage but the emitted electro-magnetic spectrum (visible to the human eye), which is desired to generate a luminous source as a technical building service.

In the context of the energy transparent factory, it is important to consider reversely mapping the whole energy chain (from the effective output of manufacturing and peripheral entities back to the distribution of intermediate and final energy types). It is advantageous to trace back each effective energy type to the initial final energy type supplied at the factory gate to gain awareness for the energetic and functional interconnection of manufacturing, conversion and peripheral entities

Generic Energy Flow Modelling

As already depicted in Figs. 2.4 and 2.5, the technical building services and the manufacturing processes are energetically interlinked. To illustrate this relationship, Schieferdecker has introduced a generic model of the factory internal energy conversion processes, as depicted by Fig. 2.12. The model is intended to describe all energy types and all internal energy conversions until the final utilisation of energy.

In Fig. 2.12, Schieferdecker draws a system boundary around the factory to create a balance of energy flows to and from the system and places three representative energy relevant entities therein—a conversion unit, a manufacturing unit and a peripheral unit. Supplied energy enters the system to supply each of the entities with final energy (Q_{SC}, Q_{SM}, Q_{SP} and the enthalpy of a good, Q_{SS}). Exergy losses (e.g. leakage) and anergy losses (e.g. insufficient insulation) make up the difference between the actual input into the entity (e.g. Q_{SCI}) and the supplied energy entering the system (accordingly Q_{SC}). Losses exit the system, originated by all entities (Q_{LC}, Q_{LM} and Q_{LP}), as well as the effective energy converted by the manufacturing and peripheral units to produce a benefit or value (Q_{EM} and Q_{EP}) and the converted energy potentially provided to the external district net (Q_{CD}). Internal

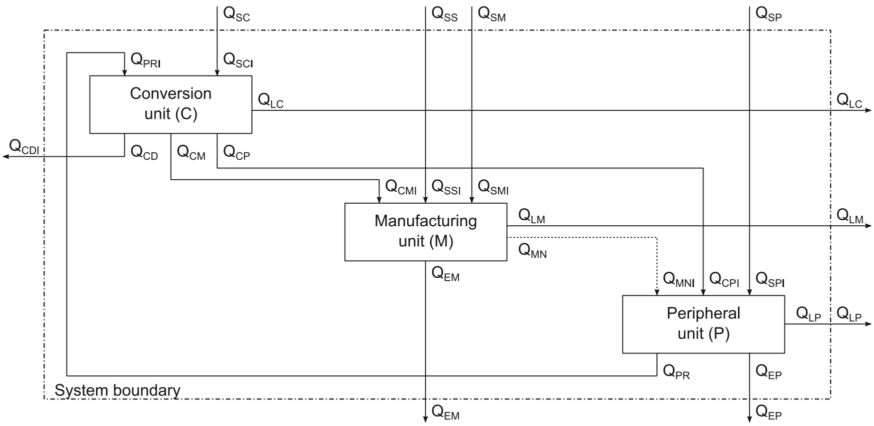


Fig. 2.12 Factory internal energy conversion (Schieferdecker 2006, p. 71)

energy flows have a similar notation—converted energy from a conversion unit (Q_{CM} and Q_{CP}) are higher or equal to the actual input flow into the manufacturing or peripheral unit (Q_{CMI} and Q_{CPI}) due to the above mentioned losses. The energetic difference between a peripheral unit and a manufacturing unit is the optional return path (Q_{RP}) to the conversion unit with the input (Q_{RPI}). A technical example for a peripheral unit with a return path is a radiant heater with a return line for lower enthalpy water (Schieferdecker 2006, pp. 62–75).

Along with the visualisation of the energetic interconnections between the central manufacturing entities and the adjacent conversion and peripheral entities, the fact becomes evident that a holistic examination of the physical and functional energetic links in a real factory is inevitable, when wanting to foster energy transparency in order to manage and control energy flows aiming at higher energy efficiency and a more effective energy utilisation.

2.2.4 Dynamics of Energy Utilisation and Related Cost Factors

Work and heat are no state quantities but process quantities and are therefore time dependent (see Sect. 2.2.1). This is also true for all internal energy conversion processes depicted in Fig. 2.12. Energy conversion processes (or entities of a factory system) are complex technical systems usually consisting of more than one energy conversion process (e.g. mechatronic or thermo-mechanic components), each with a time-dependent energetic behaviour (so called load or power curve). All of the single components have a distinct purpose to fulfil, e.g. a pump providing dynamic hydraulic pressure, a periodically running air filtering system collecting cutting oil mist, or main components like the tool spindle providing the necessary cutting force at the tool tip. Gutowski and Murphy et al. have investigated continuous improvement measures of the Toyota Motor Corporation and have found that energy demands can be allocated to different states of a manufacturing machine divided into static (constant) and dynamic (performance dependent) proportions. The authors even considered non-manufacturing related energy shares as waste, in reference to the lean philosophy of Womack and Jones et al. as well as Shingo (Gutowski et al. 2005, p. 4; Womack et al. 1990, p. 56; Shingo 1989, pp. 76–80).

Dynamic Energy Utilisation

Own investigations have shown that especially in manufacturing processes the energy demand is highly dynamic. The largest share of power over time can be allocated to mechatronic components of a machine that are solely supporting the availability of the machine in a *ready for machining* state. Figure 2.13 shows that supportive processes of an internal cylindrical grinding machine, consisting of controls, the lubrication system, the internal coolant pumps and the exhaust air system, account for more than 4.8 kW of active electrical power. The spindle motor power is differentiated into the free run (spindle running without tool and workpiece interaction) and into cutting operation. The active power demanded by the cutting operation, at varying process parameters (increasing specific volume of metal removed by the abrasive wheel over four steps), is shown in the right part of the diagram. Detailed evaluations of the more energetic impact of machine and process parameters are evaluated by (Winter et al. 2014, pp. 650–653).

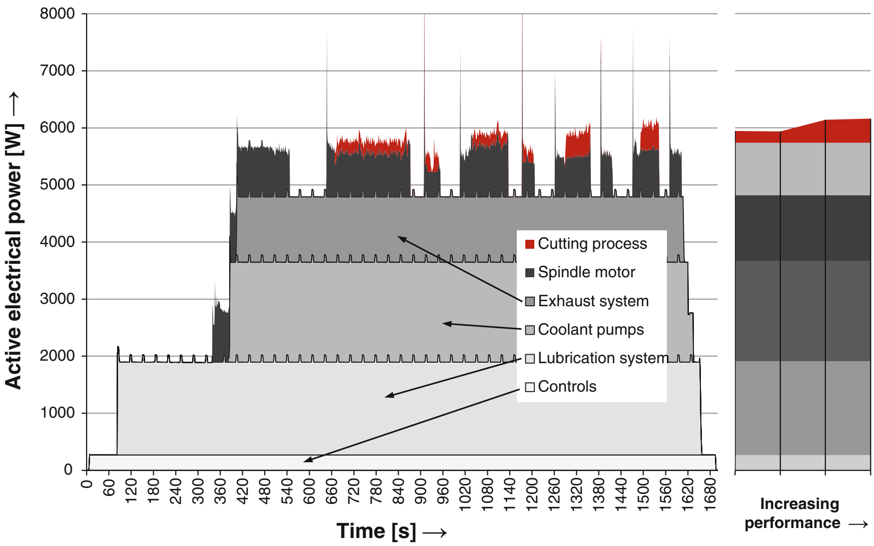


Fig. 2.13 Breakdown of the dynamic power curve of a grinding machine at four increasing performance levels. Internal cylindrical grinding of 100Cr6 (workpiece) with an aluminium oxide abrasive wheel at varying process parameters using cutting oil

Looking at Fig. 2.13, it is actually controversial to use the term "waste of energy" when looking at the power demand to enable manufacturing operations, as each component is necessary for the manufacturing operation. Moreover, it can be stated that during times of no cutting performance, comparably large amplitudes of power are needed to stay in readiness state, causing high shares of energy to be accounted for as non-value-adding (Schilling et al. 2013, p. 22–23). Energy performance limits defined by Zein, indicate that the non-production-performance related energy shares (energy overhead) are to be reduced to a theoretic minimum of zero (Zein 2012, p. 79).

Accumulated Load Curves and Related Cost Factors

From system level onward, up to factory site level, these dynamic load curves of all single entities (conversion, manufacturing and peripheral) add up to one large highly dynamic load curve of a factory site. As depicted in Fig. 2.14, a typical load curve of a medium sized machine building company with a one shift operation has a very distinctive pattern. Each working day shows a steep increase in power originating from the so-called base load of the factory. The end of the shift is represented by a steep drop-down back to base load.

During shifts, sudden drops in amplitude suggest work breaks. On weekends, commonly the minimum power demand is reached. In contrast, in between working days, the minimum power demand is not reached due to online technical building services, machines and periphery operating in idle mode.

The data extract shown in Fig. 2.14 is part of the basis for energy billing by the contracted external energy supplier. Usually, the 15 min average interval determines the charges for maximum demand rates and the energy rate over the individual billing period. Special contract conditions can also include the relation of active power to reactive power, the total harmonic distortion or other indicators as a basis for special surcharges. Other pipe-bound final energy types are billed accordingly. Energy contracts are very company specific and cannot be generalized.

Energy flows such as power and heat flows are process quantities. All single energy converting entities of a factory system have dynamic energy flow curves. The dynamic behaviour of single entities adds up to a complex energy flow (load) curve of a factory site. The dynamic energy flows at the factory gate are the basis for energy billing. Energy transparency means to be aware of quantitative energy flows of all relevant energy carriers to, within and from a factory site

Direct costs for supplied final energy types are usually summarized as electricity, heat and other fuels (like gas and oil). These direct costs are listed for each energy type in Table 2.4 in a generalized form. For industrial customers with high (usually >100 MWh/a) or very high demand rates, other very specific contract models apply. For electricity, this can include factors as usage hours and energy quality factors like the vectorial angle between active and reactive power caused by

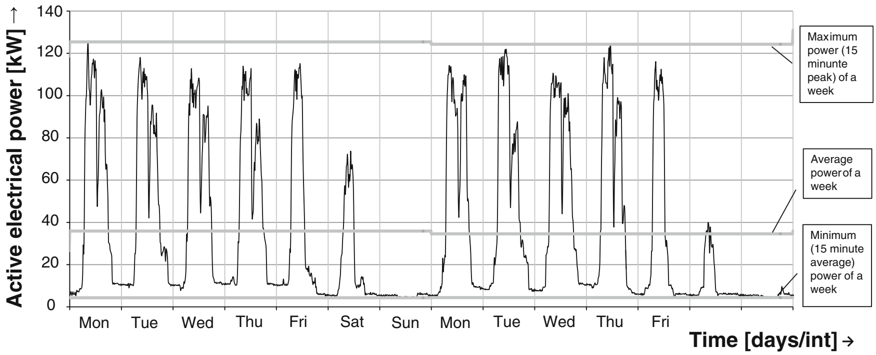


Fig. 2.14 Factory site power curve of two weeks in one shift operation (own illustration). The electrical active power profile is represented by 15 min averaging per data point as supplied typically by the local energy supply company to industrial customers

either inductive or capacitive dominating electric loads. For special contract customers it is also optional to be supplied directly by the medium high voltage grid (>1 kV) (Krimmling et al. 2008, p. 263–280).

Table 2.4 points out that most of the energy supply related costs are bound to the *energy rate*—the amount of energy supplied during a period—but for electricity and district heat an additional demand rate comes into play. The *demand rate* specifies the upper limit of the supplied power. For district heating, the demand rate costs are mostly affected by the outside temperature (space heating), or when processes and energy types are added or substituted (process heat). Since the events named above are within limits foreseeable, the energy controlling is also predictable. In the case of electrical energy, the predictability of demand rates, without additional measures, is not possible. Changes in machine park setups, utilisation

Table 2.4 Energy type specific direct cost factors of energy supply, own depiction in reference to Müller et al. (2009, p. 91–96)

Direct cost factor	Energy type		
	Electricity	District heat	Fuels
Energy rate (one/multiple tariff) (€/kWh)	●	●	●
Demand rate (€/kW/period)	●	●	○
Internal price (metering, billing, …) (€/period)	●	●	●
Energy rate bound cost			
Grid maintenance fee (€/kWh)	○	●	●[a]
Concession levy (€/kWh)	●	○	●[a]
National cost allocation (€/kWh)	●	○	○
National taxes (€/kWh)	●	●	●

[a]applies only for pipeline supplied fuels
● applies
○ does not apply

rates and in manufacturing scheduling can result in high peaks in electricity demand, possibly causing high surcharges. Depending on the energy supply contract, a new tariff grading will be done, based on a fixed number of violations of the contracted demand rate limitation. For factory sites with high shares of demand rate costs in relation to the overall costs for electricity, technical measures like *load management* are applicable (Müller et al. 2009, p. 93–97). The objective of load management is to prevent (15-min) peak loads by either temporarily shedding high loads with an inherent energetic inertness due to large physical or thermal capacities (e.g. compressed air generators or tempering furnaces), or by organisational shifting of load utilisation times (load scheduling).

Indirect Energy Costs

In operational practise, the energy costs contain not only direct costs as listed above, but additionally indirect costs dominated, according to Fuenfgeld, by five categories:

- Supply and conversion cost of internal energy types and media
- Depreciation and amortisation of fixed assets
- Labour costs
- Environment related fees
- Other additional costs

For a more detailed insight, reference is made at this point to Fuenfgeld, who demonstrates that direct and indirect costs exceed the evidential direct energy costs by 30–50 %, in a special case even by 116 %, validated by a study considering four exemplary industrial companies (Fuenfgeld 2006, pp. 108–117).

It has become evident that various tasks in regard to energy flows in factories have to be managed and controlled in order to be aware of resulting costs and to gain transparency within the drivers of different energy cost factors, as well as of related indirect cost resulting from the operation and maintenance of energy distribution infrastructures as well as internal energy conversion, storage and distribution. The field of energy management has shown to affect many of these aspects within all domains of a factory—from the technical facility perspective to the production perspective.

In the domain of energy cost controlling the perspective has to be extended from the obvious energy utilising manufacturing entities to their effects on the conversion and peripheral entities—the technical building services. To track the origin of energy demand, the internal energy conversion chain has to be disclosed going backwards, starting from the manufacturing entities, following the links to peripheral and conversion entities up-stream to the factory gate, where the final energy flow types are supplied and billed. The whole energy chain involves additional indirect energy related costs

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