Chapter 2
Manufacturing Systems and Variable Renewable Electricity Supply

After formulating the central research question(s), this chapter provides necessary background and theory required for the development of the manufacturing system energy flexibility control and improvement concept. As a starting point, Sect. 2.1 presents the background on manufacturing systems, their management and control as well as energy demand of processes and systems, with a special focus on energy flexibility. The next section starts with definitions related to energy supply and provides additional background on conventional electricity generation in the context of mitigating climate change. In the following, background on renewable electricity generation, especially decentralized generation, is given. As a combining element of demand and supply, electricity distribution, markets and related challenges regarding grid stability are discussed. After highlighting electricity demand and supply, options to integrate RE into an existing electricity system are discussed. Integration options are categorized into energy storage and demand side management (DSM) strategies to flexibilize demand. The chapter closes with a brief summary and conclusion.

2.1 Manufacturing Systems

This section starts with necessary background on manufacturing systems, including definitions, management and control strategies, energy demand and energy flexibility of manufacturing systems.

2.1.1 Definition and Classification

(Industrial) production can be defined as the creation of outputs (products) from material and non-material inputs (production factors) according to specific technical

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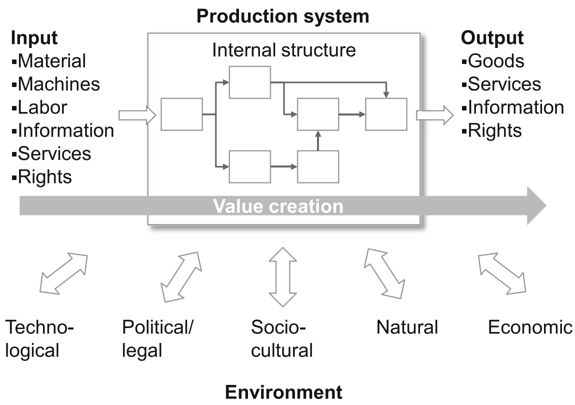

Fig. 2.1 Production system and its environment (based on Günther and Tempelmeier 2005, p. 2; Dyckhoff 2006, p. 5; Dyckhoff and Spengler 2010, p. 4, translated from German, own illustration; compare also to Wiendahl 2014; Westkämper 2006; Zäpfel 2001). Reprinted with permission from Günther and Tempelmeier (2005), Dyckhoff (2006) and Dyckhoff and Spengler (2010)

procedures (Günther and Tempelmeier 2005, p. 6, translated from German, compare also to Zäpfel 2001, p. 1).[1] In other words, production can be regarded as a transformation process to create value (Dyckhoff and Spengler 2010). *Manufacturing*, on the contrary, can be defined as "the transformation of materials and information into goods for the satisfaction of human needs" (Chryssolouris 1992, p. 2). Similar to production, a central aspect is the transformation of inputs to outputs through a transformation process to create value. Further, and more specific, a *manufacturing process* might be defined as "the use of one ore more physical mechanisms to transform a material's shape and/or form" (Chryssolouris 1992, p. 34). In general, an industrial manufacturing process transforms material objects to products using labor and machines (Günther and Tempelmeier 2005; compare also to Westkämper 2006 for definitions/delimitation of and background on production and manufacturing). Within the following, the terms manufacturing process and production process are both referring to above definition with relation to industrial production (as opposed to, e.g., production of intangible products, such as producing a movie). Consequently, the terms *production* and *manufacturing* are used synonymously in the following unless otherwise noted (e.g., in a context where an original reference uses the term production).

A *production system* encompasses several (similar or different) production processes and related infrastructure to enable material and information flow between processes (Dyckhoff and Spengler 2010; Westkämper 2006). Figure 2.1 shows the interaction of a production system with its environment: a production system with several subsystems/processes creates value by transforming inputs to outputs, and is embedded into and interacts with a broader technological, political/legal, sociocultural, natural and economic environment (Günther and Tempelmeier 2005; Dyckhoff and Spengler 2010; Dyckhoff 2006; Wiendahl 2014; Westkämper 2006).

[1]The term *production* is sometimes also used in the context of electricity production. Within this book, the term *production* refers to above definition, i.e., the creation of products, while *generation* or *electricity generation* is used in the context of energy conversion (unless otherwise noted).

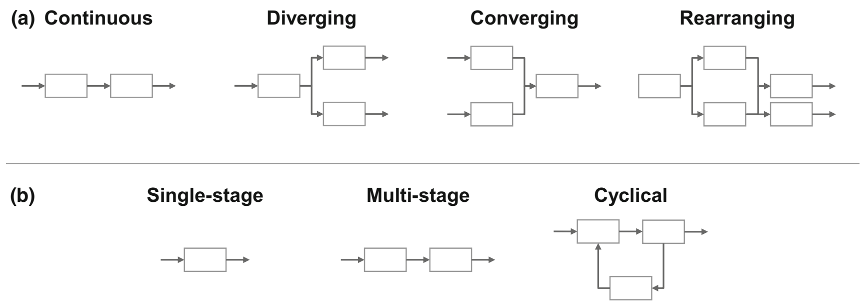

Fig. 2.2 Generic production system material flow structures (**a**) and system stages/network structure (**b**) (based on Dyckhoff and Spengler 2010, p. 22, translated from German, own illustration with additions; see also Schuh and Stich 2012; Dyckhoff 2006). Reprinted with permission from Dyckhoff and Spengler (2010)

Production system typologies can be classified into input, output, and throughput-oriented typologies (see, e.g., Dyckhoff and Spengler 2010). The throughput-oriented type is mainly used to classify and describe production systems within the following as this type focuses on the internal structure of a production system, which is of central relevance for developing an energy flexibility concept. According to the throughput-oriented typology, a production system is characterized according to natural or engineering processes, material flow structure (Fig. 2.2a), system stages/network structure (Fig. 2.2b), repetition type, and spatial alignment of production units (Dyckhoff and Spengler 2010). Different organizational production structures (e.g., job shop production, production line) are, for example, described in Wiendahl (2014).

Another perspective is offered by considering the factory as an entity with interdependent elements connected by material, energy, and information flows. Figure 2.3 shows a holistic understanding of a factory (Herrmann et al. 2014; Thiede 2012; Posselt 2016). The manufacturing system is the central (value-adding) part of the factory. However, in order to fulfill required tasks, technical building services (TBS) are

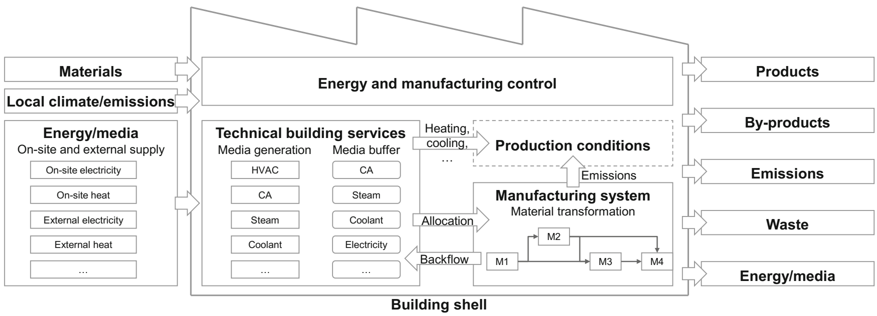

Fig. 2.3 Holistic factory understanding (based on Herrmann et al. 2014; Thiede 2012; Posselt 2016, own illustration)

required to supply media to manufacturing processes and machines, and to process media that flows back from manufacturing activities. TBS include, for example, compressed air (CA) and steam generation. Some media types can be stored before they are required in manufacturing processes. A special role is fulfilled by heating, ventilation and air conditioning/cooling (HVAC), which ensures that desired production conditions (e.g., temperature, air quality) are maintained. These conditions are influenced, aside from outside climate and emission levels, by manufacturing activities. Further, an energy and manufacturing control is used to influence activities (manufacturing, media generation) towards a desired target state. The factory is surrounded by a building shell, which determines the impact of local climate and emissions and influences the emissions released by the factory into the environment. Further, material and energy/media flows are entering the factory, while (by-)products and energy/media flows exit the factory, as well as unwanted flows such as emissions and waste.

2.1.2 *Manufacturing System Management and Control*

A manufacturing system can be understood as a control cycle, in which the *production management* fulfills the controller function (Dyckhoff and Spengler 2010, Fig. 2.4). While this approach considers a (general) management system separated into strategic, tactical, and operational management (also related to long-, mid-, and short-term planning), (direct) production control and its specific tasks (e.g., resource

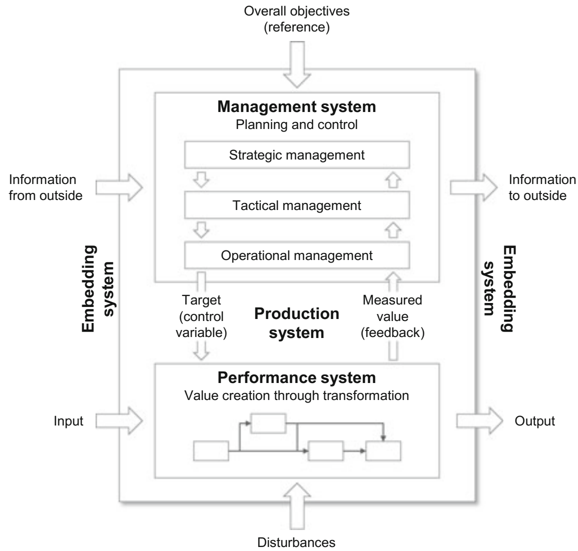

Fig. 2.4 Production management control circle (based on Dyckhoff 2006 and Dyckhoff and Spengler 2010, translated from German, own illustration, similar approach in Wiendahl 2014)

allocation) are also summarized under the term production planning and control (Schuh 2006). The production management aims at planning and controlling the physical performance system according to overall objectives, which are the reference input. Disturbances from embedding systems (the environment, compare also to Fig. 2.1) as well as internal disturbances (i.e., deviation from production schedules due to process failures) require a frequent adjustment of control variables and receiving of feedback to evaluate the effectiveness of control actions.

Depending on its planning horizon, production management can be classified into *strategic* (approx. five years), *tactical* (approx. one to five years), and *operational* (up to one year) production management (Dyckhoff and Spengler 2010; other references consider slightly different planning horizons, e.g., the strategic planning horizon in Wiendahl 2014 is ten to fifteen years or even longer). Typical tasks include

- Strategic production management: production location planning, target and strategy definition, maintaining competitiveness, research and development (products and production processes/technology).
- Tactical production management: layout planning, mid-term production program and capacity planning, technology management.
- Operational production management: short-term production scheduling, material disposition, and production sequence planning.

The operational production management constitutes the main (control) interface to the *performance system* (production system) (Zäpfel 2001). Further, the performance system itself has also several (internal) control cycles to accomplish the required physical transformation (production planning and control).

In order to understand and develop options for influencing manufacturing systems towards improved integration of VRE, the manufacturing process and system energy/electricity demand side is described in the next section.

2.1.3 Energy Demand of Manufacturing Processes and Systems

Manufacturing processes require energy to perform a transformation from inputs into outputs. Typical energy carriers demanded by manufacturing processes are, for example, electricity, compressed air, cooling, and heating[2] (Thiede 2012; Herrmann et al. 2014; Posselt 2016). For the case of electricity demand, several models have been proposed for decomposing and ultimately predicting electricity demand of processes (see, e.g., Gutowski et al. 2006; Kara and Li 2011; Apostolos et al. 2013).

A generic example, e.g., observable for material removal processes such as grinding, turning, or milling, can be found in Fig. 2.5. Electrical power demand over time (left graph) is characterized by different components. These components are demanding electricity depending on current state of the machine, which, in turn,

[2]Note that mentioned energy carriers can be transformed into each other, e.g., compressed air might be generated using electricity as input.

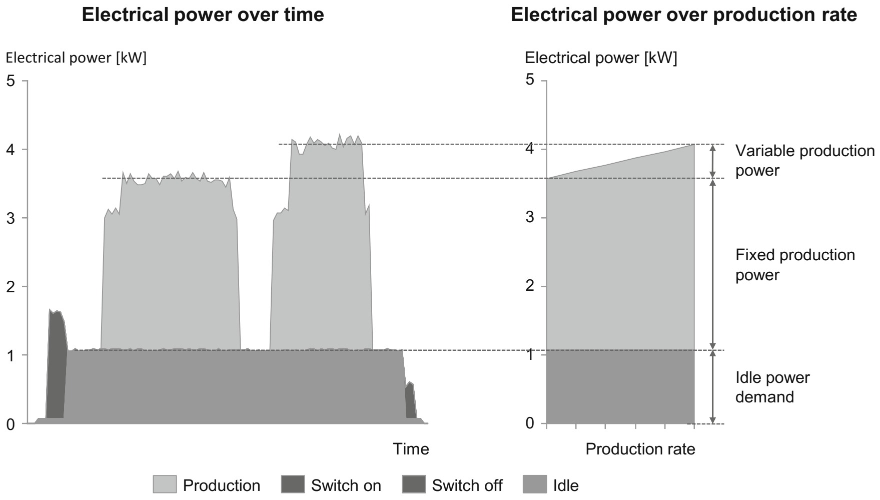

Fig. 2.5 Example manufacturing process energy demand over time and rate (based on Gutowski et al. 2005, 2006; Hesselbach et al. 2008; Kara and Li 2011; Herrmann and Thiede 2009; Weinert 2010; Thiede 2012; Apostolos et al. 2013; Posselt 2016; Duflou et al. 2012, own illustration)

depends on the current task(s) which needs to be fulfilled to complete a desired production sequence. A constant base-load demand, e.g., originating from turned-on controls, is observable throughout the process. Further, switching the machine on and off requires a certain amount of energy (and time). After the machine has been switched on, an idle electricity demand is required by supporting processes such as coolant pumps or a lubrication system (idle demand can include previously mentioned base-load demand, which is assumed in the example in Fig. 2.5). Two production sequences are shown: both sequences first demand additional power to, e.g., accelerate a spindle or tool, followed by a further increase in power demand when actual production (e.g., material removal) takes place. The second production cycle exhibits higher energy demand and a shorter duration. Note that the graph shows a generic example, demand peaks during, e.g., electrical motor switch-on and additional stochastic components are not illustrated (for more detail on classifying and characterizing energy demand of stochastic components such as chip conveyors see, e.g., Popp and Zäh 2014).

The right graph in Fig. 2.5 illustrates electricity demand for different performance levels, i.e., production rate (similar to, e.g., Gutowski et al. 2005). Total electricity demand is split into base-load power/idle demand and production power. Production power can be changed to a certain extent, i.e., by increasing production rate such as material removed per time unit. Several other manufacturing machine energy demand profiles exist, which are influenced by the machine (type), technology and process (for a method to decompose energy demand using different *Energy Blocks* see Weinert 2010 and Weinert et al. 2011). However, state-based energy demand modeling, using multiple states, also in combination with continuous factors, is widely used for energy

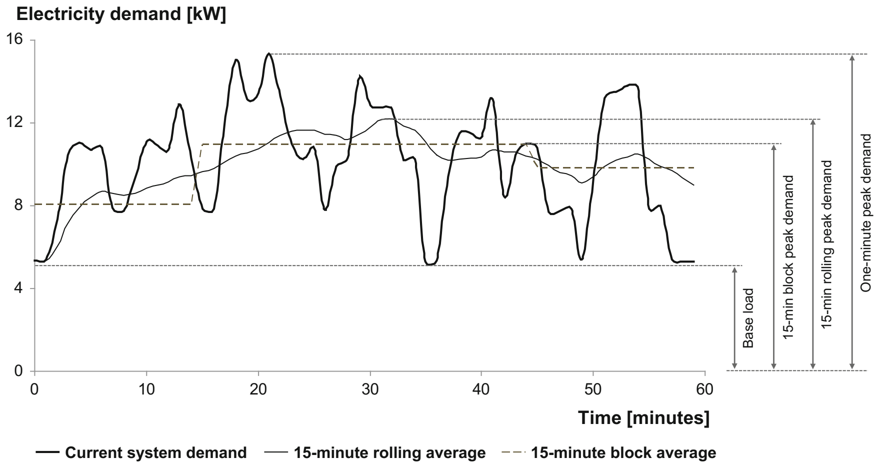

Fig. 2.6 Example manufacturing system energy demand profile (own illustration)

demand modeling of single processes. Further, state-based energy demand can also be extended to other energy carriers than electricity, for example, compressed air (Thiede 2012).

On a manufacturing system level, energy and electricity demand in particular is the sum of electricity demand of individual components. Production sequence and material flow in general as well as (random) disturbances result in highly dynamic demand profiles. Figure 2.6 illustrates an aggregated demand profile of a manufacturing system. The profile has been derived by adding electricity demand from five machines. These five machines are assumed to exhibit electricity demand profiles similar to Fig. 2.5 (only the two different illustrated production process profiles are included, with different idle times between production cycles). Overall, a highly dynamic demand profile is obtained, with four distinctive power levels:

1. System demand is characterized by a base-load (minimum load throughout time period).
2. A 15-minute maximum block average can be calculated, which might be cost relevant (*demand rate*, relevant at the metering point for, e.g., a factory, and dependent upon contract terms).
3. Alternatively, a 15-minute maximum rolling average can be calculated (Measurlogic 2015). Although calculating block averages is more common, utilizing a rolling average and determining a maximum throughout a given period is a more conservative indicator, as a rolling average always includes all block average values and thus a maximum rolling average value is always at least as high as the maximum block average value.
4. The actual (technical) peak demand can be significantly higher (especially relevant in a VRE context where direct demand/supply matching is pursued, and, e.g., for autarkical systems where peaks have to be directly compensated). The

illustrated case uses a one-minute sample rate, which omits technical peaks that can only last for sub-second periods. However, on a system level, these peaks might not be measurable as they are usually small compared to total system load (e.g., a peak from starting an electric drive compared to total load from a manufacturing line or whole factory) and as a total system might absorb small peaks, e.g., due to existing capacitance.

Stochastic influences observable on a single-process level are less significant on an aggregated level. On an overall factory level, several additional energy demanding components can be identified, most notably TBS and HVAC. Especially HVAC energy demand can exhibit strong dynamics and stochastic behavior, as energy demand is dependent on, e.g., process emissions and (stochastic) climate influences. Due to the focus on electricity in the context of VRE integration, discussion of additional flows and energy carriers is not detailed here. Detailed background can be found in references from this subsection and in particular in Hesselbach et al. (2008), Thiede (2012), Posselt (2016) and Herrmann et al. (2014). For the case of factory-wide electricity demand, distinctive demand patterns can usually be observed, similar to grid demand patterns (cf. Fig. 1.4). Factory demand patterns are mainly driven by production activities and their sustaining processes (TBS, HVAC, administration). For example, weekday and weekend, shift schedule, break times, day and night time, temperature, and to which extent sustaining processes (e.g., HVAC, CA) are operated outside regular production hours might, to different degrees, influence a factory's demand pattern. Variability and demand cycles can be within (sub-)second intervals/periods, e.g., if equipment is switched on, up to daily, weekly and seasonal patterns and cycles.

2.1.4 Energy Flexibility of Manufacturing Systems and Embodied Energy Storage

Influencing energy demand of manufacturing systems depends on the ability of processes and systems to adjust electricity demand according to control signals. The terms manufacturing (system) flexibility and, more specifically, energy flexibility are used in this context. Further, embodied energy storage in products is a closely related topic. All three terms are briefly discussed in the following.

Energy Flexibility of Manufacturing Systems

Flexibility of manufacturing systems can be defined in various ways. An early, comprehensive summary of available definitions and understanding of manufacturing flexibility has been provided by Beach et al. (2000). They refer to Gupta and Goyal, who suggested an initial definition of flexibility in manufacturing (systems) in 1989 (Gupta and Goyal 1989). Their definition, referring to earlier work from Buzacott and Mandelbaum (1985) and Mascarenhas (1981), is: "Flexibility is defined as the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment" (Gupta and Goyal 1989, p. 120). Additional definitions have been proposed later on (see, e.g., Beach et al. 2000), which reflects the breadth of the subject. Another example is an early review of manufacturing flexibility, including its integration into manufacturing objectives and measuring flexibility, from Slack (1983). Nyhuis et al. further differentiate between flexible and changeable production systems. They note that a flexible production system is capable of changing parameters (e.g., production rate) within boundaries with reasonable effort and no additional investment. In contrast, a *changeable production system* is a system which can adjust parameters' boundaries with little effort (investment), relocating the system's flexibility boundaries (Nyhuis et al. 2009).

In the context of manufacturing system flexibility, *energy flexibility* refers to the potential of manufacturing systems to change energy demand. Few approaches exist to formally define and evaluate energy flexibility of manufacturing systems. A formal definition has been provided by Graßl et al., who define energy flexibility "as the ability of a production system to adapt itself fast and without remarkable costs to changes in energy markets" (Graßl et al. 2013, p. 303). A mathematical approach to define energy flexibility based on production theory is given in Kabelitz and Streckfuß (2014). The authors propose to define energy flexibility as the curvature of a system's energy demand function, i.e., the slope of the power demand function. Essentially, if an energy demand function is known, the first derivation over time results in the power demand function, and the second derivation over time (and thus the first derivation of the power demand function) provides the energy flexibility function (or parameter). However, the approach is mainly based on mathematical principles to derive a descriptive energy flexibility indicator and lacks consideration of technical details, especially in the context of manufacturing system (energy and material flow demand) dynamics. Further, no detail on how to influence energy flexibility or how to use the proposed indicator is given.

An illustrative example for energy flexibility in the context of (decentralized) VRE integration is given in Fig. 2.7 (generic example for visualization, see also Reinhart and Schultz 2014; Popp et al. 2013, and Liebl et al. 2015 for similar illustrations, also related to volatile electricity prices). Electricity demand from, e.g., a manufacturing system or machine and volatile supply, e.g., from on-site wind generation is illustrated in the upper left graph (a1). Three different periods (1, 2, 3) are distinguished, with 15 min duration each. In the initial setup (a1), demand is initially low (period one, e.g., during setup of a process), followed by higher demand (period two, e.g., due to processing a part) and subsequently reduced (between period two and three, e.g., due to switching products) and increased again after short time to higher (processing) demand in period three. Electricity supply is variable and exhibits short-term volatility and is generally higher in period one and three than in period two. The two graphs labeled energy flexibility I (b1) and II (c1) show different load shifting/energy flexibility examples where the sequence of the three initial demand periods has been changed. The lower graphs (a2, b2, c2) from Fig. 2.7 show grid supply and feed-in as the difference between supply and demand. In the initial setup (a2), total delta between supply and demand (and thus grid electricity flows) is characterized by an initial feed-in period (period one), followed by grid supply during period two and grid feed-in and then supply during period three. Using energy flexibility on the demand side, the middle graphs (b1, b2) show a demand time series for a case where the series' periods one and two are switched. Within the first 30 min, a significantly improved match between supply and demand is achieved and grid electricity flows are nearly halved compared to the initial setup (a2 vs. b2). However, if also period two and three are switched (energy flexibility II, c1 and c2 in Fig. 2.7), demand and supply fit is further improved and total electricity flows are approx. 10 % lower than in the energy flexibility I case (c2 vs. b2) and more than halved compared to the initial setup (c2 vs. a2). However, several demand and feed-in peaks are still present. In addition, and most importantly, feasibility of proposed load shifting requires sufficient energy flexibility of underlying processes: if the initially low demand (period one in the initial setup a1) was caused by process setup, periods two and three have to occur *after* setup and thus after the demand pattern from period one. Extending this logic, if the two high-level demand patterns are caused by a mandatory production sequence (initial setup a1, process from period two is required to finish before processes in period three can start), shifting periods two and three is also not feasible. In summary, energy flexibility enables VRE integration, but is subject to several (operational, technical) constraints. Other examples for applying energy flexibility methods include matching demand with volatile electricity prices (not further discussed here).

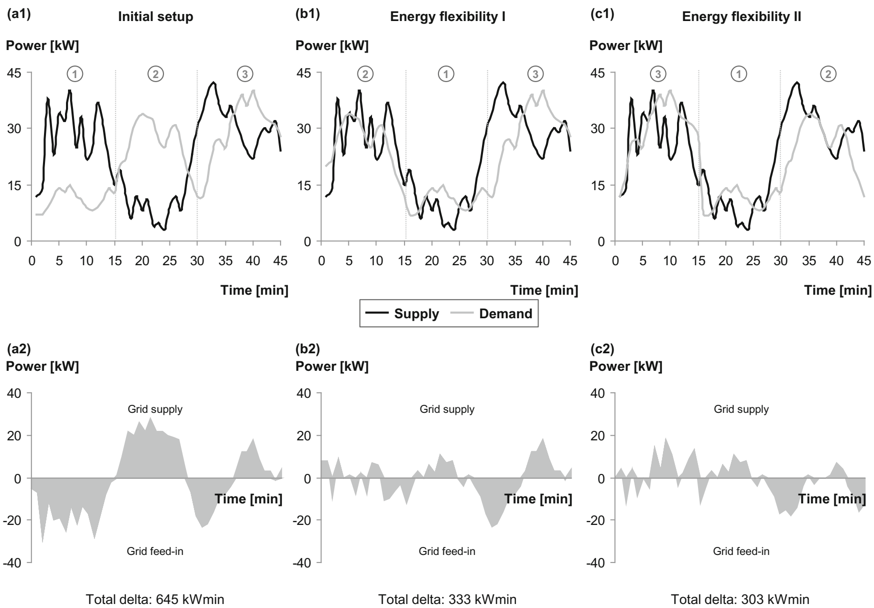

Fig. 2.7 Load shifting example for energy flexible manufacturing system (illustrative example, own illustration)

Embodied Energy Storage

Energy flexibility is used to enable and often related to *embodied energy storage* in products.[3] Assuming that processing a product requires a certain amount of energy, this energy can be allocated as embodied energy to the product. Embodied energy can be directly stored (e.g., in chemical bounds as a result of an (endothermic) reaction, e.g., in chemical process industries) or indirectly as a result of inefficiencies and thus dissipated energy into the environment of the product (not all energy required for processing is contained within the product). For example, milling and drilling of a workpiece and consequently joining with another workpiece requires a given amount of energy (see Sect. 2.1.3 for a discussion of manufacturing process energy demand). While most of the energy is not directly contained within the product but dissipated into the environment, the total amount of energy required can still be regarded as the embodied energy of the product. For further detail on embodied energy (and emissions) and embodied energy estimates for a set of materials see, e.g., Allwood and Cullen (2012) and Allwood et al. (2011).

Although not specifically referring to energy flexibility, the potential for storing electricity as embodied energy in products was already acknowledged in 1989 by Daryanian et al., who mention the option of "Rescheduling of electricity usage to the periods of lower costs, without curtailment of services. This becomes possible if the end products of electricity usage can be stored for later use" (Daryanian et al. 1989, p. 897) and further "[..] electrical energy can often be stored quite cheaply for a few hours or days on a decentralized basis, once it is embodied into intermediate or final products" (Daryanian et al. 1989, p. 899). More than two decades later, Lorenz et al. introduce the term 'energy efficiency 2.0' to include volatility of supply into the field of industrial energy efficiency (Lorenz et al. 2012). They explicitly note that industry can be used to store energy from volatile supply and that factories should be, in the context of energy efficiency 2.0, become active energy/power market participants instead of passive consumers, enabled by energy flexibility. In general, embodied energy storage can be used to store a specific type of energy (e.g., electricity from VRE supply) by demanding this type of energy during processing of a product. Consequently, the amount of embodied energy which can be stored depends on the ability to store (intermediate) products. Further, selectively increasing or decreasing energy demand to increase demand of a certain energy supply type strongly depends on the manufacturing system's ability to adjust energy demand, and thus its energy flexibility. Therefore, previously described constrains (e.g., material flow constraints, shifting and switching of processing sequence) need to be taken into account in the context of embodied energy storage.

[3]For further detail on embodied energy storage as a mean to integrate VRE see Beier et al. (2016), on which this section is partly based on.

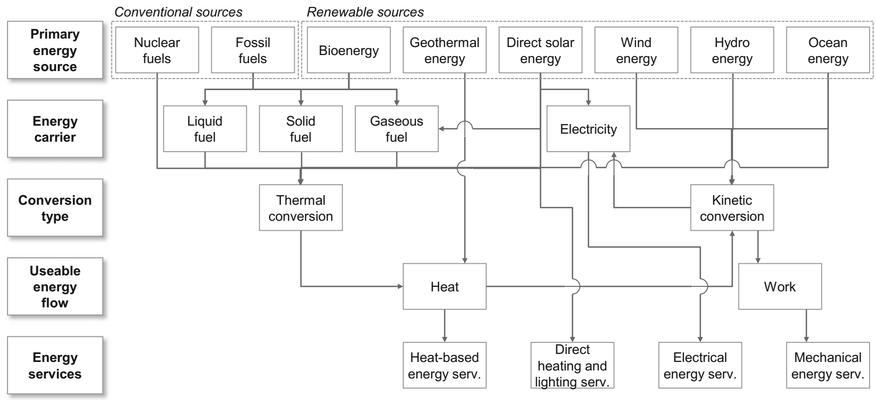

Fig. 2.8 Conversion pathways from energy source to service (original from IPCC 2011, p. 38, own illustration)

2.2 Conventional and Renewable Electricity Supply

After focusing on the electricity demand side and the case for manufacturing systems in particular, this section provides background on electricity supply. Definitions are given first, followed by detail on conventional, renewable, and decentralized electricity generation. The interaction between electricity demand and supply is then described (distribution, markets, grid stability), and VRE integration into an electricity grid discussed.[4]

2.2.1 Definition and Classification

Energy is defined as the capability of a system to generate an outside effect, i.e., to perform work (Quaschning 2011). Different primary energy sources are used to provide various energy services, enabled by energy carriers, conversion, and energy flows as illustrated in Fig. 2.8.[5] An *energy service* can be understood as "the tasks performed using energy" (IPCC 2011, p. 40), and includes, for example, mobility, space comfort, communication, lighting, or manufacturing and assembly of a product.

[4]Note that energy supply and generation are generally used interchangeably within the following. However, *generation* is commonly used when describing the (technical) conversion, while *supply* is used in a broader meaning which might include a market-related or energy distribution-related context.

[5]This visualization is one possible classification scheme, while other illustrations/classifications might be possible. However, this overview is chosen as it highlights the multitude of different conversion options from energy source to energy service.

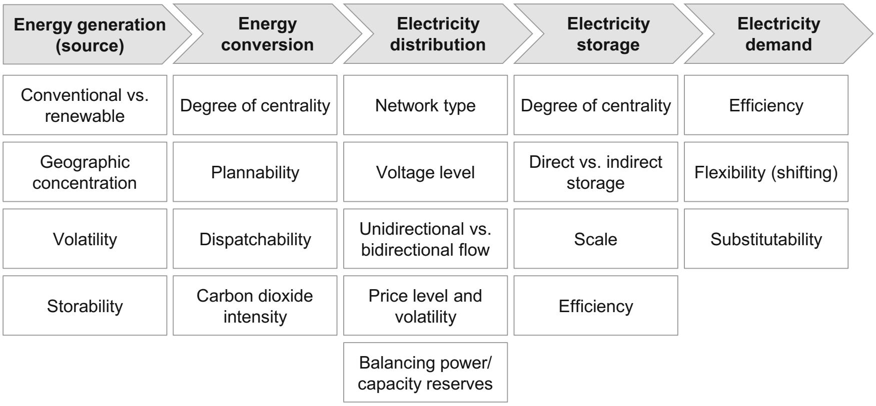

Fig. 2.9 Overview and structure energy generation to electricity demand (own illustration)

Electricity generation is commonly classified according to primary energy sources and split into nuclear energy, fossil fuels, and renewable energy (IPCC 2014; Schwab 2015). Further, the terms conventional and renewable electricity generation are used to differentiate energy sources (Kosmadakis et al. 2013). *Conventional electricity* generation entails all large-scale/commercial electricity generation from non-renewable sources (fossil fuels and nuclear energy), while *renewable electricity generation* refers to electricity generation from renewable energy sources.

Consistent with the IPCC's classification, RE resources include (photosynthetic) biomass energy, geothermal energy, direct solar energy, wind energy, hydropower and ocean energy (tide, waves and thermal energy) (IPCC 2011, 2014). Some of these RE forms are exhaustible (e.g., geothermal, biomass) and indirectly rely on solar radiation (i.e., hydropower, wind) (IPCC 2014; Ellabban et al. 2014). Within this context, *renewable electricity* is understood as electricity used as energy carrier for energy from primary renewable energy sources (compare also to Fig. 2.8).

Figure 2.9 gives an overview of different topics and characteristics which need consideration when discussing energy generation to electricity demand with a focus on (variable) renewable energy sources. As such, the structure in Fig. 2.9 highlights the different topics which are addressed in the remainder of this chapter. For energy generation, a focus is set on conventional and renewable generation and their characteristics (e.g., volatility). In this context, different energy conversion methods are discussed. Electricity distribution focuses on different network types and technology, as well as the influence of integrating VRE on electricity markets and grid stability. Electricity storage is discussed as a mean to match supply and demand (timely differences), e.g., through indirect/centralized (e.g., pumped hydro) and direct/decentralized (e.g., battery) storage. The last area, electricity demand, has already been discussed from a demand side perspective in the previous section, and therefore supply-side options for flexibilizing electricity demand are summarized.

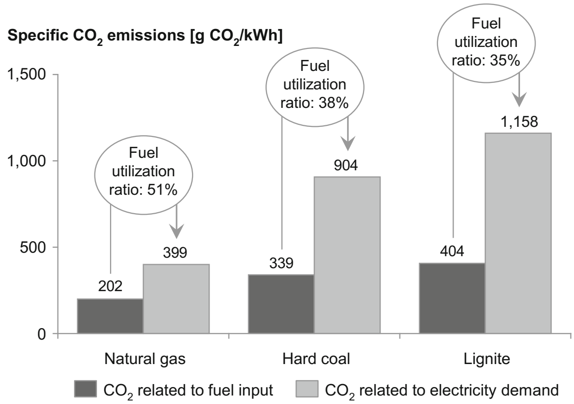

Fig. 2.10 CO_2 intensity from natural gas, hard coal, and lignite based electricity generation: related to fuel input and final electricity demand, percentages indicate fuel utilization ratio (data from Icha 2015, own illustration)

2.2.2 Conventional Electricity Generation

As outlined before, conventional electricity generation includes fossil fuel based generation and nuclear-based generation. Most important energy carriers within these categories include hard coal, lignite, mineral oils, natural gas, and nuclear fuels (e.g., uranium, thorium) (Schwab 2015). Large-scale conversion of these carriers is performed via thermal conversion (combustion or nuclear fission[6]) to heat, which is converted in turbines to kinetic energy and subsequently to electricity in generators (IPCC 2011; Schwab 2015, cf. Fig. 2.8). Common power plant types include thermal power plants (i.e., steam-driven, including, e.g., coal-fired and nuclear fission), gas power plants (natural gas) or combined cycle plants (gas power plant with attached steam power pant). Several combined and advanced technologies have been and are developed to increase efficiency of conventional power plants, e.g., cogeneration of heat and power to supply customers (e.g., industry) with both electricity and heat (e.g., steam).

As noted in the introductory chapter, a global and national target is set towards reducing GHG emissions, among others from energy and power supply. As such, a focus within this section is set on the relevance of conventional electricity generation for contributing to and reduction of GHG emissions rather than discussing technical details of conventional generation (for a technical overview and additional details on electricity generation in power plants see, e.g., Schwab 2015).

Figure 2.10 illustrates specific CO_2 emissions from natural gas, hard coal, and lignite. While natural gas exhibits lowest emissions related to fuel input, the difference between all three energy carriers for final demand is not only caused by higher input-related emissions but amplified due to worse fuel utilization ratios for hard coal and lignite (i.e., considering conversion and other inefficiencies from fuel input to final electricity demand) (Icha 2015).

[6]Nuclear fusion is not included here as not commercially mature and not used on a large-scale.

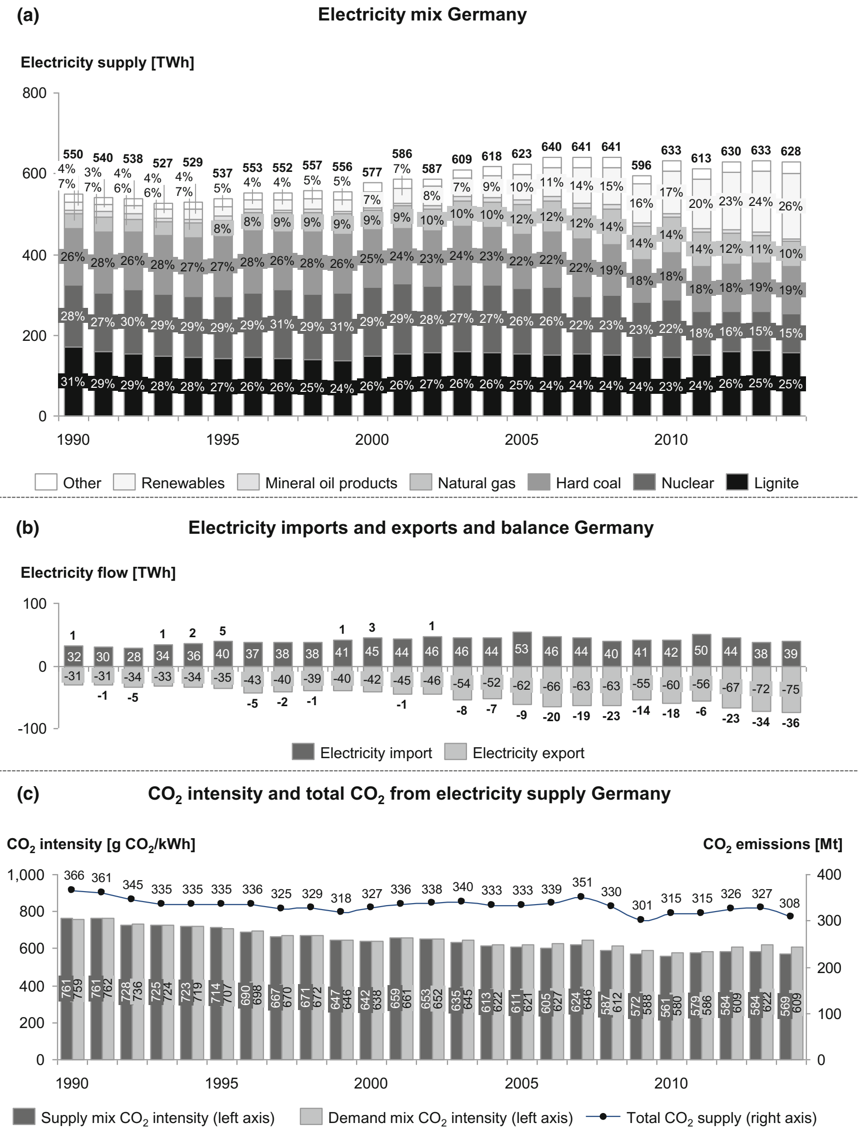

Fig. 2.11 German electricity mix (**a**), electricity imports, exports and balance (**b**) and CO_2 intensity and total CO_2 emissions (**c**) from 1990 to 2014 (data from Icha 2015 and AG Energiebilanzen e.V. 2015, own calculations and illustration)

Different specific CO_2 emissions are especially relevant when electricity supply mix changes, for example, as a result of integrating larger shares of RE generation. Utilizing Germany as an example, Fig. 2.11a illustrates the national energy supply mix from 1990 to 2015. The German energy mix is characterized by a fairly stable lignite supply share of approx. 25 %, reduced nuclear and hard coal supply shares within the last years, slightly increasing natural gas generation and significant increase in renewable energy sources as a result of the *Energiewende*. Total electricity supply has been stable within the last ten years and is slightly higher compared to 1990–2000 levels. Further, considering the shift in supply source shares, renewable generation is mainly substituting nuclear and hard coal generation (partly due to a politically driven nuclear exit and newly built and dispatched lignite capacities). Considering electricity imports and exports and thus net demand balance (b in Fig. 2.11, total electricity demand equals supply (a) plus import–export balance (b)), total electricity demand has been decreasing from an all-time high of 621.5 TWh in 2007 to 592.2 TWh in 2014. However, recent years' import and export balances indicate that a substantial share of domestically generated electricity is exported (approx. 12 % of total generation), while also importing approx. 6 % of total generation, resulting in a net differential of approx. 6 %. This indicates an increasing net oversupply, while national supply and demand are more frequently dynamically unbalanced (high imports *and* exports). For example, excessive RE supply is exported into the connected European network, while supply gaps are filled by importing electricity.

Both the shift in energy sources and increasing net negative trade balances are reflected in CO_2 emission factors for German electricity supply and demand. Figure 2.11c illustrates specific CO_2 emissions per kWh both for electricity supply and demand and total emissions from electricity supply. Comparing values from 1990–2000 in relation to most recent years, all indicators (specific and total) are reduced. However, while specific supply and demand mix emissions were relatively similar until 2002, a shift has occurred after 2002, towards higher specific emissions in the demand mix compared to the supply mix. This indicates that, on a relative basis, carbon-intensive generation was demanded domestically, while low-carbon electricity has been exported. An increased share of renewable energy generation (a in Fig. 2.11) achieved to lower specific supply emissions, however, increased exports (b in Fig. 2.11) of low-carbon intensive electricity result in relatively higher demand mix emissions.

Combining specific CO_2 emission values from Fig. 2.10 with relative supply share changes from Fig. 2.11a, it becomes evident that even though renewable share increased (which is accounted for as zero CO_2-emitting), reducing low(er)-carbon generation from hard coal and nuclear results in relatively stable, and periodically (2010–2014) increasing total emissions and demand mix specific relative emissions (c in Fig. 2.11). This highlights the requirement to not only deploy additional renewable supply sources, but to successfully integrate these into an existing supply and demand system: if possible, low(er) carbon intensive sources should not be substituted by high(er)-carbon intensive sources (e.g., as a result of profitability changes). Further, measures have to be found to increase (domestic) demand of renewable generation rather than exporting surplus generation to effectively reduce relative (per kWh) and absolute carbon emissions from electricity supply *and* demand, which directly translates to the research question formulated in Chap. 1.

2.2.3 Characteristics of Renewable Electricity Generation

Renewable energy is understood as energy from sources, which, in the sense of renewable resources, natural processes replenish at rates relevant in relation to their use (Perman et al. 2003; IPCC 2011; Ellabban et al. 2014). Renewable resources can be divided into *stock* and *flow* resources, i.e., resources which have a certain stock amount which is replenished (e.g., biomass) and resources which have a (constant) inflow (e.g., sun) (Perman et al. 2003). As such, renewable stock resources can be extinct, for example, if a biologically-based resource (biomass) is utilized at rates which prevent the resource to be replenished at a sufficiently high enough rate to replace the utilized amount. In contrast, flow resources are considered as non-exhaustible, at least within their current utilization patterns (e.g., wind) (Perman et al. 2003; IPCC 2011). Non-renewable (energy) resources include resources which are replenished over time (i.e., coal through conversion of biomass), but replenishment rates are negligible compared to utilization rates (IPCC 2011).

Certain RE sources are *variable renewable energy* (VRE) sources, which are usually non-dispatchable, i.e., power generation cannot be increased as desired (unless output was previously curtailed), and only be reduced (which results in opportunity losses of generation).[7] This characteristic substantially differentiates VRE from fossil fuel based plants, from which output can be (within certain ranges) controlled. Further, output from VRE is not only non-dispatchable, but also significantly more volatile than from dispatchable fossil fuel plants. Figure 2.12 shows the volatility of wind and solar generation. Illustrated are wind and solar generation time series from solar panels and a wind turbine installed at the Institute of Machine Tools and Production Technology (IWF), TU Braunschweig, Germany, for five days in September. Both time series are indexed to their maximum value to facilitate comparison. Referring to Fig. 2.12, the following observations with regards to variable generation and related challenges can be made:

- Short-term (minute) fluctuations can be relatively large, especially for wind generation.
- Wind generation is characterized by short-term (minute) variability, but also exhibits longer term variability (i.e., hour to daily generation-level changes).
- Solar generation can be very stable (September 6, likely a very sunny day) but can also be strongly reduced and volatile (e.g., September 7, sunny with few clouds and September 8 to 10 with short-term sunny periods during a cloudy day).
- Solar generation is, for long periods (night), zero. While this is a trivial fact, it is still relevant in combination with wind generation: wind can occur at any time of

[7] The term variable/variability and volatile/volatility are both used here to describe a set of datapoints that are not equal, i.e., distributed. While variability might usually refer to a general set of datapoints, different options or characteristic, volatility is more commonly used in the context of time series data (and is, as such, also encompassed by the term variability). For example, in finance, volatility of a time series usually refers to the standard deviation over a given period. The terms variability and volatility are both used here, while variability is regarded as a broader term (including volatility) while volatility is only used in the context of (stochastic) time series.

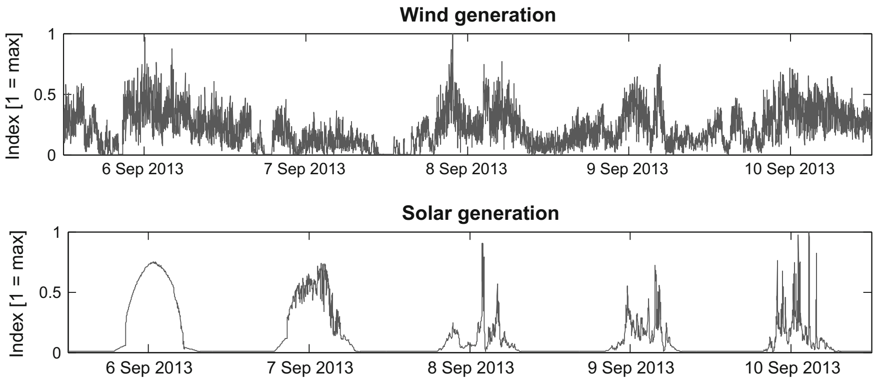

Fig. 2.12 Wind and solar generation at IWF, TU Braunschweig (latitude 52.2767, longitude 10.5369) from September 6 to 10, 2013, minute resolution, normalized to sample period's maximum generation (own data and illustration)

the day, allowing for electricity supply during night. However, as wind is a rather unstable source, high wind generation can occur during periods of high solar output (September 6) and low solar output (night from September 6 to 7), but low wind generation can also occur during periods of high solar output (September 7) and low solar output (night from September 7 to 8). As a result, combined generation can be favorable, but can also increase variability.

Table 2.1 provides a qualitative assessment of renewable energy sources (classification according to IPCC) and fossil fuel energy against their individual volatility, storability, and dispatchability. Although the assessment can only provide an indication, it becomes evident that especially wind and solar energy are unfavorable in several dimensions compared to biomass energy and hydropower, and even more unfavorable compared to (traditional) fossil fuel based generation. This comparison further highlights the need for new methods to compensate disadvantageous characteristics such as high volatility or missing dispatchability of renewable energy sources.

Further details on common RE technologies can be found in Geitmann (2010), a comprehensive overview of RE to mitigate climate change, including extensive data, is provided in IPCC (2011). Predicting electricity generation from VRE is a central concern to increase planning reliability of electricity supply and demand. For a comprehensive overview of existing research and methods for predicting solar output using artificial neural networks see, e.g., Qazi et al. (2015). Page 182 in IPCC (2011) includes an overview of 46 RE technologies and their technical maturity. In addition, 23 of these technologies are classified as decentralized (on-site) technologies, highlighting the relevance of decentralized RE technologies, which are discussed in the next section.

Table 2.1 Comparison of renewable energy sources and fossil fuel energy (very favorable (+ +), favorable (+), neutral (∘), unfavorable (−), very unfavorable (− −); own assessment based on references from this section)

	Volatility	Storability	Dispatchability
Solar energy	−	−	− −
Biomass energy	+	+ +	+
Wind energy	− −	− −	− −
Ocean energy	∘	− −	− −
Hydropower	+	+	+ +
Geothermal energy	+ +	∘	∘
Fossil fuel energy	+ +	+ +	+ +

2.2.4 Decentralized Generation

Decentralized renewable energy generation is "deployed at the point of use (decentralized) in rural and urban environments, whereas others [RE technologies] are primarily deployed within large (centralized) energy networks" (IPCC 2011, p. 7). RE sources play a vital role in decentralized generation. Decentralized renewable generation capacity has been increasing in recent years, technologies include small hydropower, photovoltaics (PV), wind generation, and biomass (IPCC 2014). Several RE sources are inherently geographically spread out, i.e., wind resources and solar radiation are not concentrated within a single, local point as, for example, fossil fuel based generation facilities (where concentrating fossil energy has been performed by transportation of fuels to a power plant). RE is commonly available within a larger geographic region, i.e., coastal areas for wind and elevated areas for PV (although some preferred local spots exist where to deploy generation capacities, e.g., hills for wind turbines).

Decentralized generation is not unique to a specific primary RE source. For example, wind-based generation can be deployed on a centralized basis using large turbines which commonly require grid integration (especially offshore), while small turbines or wind kites are used for decentralized generation (IPCC 2011). For the case of solar-based generation, PV electricity generation can easily be scaled by installing a desired set of panels (given enough space), and thus PV electricity generation can be deployed centralized (e.g., PV plants) or decentralized (e.g., on rooftops). On the other hand, low-temperature solar thermal energy is mainly used in decentralized applications as a consequence of low conversion and transportation efficiency. However, considering given examples and above definition, decentralized generation can include PV generation on household rooftops with direct use in a single house or, for example, wind generation in an urban environment and use within a local distribution grid.

Most industrial, and especially production and manufacturing companies, have extensive on-site (decentralized) electricity generation. In 2013, 8.9 % or 45 TWh of total gross German electricity generation was from industry, which equates to approximately 18 % of total industrial electricity demand (DESTATIS 2014, 2015, own calculations). The Association of German Chambers of Commerce and Industry (DIHK) estimates that approximately 25,000 companies in Germany produce and utilize their own electricity, with another 25,000 companies planning to set up own supply. In summary, 16 % of all firms enacted measures for own supply in 2013. Solar generation had the largest share of all utilized technologies (62 % realized or planned) (DIHK and VEA 2014). Solar- and wind-based generation have an inherent decentralized structure and are therefore of special interest for decentralized or industrial on-site generation. As a consequence, with an increase in VRE generation, decentralized generation is expected to increase as well (DIHK and VEA 2014). Further, the DIHK notes that for most companies investments into generation capacities are most useful when maximizing utilizing of self-generated electricity (DIHK and VEA 2014).

2.2.5 Electricity Distribution, Markets, and Grid Stability

After highlighting the different energy and electricity supply options, a brief overview of electricity distribution and the supply–demand connecting element, electricity markets, is given, followed by emerging concerns in relation to VRE integration.

Electricity grids are required to connect electricity supply sources (i.e., power plants) with electricity customers (i.e., industry). As such, different grid types exist. On the highest (voltage and regional) level, extra high voltage and high voltage networks (380 and 220 kV) fulfill transmission tasks and are therefore part of a transmission network (Schwab 2015). In Europe, 41 transmission system operators (TSOs) from 34 countries are combined in an European system, the European Network of Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E 2015). However, not all member TSOs are also part of a technically synchronized grid, which is limited to an area formerly known as the Union for the Co-ordination of Transmission of Electricity (UCTE), which included 29 TSOs from 24 continental European countries, and which supplies approx. 500 million people through a synchronized network (Schwab 2015; ENTSO-E 2015).

Aside from transmission networks, distribution networks exist to connect single customers with transmission networks. They are normally sized as high (110 kV), medium, and low voltage networks. Table 2.2 summarizes different network typologies and their characteristic voltages. A main difference between transmission and distribution networks are their main energy flow directions (in Germany/Europe): while transmission networks are frequently designed as a mesh structure where different energy flow directions are feasible, distribution networks usually exhibit a unidirectional flow structure (from transmission network to customer) (Schwab 2015). However, with an increase in decentralized (renewable) electricity generation, distribution networks are subject to an increasing amount of bidirectional energy flows, causing technical difficulties as, for example, security systems have

Table 2.2 Nominal and maximum power ratings of different electric power networks (from Schwab 2015, p. 36, translated from German and resorted)

Network type	Nominal rating (U_n)	Maximum rating (U_m)
Extra high and high voltage networks		
Transmission networks	380 kV	420 kV
Transmission networks	220 kV	245 kV
High voltage networks	110 kV	123 kV
Medium voltage networks		
Special customers	35 kV	40.5 kV
City distribution networks	20 kV	24 kV
City distribution networks	10 kV	12 kV
Industry and power plant own demand	6 kV	7.2 kV
Low voltage networks		
Large industry, own demand	400 / 690 V	
Domestic, commercial, industrial	230 / 400 V	

not been designed for this purpose. Consequently, direct/local demand of decentralized generated electricity can reduce requirements for technical and network layout adjustment measures.

Electricity markets connect electricity supply and demand via price. Depending on time horizon until fulfillment of contracts, markets are commonly separated into capacity and forward markets (months to years until delivery), day-ahead markets (commonly next day) and intraday/real-time markets (quarter hour to hours) (U.S. Department of Energy 2006; Schwab 2015). Within recent years, energy exchanges have more and more replaced direct (over-the-counter, OTC) contracting. For Europe, the European Energy Exchange (EEX) is one of the leading energy exchanges (EEX 2015; Schwab 2015).

For renewable electricity integration, the Merit Order Effect is of special interest in a supply-demand-price context. Commonly, electricity generation plants are ranked according to their marginal (variable) operating costs, resulting in an increasing step function of generation cost over capacity (merit order) (U.S. Department of Energy 2006; Schwab 2015; Sensfuß et al. 2008). Assuming a relatively (short-term) inelastic electricity demand, the power generator which marginally fulfills power demand sets the market price. If renewable energy sources with lower marginal costs than current market price or mandatory feed-in ahead of other generation capacities (e.g., in Germany) are introduced into the market, the marginal generator might be pushed out of the market and wholesale price is reduced. For the case of fluctuating RE feed-in, market prices can become more volatile and dependent on (relative) VRE supply share. Figure 2.13 illustrates the Merit Order Effect. The figure shows the hourly electricity price (Phelix) over wind and solar generation share of total load in Germany for 2013 (8,760 data points). Although the statistical relationship is not very strong (coefficient of determination is 0.2154, different total system load levels and

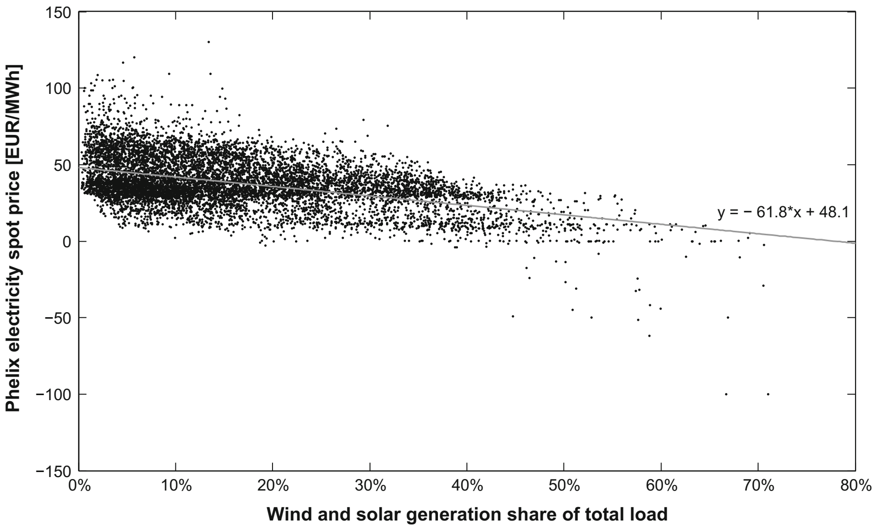

Fig. 2.13 Illustration of the Merit Order Effect: hourly spot electricity price over renewable generation load share for Germany in 2013 (own calculation and illustration, data from EPEX SPOT 2014; EEX 2014a, b; ENTSO-E 2014)

other market determining factors are also influencing the price), some observations can be made:

- Electricity price is, on average, negatively correlated with wind and solar share of total grid load.
- Extremely high prices generally occur when wind and solar share is low.
- Prices are never extremely high when wind and solar share is high.
- Negative prices are never realized when wind and solar share is low.
- Negative prices occur only when wind and solar share is high.

In summary, the Merit Order Effect has multiple effects on price as a result of integrating VRE into larger power grids and markets, and influences need to be considered and compensated by utilities and TSOs (e.g., peaking-power plants and reserve capacities might become uneconomic if pushed out of the market too often/if they are only required for a very limited number of hours per year). For more detail on the Merit Order Effect and the Merit Order in general see, e.g., Sensfuß et al. (2008) or Bundesnetzagentur (2014).

Considering time-to-delivery to differentiate electricity market contracts, the shortest time-to-delivery periods are ancillary service markets, which provide balancing power to ensure a stable power grid (grid frequency) (U.S. Department of Energy 2006; ENTSO-E 2009). Balancing power is activated to either increase or decrease supplied power to stabilize the grid frequency, i.e., power is reduced if grid frequency increases (e.g., as a result of a demand decrease or if another power supplier suddenly increases power) or power supply is increased if grid frequency decreases.

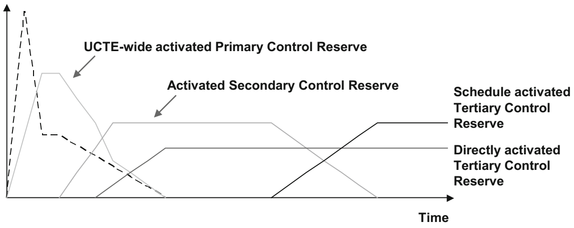

Fig. 2.14 Activation of frequency regulation as a result of a grid frequency change (*dashed line*) (from ENTSO-E 2009, p. P1-3, own illustration)

Figure 2.14 illustrates the dispatch order of primary (within seconds), secondary (within few minutes), and tertiary reserve (within minutes) capacities as a response to a grid frequency change (dashed line). Integration of VRE into the power grid might require additional balancing capacities to accommodate sudden power increases and drops due to stochastic wind and solar generation output (Bundesministerium für Wirtschaft und Energie (BMWi) 2013).

2.3 Integrating Renewable Electricity Supply

Several options exist to integrate (variable) renewable electricity supply into existing power systems. Energy storage (large-/small-scale) and influencing demand to better match supply (DSM) are common options to integrate fluctuating supply. In the context of influencing demand, energy flexibility of manufacturing systems has been discussed in Sect. 2.1.4. Therefore, energy storage and DSM as additional integration options and their sub-categories are discussed in the following (for an overview see Fig. 2.15, note that the dashed line indicates that integration options might be related and/or complement each other).[8]

2.3.1 Energy Storage for Renewable Energy Integration

Options discussed here for energy storage to integrate renewable energy include grid-wide, large-scale options (e.g., pumped hydro) and technologies which can be deployed decentralized and thus on a smaller scale, e.g., to integrate decentralized RE generation for direct (on-site) demand.

Centralized, Large-Scale Energy Storage

Since the widespread deployment of large-scale power plants which have limited options to change (reduce, increase) output within shorter (minute to hour) time

[8]This section is partly based on Beier et al. (2016).

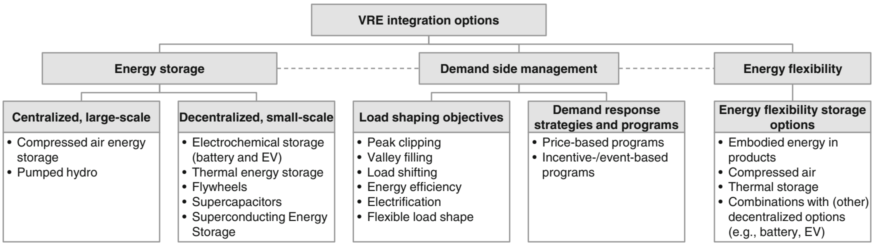

Fig. 2.15 Overview of VRE integration options (own illustration)

frames, grid-wide electricity storage has been used to overcome temporal mismatches between a relatively inelastic demand and an also inelastic base-load power plant fleet (cf. also Fig. 1.4 - electricity demand in Germany is rarely below 40 GW during night on weekdays, but as low as 30 GW on Saturday nights, while demand peaks can be above 60 GW). Power plants with low marginal generation costs (low position on Merit Order Curve, e.g., lignite and nuclear) exhibit times of oversupply, e.g., at night, while reducing output is either technically difficult or uneconomic (e.g., due to set efficient operating range or high fixed costs). As such, options for (short-term) energy storage have been developed, among them compressed air energy storage (CAES) and pumped hydro storage, which are the two main large-scale available technologies (IPCC 2011).

CAES technology is based on storing energy in compressed air. Available surplus electricity (e.g., during periods of low prices, which indicate supply surplus) is compressed in a turbine and stored in a large-scale containment, for example, an underground (natural) cavern. If electricity is required (if prices are higher), high-pressure air is released through the turbine and electricity is generated. However, as the air is cooling down as a result of its expansion, heat is required during the process, which is, for example, provided by additional natural gas firing or from heat exchangers which can store surplus heat from compression. Consequently, round-trip efficiency for CAES is relatively low and within the range of 50 %. Currently operated plants can be found in McIntosh, Alabama, USA (110 MW, commissioned 1991) and in Huntorf, Germany (290 MW, from 1978) (Crotogino et al. 2001). Low conversion efficiency of CAES provides economic challenges as profitable operation strongly depends on electricity price volatility. Further, ecological challenges and additional environmental impact is caused by plant setup and operation (compared to direct electricity demand). Therefore, several new CAES-based technologies are subject of research and development efforts. Among them is the isobaric adiabatic compressed air energy storage plant with combined cycle (ISACOAST-CC) with a targeted 80 % efficiency and the advanced-adiabatic compressed air energy storage technology (AA-CAES) with 70 % target (Bullough et al. 2004; Zunft et al. 2006; Nielsen and Leithner 2009; Karellas and Tzouganatos 2014).

Another large-scale energy storage technology, pumped hydro storage, is a mature technology for grid-wide electricity storage. Water is pumped from a lower-level reservoir (e.g., a pond or river) into a higher-level storage basin. The process is reversed for electricity generation, energy stored as potential energy is converted back to electricity. Energy efficiency varies between 70 and 80 % in practice (Rehman et al. 2015).

Both CAES and pumped hydro have the additional advantage of relatively fast response times and can thus be (depending on specific technical realization) also used to provide ancillary services, such as tertiary reserves. Their fast response times make especially CAES plants interesting for VRE integration (Lund and Salgi 2009; Lund et al. 2009). Pumped hydro storage has relatively high conversion efficiencies and low marginal costs, making it the only currently economic viable large-scale storage solution (Deutsche Energie-Agentur GmbH (dena) 2010). However, installing pumped hydro not only depends on the presence of suitable geological conditions, but might also be subject to ecological and political resistance, even if options for additional storage would exist (Germany Trade and Invest 2015). Consequently, capacities for additional storage is limited in several regions, for example, in Germany. In order to further increase electricity storage options in the Central European Grid, additional pumped hydro capacities exist in Scandinavian countries and the Alps. Norway alone is estimated to have another 10–25 GW of pumped hydro storage capacity, which is about equivalent to currently available capacity (IPCC 2011). Nonetheless, transportation of surplus electricity from Central to Northern Europe requires a significant increase in transmission capacities (e.g., sub-sea cables).

Several additional storage technologies are known and their suitability for large-scale energy storage investigated. Nonetheless, technical, economic, and environmental barriers exist, e.g., economic challenges for hydrogen (fuel-cell) conversion strategies/other power-to-gas methods, environmental impact challenges from electrochemical (battery) storage or high self-discharging rates of flywheels, which are a technical challenge (while most named challenges are related to each other) (Deutsche Energie-Agentur GmbH (dena) 2010).

Decentralized, Small-Scale Energy Storage

Decentralized energy storage is used to overcome temporal mismatches between on-site electricity demand and decentralized supply. Although decentralized generation could be fed into the grid and stored in previously discussed large-scale energy storage facilities, several advantages of decentralized storage exist. On a grid-wide scale, less infrastructure (transmission capacities) is required to transport decentralized generation to centralized storage and back to customers. Further, if decentralized storage achieves to flatten grid demand and feed-in peaks from on-site generation, less ancillary services (backup generation) within the power grid are required. From a local (company) point of view, direct demand of on-site generated electricity is favorable due to economic benefits: on-site capacities have usually lower marginal generation costs than external grid supply costs and network charges and taxes can be (partly) avoided, for example, on-site demand is subject to lower/no subsidy-tax under the *Erneuerbare-Energien-Gesetz* in Germany (DIHK and VEA 2014). Table 2.3 summarizes five decentralized energy storage technologies, including a brief description, and factors for application in a VRE integration context.

Table 2.3 Overview of energy storage technologies in the context of decentralized VRE integration (based on references from this section and from Beier et al. 2016)

Technology	General principle	Current application for VRE integration	Advantages	Disadvantages
Electrochemical storage (battery)	Chemical reactions to store and release energy	Short-term demand/supply matching (minutes to hours) and for ancillary services	• Input and output is electricity • Fast response • High energy storage feasible • Several different technologies and characteristics	• Economic challenges • Fast degradation (cycle lifetime) • Hazardous materials
Thermal energy storage	Temperature or latent (phase changing) heat storage	Direct heating/cooling (solar energy) or from electricity if economic (e.g., fuel switching)	• High capacity • Low losses • Direct use (heat/cool) possible • Ecological, save	• Round-trip (back to elec.) inefficient • Without conversion: direct use limits applicability • Sufficient material/mass for storage necessary
Flywheels	Rotating mass energy storage	(Very) short-term demand/supply matching, special applications (e.g., sensitive environment)	• Fast charging/discharging • Nearly no hazardous materials • Low degradation, wear-out and maintenance	• High investment required (economically challenging) • Low total energy storage • Significant energy losses over time
Supercapacitors	Electric field energy storage	Very short-term storage and smoothing of, e.g., power output and frequency control	• Fast charging/discharging • Low maintenance and long lifetime • (Direct) electricity storage • Relatively high efficiency	• Energy per volume low • Economic challenges
Superconducting Magnetic Energy Storage	Electromagnetic field energy storage	Useful for frequency regulation, power quality applications (e.g., uninterrupted supply)	• Fast charging/discharging • Electricity conversion efficient • Limited hazardous materials	• Energy per volume very low • Energy losses over time high • Economic challenges • Long-term efficiency due to cooling reduced

Electrochemical storage options (batteries) are a well-known technology for decentralized electricity storage. However, technical maturity is largely dependent on considered technology. In general, three different technology types are common (Deutsche Energie-Agentur GmbH (dena) 2010; Oberhofer 2012; Oertel 2008):

- Conventional batteries (e.g., lithium-ion/-air/-polymer, lead–acid, nickel–cadmium, zinc-air, sodium–sulfur batteries)
- Redox-flow batteries (e.g., zinc–bromine, vanadium redox)
- High temperature batteries (e.g., sodium–sulfur, sodium–nickel chloride).

Conventional batteries include technical mature types like lead-acid batteries, which are frequently used for decentralized autarkical VRE integration with backup generation (e.g., diesel) (Bernal-Agustín and Dufo-López 2009). Availability of more cost efficient options like pumped hydro has prevented large-scale deployment of lead-acid batteries in applications with grid access (Oberhofer 2012). Further, their relatively low energy density (volume and mass) limits applications, especially in mobile application, which has caused extensive research towards improvement of lithium-based batteries. Strong research efforts are improving technical, economic, and ecological factors of lithium-based batteries, especially for use in electric vehicles (EVs) (Gallagher and Nelson 2014). Future development, especially reduced cost, might allow utilizing lithium-based batteries for widespread VRE integration, while they are currently mainly used for balancing power (as opposed to large-scale energy storage) applications.

Redox-flow batteries are based on a similar technological principle than conventional batteries. However, their electrolyte is stored in attached tanks and can be changed during operation. Therefore, energy and power parameters can be configured separately, and energy capacity simply be increased by adding additional electrolyte holding capacity. Further, spent electrolyte might be replaced, making redox-flow batteries potentially suitable for mobile applications (Oertel 2008; Oberhofer 2012; Deutsche Energie-Agentur GmbH (dena) 2010; Denholm et al. 2010). An example for a scalable vanadium redox battery system is the so-called *CellCube* by Gildemeister energy solutions (part of DMG MORI), which is, among others, used for energy-autarkic systems and to smooth VRE output (Gildemeister energy solutions GmbH 2016).

High-temperature batteries need to be heated during operation (commonly above 300 °C) as their electrolyte is solid and electrodes are liquid (molten). Their reduced efficiency due to heating and hazardous operation is offset by a long lifespan and high energy density (Oberhofer 2012; Oertel 2008).

Considering batteries for VRE integration, main characterizing differences between battery types and technology are their power and energy configurability. Round-trip efficiency and response time are usually high, which is offset by potential use of hazardous (toxic/flammable) and environmentally unfriendly materials, combined with (currently) relatively high costs and limited lifetime (Deutsche Energie-Agentur GmbH (dena) 2010; Oberhofer 2012).

Thermal energy storage relies on the principle of using heat and cooling capacities of thermal mass to store energy, i.e., in building thermal mass, cool storage tanks (water and ice) or subsurface solid rock formations. Either temperature difference or latent energy storage (phase change of materials) can be applied (Arteconi et al. 2012; Oertel 2008). Different conversion pathways exist, for example, electricity-heat, electricity-heat-electricity, heat-electricity or simply storing and using heat without conversion (Denholm et al. 2010). Converting heat (back to) electricity usually reduces efficiency significantly and therefore most applications aim at direct use of heating/cooling capacities. A common application for load shifting and thus VRE integration is using building thermal mass for storing heat or cooling capacities, i.e., by pre-cooling or heating a building during high electricity supply periods (or low price periods) (Reynders et al. 2013; Braun 2003). This approach might be extended (amount of energy and control options) by adding additional capacities, e.g., in underground or rooftops storage tanks (frequently water) (Rankin and Rousseau 2008; Arteconi et al. 2012; Ashok and Banerjee 2003). Within industry, process cooling and heating can be used for applying thermal energy storage with direct use. Examples are also chilled water and ice storage as well as supercritical steam and thermo oil (Oertel 2008).

Flywheels use rotating masses in (close-to) vacuum containments for converting electricity to kinetic energy and back to electricity when needed. Once set up, they exhibit a very long lifetime, low maintenance times, high cycle efficiency (>90 %), little use of hazardous materials and (very) fast response times. However, discharge losses are within several percent per hour and initial investment is significant. Therefore, flywheels are rather used for reserve market applications (Deutsche Energie-Agentur GmbH (dena) 2010; Denholm et al. 2010; Oberhofer 2012). A large-scale flywheel energy storage facility is operated in Stephentown, New York since 2011 (Beacon Power 2015). With 20 MW power and 5 MWh capacity, its main purpose is providing backup capacity.

Supercapacitors (sometimes called ultracapacitors) store energy in an electric field. The absence of moving parts and (direct) energy storage result, among others, in a very high cycle stability (beyond 100,000 cycles), low maintenance cost and relatively high round-trip efficiencies of 80–95 %. However, costs of approx. 320 EUR per kW and a low volumetric energy density of 20 kWh/m^3 prevent large-scale energy storage deployment (Denholm et al. 2010; Deutsche Energie-Agentur GmbH (dena) 2010). Their extremely fast response times make them especially usable for frequency control (Denholm et al. 2010).

Superconducting Magnetic Energy Storage (SMES) uses an electromagnetic field for energy storage. In order to achieve superconductivity, very low temperatures have to be reached and held, which significantly reduced total efficiency. In addition, high investment cost and single-percent discharge losses per day, combined with very fast response times, efficiencies greater than 90 % and low total energy storage determine their main application area within frequency control (Denholm et al. 2010; Oberhofer 2012).

Above energy storage technologies might also be used in combination (hybrid storage technologies), i.e., to achieve fast response times (e.g., capacitor) combined with higher energy density (e.g., from batteries). This approach is, aside from VRE integration, also used in EVs to accommodate short-term high power requests (Neugebauer 2014; Butterbach et al. 2011).

Main challenges of discussed decentralized energy storage options are economically driven: in the presence of grid access and other energy storage options, e.g., pumped hydro, decentralized energy storage needs to be individually evaluated. As such, options which include direct electricity storage or conversion back to electricity have their main application in power quality and backup services applications, but might become favorable options for energy storage in the future. The next section discusses flexibilizing demand to better match supply from a utility perspective, which is another central option to integrate VRE.

2.3.2 Demand Side Management for Renewable Energy Integration

In the context of matching electricity demand and supply by influencing the demand side, DSM is a method driven by the supply side (utilities) to influence demand of customers (compare to Fig. 2.16). As such, DSM is closely related to energy flexibility of manufacturing systems (cf. Sect. 2.1.4), but focuses on influencing demand in general (and therefore also includes, for example, energy efficiency and demand shifting). Further, energy flexibility of manufacturing systems is mainly concerned with changing energy demand under given constraints (e.g., technical, operational), while DSM focuses on setting incentives for customers and providing the required operational background to enable customers and utilities to effectively influence demand.

Utilities recognized already more than a hundred years ago that electricity prices should be varied within a day to improve supply economics (Cappers et al. 2010). As such, DSM is a much better covered field than energy flexibility and provides useful insight on methods and tools to influence (electricity) demand. In general, DSM aims at influencing the demand for a good or service by the supply side. DSM is not limited to electricity markets, and, for example, also applied for other infrastructure components, e.g., water (Guy 1996). In the context of electricity markets, DSM can

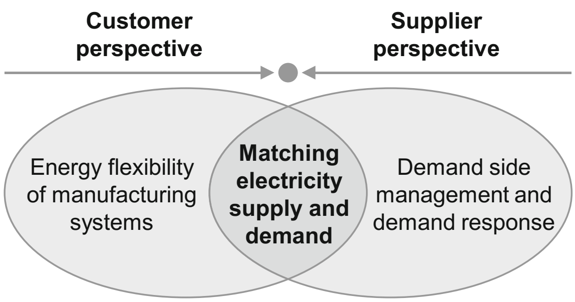

Fig. 2.16 Energy flexibility and demand side management as two perspectives to match electricity supply and demand (own illustration)

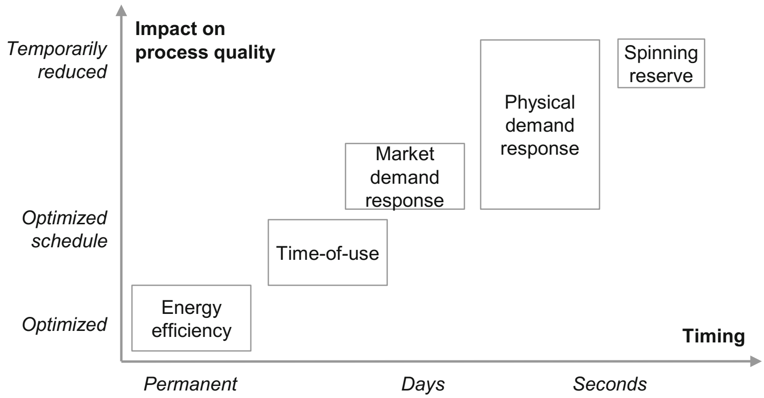

Fig. 2.17 Different categories of demand side management (from Palensky and Dietrich 2011, p. 381, own illustration, original copyright 2011 IEEE)

be defined as "organized utility activities that are intended to affect the amount and timing of customer electricity use" (Electric Power Research Institute 1993, pp. 2–2). Historically, electricity demand volatility was regarded as a given fact by electricity suppliers and distributors, which had to be accommodated by flexible supply. DSM programs are designed to increase demand flexibility, i.e., elasticity of demand, to increase efficiency of electricity systems (electricity suppliers, customers and connecting grid) (Spees and Lave 2007; Aalami et al. 2010). As a general principle to match demand and supply, DSM is a central part of integrating VRE into a power system.

From a timing perspective (duration of impact on load, compare to Fig. 2.17), DSM can be classified into energy efficiency, time of use, (market and physical) demand response, and spinning reserve (Palensky and Dietrich 2011). Depending on the time horizon for upfront notification of a customer by the utility, changes have a different (unwanted) impact on customer processes. From a total energy demand perspective, DSM is categorized into energy efficiency and demand response (Paulus and Borggrefe 2011). Energy efficiency aims at reducing total energy demand, while demand response shifts the timing of demand, leaving overall demand potentially unaffected.

The next two subsections briefly discuss general DSM objectives and then DR as part of DSM. As outlined before, DSM and DR in particular are closely related to energy flexibility of manufacturing systems as they summarize the supply-side perspective on influencing demand. Therefore, the following brief overview highlights relevant objectives and DR methods which can also be found in the context of energy flexibility.

Demand Side Management and Load Shaping Objectives

General load shaping goals are illustrated in Fig. 2.18. As mentioned before, DSM aims at influencing the amount and time of electricity demand. As such, illustrated

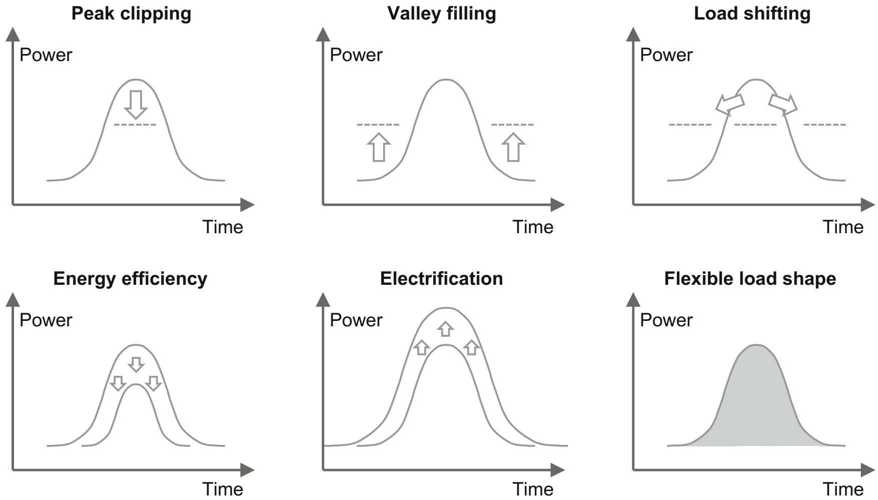

Fig. 2.18 General load shaping goals (own illustration based on Gellings 1985, p. 1469, original copyright 1985 IEEE, Elkarmi and AbuShikhah 2012, p. 102 and Charles River Associates 2005, p. 7)

generic load shaping goals can also be found in reshaping demand of manufacturing systems using energy flexibility, for example, illustrated in Fig. 2.7. A load shape with regards to time can refer to daily, weekly or seasonal changes in demand (Gellings 1985). Goals and corresponding objectives are:

- **Peak clipping** aims at reducing system peak demand to reduce the need for backup generation capacity or other forms of reserve capacity (i.e., direct load control).
- **Valley filling** aims at increasing off-peak electricity demand. This can be beneficial to the utility and customer if long-run costs are lower than electricity price (improved utilization of base-load generation).
- **Load shifting** also aims at reducing peak demand (as peak clipping), but without (substantially) reducing total demand. This is commonly achieved by rescheduling electricity demand, i.e., by using thermal storage capacities (e.g., water heaters) or by using general timing flexibility (e.g., running a sintering machine or electric arc furnace at night).
- **Energy efficiency** aims at (uniformly) decreasing total electricity demand, most common to preserve (natural) resources. Measures include, for example, installing more efficient equipment.
- **Electrification** or load growth increases total electricity demand, for example, to increase utility sales and/or improve load factors of generation plants. Examples include fuel switching (i.e., electric vehicles) and general increase in (electric) energy demand through economic growth.

- **Flexible load shape** refers to a policy where utilities can influence customer demand as needed, commonly to accomplish reliability goals. To achieve a flexible control, the utility needs to be able to dynamically influence customer demand, for example, through direct load control.

Demand Response Strategies and Programs

The idea of DR has been known since the early days of the (U.S.) electric power supply industry. In the late nineteenth century, engineers discussed pricing methods which included different charges dependent on the time of the day in the U.S. (Cappers et al. 2010; Hausman and Neufeld 1984; Isser 2015). Discussed pricing structures aimed at economically efficient allocation of short-term/marginal (generation) costs and long-term costs incurred by providing capacity and required assets to meet different levels of (peak) demand. In the context of VRE integration, DR summarizes a variety of supply-side methods to accommodate increased non-dispatchable VRE share. Without DR, more but less frequently used backup generation capacity might be required to integrate VRE (cf. Sect. 2.2.5, Merit Order Effect).

DR can be defined as "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (U.S. Department of Energy 2006, p. 6). The definition differentiates between two customer-side mechanisms for influencing demand, (1) response to price changes or (2) response to incentives, which are commonly used to classify DR programs.

Several different types of DR programs exist. As mentioned, programs are separated into price-based programs or incentive-/event-based programs (Goldman et al. 2010; Albadi and El-Saadany 2007, 2008; U.S. Department of Energy 2006; Elkarmi and AbuShikhah 2012; Charles River Associates 2005):

- **Price-based programs**: Rates for electricity demand are varied over time, inducing an incentive for customers to reduce demand during periods with high prices:
  - Time-of-use (TOU): Different, previously (i.e., for one year) fixed prices depending on time of the day (e.g., multi-hour blocks).
  - Real-time pricing (RTP): Continuously varying prices (hourly or quarter-hourly), dependent on wholesale market.
  - Critical peak pricing (CPP): Mixture of TOU and RTP. Very high rates during a multi-hour CPP event while lower TOU rates during non-CPP events.
  - Extreme day pricing (EDP): Similar to CPP, but critical pricing period is a full day (24 h).
  - Extreme day critical peak pricing (ED-CPP): Very high electricity prices for a number of hours during extreme days (similar to CPP), but otherwise flat.

- **Incentive-/event-based programs**: Customers receive a payment when altering (reducing) loads upon request from the utility:
  - Direct load control: Utilities are enabled to (externally) reduce demand of customers, usually with short upfront notice and only for certain equipment (e.g., water boilers, air conditioners) in exchange for a payment.
  - Demand bidding/buyback programs: Customers bid for reducing loads and receive a monetary compensation if bids are successful (Saebi et al. 2010).
  - Emergency DR: Customers receive a (fixed) compensation during times when load reductions are required and loads are curtailed.
  - Interruptible/curtailable programs: Customers reduce demand upon request from the utility in return for lower rates.
  - Capacity market programs: Load reductions are offered by customers to substitute for system capacity (i.e., conventional generation or distribution capacity). Customers commit (typically day-ahead) to reduce loads during a prespecified time period and receive a payment in return, also when load reductions are not called. In return, customers face penalties if requested reductions are not achieved.
  - Ancillary services market programs: Customers offer to cut loads on a market typically operated by an ISO/regional transmission organization (RTO) and therefore act as operating reserves. If bids are successful, payments are received for providing the option to reduce loads upon request from the operator.

Empirical evidence for DR impact and potential has been surveyed, for example, in Cappers et al. (2010). Existing peak load reduction potential through DR programs was estimated to be in a single-digit percentage range in the U.S. in 2008 and increasing. Although the concept of DR is not new, implementation in electricity markets is still slow. In most markets, utilities charge customers an energy and a demand rate dependent on their electricity usage pattern rather than based on their demand in relation to current system load.

2.4 Intermediate Summary and Conclusion

This chapter starts with relevant background on manufacturing systems. In order to provide the required detail on the energy/electricity demand side, energy demand of production is discussed, including energy flexibility as a novel approach towards VRE integration from a demand side perspective. The second section highlights the energy supply side and includes background on conventional and renewable energy generation (compare also to Fig. 2.9 for an overview of highlighted topics). Characteristics and emerging challenges from renewable and, as most renewable generation is locally spread out, specifically decentralized generation are discussed. The connecting elements of electricity demand and supply, electricity distribution, markets and related grid stability challenges due to VRE integration, are then briefly summarized.

The third section details specific options for integrating VRE into power systems, starting with energy storage options. Subsequently, DSM and DR in particular are discussed, as both areas summarize approaches for VRE integration from a supplier (utility) perspective. Due to their relatively long history, these approaches can provide valuable insight into methods for demand and supply matching. Further, as outlined before, DSM and DR methods are closely related to energy flexibility, which is the equivalent, thus relatively young (compared to DSM) area from a demand side (industry) perspective. The objective stated in Chap. 1 aims at developing a concept for VRE integration from a demand side and thus energy flexibility perspective. As such, existing research in the field of energy flexible manufacturing systems is analyzed in the next chapter.

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