Chapter 2
Integrating Variable Renewable Electricity Supply into Manufacturing Systems

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Abstract Expanding renewable energy (RE) generation has been increasingly recognized as a central strategy for climate change mitigation. A substantial share of renewable energy generation comes from variable renewable energy sources (e.g. wind and solar), which are increasingly installed in decentralized structures. As such, integrating decentralized, variable RE generation into existing supply and demand structures is required to successfully further increase their share. Several different approaches and technologies are available for overcoming intertemporal and spatial demand and supply mismatches. Among them are conventional energy storage technologies as well as implicit energy storage options such as embodied energy in products, enabled through load shifting of energy-flexible production and manufacturing systems. This contribution begins with an overview of current challenges toward RE integration, followed by a discussion of available large-scale grid integration measures. Within the following, a focus is set on options for integrating decentralized variable RE. A promising approach is storing embodied energy in products. Its enabling method, energy flexibility of manufacturing systems, is detailed. A method to improve energy flexibility is discussed and its potential application demonstrated in a case study.

2.1 Decentralized Electricity Generation from Renewable Energy Sources

For decades, most energy systems have been relying on fossil fuel-based energy generation. Especially the energy and power sector is characterized by utilizing

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carbon-based fuels for electricity generation, among them black coal, lignite, natural gas, and petroleum. Global anthropogenic greenhouse gas (GHG) emissions from the energy supply sector amounted to approximately 35% of all GHG emissions in 2010. Without mitigation strategies, emissions from energy generation and utilization are expected to increase between 80 and 130% until 2050, compared to 2010. A central strategy for climate change mitigation is centered around switching energy and electricity generation from carbon-intensive (and thus GHG intensive) sources to alternative, less carbon-intensive sources such as renewable energy (RE) sources (IPCC 2014).

The importance of increasing the share of RE sources, especially for electricity generation, has been recognized by several nations, and thus targets for the increasing contribution of RE to (national) energy and electricity mixes have been formulated. For example, Germany has enacted a national policy called *Energiewende* (lit. *energy turnaround*) to reduce carbon emissions from energy and electricity generation while achieving a nuclear-free energy supply. Specifically, quantitative goals include cutting primary energy demand into half by 2050 compared to 2008 while increasing RE generation as share of final energy demand to 60%. Further, electricity generation from renewable sources is targeted to contribute 80% of the gross electricity demand in 2050 (Bundesministerium für Wirtschaft und Energie (BMWi) 2014).

Consequently, a set of incentives to increase electricity generation from RE sources has been enacted. Guaranteed grid feed-in tariffs for RE electricity generation were enacted, providing required financial predictability to promote investments in RE electricity generation capacities. Figure 2.1 illustrates German renewable electricity generation in 2000 and 2014. From 2000 to 2014, electricity generation from renewable sources increased from 6% to more than 27% in 2014. In particular, generation from wind and solar increased most significantly, with two-digit annual growth rates, surpassing all other renewable sources in 2014. Considering remaining opportunities for deployment of RE generation sources, (offshore) wind and additional photovoltaic (PV) systems for solar-based generation are expected to further increase their share toward fulfillment of stated RE energy generation goals within the next years (Bundesministerium für Wirtschaft und Energie (BMWi) 2014). Another factor is the relatively high social acceptance of RE generation, arising, for example, from environmental concerns, which supports future increase in RE penetration, also in other regions than Europe (Yuan et al. 2015).

When RE starts to supply a substantial share of total energy and electricity demand, integration into an existing energy system needs to be performed. Some RE sources are characterized by intermittent availability, i.e. power/electricity output varies over time. Output from conventional power generation facilities, e.g. fossil fuel or nuclear power plants, is controllable. Depending on the specific technology, electricity output can be increased or decreased, with varying time periods required for adjustment (e.g. minute ramp-up and -down times for gas turbines and up to multi-hour lead times for coal-fired plants). For the case of variable renewable energy (VRE)-based electricity generation, output can generally only be decreased. For example, wind and solar generation are, among others, dependent upon local weather conditions and solar radiation. Output can be reduced, e.g. by reducing the rotation speed of a

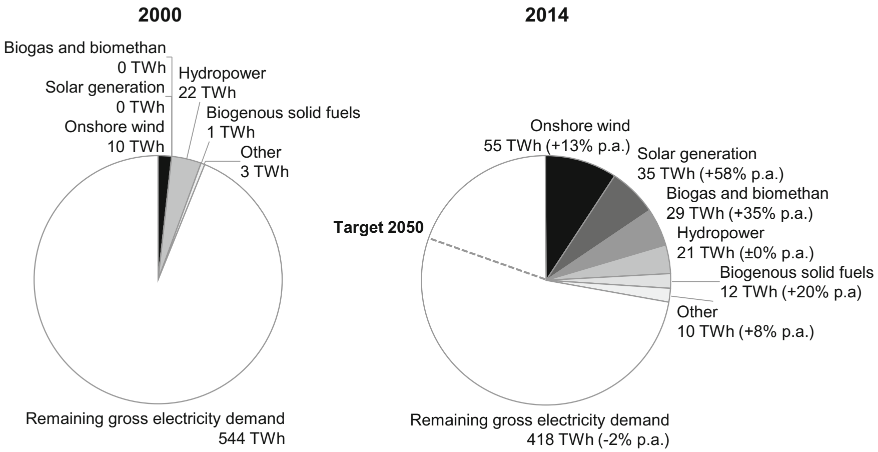


Fig. 2.1 German renewable electricity generation by source and remaining gross electricity demand in 2000 and 2014, percentage increase per annum (p.a.) from 2000 to 2014 (Bundesministerium für Wirtschaft und Energie (BMWi) 2015, own calculations)

wind turbine, while it cannot be increased (if output has not been curtailed before). Further, reducing output is usually unfavorable as marginal costs of VRE generation are low compared to other generation sources and maximum output is targeted to fulfill RE goals (IPCC 2012). To illustrate variation and time dependency, Fig. 2.2 shows wind and solar outputs from installations based in Braunschweig, Germany, over five days in October 2013. The first two days are characterized by high solar output during daytime and high, but fluctuating wind output, also during the night. The third day depicts a change in weather conditions. Solar output fluctuates during the day, indicating partly cloudy weather, while wind output declines at the end of the day. During the last illustrated two days, wind and solar outputs are both very low (10–20%) compared to the first three days. In summary, VRE generation can substantially vary over time, with second, minute, hourly, daily, and seasonal changes. Predicting VRE generation is a complex and difficult task due to inherent dynamics and stochastic behavior of several influencing factors. Substantial effort has been made to increase reliability of forecasts, for example, conditioning artificial neural networks (Qazi et al. 2015). However, residual deviations are unavoidable as a result of stochastic components (IPCC 2014).

Another characteristic of VRE is its decentralized generation. Wind and solar resources are usually geographically spread-out, i.e. geographic conditions determine the potential for RE generation (e.g. high wind resources are usually found within coastal regions, solar radiation increases in southern regions and with height). Consequently, electricity generation takes place where efficiency is expected to be high. Technologies which are used for decentralized generation are PV, wind-based generation, small hydropower, and biomass. Decentralized generation is expected to also increase within the next years (IPCC 2014).

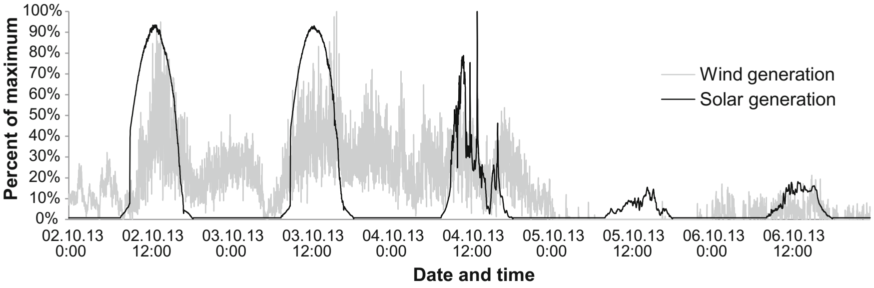


Fig. 2.2 Wind and solar generation at IWF, TU Braunschweig (latitude 52.2767, longitude 10.5369) from October 2 to 6, 2013, one-minute averages (second sample period), normalized to period's maximum demand

From an industry perspective, decentralized (on-site VRE) generation plays a vital role to reduce cost and increase independence from grid supply. About 18% of total industrial electricity demand was supplied by industry itself in Germany in 2013, which is equivalent to 45 TWh or 8.9% of Germany's gross electricity generation (DESTATIS 2014, 2015, own calculations). In 2013, approx. 16% of all companies have enacted measures for own supply in Germany, which is expected to increase in the following years. With 62%, realized and planned PV generation had the largest share of all utilized technologies (DIHK and VEA 2014). Due to economic benefits (e.g. reduced network charges), companies usually aim at maximizing the demand of on-site generated electricity.

Taking above considerations toward mitigating climate change through RE generation capacity increase, combined with decentralized generation in industry, into account, integrating VRE into an existing grid infrastructure is of special interest. As outlined above, VRE generation can only be influenced to a certain extent, and dispatchability is limited. Consequently, measures are required to overcome intertemporal and local discrepancies between volatile electricity supply and demand. Aligning electricity demand and supply can either be targeted on a grid level, i.e. large-scale storage, or performed on-site for the case of decentralized generation. Within the following, options for both strategies are discussed (compare to Fig. 2.3), starting with large-scale grid storage options.

2.2 Large-Scale Electricity Storage for Grid Integration

On a power grid level, large-scale electricity storage aims at overcoming temporal demand and supply mismatches, traditionally caused by low demand during nighttime and a (relatively large) baseload power plant fleet with limited adjustability (e.g. nuclear power plants). Common energy storage technologies currently used on

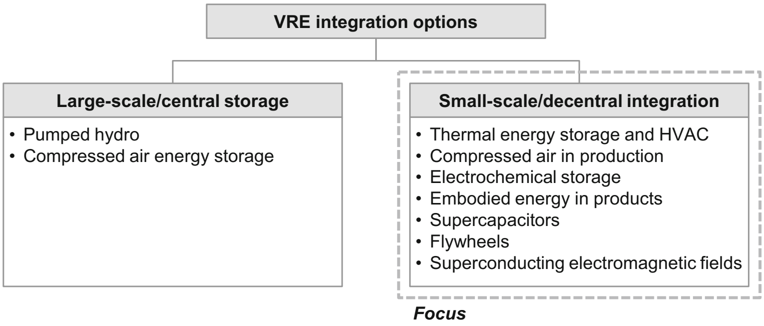


Fig. 2.3 Overview of electricity storage options

a commercial scale include pumped hydro storage and compressed air energy storage (CAES) (IPCC 2012).

Pumped storage is regarded as the only economic method for large-scale electricity storage at present (Deutsche Energie-Agentur GmbH (dena) 2010). During charging, water is pumped in a reservoir which lies geographically elevated. During discharging and thus electricity generation, the process is reversed, and water is released through turbines for electricity generation. However, remaining potential for additional pumped storage is, depending on the region, limited due to lacking geographic conditions, ecological concerns or political resistance (Germany Trade and Invest 2015). For the case of Central Europe, options for additional pumped storage in Scandinavian countries and the Alps are investigated, which would cause substantial transportation requirements. However, Norway, for example, has the potential for an additional 10–25 GW pumped storage capacity, which would result in about doubling the currently available capacity (IPCC 2012).

CAES plants store energy in compressed air, e.g. in an underground cavern. During excessive electricity supply periods, air from the surrounding environment is compressed into the cavern. However, during discharge and thus electricity generation, heat is required as the air temperature is reduced during expansion. Heat exchangers (storing heat from compression) or additional firing, e.g. using natural gas, are commonly used. Currently operated CAES plants include the 1978-built, 290 MW plant in Huntorf, Germany, and a 110 MW plant from 1991 in McIntosh, Alabama, USA (Crotogino et al. 2001). Initially, CAES was built to compensate mentioned demand/supply mismatches between night and day caused by baseload power plants. CAES integration into a system with a large VRE share has recently been investigated, among others due to their fast response times (Lund and Salgi 2009; Lund et al. 2009). Conversion inefficiencies of around 50% and related challenges for economically profitable operation currently prevent widespread application of CAES. Recent developments mainly target increasing conversion efficiency, e.g. adiabatic compressed air energy storage technology (AA-CAES) with an approximate conversion efficiency of 70% and, with an expected efficiency of 80%, isobaric adiabatic compressed air energy storage plant with combined cycle (ISACOAST-CC)

(Zunft et al. 2006; Bullough et al. 2004; Karellas and Tzouganatos 2014; Nielsen and Leithner 2009).

Other grid-wide/large-scale storage options which are currently investigated include batteries (chemical/redox-flow), fuel cells and thus hydrogen storage, (other) power to gas methods, flywheels, and supercapacitors (Deutsche Energie-Agentur GmbH (dena) 2010). However, technical (e.g. high energy losses in flywheels over time), environmental (e.g. batteries), and economic (e.g. conversion and economic efficiency of fuel cells) challenges prevent current implementation for large-scale electric energy storage. However, some of the mentioned technologies are used for providing ancillary services, e.g. frequency control.

2.3 Options for Integrating Decentralized Generation

Integrating decentralized generation into an existing power grid can either be targeted by applying previously discussed measures on a grid-wide scale or by increasing direct demand of on-site generated electricity. Increasing direct demand for decentralized electricity has multiple benefits: From a utility perspective, less transportation requirements and thus grid infrastructure is required to supply companies with electricity and to transport surplus on-site generated electricity to other customers. Further, if on-site electricity generation demand achieves to reduce volatility in grid demand and supply, less backup generation resources are required. From a company perspective, direct demand is favorable as companies which have on-site generation facilities usually face a lower marginal cost of on-site generation than grid supply costs, i.e. demanding a kWh of on-site generated electricity is usually cheaper than demanding one kWh from the public grid. Related to this are additional economic incentives, for example, avoiding grid charges and taxes (e.g. subsidies for RE integration, for example, under the German *Erneuerbare Energien Gesetz*) (DIHK and VEA 2014).

Within the following, options for increasing direct demand of on-site VRE generation are discussed. A focus is set on a production/manufacturing perspective. For each option, the general idea is briefly discussed, followed by advantages and disadvantages. Challenges toward implementation and main influences, which need to be considered, are included.

2.3.1 Thermal Energy Storage and HVAC

Thermal energy storage can be used for VRE generation in two different ways: (1) thermal storage can be used to store heat, e.g. from solar radiation, to be converted to electricity at a later point in time and (2) electricity can be converted to thermal energy for later use, e.g. by converting thermal energy back to electricity or for heating/cooling purposes (which might substitute electricity use) (Denholm et al. 2010).

Utilizing thermal storage for later conversion to electricity is, for example, applied in concentrated solar power plants. However, round-trip efficiency for electricity-heat-electricity cycles is usually relatively low.

Utilizing thermal energy storage for air conditioning (cooling/heating) purposes is a well-known approach to accommodate variable energy supply and/or to profit from variable prices. Storage options include thermal building mass, where a building's heat capacity is used for pre-cooling or -heating in periods where high (VRE) electricity supply is present (Braun 2003; Reynders et al. 2013). Utilizing building thermal mass to shift electricity demand for heating is considered a promising approach toward influencing the demand for VRE integration (Reynders et al. 2013). Further, chilled water and ice, e.g. on rooftop tanks or submerged underground, can be used to increase control range and/or heat capacity (Ashok and Banerjee 2003; Arteconi et al. 2012; Rankin and Rousseau 2008). This might also include utilizing underground rock formations for heat/cool storage capacities, where hot/cold water is pumped into suitable geological patterns, which can even be used for seasonal load shifting.

Related to cooling and heating applications as part of heating, ventilation, and air conditioning (HVAC) is ventilation, especially in industrial setting. Clean air is used for load shifting, i.e. ventilation is switched-off during low electricity availability if emission levels allow for reduced ventilation, and emission reduction is performed during periods of high electricity availability. Further, increased heating might be required if ventilation is switched on, which can increase emission-related load-shifting opportunities (Junge 2007).

Other thermal storage applications, especially in the context of VRE integration into a production facility, include process cooling and heating. For example, supercritical steam can be stored and supply process heat in production facilities (Oertel 2008). Further technologies include thermo oil and solid materials, while the latter is not (yet) commercially established. Process cooling can be supplied similarly, e.g. by chilled water or ice storage.

From a technology perspective, thermal energy storage can be realized by changing the temperature of a material or by latent thermal storage (Oertel 2008; Arteconi et al. 2012). The latter principle is based on a change of state of matter, i.e. from liquid to solid. These so-called phase-change materials have the advantage of storing a significantly higher amount of energy (per volume/mass), while energy flows are realized at nearly constant temperature. However, challenges include low heat transfer capabilities, requiring large surfaces for transmission.

2.3.2 Compressed Air

Compressed air (CA) used in production and manufacturing can be used as direct energy storage option. In general, compressed air can be generated during times of high electricity availability and stored in tanks and within the CA system volume (e.g. pipes). Shifting CA production can, for example, be used to profit from fluctuating electricity prices (Kleiser and Rauth 2013) or to integrate VRE generation into a production/manufacturing facility (Beier et al. 2015). An advantage compared to e.g. CAES or battery storage is the avoidance of an additional conversion cycle, as CA is generated and stored for direct use in production. CA is required independent of the point in time when it is generated. Therefore, conversion inefficiencies are not a result of possible load-shifting and related energy conversion actions, as long as technical parameters are held constant. Nonetheless, in order to increase the amount of storable energy, the operating pressure band needs to be adjusted and/or the CA system (tank) size increased. While the first measure can increase compression inefficiency, the latter requires additional investments. Further, CA losses need to be accounted for, which can also increase as a result of load-shifting actions (e.g. higher pressure level over longer periods of time increases losses through leaks). Another limitation is provided by production system characteristics: only the share of total energy demand which is supplied by CA can be used for load shifting, i.e. even with high compressor capacities and large storage tanks, total CA demanded by processes and facilities defines the amount of load that can be potentially shifted. In addition, operational constraints for compressors, such as switch-on time and maximum allowed number of switches to prevent motor wear-out need to be taken into consideration (Ruppelt 2003).

2.3.3 Electrochemical Storage

Considered electrochemical storage options for VRE integration include conventional, high-temperature and redox-flow batteries. Conventional rechargeable batteries include, for example, lead–acid batteries, nickel–cadmium, sodium–sulfur, lithium-ion, zinc–air and lithium-air batteries (Oberhofer 2012; Deutsche Energie-Agentur GmbH (dena) 2010). Under the goal of VRE integration, most relevant parameters include energy and power density (e.g. per mass and volume), investment/operating costs and environmental impact (caused mainly by utilized materials). As the amount of different battery technologies indicates, a wide range of technical and economic parameters can be achieved. For example, lead–acid batteries are a mature technology which is frequently used for hybrid energy systems, e.g. VRE and battery/diesel backup generation (Bernal-Agustín and Dufo-López 2009). Their relatively low energy density is offset by possible high discharging power (which has also established their use as starter batteries in cars) and relatively low cost. However, availability of other, more economic storage options in a grid infrastructure (such as pumped hydro) has so far limited lead–acid battery applications mostly to stand-alone/island scenarios where no grid access is provided (Oberhofer 2012). A second battery type is lithium-based (e.g. lithium-ion, lithium polymer, lithium–air) batteries. They currently undergo a rapid development toward their use in mobile applications such as electric vehicles (Gallagher and Nelson 2014). Their energy density compared to lead–acid batteries is relatively high, cycle lifetime is significantly increasing as a result of ongoing research efforts and the main material, lithium (and currently graphite) is an abundant mineral resource (Oberhofer 2012). However, current technical parameters combined with costs make lithium-based batteries mainly suitable for balancing power applications in a VRE context.

Considering advantages and disadvantages of batteries for VRE integration, charging and discharging efficiency of batteries can be very high with values above 95%. Self-discharge losses are relatively low, with single-digit percentages per month (depending on technology and operating parameters such as temperature) (Deutsche Energie-Agentur GmbH (dena) 2010). Response rates are fast, making them suitable for both decentralized energy storage and balancing power-related applications. Depending on technology, batteries can impose serious environmental and operational hazards, which can include toxicity (e.g. large amounts of lead in lead–acid batteries) or flammability when ruptured (e.g., lithium is flammable when exposed to atmospheric moisture) (Oberhofer 2012). Further, especially in a VRE setting where demand and supply peaks are shaved, batteries might experience a high number of charge and discharge cycles, causing fast deterioration and wear-out, reducing economic and ecologic efficiency (Deutsche Energie-Agentur GmbH (dena) 2010). However, current research and development efforts are indicating that especially lithium-ion batteries might be a promising technology for future VRE integration.

High-temperature batteries, among them the mature sodium–sulfur (NaS) and the newer sodium–nickel chloride (ZEBRA) battery, have a solid electrolyte and liquid electrodes (Oertel 2008; Oberhofer 2012). As such, temperatures above 300 °C are required to keep the electrodes molten. Challenges include operational safety (fires) and reduced efficiency due to required heating. However, their energy density is relatively high and their lifespan is favorable. For example, Japan extensively uses NaS batteries, mostly for balancing power. Recent developments indicate that operational and economic improvements can make high-temperature batteries suitable for VRE integration.

The technical principle of redox-flow batteries is similar to conventional batteries, with the difference that the electrolyte within a cell can be exchanged during operation. This feature allows advanced configuration of redox-flow batteries, i.e. power and energy can be changed separately from each other. Capacity can be adjusted by altering the size of electrolyte storage tanks. Recharging the battery is possible by replacing the electrolyte, which favors mobile applications, e.g. in electric vehicles. Cycle and temporal lifetime, start-up time and efficiency (around 80%) are relatively high. However, costs prohibit large-scale industrial applications if other (e.g. compressed air, pumped storage) options are available. Common technologies include vanadium redox and zinc–bromine redox-flow batteries (Denholm et al. 2010; Deutsche Energie-Agentur GmbH (dena) 2010; Oberhofer 2012; Oertel 2008).

In summary, electrochemical storage options are currently mainly used for hybrid-/stand-alone energy systems and to provide balancing and regulatory power. Cycle lifetime, costs and environmental concerns are main barriers for increased utilization for VRE integration. However, strong R&D efforts cause electrochemical storage to become increasingly competitive.

2.3.4 Embodied Energy in Products

Embodied energy in products can be used to store energy by shifting production from times with low electricity availability to times with high electricity availability. As such, embodied energy in products can contribute to integrate VRE and/or account for volatile supply and/or prices in general. In contrast to other storage options, recovering energy is not targeted, i.e. the stored energy is already in the form of its desired end-use. For example, energy can be stored in chemical bounds, e.g. in free aluminum during aluminum electrolysis (reduction of aluminum oxide), steelmaking from iron ore or, in general, contained in chemicals obtained by (endothermic) reactions (Allwood and Cullen 2012). Another example is joining two workpieces, e.g. by drilling, threading, and connecting both parts with a screw. Most of the energy demanded during the process is dissipated into the environment as a result of inefficiencies and thus energy storage is rather latent. However, assuming that a value-creating process requires a certain amount of energy to be fulfilled, this total energy can be regarded as embodied energy in the product (for an overview of energy demand modeling of manufacturing processes and discussion of components see, e.g., Gutowski et al. 2006). Consequently, utilizing, for example, VRE during value creation of a product and not (fossil fuel)-based supply improves integration of VRE and reduces demand for conventional supply. Nonetheless, opportunities for increasing demand of VRE and thus load shifting are subject to operational constraints, most notably potential impact on throughput and technical constraints. Further, opportunities to increase demand of VRE supply is limited to energy/electricity demand of processes. For example, a battery could be used to supply electricity to processes and, e.g. HVAC facilities and thus increase the use of VRE for both applications. Embodied energy flow into products is limited to the influenceable demand of processes. Further, the amount of embodied energy which can be stored is strongly dependent on (intermediate) product storage opportunities (more storage space results in more embodied energy storage), i.e. energy demand of processes can only be flexibly adjusted if material flow is sufficiently decoupled.

The inherent advantage of embodied energy storage is avoidance of additional energy conversion (similar to compressed air). Assuming that electricity demand is only shifted and not decreased or increased in its total amount, and holding (technical) parameters constant, results in no additional inefficiencies (compared to traditional energy storage technologies such as pumped hydro, CAES or batteries). However, the dynamic nature of production and manufacturing systems, compared with nonlinear energy demand (e.g. idle and production demand), requires detailed evaluation of embodied energy storage opportunities and their change of operational, technological, and environmental impacts.

From a production technology perspective, embodied energy in products to implicitly store (renewable) energy is discussed in the context of energy flexibility of manufacturing systems (while other options to flexibly adjust energy demand, such as battery storage, might also be included in a wider energy flexibility definition). Energy flexibility can be defined as “[...] the ability of a production system to adapt itself fast and without remarkable costs to changes in energy markets." (Graßl et al. 2013). Examples which explicitly consider intermediate product storage to shift electricity demand of manufacturing systems include (Ashok 2006; Middelberg et al. 2009; Li et al. 2012; Fernandez et al. 2013; Sun et al. 2014; Schultz et al. 2015; Keller et al. 2015; Beier et al. 2015). Utilizing energy flexibility of manufacturing systems to integrate VRE, especially decentralized generation, is regarded as a promising approach and can reduce requirements for traditional energy storage, which involve additional conversion cycles and infrastructure. Further, utilizing energy flexibility of industry provides additional opportunities for creating new business models (Lorenz et al. 2012). Dependent upon specific system design and technology and thus required investments and additional operating costs, companies can generate additional profit by, e.g. reduced energy costs and participating in reserve markets.

Energy flexibility of manufacturing systems can also be used for grid-wide integration of VRE. From a power system operator's/utility's perspective, demand-side management (DSM) encompasses the two main strategies energy efficiency and demand response (Paulus and Borggrefe 2011). Demand response aims at reshaping demand of customers to increase demand and supply matching, but is, in contrast to energy flexibility, driven by utilities (and not an electricity customer-centered method) (Elkarmi and AbuShikhah 2012). Common strategies include price-based and incentive-based programs, i.e. customers are faced with time-dependent electricity prices or they receive an incentive if demand is altered upon request from the utility (Albadi and El-Saadany 2008).

2.3.5 Supercapacitors, Flywheels, Superconducting Electromagnetic Fields

Supercapacitors (also called ultracapacitors), flywheels, and superconducting electromagnetic fields (sometimes called superconducting magnetic energy storage (SMES)) are summarized as they are rather used for power quality and frequency regulation than for substantial (VRE-) energy storage (Denholm et al. 2010).

Supercapacitors are mostly used for frequency regulation and to smooth output/stabilize power in VRE-based electricity generation settings (Seo et al. 2010; Denholm et al. 2010). Supercapacitors can reach an energy density beyond 20 kWh per cubic meter, and they exhibit high cycle stability values with more than 100,000 charge and discharge cycles. Their efficiency might reach 80–95%, and maintenance costs are relatively low compared to other available technologies. Costs were estimated to be around 320 EUR per kW, while both energy density and cost are expected to improve significantly in the future (Deutsche Energie-Agentur GmbH (dena) 2010). However, due to their relatively low energy capacity, supercapacitors are unlikely to be used for extended energy storage, also in the near future.

Flywheels store energy in a rotation mass by converting electricity into kinetic energy during charging and back to electricity during discharging. Fast response but limited capacity make them especially useful for frequency regulation rather than (long-term) energy storage (Denholm et al. 2010). Single flywheels can have capacities of 100 kWh and are installed in larger arrays to increase capacity. Their relatively high cycle efficiency of more than 90% is offset by high discharge rates of several percents per hour (Deutsche Energie-Agentur GmbH (dena) 2010). Advantages of flywheels include their relatively high reliability and utilization of less hazardous materials than, for example, in batteries. Further, expected lifespan and cycle stability are high, with nearly no maintenance required if magnetic bearings are used (Oberhofer 2012). One of the first large-scale flywheel energy storage plants started operation in 2011 in Stephentown, New York (Beacon Power 2015). The plant has a capacity of 5 MWh at 20 MW charge and discharge rate and consequently mainly participates in reserve markets. However, current large-scale application still faces economic challenges, indicated by, e.g. bankruptcy of the first operator of the described plant. Therefore, utilizing flywheels for decentralized VRE integration is only suitable under specific circumstances, e.g. high temperatures or if hazardous materials cannot be used.

SMES can reach efficiency values of beyond 90% with very fast response times, which is offset by their relatively low capability to store energy (Oberhofer 2012; Denholm et al. 2010). As such, they are mostly used for power quality and frequency stabilization. In addition, costly setup and operation, partly induced by required cooling to achieve superconductivity, combined with two-percent discharge losses per day, prevent SMES to be (solely) applied for VRE integration.

Storage technologies discussed in this subsection (supercapacitors, flywheels, SMES) are also used in hybrid storage technologies to increase efficiency. For example, one application is their combination with conventional batteries in electric vehicles to improve efficiency and response to short-term, high-power requests, e.g. during acceleration or braking (energy recovery) (Neugebauer 2014; Butterbach et al. 2011).

2.3.6 Intermediate Summary

Several different approaches and technologies exist to directly and indirectly store energy from decentralized VRE generation for integration into industry and manufacturing systems. An overview, including advantages and disadvantages and factors for application, can be found in Table 2.1. Depending on system structure, VRE supply and individual goals for VRE generation and integration, different options are available. These options need to be evaluated in detail, e.g. under economic, ecological, and operational aspects, to support decision making.

In order to integrate decentralized VRE-based electricity generation, embodied energy in products, compressed air and battery storage, including electric vehicles, are promising approaches. As mentioned, energy storage in embodied energy of products and flexible compressed air generation has the advantage that no additional conversion cycle is required (as, for example, compared to battery storage). However,

Table 2.1 Selected energy storage options for decentralized VRE integration into production and manufacturing systems

Storage technology	General principle	Advantages	Disadvantages	Factors for application
Thermal energy storage and HVAC	Store energy in heat/cooling capacities (temperature and phase-changing) and emission levels	• Very high capacity • Direct use can be cost efficient (heating/cooling) • Depending on technology, losses relatively low • Safe and environmentally friendly	• Conversion efficiency (to electricity) low • Recovering electricity from thermal energy potentially uneconomic • Requires available thermal mass • Limited to amount of required heating/cooling/ emission reduction if not converted back to electricity • Potential complex dynamics	Suitable for heating, ventilation and air conditioning and, depending on technical processes, to supply process cooling and heating when dynamics can be controlled
Compressed air (CA) in production	Shift CA production to times of high electricity availability, store energy in CA	• Infrastructure already present • Avoidance of additional conversion cycles • Fast response time • Environmentally friendly	• Limited by total CA demand • Increased inefficiency if technical parameters changed • Additional investment and cost if new installations required	Suitable where CA is required for production and CA storage capacities are sufficient
Electrochemical storage	Energy storage via chemical reactions	• Storage and supply of electricity (flexible use) • Several configurations possible • Fast response times • Potential for high energy storage	• (Not yet) cost efficient • High wear-out (limited cycles) • Environmental concerns	Depending on technology, used for peak shaving, as reserve capacity and energy storage: to be compared to other available options
Embodied energy in products	Store energy in embodied energy of products by shifting production demand	• No additional conversion cycle required • Utilization of existing infrastructure • Environmentally friendly	• Requires flexibility of production system • Limited to amount of flexible demand from machines/system • Might adversely affect technical, operational and other indicators	Applicable for production (systems) with sufficient energy flexibility: scheduling flexibility, product storage and direct control required
Supercapacitors	Energy storage in electric field	• Very fast response • Nearly no maintenance • High cycle stability • Moderate to high efficiency	• Relatively costly • Low volumetric energy density	Only suitable for frequency regulation/power quality application and power smoothing and/or very short-term storage
Flywheels	Energy storage in rotating mass	• Fast response • Environmentally friendly • Long lifespan • Low maintenance	• High self-discharge • Energy storage limited • High initial costs	For fast response, high temperature, environmental sensitive environment, short-term storage
Superconducting Magnetic Energy Storage	Energy storage in electro-magnetic field	• Very fast response • High cycle efficiency • Low environmental impact and hazardous materials	• Lower efficiency during stand-by (cooling) • Costly to set-up and operate • Very low energy density • Discharge losses	Useful for frequency regulation, power quality applications (e.g. uninterrupted supply)

as a result of inherent dynamics of energy supply and manufacturing systems, several challenges exist. Within the following, energy flexibility of manufacturing systems to enable embodied energy storage is discussed in more detail.

2.4 Enabling, Improving and Evaluating Embodied Energy Storage in Manufacturing Systems

Energy flexibility of manufacturing systems for embodied VRE energy storage is enabled through load shifting of manufacturing system energy demand. Within this section, a focus is set on electricity demand as a primary energy carrier in most manufacturing systems and on embodied energy storage using energy flexibility as an emerging method to integrate VRE. However, discussed approaches, including challenges and requirements toward implementation, are also applicable for other energy carriers, e.g. direct heat demand from solar radiation.

Figure 2.4 illustrates an example for load-shifting opportunities to accommodate (on-site, renewable) variable electricity generation (note that the given example is for illustrative purposes only and includes no measured values). Before load shifting, demand is characterized by two (flattened) peaks, e.g. from running production equipment with a dedicated production and thus energy demand cycle. The two peaks are followed by a fluctuating demand pattern. Electricity supply exhibits an unstable pattern with small-scale, short-term volatility combined with longer term, larger volatility, for example, found in wind generation output patterns (compare also to Fig. 2.2). The difference between supply and demand is compensated by a connected grid, i.e. if demand is higher than on-site supply, electricity is drawn from the grid and, for the case of an excessive on-site generation, electricity is fed into the grid. Before load shifting, total absolute difference between demand and supply (area under the curve from the lower graph in Fig. 2.4) is 399 kW · time units (203 kW · time units grid supply and 196 kW · time units grid feed). Shifting demand by postponing the two peaks in demand and scheduling the fluctuating demand first results in an improved match between demand and supply (right graphs of Fig. 2.4). Total absolute deviation is decreased to 171 kW · time units (89 kW · time units grid supply and 82 kW · time units grid feed), resulting in more than halving grid support requirements (electricity supply and feed-in). However, load-shifting opportunities depend on process characteristics, system dynamics, and operational constraints, e.g. if the fluctuating pattern has been caused by cleaning or setting-up the machine *after* processing two parts which caused the spikes, load shifting is not possible (at least not in the way the example assumes).

The capability of a manufacturing system to store embodied energy in products via load shifting is influenced by process-related and system-related factors. For example, Graßl defines a dimensionless indicator for evaluating energy flexibility of a manufacturing process (Graßl 2015). Among others, flexibility is enabled through the variation potential of process energy demand. For example, a machine which can

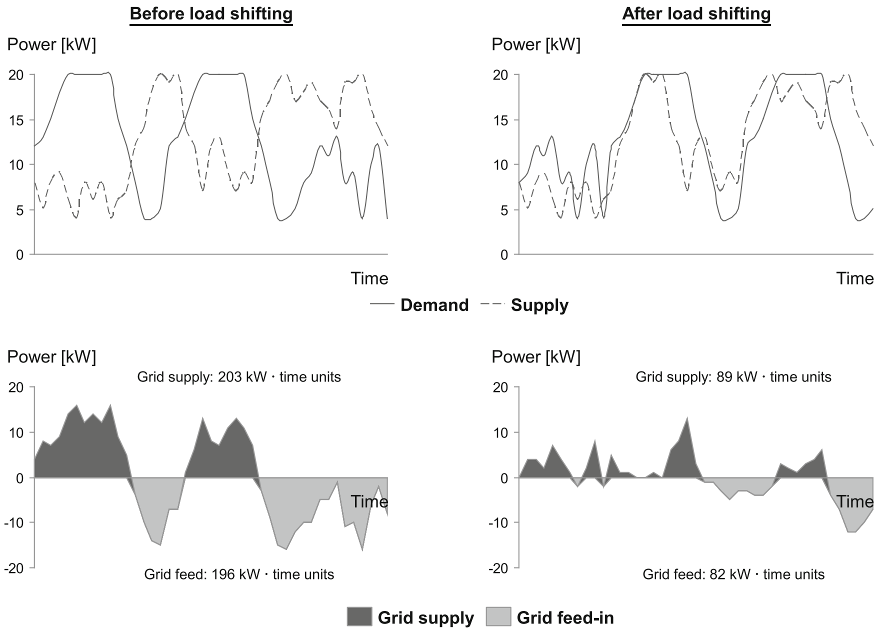


Fig. 2.4 Example for industrial load shifting under variable (renewable) electricity supply (illustrative example)

c.p. assume more different energy states than another machine is considered more energy flexible. Further, reflection of a broad energy demand continuum (i.e. different states with significantly different electricity demand as opposed to states with similar electricity demand) is beneficial for energy flexibility. In addition, further indicators such as costs or required time for adjustment are discussed. In (Graßl and Reinhart 2014), a set of measures to enable energy flexibility is discussed, among them altering machine schedules and process starts (compare to graphical load shifting example in Fig. 2.4), operational measures such as adjusting workforce schedules (free time and shift times) and switching of energy carriers.

For the case of interlinked manufacturing systems, discussed load-shifting methods for single processes are also applicable. However, material flow dynamics deserve special consideration as energy flexibility measures might have an impact on the overall system performance. In connected manufacturing systems (i.e. the number of possible ways a product can take through the system is fixed and product storage between processes is limited), rescheduling of a process can impact adjacent processes (upstream and downstream). For example, deferring a process start can block an upstream process if the storage capacity between the two processes is exhausted. For the case of downstream processes, processes might be starved if no intermediate products in a connecting buffer are available (Beier et al. 2015; Fernandez et al. 2013). For multi-product systems, altering schedules including job sequencing might cause a required input product type for downstream processes not to be available on time. From a total system perspective, rescheduling processes can result in missing required delivery time of products. Further, maximum throughput of a manufacturing system is determined by one or more bottleneck processes (Zhai et al. 2011). If a bottleneck process is rescheduled, blocked or starved (i.e. increasing nonproductive time), the total throughput of the system is reduced. As a consequence, energy flexibility benefits (such as integrating VRE and reducing grid electricity costs) need to be compared to economic disadvantages due to lost production (e.g. lost product margin of sales). Another option is introducing a control method which ensures that no throughput due to energy flexibility measures is lost.

In general, energy flexibility via embodied energy storage of a manufacturing system, i.e. how much energy can be stored in embodied energy, is influenced by two components: the amount of electricity demand that can be shifted and used for energy flexibility purposes and secondly the amount of products and thus embodied energy that can be stored. The first component is closely related to energy flexibility of single machines as outlined above: a machine which has a nearly fixed energy demand (e.g. a washing machine) independent of state/throughput (excluding switch-off) is not suitable for load-shifting purposes. In general, machines with a high idle electricity demand and small production-related demand only offer limited opportunities for rescheduling as their main demand (idling) cannot be influenced by production scheduling. Another aspect is the adjustment time of processes, i.e. a process which requires significant time to change its energy demand state compared to the frequency in which energy supply changes is less suitable for energy flexibility purposes than a process which can rapidly adapt itself. For example, a machining process with a cycle time of several minutes, which is not interruptible, might not be suitable to follow minute or second-based changes of electricity supply. However, combining inert processes and systems with short-term electricity storage (e.g. batteries, flywheels, capacitors) can overcome differences due to delayed adjustment or supply/demand peaks. The second important metric, embodied energy storage amount, is influenced by (intermediate) product storage opportunities. If more products can be stored in between processes, more opportunities (in general) exist to shift demand of a single process without impacting adjacent processes. For example, if processes can run through times of high electricity availability (e.g. a sunny day and PV generation) and store products in intermediate buffers, processes can be switched-off or set to idle longer during times of low electricity availability while adjacent (bottleneck) processes are not required to curtail production as a result of missing inputs or insufficient output product storage. Another influencing parameter is the position of product storage buffers within the value chain: installing storage after processes with low electricity demand and thus less added embodied energy compared to processes with high electricity demand and added embodied energy results in less embodied energy storage capabilities (compared to installation after a process with high energy demand and flexibility).

In general, energy flexibility of manufacturing systems and embodied energy storage are enabled and increased by multiple factors, including system design and operation. Further, energy flexibility and embodied energy storage in products can be enhanced by including, for example, flexible compressed air generation. However, mutual influences and dependencies of material and energy flows require a dynamic approach to enhance energy flexibility of manufacturing systems. The next section describes an initial system design and real-time control approach toward energy flexibility improvement and illustrates its applicability and effectiveness in relation to other energy storage options using an example case study.

2.5 Example Case Study: Self-Sufficient Manufacturing System

A case study is used to demonstrate the potential of integrating VRE into an (existing) manufacturing system via different (direct and indirect) energy storage options.

2.5.1 Concept Description

Figure 2.5 illustrates the basic steps of the proposed concept and their application in the example case study. Initially, energy flexibility objectives (1) need to be defined. Within this example, achieving an electricity self-sufficient factory/manufacturing system (i.e. autarkical factory), which is independent from external grid supply, is set as a goal. Based on this goal, hypotheses are formulated (2) to achieve the stated goal. For example, embodied energy storage, battery storage, energy efficiency measures, VRE supply capacity, and their combination could be investigated. In a third step, the considered dynamic system needs to be modeled (3), bearing in mind the formulated hypotheses. Dynamic system modeling is required to investigate dependencies between energy and material flows in a (highly nonlinear) system. The case study uses an example manufacturing system from an experimental laboratory in combination with recorded wind and solar supply data. The next step is to derive scenarios (4), which are capable of providing results for previously defined hypotheses. For example, different intermediate product storage sizes or battery sizes are examined. Dynamic system behavior is calculated based on model and scenario input parameters (5). In this study, a simulation prototype is used to evaluate the system behavior over time. Based on the obtained results for different indicators (e.g. self-sufficiency of the manufacturing system's electricity demand), results are interpreted and conclusions are drawn (6). If desired results toward defined objectives are achieved (7), the preferred solution can be implemented. If goals are not (yet) reached or additional findings result in new hypotheses to be tested, hypotheses are restated and re-tested. The next section describes the application and results in more detail.

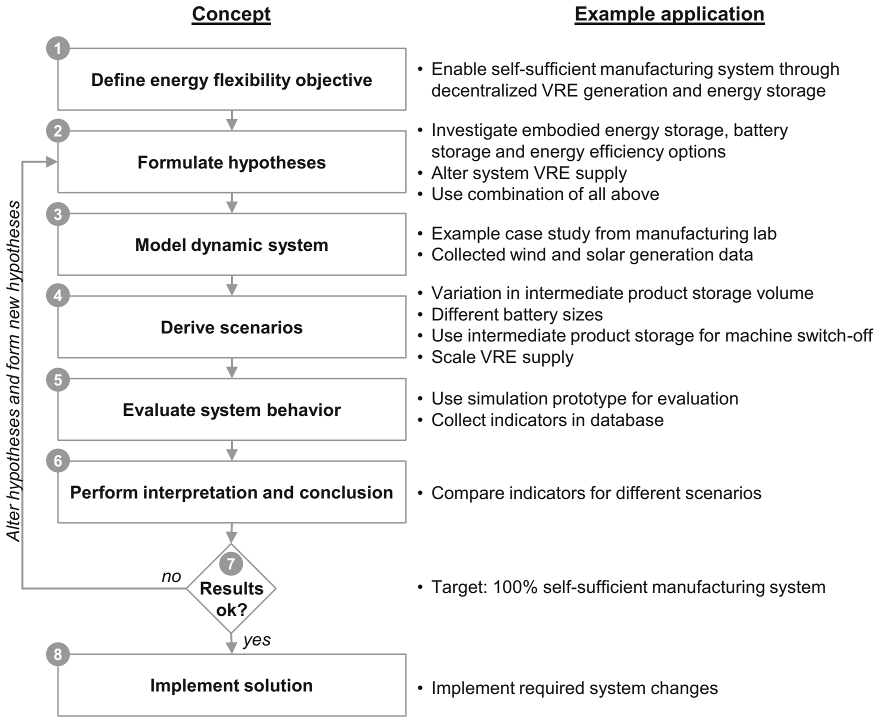
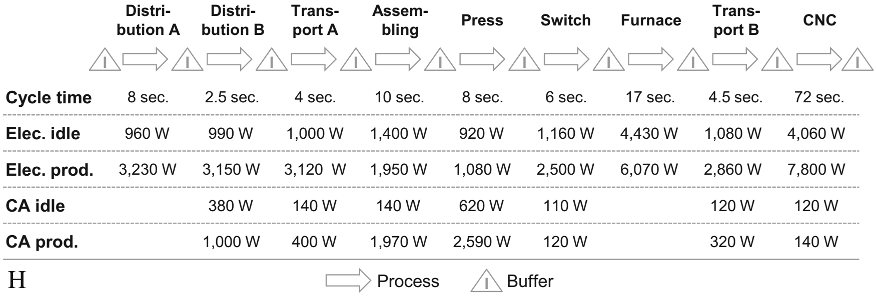


Fig. 2.5 Energy flexibility concept and example application case

2.5.2 *Case Study Manufacturing System and Results*

The considered manufacturing system layout and energy demand parameters are illustrated in Fig. 2.6. The manufacturing process that consists of nine connected steps, cycle time, and state-based energy demand data has been obtained. The process *CNC* (last process) has the longest cycle time of all processes (72 s) and thus establishes the bottleneck of the system. To enable some operational flexibility, the manufacturing system is assumed to have a target production rate of one product every 80 s, thus denoting 90% system output of maximum possible output. A compressor park is attached to the system with three compressors and a seven cubic meters storage tank. Energy supply profile data has been collected from wind and solar generation facilities located in Braunschweig, Germany, from September 3 to 31, 2013, with one-second sample rate and aggregated to one-minute arithmetic average values.

In order to achieve an energy self-sufficient manufacturing system, different hypotheses are formulated (compare to Fig. 2.5) and scenarios derived. In particular, the following experiments are conducted:



	Distribution A	Distribution B	Transport A	Assembling	Press	Switch	Furnace	Transport B	CNC
Cycle time	8 sec.	2.5 sec.	4 sec.	10 sec.	8 sec.	6 sec.	17 sec.	4.5 sec.	72 sec.
Elec. idle	960 W	990 W	1,000 W	1,400 W	920 W	1,160 W	4,430 W	1,080 W	4,060 W
Elec. prod.	3,230 W	3,150 W	3,120 W	1,950 W	1,080 W	2,500 W	6,070 W	2,860 W	7,800 W
CA idle		380 W	140 W	140 W	620 W	110 W		120 W	120 W
CA prod.		1,000 W	400 W	1,970 W	2,590 W	120 W		320 W	140 W

Fig. 2.6 Case study manufacturing system process structure and parameters (scaled by factor 100 from original system)

- **Buffer size** indicating different intermediate product storage capacity is varied from 5 to 700 pieces in every buffer between processes. In order to enable energy flexibility, an energy-related scheduling is required. The scheduling approach described in Beier et al. (2015) is applied, which finds the combination of non-throughput critical processes for which system demand is expected to fit VRE supply best, considering operating constraints such as non-interruptible processing. Both manufacturing processes and compressors are controlled according to energy flexibility targets (for additional background on, e.g. CA tank size variation to support flexible CA generation see also Beier et al. (2015)).
- **Battery size** is varied from 0 to 700 kWh capacity, with charge and discharge time of three hours in every scenario, and a one-piece flow for products (replacement of a product if withdrawn from a process' outgoing buffer, compare also to Beier et al. (2015)).
- **Different VRE supply levels** indicated by the ratio between total VRE supply and total system demand under one-piece flow control over total simulation time are varied. For example, a VRE factor of 1.2 indicates that average VRE supply is 1.2 higher than average total system electricity demand.
- **Process switch-off** indicates that processes switch themselves off if a one-minute idle wait time has passed and sufficient products are in outgoing buffers to have downstream processes prevented from being starved (which is also an energy efficiency control measure). For the case of battery size variation and process switch-off, an intermediate product storage of 200 pieces has been chosen, with switched-on energy flexibility control.

The results for described scenarios can be found in Fig. 2.7. The indicator *self-sufficiency* is used to describe the system's time-dependent energy demand ratio from VRE supply (i.e. a 70% self-sufficiency indicates that 70% of total electricity demand was supplied by VRE, considering temporal dynamics). Constant throughput was achieved for all scenarios.

Looking into different intermediate product storage levels (left graph in Fig. 2.7), self-sufficiency can be increased by up to four percent by deploying additional buffer

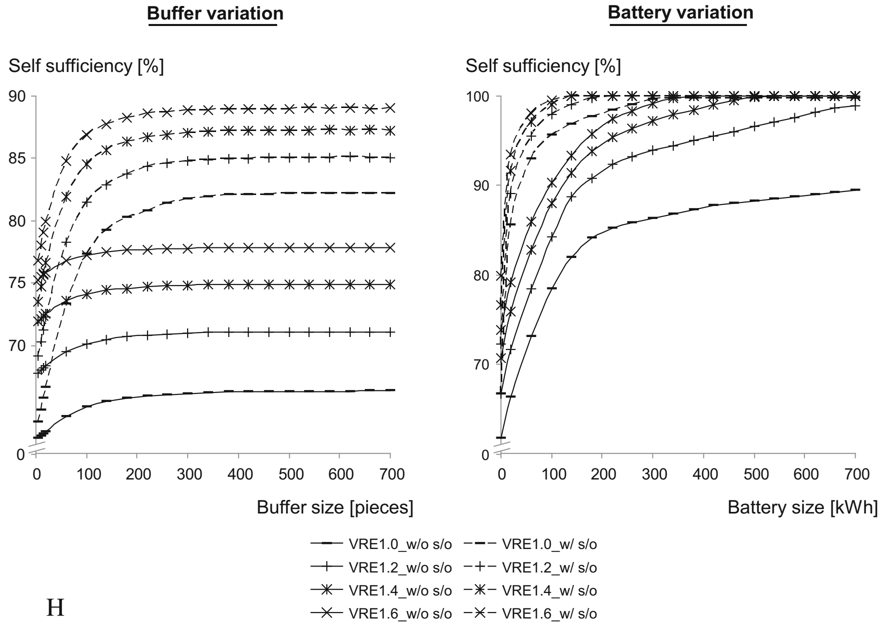


Fig. 2.7 Values for self-sufficiency indicator under different scenarios (w/o s/o: without process switch-off, w/ s/o: with process switch-off)

capacities (for a 1.0 VRE supply case) compared to a case with low buffer capacity. However, increased intermediate product storage is only beneficial up to a certain level (between 200 and 300 pieces), where marginal improvement is getting very low. Further, intermediate product storage is relatively more beneficial for lower VRE supply scenarios than for high VRE scenarios. In summary, the example illustrates that the amount of embodied energy storage is defined by both flexible and thus variable demand of processes and intermediate product storage. Increasing product storage above a certain level is not beneficial, as the variable share of demand limits further increase in embodied energy storage potential. For the case of switching processes off when enough intermediate products are available (dashed lines in left graph), self-sufficiency can be significantly increased if enough intermediate product storage is available. However, even with high VRE supply levels and process switch-off, increasing self-sufficiency beyond 90% is not achievable.

The right graph of Fig. 2.7 illustrates the results for different battery capacity values. First, considering different VRE supply levels without embodied energy storage, battery capacity beyond 700 kWh is required to enable full self-sufficiency for the case of 1.0 and 1.2 VRE supply capacity. The first full self-sufficient case within evaluated scenarios is achieved at approx. 500 kWh battery storage and 1.4 times VRE supply. However, including energy flexibility and thus added embodied energy storage and process switch-off, a fully autarkical scenario can be obtained with a 350 kWh battery for a 1.0 VRE supply ratio, and a 150 kWh battery is sufficient in a 1.6 VRE supply case. Further, significant improvement, also below full autarkical operation, can be achieved with small batteries in combination with energy flexibility.

In summary, the case study illustrates that self-sufficiency and thus energy storage and integration of VRE can be enabled by different methods, including embodied energy storage and battery storage. Embodied energy storage can result in higher utilization of VRE by increasing intermediate product storage. Nonetheless, in order to obtain a fully self-sufficient setup, battery storage is unavoidable. However, required battery storage can be significantly reduced in combination with embodied energy storage. A combination of different storage options, including, for example, embodied energy storage and batteries, appears to be a favorable solution. Depending on system-specific values, substantial economic and environmental benefits might be gained by avoiding additional battery capacity or avoiding VRE overcapacity. However, operational indicators such as system residence time and increased inventory levels might need further detailing before deriving a (cost efficient) strategy.

2.6 Discussion, Conclusion, and Outlook

Integrating VRE into an existing electricity grid and decentralized generation into a local grid can be achieved utilizing different methods to match volatile energy supply and demand. Most common methods include electricity storage through conversion into an energy form/carrier which is easily storable, e.g. potential energy. For example, pumped hydro storage is the most common application for large-scale electricity storage. For the case of decentralized VRE generation, especially wind and solar-based electricity generation, currently available energy storage technologies include, for example, thermal energy storage or electrochemical batteries. However, all technologies which involve additional conversion cycles induce inefficiencies, i.e. the amount of usable energy is reduced. A novel approach is embodied energy storage, for example, in intermediate products or compressed air. The difference is the avoidance of an additional conversion cycle, i.e. rather than storing VRE in a battery through charging and discharging, manufacturing systems can be enabled to process products or generate CA when VRE is available and reduce energy demand when VRE is not available. This method is enabled by decoupling manufacturing processes, i.e. by introducing intermediate product storage or CA storage. Within this context, the term energy flexibility can be used to describe the ability of a manufacturing system to adapt energy demand to volatile supply. However, several challenges exist, among them operational challenges such as keeping throughput constant or avoiding excessive increase of products' system residence time. As such, a manufacturing system control approach is required to enable energy flexibility of manufacturing systems.

A concept for successfully integrating and improving energy flexibility of manufacturing systems is presented. A case study from a manufacturing laboratory is used to test different hypotheses toward full self-sufficiency of the manufacturing line. The results indicate that a combination of embodied energy storage and battery storage is a promising approach to enable electricity autarky of the system.

Summarized, new methods such as embodied energy storage can complement traditional energy storage options for VRE integration. Their clear advantage is the avoidance of (substantial) additional infrastructure (e.g. batteries) and conversion inefficiencies. However, operational challenges and dynamic system behavior require careful evaluation of energy flexibility methods. A combination of available options, e.g. thermal storage, batteries, embodied energy storage, and potentially dispatchable backup generation (e.g. diesel generator) can be used to successfully integrate decentralized VRE generation. Further, grid feed-in and central, large-scale storage can complement decentralized integration efforts. Available measures can support each other and partly be substituted for each other. As such, a preferred/optimal solution for widespread VRE deployment and integration is likely to include several options in combination. Multi-criteria evaluation and combined modeling of methods are required to find this preferred solution, which is a central research lead in the context of VRE deployment to mitigate climate change.

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