WGP
Wissenschaftliche Gesellschaft für Produktionstechnik

WGP-POINT OF VIEW

ENERGY EFFICIENCY, ENERGY FLEXIBILITY AND DECARBONISATION

WGP-POINT OF VIEW »ENERGY EFFICIENCY, ENERGY FLEXIBILITY AND DECARBONISATION« 2025

The WGP (German Academic Association for Production Technology) is an association of leading German professors of production science. It represents the interests of research and teaching in politics, business and the public sphere. The WGP brings together 64 professors from almost 40 universities and Fraunhofer Institutes and represents around 2,000 scientists in the field of production engineering. Its members enjoy a high reputation both in the German scientific community and internationally and are networked worldwide. The members' laboratories are state-of-the-art, enabling WGP professors to conduct cutting-edge research and practice-oriented teaching in their respective fields. The WGP has set itself the goal of highlighting the importance of production and production science for society and for Germany as a business location. It takes a stand on socially relevant topics ranging from Industry 4.0 and energy efficiency to 3D printing.

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1 Management Summary

Industrial value creation is an important driver of prosperity in Germany. At the same time, the production of goods has a significant environmental impact, particularly due to high energy consumption and the greenhouse gas emissions associated with production. Caught between the conflicting priorities of global competitiveness and the requirements of a climate-neutral future, the challenge is to make industrial value creation sustainable and future-proof. The political framework conditions – from the national energy transition to the European Union's net-zero targets – call for far-reaching structural changes in industrial energy supply and use. This requires not only new technologies, but above all new systemic approaches: energy efficiency, energy flexibility, and decarbonization must be conceived and designed together. This presents companies with a wide range of opportunities to increase their competitiveness in conjunction with product and process innovations as well as new service and business models. This is precisely where the WGP's point of view comes in, showing ways in which the transformation of industry can succeed.

What is new?

It is not individual efficiency measures or the mere substitution of fossil fuels that are the real lever, but rather the systemic optimization of entire production systems – from the machine to the process chain to the networked factory in its industrial environment. Another new development is the extension of flexibility considerations to previously neglected areas, in particular heat-based processes. While many previous approaches have focused on load shifting on the electricity side, the flexibilisation of thermal processes – for example, through thermal storage, hybrid generators, or hydrogen integration – offers great, as yet untapped potential.

What are the benefits?

The combined increase in energy efficiency and flexibility at the system level boosts energy productivity, reduces greenhouse gas emissions, and creates economic benefits, for instance through improved grid utilization and the adjustment of energy consumption to the pricing conditions in the energy market. In energy-intensive production processes in particular, differentiated process control can achieve significant savings while maintaining consistent quality and delivery reliability. At the same time, a systemic view of efficiency, flexibility, and decarbonization can create new opportunities for innovation for companies, cross-sector energy flows, and grid-friendly factories. The WGP's research institutions can make an essential contribution to the transfer of knowledge across the industry – especially to small and medium-sized enterprises—through model infrastructures such as the ETA-Factory and learning factories of the WGP initiative.

What does this mean for research, industry, and politics?

The WGP (German Academic Association for Production Technology) advocates for the consistent integration of systemic approaches into funding programs, regulatory frameworks, and industrial practice. Furthermore, efficiency and flexibility are not inherently conflict-free – political instruments must therefore address conflicting goals and evaluate both the impact on individual actors and the overall impact on the energy system. What is needed is an innovation-oriented industrial policy that remains open to technology, utilizes existing research infrastructure, and provides targeted support to small and medium-sized industrial enterprises during the transformation.

How is this paper structured?

An introductory presentation of the relevance of the WGP point of view is followed by the classification and definition of the most important terms. Examples of significant research contributions that have been made within the framework of funded projects and are relevant to the topic under discussion are then being highlighted. In addition, it discusses the research infrastructure that already exists in this area. This paper then concludes with concrete recommendations for policy makers. The focus is on the topics of systemic efficiency strategies, grid-connected factories, flexibility in heating processes, digitalization, standardization, and competence building.

2 Why this WGP-Point of View?

Germany is a leading production location for industrial goods and, at the same time, a relevant supplier for the global industry in the field of machinery and plant engineering. Machinery stands for advanced and robust manufacturing technologies, precision and innovative strength in equal measure. This status was achieved in the past despite comparatively high labour costs at the location and is based not only on innovative strength but also on a high level of qualification and previous productivity increases.
The location is currently facing the challenge of maintaining its competitiveness despite rising energy costs and the necessary decarbonisation. However, this challenge also presents an opportunity to further increase productivity in order to achieve a competitive position through high productivity, as before. Potential exists in the efficient use of energy and materials and in the utilisation of flexibility in energy demand. Exploiting this potential promises cost advantages for industrial production in Germany. At the same time, energy efficiency, energy flexibility and decarbonisation are becoming increasingly important in many export markets for the local mechanical and plant engineering industry. Innovations in energy productivity and material efficiency not only offer cost advantages, but also increasingly sought-after characteristics for export. The expansion of renewable energy producers is an essential component of decarbonisation. At the same time, many renewable energy generation technologies are characterised by low costs compared to fossil fuels. The growing prevalence of photovoltaic systems on the roofs of industrial properties is just one example that underlines the economic potential of renewable solutions. Nevertheless, it is evident that complete decarbonisation of industry cannot be achieved solely by purchasing electricity from renewable sources. On the one hand, renewable electricity sources – despite their clear advantages over fossil fuels – are not completely greenhouse gas-neutral. On the other hand, the availability of renewable energy sources is limited by generation and grid capacities. This becomes even more significant when the demand for process heat, which is still widely supplied by fossil fuels today, is replaced by electrical energy. The scale of this transformation becomes clear when looking at the energy mix for industry and other sectors in Germany (see adjacent chart). Measured in terms of final energy demand in Germany, industry currently accounts for over a quarter. At the same time, fossil fuels such as natural gas and coal are still widely used as energy sources. This must be comprehensively replaced in the coming years. Efficient and thoughtful use of energy sources is therefore an urgent necessity for sustainable industrial production. By increasing energy efficiency and energy flexibility, companies can become more resilient to fluctuating and rising energy prices and at the same time contribute to the decarbonisation of the energy supply.

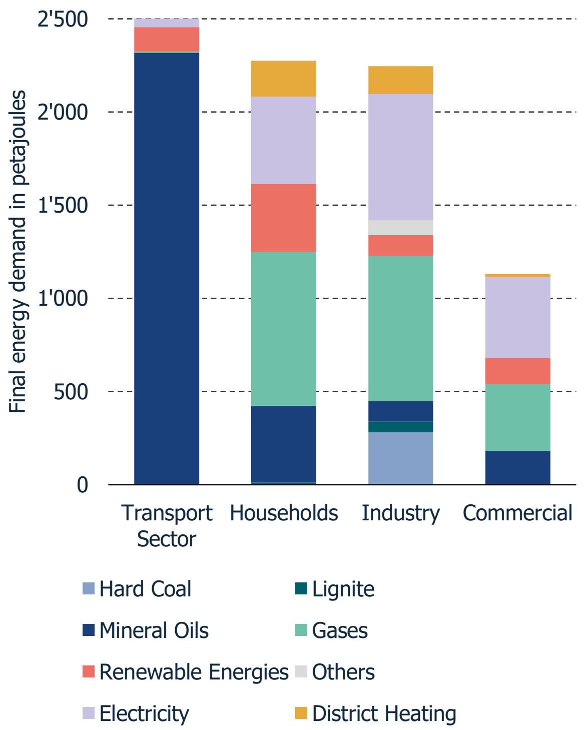

Figure 1: Final energy consumption by sector and energy source in Germany in 2023 (data source: AGEB [1])

The institutes of the German Academic Association for Production Technology (WGP) have been conducting research into energy-related issues in production technology for more than 20 years. The institutes' expertise ranges from the fundamental processes itself, to the necessary plant technology and entire process chains, to systematic analysis at factory level and interaction and integration beyond factory boundaries. The research activities cover established fields, such as the further development of electric drives for production machines, as well as paving the way for new technologies, such as applications of artificial intelligence in energy management. This article provides an insight into the progress made in production engineering research during this period. In addition to research work from a wide range of production technology, examples are presented that show the potential of transferring research results to industry. The examples presented highlight the expertise that has been built up at the institutes and the research infrastructure that has been created as a basis for future innovations. Building on the comprehensive experience, expertise and research infrastructure developed at public institutions, this position paper identifies areas of action that are promising for future innovations.

3 Definitions

Climate Neutrality

The manufacturing of products has various environmental impacts, including those that affect the global climate. In order to characterise their efforts to reduce their climate impact, companies often formulate their goals in the form of neutrality claims that are to be achieved by a specific target date [2]. A distinction must be made between various terms: Climate neutrality refers to a state in which anthropogenic influences on the climate balance each other out, so that global warming no longer progresses [3]. This state is virtually impossible to achieve in practice [3]. At the company level, climate neutrality claims are often achieved by offsetting emissions through the purchase of emission certificates, which may also relate to reductions outside the value chain [4], [5]. Greenhouse gas neutrality restricts the concept of climate neutrality in that it only refers to greenhouse gas emissions and does not take into account other effects such as changes in albedo [3]. Net-zero approaches differ from climate neutrality in that they involve the actual removal of greenhouse gases from the atmosphere [4], [6]. They also generally require a reduction in emissions [6].

Decarbonization

With decarbonization, companies are pursuing the goal of decoupling their business activities from the use of fossil carbon (e.g., in the form of natural gas, oil, etc.) and thus reducing carbon-based greenhouse gas emissions [2], [7]. Companies have various combinations of measures at their disposal to achieve this. Pathways to achieving the defined target state for each company under consideration are derived from the various possible combinations of measures. Many companies now follow the guidelines of the Science Based Target Initiative, which can be used to define scientifically based climate targets in the context of the globally necessary reduction in emissions [8].

Energy efficiency

Energy efficiency refers to the ratio between the benefit achieved – such as mechanical work to tighten a screw or process heat required – and the amount of energy used to achieve it. It is a measure of how sparingly energy is used. The less energy required to achieve the same benefit, the higher the energy efficiency. In production, this means that machines, processes, areas, etc. are more energy-efficient the less energy they require to manufacture the planned products [9]. The term energy productivity is also often used for this performance variable. In this context, the term energy efficiency focuses on the energy productivity of a technology under investigation in relation to the energy productivity of the best available technology of this type or the thermodynamic optimum of this technology [10]. Both definitions are closely linked by the underlying measures to increase efficiency and are therefore used in parallel in research, development, and industry.

Electrification

The term electrification describes the conversion of processes, machines, and systems from fossil fuels (e.g., natural gas, coal, oil) to operation with electrical power. Electrification can be direct (immediate conversion of electricity into the desired form of useful energy) or indirect (indirect conversion of electricity into another final energy source with subsequent conversion into the desired form of useful energy). The aim in each case is to make energy supply as environmentally friendly as possible by using electricity from renewable sources and to contribute to decarbonization. There is great potential in this regard, particularly in the electrification of the process heat supply for production systems, as this is currently based predominantly on fossil fuels such as natural gas [11].

Sector coupling

Sector coupling refers to the interaction of systems from the perspective of sectors. A distinction can be made between the energy sectors of electricity, heating/cooling, fuels and combustibles, and the consumption sectors of industry, commerce, trade, services, transportation and households. The term sector coupling can be used in the context of both the energy sectors and the consumption sectors. Sector coupling is realized by so-called sector coupling technologies, which are capable of converting energy from one form to another or making it available from one consumption sector to another. The most widespread application is the transformation of electricity into heat or energy carriers, such as solids, liquids or gases (cf. electrification). The term "power-to-X" summarizes these technologies, whereby X is replaced by the desired final form of energy. Power-to-gas, power-to-heat and power-to-liquid are prominent examples of sector coupling. The scheme is also known in the context of the consumption sectors, for example as power-to-mobility. Due to the inherent conversion losses, the principle applies to all indirect Power-to-X technologies so that they should primarily be used where direct electrification is not possible. The corresponding industries are also referred to as hard-to-abate sectors [12].

Industrial symbiosis

Industrial symbiosis refers to the deliberate connection of otherwise separate sectors or industrial systems in a collaborative approach to create competitive advantages through the physical exchange of materials, energy, water, and/or by-products. [13]. The concept of industrial symbiosis is closely linked to the concept of sector coupling. Industrial symbiosis can be understood as the coupling of several industrial systems from different or the same industrial sectors. Prominent examples can be found in the joint provision and/or use of heat or energy sources. For example, the waste heat from one company can be used to supply heat to another company. Similarly, waste streams can be used to generate energy. Industrial symbiosis can also be found in non-industrial systems, for example in the context of urban-industrial symbiosis. The use of process waste heat to supply nearby industrial systems via local and district heating pipes has been an established example for decades.

Energy flexibility

Energy flexibility refers to the ability to adjust energy feed-in or withdrawal in response to external signals. Such a signal could be, for example, a change in market price or a request for power adjustment from the grid operator. The aim is to provide a service (e.g. frequency stability) in the energy system [14].

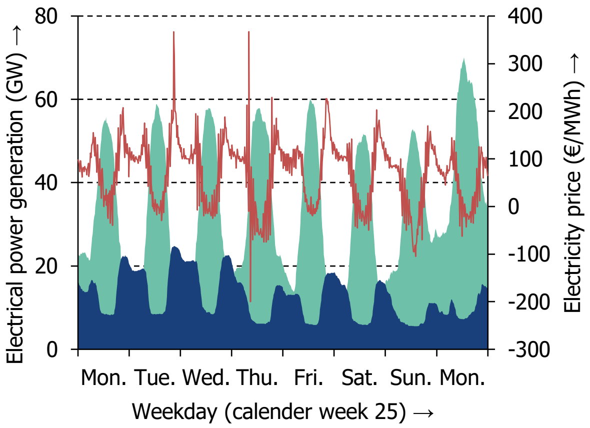

Figure 1: Electrical power generation and day-ahead electricity prices in Germany in calender week 25 of 2025 (Data source: ENTSO-E)

A key aspect of energy flexibility is the concept of demand response. According to the U.S. Department of Energy, this refers to changes in end users' electricity consumption relative to their normal usage patterns in response to time-varying electricity prices or incentives aimed at reducing electricity consumption during periods of high wholesale prices or when system reliability is at risk [15].

Demand response can thus be understood as an operational manifestation of energy flexibility that focuses on the consumption side of the electricity system. Energy flexibility in the broader sense is more comprehensive: it includes not only flexible consumption, but also the adjustment of generation, the use of storage facilities, cross-sector coupling (e.g. electricity-heat) and overarching measures for system optimisation. In concrete terms, flexible behaviour in the electricity system means that energy is either fed into the grid or withdrawn from it, depending on the system situation. The objectives are to provide system services such as ensuring grid stability, congestion management, the provision of balancing energy or improved load management [16].

4 A glimpse into production technology research

With its public institutions, Germany has an established re-search infrastructure that has already made a significant con-tribution in the past to developing the first elements of new innovations for energy efficiency, energy flexibility, and de-carbonization. These institutions have the potential to play a leading role in the future in developing forward-looking solutions and enabling further development and application, particularly in medium-sized industrial companies.

Production technology research addresses a wide range of energy-related issues at various levels and can resort to a broad foundation of existing knowledge. A central component of this research work is the integrated consideration of ener-gy efficiency and energy flexibility strategies, which contrib-ute significantly to the sustainable transformation of industri-al value-added processes.

The focus is on the increasing interactions between the levels of analysis: process, process chain, production system, fac-tory, and surrounding system. It has already been shown that the knowledge gained, particularly in the area of developing methods and tools, is largely transferable across different industrial sectors.

The following section discusses selected examples of the WGP efficiency initiative and highlights the interrelationships between the research areas and methods. Figure 3 classifies the exemplary contributions of the WGP efficiency initiative according to their thematic research focus across the area of consideration.

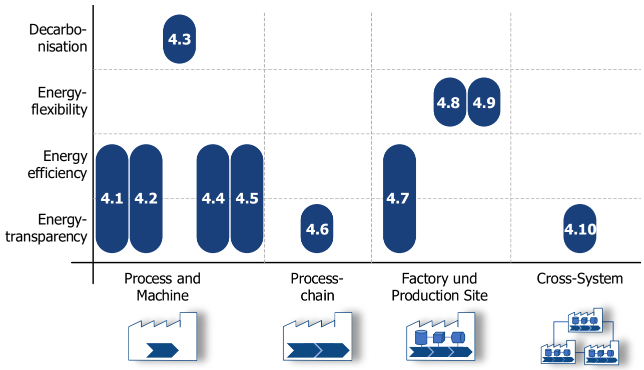

Figure 3: Overview and classification of the examples from the WGP efficiency initiative

4.1 Adjustment of process parameters in the cleaning of metallic components in the LoTuS project

In the field of component cleaning, a fundamental part of numerous process chains in the metalworking industry, significant progress has been made in energy efficiency research in recent years. As part of joint research projects such as ETA-Fabrik (grant number 03ET1145), LoTuS (grant number 03EN2026) and ETA im Bestand (grant number 03EN2048) [17], [18], [19], the cleaning and drying processes were investigated in collaboration with manufacturers and users of component cleaning systems. Practical measures to improve energy efficiency were developed and successfully validated. Based on Sinner's circle of cleaning [20], interactions between the four factors of time, mechanics, temperature and chemistry were used to design an energy-efficient process. With the help of mechanical optimisation of the spray nozzles in aqueous cleaning, the energy-intensive factor of temperature was reduced by lowering the temperature [17]. In addition, digitalisation measures have helped to provide insights into the drying process, which usually has to be adjusted iteratively due to its complexity. This transparency provides the basis for demand-oriented process design. Using artificial intelligence methods and imaging techniques such as thermography [21], solutions have been developed to automatically assess the dryness of components. This is an essential step towards adjusting the process to specific components, avoiding over- or under-drying [18] or even enabling a closed control loop. A proven fuzzy logic approach to control, for example, shows over 60% savings in power consumption in the drying system with the same drying result and the same process duration [22].

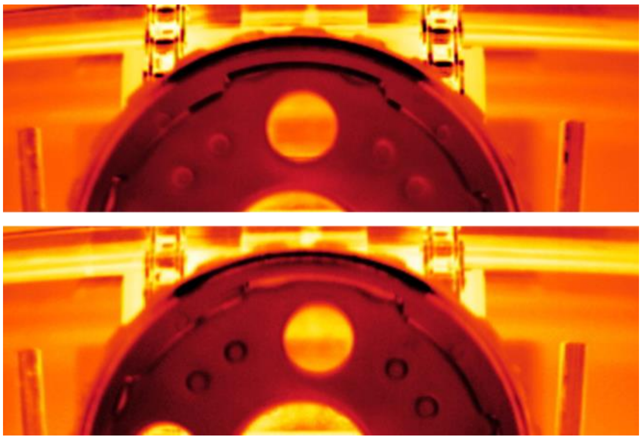

Figure 2: Detection of water residues on components using thermography (Image source: PTW, TU Darmstadt)

In addition, further measures were developed for the technology of continuous and chamber cleaning systems in the LoTuS and ETA im Bestand projects in order to leverage further energy efficiency and energy flexibility potential – for instance, by utilizing internal and external waste heat sources [18], [19], [23]. By utilising waste heat, the total power demand in the case under consideration can be reduced by 20%. The use of alternative drying technologies enables savings of 10–20% of the total power demand of a cleaning system [24].

4.2 Energy analysis and potential of machine tools

Machine tools, such as milling, turning and grinding machines, are used in a wide variety of designs in the manufacture of industrial intermediate and end products. Accordingly, machine tools are very widespread and have long been the subject of extensive research in production engineering. Research into machine tools with regard to energy-related aspects has yielded significant findings in recent years compared to the existing state of the art. Studies conducted by several institutes on various machines show that a large proportion of the energy required by these machines is attributable to machine conditioning – for example, for cooling, hydraulic systems or compressed air supply [25]. Furthermore, production engineering research has investigated measures to increase the energy efficiency of machine tools. For example, it has been shown that lightweight construction approaches in the design of the machine structure can reduce the energy required for acceleration without compromising the necessary functionality [26].

Further measures examined show that machine cooling, which accounts for a significant proportion of the energy demand of machines, can be improved in various ways compared to conventional cooling technologies. In the past, different strategies for controlling cooling units and various compressors in the cooling circuit have been investigated [25]. A practical test conducted as part of the ETA-Transfer research project showed that modern units can reduce the electrical power required for machine cooling by over 50%. A saving of 85% was achieved for the cooling of control cabinets [27]. Studies have also shown efficiency potential for other machine functions, such as the provision of the cooling lubricant required for the process. Previous studies show that simulation-based, demand-driven adjustment of the cooling lubricant supply can reduce the electrical energy consumption of the cooling lubricant pump by 81%, resulting in a total saving of 37% for the machine tool under consideration [28]. Studies on various machine tools show that up to 10% of the electrical energy required by machine tools is accounted for by hydraulic units [9]. The MAXIEM research project investigated how machine hydraulics can be operated more efficiently. To this end, the buffer storage tank, which was already necessary, was enlarged and the system parameters adjusted. In a test setup, the pump's rated power was reduced from 4.1 kW to 2.8 kW and operated less frequently. By using different valves in the hydraulic system in combination with the adjusted storage tank, the power consumption of a hydraulic system was reduced from an average of 826 W to 5 W in standby mode [29].

In addition to efficiency gains, production technology research has also identified potential for flexibility in production facilities such as machine tools. For example, the SynErgie project (grant number: 03SFK3A0-2) demonstrated that the energy costs of an entire grinding machine can be reduced by 6.6% or 1.9% per workpiece if order planning is optimized [30]. In this project, an energy flexibility data model was created for a grinding center. This enables cost-optimized control of production orders adapted to actual prices on the electricity market.

4.3 Direct use of wind power to decarbonize energy-intensive melting processes in the foundry industry in the WindMelt project

The foundry industry causes annual greenhouse gas emissions of approximately 1.9 million tons of CO_2 equivalents in Germany [31]. A significant proportion of energy consumption is accounted for by smelting operations, which make up around 40 to 45 percent of the total energy demand of a typical foundry site. Energy costs account for around 25 percent of the gross value added by foundries [32]. As part of the WindMelt research project (running from July 1, 2021, to December 31, 2021), the direct use of wind power for aluminum liquefaction was investigated with the aim of significantly reducing the industry's ecological footprint while at the same time tapping into new economic potential [33]. The core idea of the approach was to relocate the energy-intensive process step of melting aluminum to renewable energy production sites. By using electrically powered induction melting furnaces in the immediate vicinity of wind turbines, electricity that would otherwise be curtailed as part of feed-in management can be used directly. In 2020, grid bottlenecks resulted in compensation payments of over €760 million, of which around 67.4% was attributable to onshore wind farms [34].

To assess the ecological impact, a simulation-based model was developed that maps the operating conditions of melting furnaces on an hourly basis. In addition to wind power availability, the model also takes into account heating and holding phases as well as transport processes. External life cycle assessment software was used for the ecological evaluation. As a reference, weekly melting quantities of 120 tons of aluminum were simulated using three melting furnaces, each with a connected electrical load of 3 megawatts. To determine the gross energy consumption per ton, an assessment was made between melting cycles as to whether energy-intensive heating with 600 kW over four hours or continuous heat retention with 100 kW was more economically advantageous. The associated logistics are handled by liquid metal containers with adapted capacity and fixed circulation times.

The project results show that the targeted use of wind power can achieve specific melting costs of between 42.20 € and 74.30 € per ton, provided that a reduced Renewable Energy Sources Act surcharge is considered. By way of comparison, when using only grid electricity in decentralized smelting operations, the costs range between 86.20 € and 171.80 € per ton [35], [36]. The approach is also advantageous from an ecological point of view. When using only renewable energy, the greenhouse potential can be reduced by up to 97 percent compared to conventional natural gas-based processes [36]. At the same time, the analysis highlights technical and organizational challenges. These include the limited availability of transport tanks, fluctuating wind power generation, and infrastructural restrictions. The project results also show that transporting the melt by truck to foundries over distances of up to 200 kilometers can be economically viable. Making foundry processes more flexible and specifically expanding the decentralized infrastructure are key levers for further increasing the efficiency of direct use of renewable energy [36].

4.4 Energy efficiency through optimised cooling lubricant supply – Project: E-KISS

In the context of modern machine tools, and especially in machining and forming processes, cooling lubricants are still considered indispensable. They perform key functions such as cooling, lubrication and chip removal, thereby enabling technically and economically successful manufacturing processes. In addition, they have an often underestimated potential for increasing resource and energy efficiency, both within the machine and at the level of the entire cooling lubricant periphery. In the area of resource efficiency, bio-based fluids are increasingly being used in this context. In the context of energy efficiency, there are various approaches: from optimizing the cooling lubricant supply in the process to intelligent control of peripheral systems to switching to alternative strategies such as minimum quantity lubrication (MQL).

Even simple design measures can lead to significant savings in cooling lubricant supply. For example, intelligent configuration of the nozzles and targeted control of the volume flow can significantly improve energy efficiency. The targeted supply of cooling lubricant, tailored to the process, reduces friction and improves heat dissipation.

A case study shows an example of potential energy savings of up to 23.5% through a suitable nozzle configuration while maintaining the same technical performance [37]. An often overlooked but particularly effective approach to increasing energy efficiency can also be found in the area of cooling lubricant peripherals. Treatment and recirculation systems, such as high-pressure pumps, filter systems, and extraction systems, often run continuously in practice, regardless of their actual utilization. Frequency-controlled pumps and regulated extraction systems enable a significant reduction in energy consumption without compromising technical performance by continuing to provide a sufficient supply of cooling lubricants. The Institute of Machine Tools and Production Technology (IWF) at the Technische Universität Braunschweig pursued a systematic approach to realizing such saving potentials with the E-KISS research project. The aim of the project was to develop intelligent control concepts and an adaptive design for cooling lubricant peripherals in order to measurably increase energy efficiency in machine tools. Savings of up to 25% were achieved by the use of a cyber-physical production system for customized control [38], [39].

Another significant efficiency potential lies in reducing the volume flow of cooling lubricant supply. The use of MQL represents a particularly effective approach in this context. Instead of large quantities of circulating cooling lubricant, MQL applies just a few milliliters of lubricant per hour directly to the point of action. There is no need to recirculate the medium. This principle not only leads to a significant reduction in resource consumption, but also eliminates the need for large parts of the conventional cooling lubricant peripherals. In particular, consumers with high energy requirements, such as high-pressure pumps and filtration systems, can be eliminated. In a direct comparison, the conventional cooling lubricant system has 27 times higher energy requirements than MQL [40].

4.5 Plastic injection moulding

Plastic injection molding is one of the most important processes in plastic forming [41]. In 2017, injection molding machines accounted for 21% of the production value of rubber and plastics machinery. The process enables the repeatable production of large-volume components with complex geometries in short cycle times and is used particularly in the medical sector, the toy industry and the automotive industry [42].

Injection molding machines are predominantly powered electrically. Fully electric drives for pumps and dryers offer considerable advantages in terms of energy efficiency compared to hydraulic variants [43].

A key indicator for assessing energy efficiency is the specific energy requirement, measured in kilojoules of energy input per kilogram of product. Depending on the machine used, process parameters, and operational capacity, this varies between three and 30 kilojoules per kilogram of product [41]. According to this definition, mass-specific energy requirements can be achieved by a higher operational capacity. Projects of the IWF to develop suitable energy performance indicators in plastic injection molding (EU FP7, Grant Agreement No. 247831) have led to a more differentiated assessment of the process. In addition to material output rate, product mass and processing time are also taken into account. This means that different material groups, such as PLLA, CA, PLA, PP, and Bio-PE, are also taken into account. The energy requirements of planned processes can be predicted by regression, which is a basic prerequisite for energy-flexible process operations [44].

Operational capacity and thus specific energy requirements depend largely on the weight of the molded parts, the injection time and the cooling time. The scope for optimizing these three variables is already limited by the choice of material, as this determines specific characteristics such as density, melting temperature, and possible flow rates. In the product design phase, energy-optimized production can be achieved by minimizing the product volume and component thickness. Energy optimization in process control is also possible, taking into account the resulting product quality.

Furthermore, the design of the injection molds opens up scope for optimizing energy efficiency. The injection cycle can be shortened by using a cooling system adapted to the product shape [41]. The number of product cavities per injection mold is also proportional to the operational capacity and must therefore be taken into account during the design of the injection molds.

Given shorter product life cycles, growing variety, and the increasing use of recycled materials, the injection molding process must be made more flexible in the future. This applies to both material handling and the integration of renewable energies into process control. At the factory level, making plastic injection molding more flexible in the context of fluctuating power availability should be understood and promoted as the key to sustainable production.

The joint research project DIAZI is currently conducting research at the IWF on predictive digital production systems with a focus on plastic injection molding. The focus here is on the energy requirements of the systems at the interface with flexible production planning strategies. Real-time capable and AI-based surrogate models are currently under development and are to be transferred to industry in order to support relevant stakeholders in production.

4.6 Energy-efficient battery production – Project: InZePro Cluster InMiTro

As part of the InMiTro research project, the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich investigated the relationship between the storage conditions of cathode active materials (CAM) and their electrochemical properties. The focus was on the materials NMC622, NCA, and NMC811, as these are considered industrially relevant, while NCA and NMC811 are known to be moisture-sensitive due to their high nickel content. In this regard, the current industry practice was critically questioned: Since moisture sensitivity is known, CAMs are typically stored in a dry environment with a dew point between -40 and -60 °C, which requires large amounts of energy. The drying rooms account for between 30 and 50% of the total energy consumption of battery production [45], [46].

A special glove box-based powder handling system was developed to carry out the experiments. This enabled storage, processing, and cell production under defined atmospheric conditions. The KAM was stored for varying periods of time (10 minutes to 30 days) in ambient air, controlled drying air (e.g., dew point of -40 °C), and inert gas (argon, < 1 ppm H_2O). After storage, the powders were processed into electrodes under protective gas conditions and assembled into button cells (CR2032 format). This ruled out the possibility of additional moisture ingress during cell production. The electrochemical properties – in particular the specific discharge capacity – were then analyzed during formation and over several charge/discharge cycles.

Figure 3: Experimental coating and drying system for electrodes in an argon atmosphere (Image source: TUM / Andreas Heddergott)

The results show clear differences between the materials. While NMC622 remained largely stable, NMC811 and NCA reacted sensitively to storage in a humid environment. After two weeks of storage in ambient air, NCA showed a reduction in specific discharge capacity of up to 10%, while NMC811 showed a loss of around 5%. Storage in dry conditions (dew point of -40°C), on the other hand, led to no significant deterioration in performance. Further analysis showed that short-term exposure (e.g., less than 5 hours) does not cause any negative effects, even in ambient air. This differentiation made it possible to define material-specific thresholds for storage duration and humidity.

Based on these findings, a three-stage storage concept was developed that reconciles technical requirements with economic and energy aspects. Scenario 1 describes short-term exposures such as sampling or internal transport (< 10 minutes), for which storage in ambient air in a clean room (ISO 7–8) is considered uncritical. Scenario 2 covers typical process times (< 5 hours), for which a very dry environment is also not necessary. Only in scenario 3 – storage over several days or weeks – is an atmosphere with a dew point ≤ -40 °C required to maintain the electrochemical properties. This differentiated concept enables targeted, demand-oriented control of energy use.

The energy-related benefit of these findings lies in the avoidance of oversized drying rooms, which have been in widespread use to date. The differentiation between short-, medium-, and long-term storage allows energy-intensive drying conditions to be used only where they are necessary. The results obtained in the project thus contribute significantly to the development of energy-efficient and quality-assured cell production.

4.7 Waste heat utilisation at factory level

In addition to energy-saving measures at the machine level, considering the interaction between machines and systems offers significant potential.

In most applications, waste heat occurs as a result of the conversion of other energy sources such as electricity or as excess process heat at the end of a production run. This heat is often dissipated into the machine environment or vented outside the factory building into the ambient air, which requires additional energy to operate the cooling systems. At the same time, machines require thermal energy for process control, for example for component cleaning. The PTW at TU Darmstadt demonstrated in the ETA-Factory and ETA-Transfer projects that the use of electricity or natural gas as an energy source for heating cleaning baths can be almost completely replaced by unused waste heat from other processes. In an initial project, an exhaust gas heat exchanger was installed on a hardening furnace at the ETA-Factory research facility at TU Darmstadt. The thermal energy recovered from the hot exhaust gas stream was used to heat the cleaning bath of a component cleaning system, so that the actual heating by electricity could be reduced [17]. In a subsequent project, the industrial suitability of the solution was demonstrated. In collaboration with Bosch Rexroth AG, three heat treatment furnaces at one of the company's sites were retrofitted with appropriate heat exchangers in the exhaust gas stream, and the waste heat was fed into the cleaning baths of several cleaning machines via heat exchangers. The previously installed electric heaters in the cleaning systems were not dismantled, so that the availability of the cleaning systems was maintained independently of the operation of the furnaces. This setup made it possible to replace 95% of the electrical heating of the baths with previously unused waste heat. This results in annual savings of 420,000 kWh of electricity [47]. The approach can also be extended to other heat treatment furnaces.

4.8 Energy flexibility potentials in food and beverage industry

In addition to applications in the metal and plastics processing industries, production technology research has also considered solutions for other sectors. For example, promising approaches to increasing energy efficiency have been developed in the food industry as part of the SynErgie project (grant number: 03SFK3A0-2). In the processing and production of dairy products, a significant portion of operating costs is attributable to energy requirements – in particular for the provision of heat, process cooling and the maintenance of the cold chain [48].

At a dairy site, the operation of the refrigeration systems was examined for energy flexibility potential and a corresponding strategy was designed. The refrigeration systems in the case study have a connected load of 600 kW and an average of 5000 operating hours per year. Through the targeted use of inherent storage capacities – for example, in cheese storage rooms or saltwater basins – it is possible to provide cooling capacity at times when renewable electricity is being generated and electricity prices are lower. In the case studied, this enabled gross energy costs to be reduced by around 10% [49]. In another example from the food and beverage industry within the SynErgie research project, the provision of process cooling required in the brewing process was made more flexible and energy costs were reduced through optimised plant operation. In the process under consideration, approximately 45% of the cooling requirements for production are accounted for by the cooling of storage tanks for beer. Investigations of the process show that these tanks have an inherent storage capacity that allows the cooling line to be shifted by up to 96 hours. This flexibility potential makes it possible to operate the cooling units specifically at times when electricity prices are low or renewable energies are highly available – resulting in cost savings of around 9% [50].

4.9 Energy-flexible plastic injection molding – Project: SynErgie III

As part of the SynErgie III research project, the iwb at the Technical University of Munich has been looking at the implementation of energy flexibility measures at the factory level, among other things. For an exemplary application case of an SME in the field of diverse plastics processing, methods and approaches were developed to control the existing machinery in an energy-flexible manner and to integrate energy consumption as an essential decision-making factor in production planning.

Energy-oriented production planning represents a major economic lever, especially for companies with high energy consumption, as energy costs represent a significant portion of their expenses that needs to be reduced [29]. Nevertheless, companies with lower energy consumption can also benefit from such planning, e.g., by smoothing out their peak loads, thereby reducing power costs [51]. To enable corresponding savings, the first step was to examine the relationship between production orders and the energy consumption of the existing injection molding machines. The company has an extensive digital database for this purpose, which was used for the analysis. The regression-based evaluation confirmed the results of

the aforementioned project in the field of plastic injection molding, namely that the mass throughput and the total energy consumption of an injection molding machine are correlated. Since the mass throughput can be calculated before production starts, it is possible to forecast the machine- and order-specific energy consumption.
Based on these findings, an energy-oriented planning algorithm was developed that can reschedule an existing order sequence in such a way that the load peaks that occur are minimized. A prototype implementation for selected machines and a subsequent comparison with the production plan that maps the fastest order processing have shown that the maximum load peaks can be reduced from approximately 300 kW to 200 kW. However, this smoothing comes at the expense of production time, which was approximately 1.5 days longer in the case of lower load peaks than in the reference case. Nevertheless, extending energy-oriented planning to the entire machine park can contribute to a reduction in energy costs and thus to an increase in the company's competitiveness [9].

4.10 Cross-sector potential using the example of factories and vehicle fleets

Factory buildings and industrial parks often consist of a large number of units that operate separately in organisational or technical terms, each with its own objectives. At the same time, they are connected to each other via central hybrid energy networks, for example for electricity or heat. This structural separation combined with simultaneous energy networking often leads to inefficiencies in the operation and control of energy systems. The KI4ETA project (grant number: 03EN2053 A–L) therefore investigated approaches for integrating the factory system with external energy systems such as the electricity grid and electromobility. One focus was the integration of electric vehicles into the electrical supply system of the ETA research factory at TU Darmstadt. As part of this sector coupling of industry, the electricity grid and transport, a bidirectional charging infrastructure was set up that enables electric vehicles to be integrated into the factory network as mobile storage devices. In addition to the existing unidirectional AC charging station (type 2, 22 kW), a DC-based charging facility was installed, which is supplied via the DC link of the existing hybrid energy storage system.

Figure 6: Test vehicle and charging station next to the ETA research factory (Image source: PTW, TU Darmstadt)

Bidirectional charging allows excess energy from the factory system to be temporarily stored in the vehicle and fed back into the grid when needed. This improves energy flow, increases flexibility and supports more efficient use of renewable energies. The project demonstrated the technical benefits and feasibility of the vehicle-to-grid concept. The overall concept developed, consisting of bidirectional charging infrastructure and a hybrid energy storage system, was published in a scientific publication [52].
At the interface between industry, commerce, mobility and households, the IWF and elenia Institute for High Voltage Technology and Energy Systems at Technische Universität Braunschweig have dedicated themselves to the intelligent aggregation of consumption-side energy flexibility potentials as part of the *flexess* research project (grant number: 03EI4005 - 03EI4005G). Using flexibility schedules, the joint project used simulations to forecast flexibility potential for the current day (intra-day) and the following day (day ahead) and synchronised this with grid congestion forecasts via a central authority. Individual grid-friendly schedules were then fed back to the supplying parties. On the industrial side, the drying room at BatteryLab Factory Braunschweig and the coating, drying and calendering processes were used to demonstrate how flexibility schedules could be generated, communicated and implemented. Beyond the industrial sector, the IWF has also been involved in the analysis, simulation and evaluation of flexibility strategies for refrigeration systems in the commercial sector. The project results show that thinking across sector boundaries is also necessary for successful consumer-side flexibilisation and thus the realisation of higher shares of fluctuating, renewable energies in the energy system [53].

5 Learning and research factories in energy-related production research

Over the past decade, institutes in Germany have developed a strong research infrastructure to complement technical expertise in energy-related aspects of production technology. A key element of this infrastructure is the establishment of learning and research factories, which replicate the equipment and systems of entire production facilities. These factories provide realistic experimental environments where new approaches can be tested, systemic interdependencies explored, and holistic relationships simulated and experimentally validated. Learning factories expand these structures with didactic concepts alongside real equipment and processes, thus creating a realistic and problem-oriented environment for knowledge transfer [54].

Examples of this type of research infrastructure include the *ETA-Factory* in Darmstadt, the *learning factory at the Technical University of Braunschweig* and *the Green Factory in Augsburg*.

Figure 7: ETA-Factory in Darmstadt
(Image source: PTW, TU Darmstadt / Eibe Sönnecken)

The ETA-Factory (Energy Technologies and Applications in Production) has two production lines for research and teaching that involve typical processes in the metalworking industry. These include machining, component cleaning, heat treatment, robot handling and assembly. For teaching purposes, one of the lines can be used to simulate common types of energy waste and to train students in identifying and evaluating them. In addition, a wide range of energy efficiency and energy flexibility measures have been implemented in a tangible way. In addition to the equipment, the ETA-Factory has a complex supply system that allows the heating and cooling supply of a metalworking production facility and systems in the process industry to be mapped and experimentally investigated. A systemic approach is pursued, which aims to use energy efficiently within the factory or holistically and, for example, to use waste heat from a machine for other processes at a later time. In addition, measures are being implemented to adapt the factory to a more volatile energy supply and fluctuating energy markets. The production line is already regularly operated by a team of students and research assistants, with daily energy market data being taken into account in production planning.

Figure 8: Production lines in the ETA-Factory
(Image source: PTW / Eibe Sönnecken)

The learning factory at the Technische Universität Braunschweig supports companies from all industry branches, with a focus on manufacturing companies, and addresses the key areas of energy and resource efficiency, digitalization and urban production. Following extensive modernization, the newly created learning factory for "circular battery cell production" will feature small-scale, modular learning stations, each representing individual process steps in battery cell production and designed to be flexibly combined into process chains. These will be supplemented by peripheral systems and systems for representing technical building equipment (TBE). As shown in Figure 9, this also includes the integration of renewable energy generation using wind power and photovoltaic systems, which, in combination with a battery storage system, will enable teaching and research activities on the topic of optimized self-consumption of electricity through energy flexibility.

Figure 9: Infrastructure for self-sufficient electricity supply using wind turbines and photovoltaic systems for the learning factory at the IWF of the Technische Universität Braunschweig (Image source: IWF TU Braunschweig)

The physical learning stations and facilities are embedded in a virtual environment (cyber-physical system), which allows individual stations to be emulated by virtual learning stations. This means that the teaching and learning environment can be quickly adapted to different issues and future trends. The integration of forward and backward process chains into a circular battery cell production process enables the teaching of technical and methodological skills in the following areas:

- Energy- and resource-efficient process and manufacturing technologies for the production and recycling of traction batteries as the basis for closed material cycles
- Implementation of Industry 4.0 technologies for the intelligent design of processes and material and substance cycles
- Circular product design and material selection as well as their characterization as a basis for closed cycles
- Quantitative sustainability assessment and ensuing life cycle engineering

The learning factory "Circular Battery Cell Production" expands the equipment available at the Technische Universität Braunschweig and provides infrastructure specifically for the training and further education of young scientists. It is embedded into a comprehensive research network as shown in Figure 10, which consists of other battery cell production and battery recycling facilities at Braunschweig firming under the name BatteryLabFactories and More (BLB+) at the research airport in Braunschweig as well as the hydrogen campus in Salzgitter, which is operated jointly with the Fraunhofer Society and other industrial stakeholders.

Figure 10: Research network and infrastructure at TU Braunschweig related to the learning factory (Image sources: TU Braunschweig / Braunschweig Labfactories for Batteries and more / Fraunhofer ZESS / HDR GmbH)

A deep understanding of closed material cycles is a central pillar for training and promoting the next generation of energy storage specialists and a prerequisite for the intelligent and efficient production of sustainable storage technologies in Germany as a business location. The learning factory is based on the principle of research-based learning. The training measures are geared toward the latest research findings and the needs of industry. New technologies and methods for circular battery cell production can be integrated into the test environment at an early stage and made available for the training of skilled workers and, in particular, young scientists.

Another example is the "Future Factory" of the *iwb* (see Figure 11) at the Technical University of Munich, which unlocks synergies from interdisciplinary collaboration across all levels of the value chain. The production environment is based on a modular infrastructure that can be flexibly assembled from different battery production steps.

Figure 11: iwb production hall (Image source: TUM / Andreas Heddergott)

It provides a real-world demonstration and research environment in which new technologies can be tested and further developed under practical conditions. The environment is accessible both physically and digitally, enabling hybrid experiments and analyses. This allows forward-looking trends to be identified at an early stage, integrated, and evaluated on a scientific basis.

Since February 2020, research operations have been underway at the Green Factory, Fraunhofer IGCV's second location in Augsburg's Innovation Park (see Figure 12). There, manufacturing companies are supported in reducing their energy and resource consumption. This is reflected in both the innovative building concept and the ongoing research and demonstration activities. The Green Factory's energy concept incorporates photovoltaics, a heat pump, a district heating connection, a refrigeration machine utilising waste heat and concrete core activation. Digital energy monitoring provides real-time data on energy consumption and the sustainability of the production facilities, which is displayed on a monitor in the entrance area. Efficiency measures, such as reducing room air conditioning at night, are evaluated and implemented as part of continuous energy management. The building's modular design allows its technical infrastructure to be flexibly adapted to different research and application requirements. Practical research focuses on additive manufacturing, automation, energy storage, sustainable factory planning and operation, and digitalisation and artificial intelligence. Production processes are designed to be energy- and resource-efficient by considering and evaluating material and energy flows. The Green Factory is a demonstration platform for sustainable production systems. It supports the transfer of technology to small and medium-sized enterprises and promotes the practical training of future skilled workers.

Abbildung 12: Green Factory of the Fraunhofer IGCV in Augsburg (Image source: Fraunhofer IGCV / Johannes Huismann)

As facilities at the respective universities, the factories are integrated into the training of young engineers and help to convey current research topics in a direct and practical manner. In addition to imparting knowledge in academic education, workshops are regularly held for personnel from industry.

Figure 13: Students operating assembly workstations on the production line for energy-related training and upskilling at the ETA-Factory (Image source: PTW, TU Darmstadt)

Networks of companies have sprung up around these locations, facilitating close cooperation between industry and university research. This collaboration allows research findings to be transferred into industrial practice while also feeding back requirements and future research questions to the institutes.
The examples presented are representative of structures and centers of excellence that exist at research institutions throughout Germany and are working towards an energy-efficient, energy-flexible, and decarbonized future industry. Further examples can be found in Chemnitz and Stuttgart, among other places.

6 Recommendations for action

In the fields of energy efficiency, energy flexibility and decarbonization, WGP has a full range of expertise and experience in production technology applications. This is complemented by a well-developed research infrastructure, which serves as a basis for future research questions concerning the energy system of industrial applications. However, the scope for possible innovations is far from exhausted and offers potential for new competitiveness. The existing research landscape provides a good starting point for this, which should be taken advantage of. The fields of action listed below represent some of these potentials, which offer opportunities for the future development of Germany as an industrial location.

6.1 Decarbonisation and transfer of measures

In order to achieve the goal of net-zero production in the manufacturing industry as a contribution to the overarching politically anchored goal of climate neutrality by 2045, a holistic view of the implementation options is required, from the formulation of goals to the implementation of individual measures. While many companies have already formulated long-term climate targets, the path to achieving them in the form of a concrete roadmap of technical measures often remains unclear. In many cases, targets are pursued through mere compensation of emissions rather than actual reduction. Further research is therefore needed to identify different transformation paths for achieving a company's long-term climate targets, evaluate them quantitatively and thus contribute to objective decision-making. Many of the technologies required for this are already available today. Nevertheless, in practice there is a gap between long-term climate targets and the implementation of concrete, coordinated measures in a complex system. This is where research into overcoming transformation barriers comes in. It is necessary to investigate how, on the one hand, technical solutions can be transferred from research to industrial application and, on the other hand, how the skills required to understand complex industrial energy systems can be taught. Important instruments for this are model and learning factories, which, as best-practice factories on an industrial scale, demonstrate the state of net-zero production in a realistic manner and impart skills to companies in practical training courses and to students in additional courses.

6.2 AI-assisted systems as enablers of energy efficiency and energy flexibility

The use of AI-based assistance systems in industry enables targeted energy load management and empowers companies to implement various measures to increase energy flexibility. In this way, energy losses can be effectively reduced through intelligent process optimisation. In addition, energy consumption forecasts enable early detection of peak loads and targeted countermeasures. At the same time, predictive maintenance helps to identify and remedy inefficient and energy-intensive machine conditions in good time. Intensive research is necessary to ensure that such systems can be used effectively on a broad scale, particularly with regard to resilient and cost-effective implementation in small and medium-sized enterprises. In addition, it is important to transfer already developed demonstrators to higher technology readiness levels (TRL) and to ensure the long-term maintenance of such digital AI-assisted systems.

6.3 Systemic consideration of energy efficiency

Energy efficiency must be consistently understood as a systemic optimization goal and should be supported by politics accordingly. Isolated measures at the machine level fail if potential at higher levels, such as intelligent process chain control, holistic energy management in the factory or cross-sector networking, remains untapped. Political support instruments should therefore focus more on integrative approaches that aim at increasing efficiency on several levels simultaneously: from components to production processes to factory structures and their energy-related environment. Real-world laboratories and learning factories can serve as catalysts in this regard, making complex system relationships researchable and applicable.

6.4 Systemic consideration of energy flexibility and dealing with conflicting goals

Energy flexibility, like energy efficiency, must be considered systematically across all levels of industrial value creation. Flexibility potential arises not only from technical adjustments at the machine level, but above all from intelligent process planning, organizational adaptation of operational procedures, and the coupling of production systems with energy storage facilities and higher-level energy management systems. This systemic perspective opens up new scope for action, but also brings with it conflicting goals: In certain cases, measures to increase flexibility can conflict with the energy efficiency of individual processes, for example when deliberately inefficient operating modes have to be chosen in favor of grid-friendly flexibility. Political framework conditions and support mechanisms should recognize this conflict of objectives and focus not only on maximum efficiency of individual subsystems, but also on resilience and system services. The framework conditions should therefore be designed in such a way that they explicitly take into account the trade-off between efficiency and flexibility—for example, through technology-neutral evaluation criteria or by giving equal consideration to system-friendly flexibility alongside efficiency indicators.

6.5 Consideration of energy flexibility in the context of heat-based production processes

Until now, industrial energy flexibility has primarily been considered in the context of electrical consumers. Heat-based processes—which are often more difficult to render flexible but are particularly relevant from an economic and ecological perspective—have largely been ignored. However, particularly in relation to energy-intensive and scalable processes such as drying and conditioning in battery cell production, there is significant potential for flexibility that can be leveraged, for example, through the use of thermal storage, the switch to hybrid heat generators, or the targeted use of alternative energy sources. Over many years, excellent research infrastructures have been established at the WGP institutes, enabling such concepts to be investigated under realistic conditions and put into practice in collaboration with partners from industry, especially small and medium-sized enterprises. This existing expertise and the established transfer structures need to be further developed in a targeted manner. Stronger political support for demonstration projects in the field of heat-based energy flexibility – even beyond large industrial flagship projects – is crucial in order to effectively integrate this hitherto underrepresented area into the transformation of the energy system.

6.6 Automated energy-aware production control

Initial studies indicate that integrating energy indicators into production planning can yield significant cost advantages over traditional planning methods, such as those based on manufacturing and throughput times. This link opens up new potential for energy-aware production control, which offers both economic and ecological advantages. At the same time, automated systems address the challenge for manufacturing companies of finding qualified personnel and scaling expertise. Innovations that contribute to a higher degree of automation in production control thus represent a significant step towards a sustainable industrial location.

Increasing automation requires greater networking of production machines and the consistent integration of energy consumption data into existing IT systems. Energy-aware production planning can then contribute significantly to reducing energy costs.

This progress can be fostered through political action by establishing appropriate framework conditions. Abolishing the usage-hour rule could help to remove false incentives for the introduction of demand response measures. At the same time, this would create economic incentives to take energy flexibility potential into account in planning and to exploit it through automated order management.

6.7 Standardization, data interfaces for energy flexibility

Further research is needed in the areas of standardization, interoperability, and open system architectures to successfully implement cross-sector flexibility solutions. In particular, uniform interfaces need to be developed to connect facilities and IT systems securely, easily, and efficiently across companies and sectors. Open, interoperable data exchange must meet both technical and regulatory requirements and comply with high standards of data protection and IT security. Future developments should be more closely aligned with European guidelines such as the Network Code on Demand Response in order to ensure long-term connectivity. This requires decentralized, open-source-based flexibility management platforms with a high degree of maturity that enable modularity and avoid lock-in effects. In addition, there has been considerable progress in recent years by private providers of energy management systems, which are increasingly integrating flexible consumers such as heat pumps, battery storage, electric cars, and smart home components. Another focus of future research should be the transfer and linking of solutions developed in the building sector to industry in order to achieve cross-sector flexibility management.

6.8 Driving energy productivity

The examples described in this position paper show that the current state of the art offers considerable potential for increasing energy productivity, i.e., economic output per unit of energy used. Progress has been demonstrated for several widely used manufacturing technologies, such as machining, injection molding, and component cleaning. The aim here is to build on the expertise that has been developed and to achieve further efficiency gains. In particular, a holistic view of energy, material, and operating resource flows as well as new, efficient cross-sectional technologies, promise a leap in productivity. The same applies to other fields of technology, such as heat treatment and forming and shaping. In particular, further innovations in the provision of process heat and the use of waste heat within processes and beyond process boundaries are of great importance for decarbonization.

6.9 Promoting skills, acceptance and user-friendliness for the integration of energy flexibility into business processes

Integrating energy flexibility measures into operational processes is complex and presents a number of challenges. Initial approaches are already in place, for example for the technical and economic assessment of flexibility potential, system enablement and practical implementation. Despite existing pilot projects and technical tools, many companies are still somewhat reluctant to embrace such changes. In order to successfully anchor energy flexibility in everyday operations, not only functioning technologies are required, but also clear political framework conditions and regulations. Further development of grid fee regulation to strengthen demand flexibility is an essential starting point here. This would strengthen economic incentives and motivate companies to adapt their operational processes.

On the corporate side, this requires the promotion of skills, acceptance and user-friendly processes – for example, through practice-oriented training programmes, transparent communication of scientific findings and economic benefits, and employee-friendly implementation. The complementary promotion of basic research together with transfer efforts is an essential lever in this regard.

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