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# Exploring the Energy Flexibility Potential in Battery Cell and Electric Vehicle Manufacturing in Europe

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**Abstract**

Battery cell and electric vehicle (EV) manufacturing have emerged as key pillars in Europe's industrial landscape, potentially playing a crucial role in the region's energy transition and economic development. The advanced technological nature of these industries provides untapped potential for energy flexibility. This paper explores the energy flexibility capabilities within battery cell and EV manufacturing. It demonstrates how these industries can adapt their energy consumption by identifying and quantifying the potential for demand-side management within crucial manufacturing processes. Findings indicate that battery cell production offers high flexibility potential due to the intermittent energy demand of critical processes like electrode drying and formation cycles. Similarly, the automotive assembly line for EVs presents opportunities to modulate electricity consumption without compromising productivity. Scaling these energy flexibility potentials in line with the projected growth of battery and EV manufacturers in Europe, it becomes evident that these sectors can contribute significantly to the electricity grid's stability. This paper underscores the role of sector-specific flexibility strategies as a pillar of Europe's energy transition.

**Keywords**

Energy Flexibility; Battery Cell Manufacturing; Electric Vehicle Manufacturing; Demand-Side Management; European Union

## 1. Introduction

Europe's commitment to achieving carbon neutrality by 2050 has accelerated the adoption of renewable energy sources, reshaping the energy landscape [1]. This transition is characterized by a shift from conventional, centralized power generation to a decentralized grid with a growing share of wind, solar, and other renewable energy sources [2]. The variable nature of renewable energy poses challenges for industrial manufacturers, whose processes often demand a stable and continuous power supply. In particular, grid operators in high-renewable-penetration regions face rising costs and complexities managing peak loads, as evidenced by Germany's re-dispatch costs in 2023 [3]. Consequently, the European energy system requires advanced demand-side management (DSM) strategies to ensure grid stability, reliability, and efficient energy use during high and low renewable energy availability [4].

Battery cell and electric vehicle (EV) manufacturers can help alleviate peak loads by temporarily shifting or modulating their energy consumption, thus offering a practical solution to grid instability. Driven by technological advancements and strong policy support, these industries are projected to expand across the continent, with Europe aspiring to lead in the global market for sustainable mobility and energy storage solutions [5,6]. Battery cell manufacturing is crucial for supplying both EVs and grid storage solutions,

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enabling the integration of renewable energy sources. Meanwhile, the EV manufacturing sector is central to Europe's vision of a carbon-neutral transportation systems. Its highly modular and automated production processes offer substantial potential for flexible energy consumption. By examining the energy flexibility potential within battery and EV manufacturing, this paper assesses how these sectors can dynamically adjust their energy usage to align with renewable energy supply patterns. Through demand-side management techniques such as load shifting (e.g., by energy storage management) and real-time responsiveness, these industries not only enhance operational efficiency but also contribute to the resilience of the European energy grid. Scaling these flexibility potentials across Europe's growing industries could provide a crucial lever for balancing supply and demand, thus fostering a more sustainable and resilient European energy system.

To address this topic, this paper adopts a structured methodological approach that first establishes a foundational understanding of energy flexibility in industrial processes and then applies a focused use case analysis to quantify potential load-shifting opportunities:

- Section 2 clarifies the concept of energy flexibility, establishing a shared understanding of this term and reviewing the fundamentals.
- Section 3 introduces our research methodology, focusing on two use cases, battery cell manufacturing and EV manufacturing, to identify and quantify energy flexibility measures.
- Section 4 discusses the scenario-based extrapolation of identified flexibility potentials to the European scale, linking these scenarios to existing forecasts.
- Finally, Section 5 summarizes key findings, highlights limitations, and outlines avenues for future research.

## 2. Industrial energy flexibility

Energy flexibility refers to the capacity of industrial processes to adjust their power demand by increasing, decreasing, or shifting consumption in response to energy availability or market signals [7]. This concept is especially relevant for industries with high or variable energy use. It enables them to reduce costs and support grid stability by aligning their energy consumption with variable renewable energy generation [8]. Energy flexible behavior is achieved through energy flexibility measures (EFMs), deliberate actions taken within industrial processes to modulate energy consumption at the grid connection point. EFMs provide industries with an efficient mechanism for responding to energy supply variations, which is increasingly vital as grids experience higher levels of renewable energy integration [7].

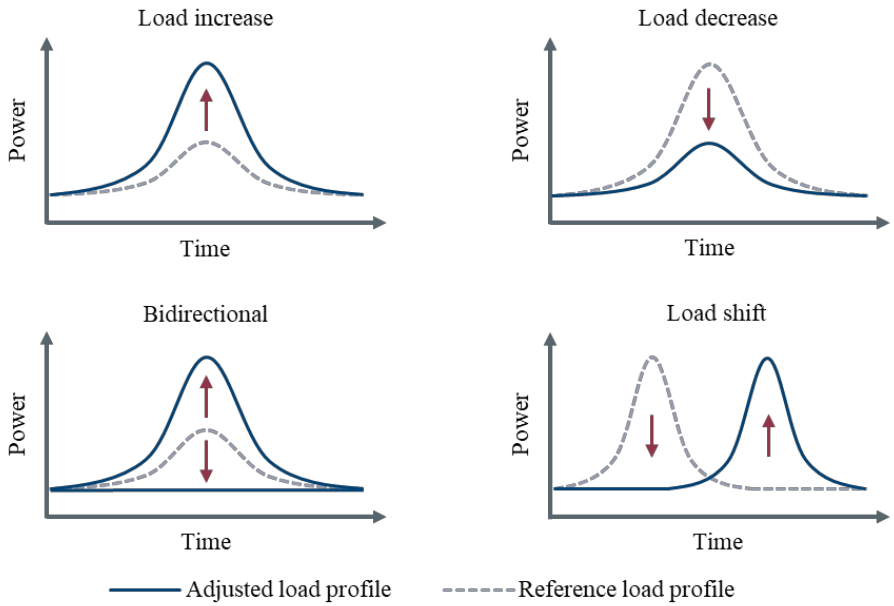


Figure 1: Different flexibility types of energy flexibility measures [9].

The different types of EFMs are characterized by their adjustment to energy consumption, as depicted in Figure 1. Load increase involves a deliberate rise in energy consumption during specific periods, often to absorb surplus renewable energy. Load decrease reflects a controlled reduction in energy usage, e.g., to ease grid stress during peak demand times. A bidirectional adjustment demonstrates flexibility in increasing and decreasing energy consumption, allowing for dynamic responses to market conditions or energy supply fluctuations. Finally, load shifting redistributes energy demand by reducing usage in one period and increasing it in another, aligning consumption with renewable energy availability or lower energy costs. These adjustments highlight practical approaches to optimizing industrial energy use while supporting grid stability. The demand-side energy flexibility in the industry offers numerous benefits, including enhanced grid stability by matching demand with intermittent renewable energy supply, minimizing the need for curtailment, and potentially reducing grid charges [10].

Realizing these benefits faces several barriers, such as technical limitations, regulatory challenges, and uncertain compensation. Despite these obstacles, recent efforts, such as the German research project "SynErgie," have demonstrated significant progress in enabling energy flexibility [8]. SynErgie, funded by the German Federal Ministry of Education and Research (BMBF), has pioneered methods to synchronize industrial energy demand with renewable energy fluctuations. By developing standardized models for identifying and implementing EFMs, this project has laid a foundation for automating flexibility in industrial processes and integrating flexibility measures into energy management strategies [4,9].

Scientific works in literature have contributed decision models and optimization techniques to maximize the economic benefits of energy flexibility for industrial users [11–13]. Stochastic programming models have been developed to optimize energy bidding, particularly on the Day-Ahead Market (DAM), which allows companies to balance their energy procurement costs with the revenues from reserve markets [12]. Approaches include mixed-integer linear programming, which enables large industrial consumers to optimize their energy portfolios, drawing from sources such as on-site generation, flexible loads, and storage systems [11,13]. Furthermore, cost-optimization models simulate the activation of EFMs, adjusting the load profile of energy consumers to align with market conditions, thus enabling companies to leverage demand-side flexibility for cost savings across various market combinations [11,14]. Technical advances also support integrating EFMs at multiple production levels, enhancing their scalability and effectiveness. For instance, approaches for embedding energy flexibility into production planning and control (PPC) systems have been developed to align traditional PPC frameworks with flexibility requirements. Methodologies have even been proposed to apply EFMs down to the machine level, such as in compressed air systems, enabling real-time responsiveness and bridging the gap between shop floor operations and high-level energy management strategies [15,16]. Such efforts demonstrate the potential of EFMs to create a standardized, market-compatible basis for assessing and trading energy flexibility across various industries.

## 3. Energy flexibility analysis

This study employs a use-case-based approach to assess energy flexibility in two manufacturing domains: battery cell production and electric vehicle assembly. It focuses on flexibility measures and energy consumption patterns and combines a literature review with process-level data from existing manufacturing plants to identify key energy-intensive steps. These are then quantified regarding the theoretical flexibility potentials based on the share of total process energy consumption that can be modulated (e.g., shifted to off-peak times or temporarily reduced) without hindering product quality. Given this analysis's general and exploratory nature, a constant load profile for each process stage is assumed to simplify comparisons across different facilities and minimize variations stemming from specific production scheduling. To ensure transparency in these estimates, reference values (e.g., kWh per unit) from peer-reviewed studies and plant data are used, and they are applied to each stage where detailed figures are available. The subsequent subsections detail these energy-intensive processes step by step.

### 3.1 Energy flexibility in battery cell manufacturing

This section considers a large-scale battery cell manufacturing facility with an annual output of several gigawatt-hours of battery capacity. The plant operates at high capacity, with 250 production days per year under a three-shift model, ensuring continuous production for 24 hours daily. In battery cell manufacturing, the primary cell designs include pouch cells, cylindrical cells, and prismatic cells. However, the differences in production processes for these cell types will not be further elaborated in this analysis, as the flexibility potential is primarily independent of the type of cell being manufactured.

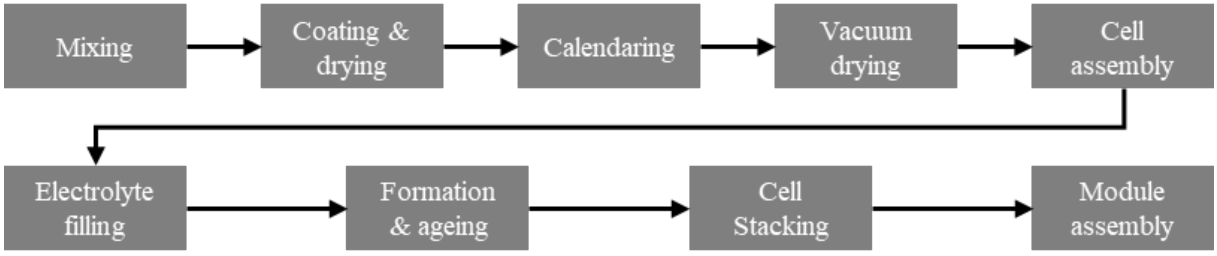


Figure 2: General process steps of battery cell manufacturing [17].

The process of battery cell manufacturing is depicted in Figure 2 and can be described as follows:

- Mixing: Active ingredients, binders, and solvents are combined to form a homogeneous slurry.
- Coating and drying: The slurry is applied to a pantograph, requiring precise temperature and pressure control for uniform coating. Then, the solvent in the slurry is evaporated using large drying equipment.
- Calendaring: The coated electrode is compressed to the desired thickness and density using high-pressure rollers and then cut to size for assembly.
- Vacuum drying: After cutting, the electrodes undergo vacuum drying to remove residual moisture, ensuring quality.
- Cell assembly: Electrodes and separators are assembled into their final form, and the cells are placed in protective casings.
- Electrolyte filling: The cells are filled with electrolyte.
- Formation and ageing: Cells undergo charge and discharge cycles to stabilize the solid electrolyte interphase.
- Cell Stacking: Cells are stacked in layers to form the battery pack, ensuring optimal arrangement and energy density.
- Module assembly: The battery packs are assembled into their final form as modules.

One of the most flexible steps in the process is mixing, as the slurry can be stored for up to two hours after mixing before phase deagglomeration begins [17]. This storage capability provides notable flexibility potential. If the mixing equipment's capacity allows, shifting this process can yield flexibility equivalent to nearly one percent of the total energy demand of the battery cell manufacturing process. Drying and coating are other manufacturing steps with significant flexibility potential and are among the most energy-intensive steps. As discussed in [18], drying processes can be more flexible using suitable heating systems, such as infrared or hybrid heating. Substantial energy flexibility can be achieved by introducing bivalent heating technologies that allow switching between electrical and non-electrical energy sources. Thus, over 30% of the battery cell manufacturing process's total energy demand can be utilized flexibly. The formation step in battery cell manufacturing presents significant energy flexibility potential due to its prolonged charging and discharging cycles. The process typically lasts 24 to 25 hours, with multiple cycles involving varying C-rates, which quantify the rate at which a battery is charged or discharged relative to its capacity (1C = full charge or discharge in one hour). During the first charge cycle at 0.1C over 10 hours, the total energy demand exceeds three times the actual charging power, as additional energy is required for the formation process,

and none of this energy can be recovered during subsequent discharge. In the discharge phase at 0.1C, energy is primarily dissipated through resistive heat, which must then be cooled. In contrast, the second and third charge cycles at 0.5C consume less energy for formation and are shorter in duration (two hours and one hour, respectively), offering more significant potential for energy recovery, though this potential remains largely untapped. Overall, the theoretical energy flexibility for the formation process can reach up to 24%. This flexibility is mainly concentrated in the charging phases, which can be shifted to off-peak times or synchronized with renewable energy availability, optimizing energy use and supporting grid stability. [18]

Based on the distribution of energy consumption and the identified EFMs in the battery cell manufacturing process, as depicted in Table 1, the theoretical maximal energy flexibility potential is estimated to be up to 55%, excluding technical building systems (TBS), which is highly dependent on specific factory consumption patterns. As noted above, this again suggests that even more significant flexibility potential may be achievable, especially considering the viability of energy storage as an option for implementing EFM.

Table 1: Energy consumption share and flexibility potential for load shifting in battery cell manufacturing.

| Manufacturing stage | Energy consumption share [19–22] | Energy flexibility potential for load shifting [18,17] |
|---|---:|---:|
| Mixing | 0,5 – 1% | 1% |
| Coating and drying | 22 – 28% | 30% |
| Calendaring | 1 – 2% | – |
| Vacuum drying | 3 – 4,5% | – |
| Cell assembly | 12 – 15% | – |
| Electrolyte filling | 0,5 – 1% | – |
| Formation and aging | 21 – 24% | 24% |
| Cell stacking | 0,6 – 1% | – |
| Module assembly | 0,9 – 1,3% | – |
| Overall (without TBS) | 68 – 75% | 55% |
| TBS | 25 – 32% | Consumption profile dependent |

### 3.2 Energy flexibility in electric vehicle manufacturing

This section examines the energy flexibility potential within automotive manufacturing, focusing on primary on-site operations typically conducted in a factory environment. These processes are generally divided into four key shop floor categories: press shop, body shop, paint shop, and assembly, excluding technical building services (TBS). Each category is dedicated to specific production stages and utilizes highly specialized equipment and quality control procedures. By examining these energy-intensive processes, this section highlights the numerous opportunities for implementing flexible energy consumption strategies across the automotive value chain.

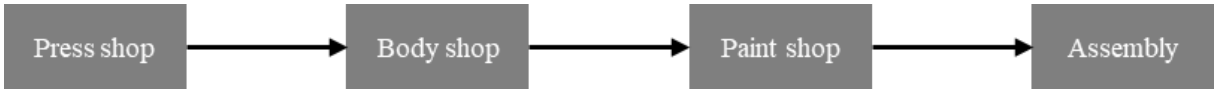


Figure 3: Main process steps of electric vehicle manufacturing [23]

The process of EV manufacturing is depicted in Figure 3 and can be described as follows:

- Press Shop: Large presses stamp and shape metal sheets into essential body parts such as doors and hoods.
- Body Shop: The stamped parts are transferred, welded, and assembled into a complete vehicle body, often using industrial robots.
- Paint Shop: The car body undergoes preparation, coating, and drying across multiple stages.
- Assembly: All vehicle components, including the engine, transmission, and interior features, are integrated into the car, and quality checks are conducted at each station to ensure functionality and safety compliance.

The methodology outlined in [9] was applied for the assessment to evaluate and quantify the feasibility of various EFMs as specified in [24]. Several EFMs, particularly organizational ones, are viable across multiple systems within the car manufacturing process, though only a few systems possess the inherent flexibility necessary to enable unique measures. One example is intelligent production planning, which could allow for a shift in energy consumption of approximately 10-20% across systems capable of adapting their production on short notice. By prioritizing manufacturing more energy-intensive parts during high renewable energy availability periods, quickly storable parts can be produced with better cost-effectiveness. Additionally, production could be interrupted in response to sudden peaks in energy costs, enabling flexibility options for systems that can shut down rapidly without compromising the quality of manufactured parts. Another cross-cutting flexibility option lies within the TBS, which generates the energy required by the manufacturing processes within each shop. The facility can achieve substantial energy flexibility by incorporating energy storage into central TBS without impacting production continuity or quality.

As the most energy-demanding operation, the paint shop also contains diverse production stages. Specifically, the numerous thermal energy requirements in paint processing enable further flexibility opportunities, such as applying inherent energy storage and bivalent heating systems. In automotive paint shops, bivalent heating systems, particularly in degreasing baths and drying ovens, allow for flexible energy use by combining dual heat sources, such as gas and electricity. These heating systems could prioritize electricity for thermal energy during high renewable energy generation. By alternating between primary and secondary sources, the bivalent setup extends the life span of heating components and reduces carbon emissions associated with gas heating. A bivalent thermal energy supply has previously been examined and validated in [25]. By elevating the degreasing bath's temperature slightly above its normal operating level, the bath's thermal inertia can serve as temporary heat storage, allowing the heating unit to be turned off for a certain period while maintaining the required temperature. The stored thermal energy helps shift the load from peak times, reducing energy costs and emissions while ensuring continuous operation [26].

Table 2: Energy consumption share and flexibility potential for load shifting in electric vehicle manufacturing.

| Manufacturing stage | Energy consumption share [27,23,28–30] | Energy flexibility potential for load shifting |
|---|---:|---:|
| Press shop | 3 – 12% | 1,5% |
| Body shop | 10 – 24% | 1,5% |
| Paint shop | 28 – 65% | 20% |
| Assembly | 8 – 42% | – |
| Overall (without TBS) | 90 – 92% | 23% |
| TBS | 8 – 10% | Consumption profile dependent |

Based on the distribution of energy consumption and the identified flexibility measures in the automotive manufacturing process, as shown in Table 2, the overall energy flexibility potential is estimated at approximately 23%, excluding TBS, which depends heavily on specific factory consumption patterns. This suggests that even higher flexibility potential may be achievable, especially considering energy storage's viability as a cost-effective EFM option.

## 4. Results and Discussion

Following the identification and quantification of the flexibility potential in three scenarios for battery manufacturing and EV manufacturing, this section extrapolates the flexibility potential for the European Union (EU). For this purpose, a continuous power demand and a constant load profile during manufacturing are assumed. The potential is determined for 2024 and projected for 2030 based on forecast data from S&P Global Mobility [31]. The estimated EV production in the EU facilitates these projections, which are estimated to be around 3 million vehicles. For future projections, the EV production and battery production capacity are divided into three scenarios, classified as pessimistic, realistic, and optimistic. Under the pessimistic scenario, annual EV production reaches approximately 9 million vehicles, alongside 530 GWh of battery manufacturing capacity. In the realistic scenario, EV production is projected to be 12.5 million units annually, and battery capacity rises to 900 GWh annually. Finally, the optimistic scenario anticipates 15 million EVs produced per year and 1,500 GWh of battery output.

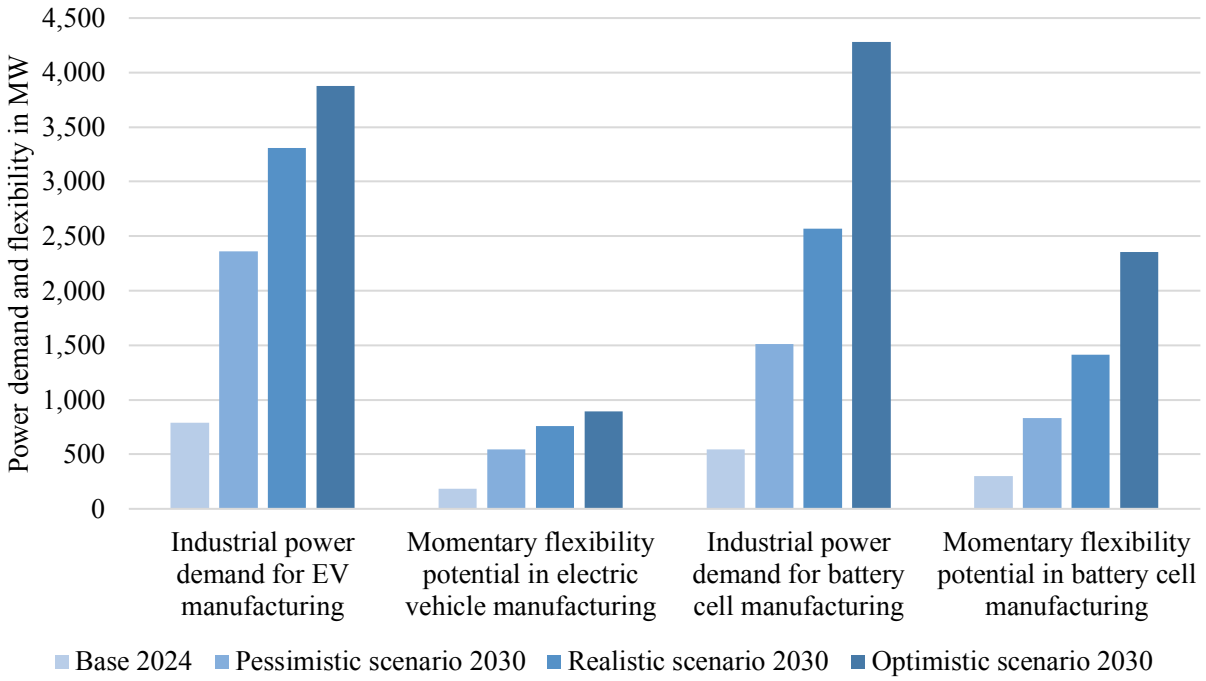


Figure 4: Development of industrial power demand in the battery cell (on the left) and electric vehicle (on the right) manufacturing industries in the EU and the respective momentary flexibility potentials [31].

Building on the use case–based flexibility estimates from the preceding sections (e.g., up to 55% load-shifting potential in specific battery cell processes), the momentary flexibility potential was calculated under each scenario. The summarized results are depicted in Figure 4, which illustrates the 2030 flexibility potentials under each scenario. For instance, in the realistic scenario of 900 GWh battery capacity, the projected peak power demand could accommodate more than 1,400 MW of flexible load in battery manufacturing alone. Similarly, EV production growth to 12.5 million vehicles per year implies a proportionate increase in demand-side flexibility to around 750 MW, which can further stabilize the grid during fluctuating renewable energy generation periods. Notably, EV manufacturing capacity could grow

by three- to five-fold, resulting in a momentary flexibility potential of around 550 MW to 900 MW, depending on the scenario. Battery cell manufacturing shows an even higher scaling factor, three- to eight-fold by 2030, translating into a potential range of 830 MW to 2,400 MW of flexible load. It must be added that all calculations assume continuous production (24 hours a day, 365 days a year) for each facility, allowing for a direct comparison of baseline and future capacity.

These findings underscore that by modulating energy demand across critical processes, battery cell, and EV manufacturing can play a pivotal role in balancing Europe's power grid. As production ramps up, strategic demand-side management in these sectors could significantly bolster the integration of renewable energy and reinforce the EU's transition toward a more resilient energy system.

## 5. Conclusion

The analysis presented in this paper highlights the critical influence of energy flexibility on advancing Europe's renewable energy transition, particularly within battery cell and electric vehicle (EV) manufacturing. By systematically identifying, quantifying, and extrapolating the flexibility potentials of these sectors, this study demonstrates the potential of intelligent load modulation in aligning industrial demand with the variable supply of renewable energy sources.

The findings underscore that battery cell manufacturing, leveraging energy-intensive stages such as electrode drying and formation cycles, exhibits a theoretical momentary flexibility potential of up to 55% of its process step energy demand. This potential could translate into as much as 2,400 MW of momentary flexibility by 2030 when scaled to Europe's projected production levels. EV manufacturing also shows considerable promise, offering an overall flexibility potential of approximately 23%, with paint shops and thermal energy systems emerging as pivotal points for demand-side management. Under scenario-based forecasts, EV production could deliver up to 900 MW of flexible load by 2030, creating substantial economic and operational benefits. These scenarios illustrate how varying growth trajectories in EV and battery cell production amplify or constrain the potential for industrial load shifting; even the most conservative projections suggest that aggregated flexibility can relieve pressure on Europe's power infrastructure and improve overall grid stability.

On a practical level, the projected momentary flexibility potentials can help mitigate peak-load problems, reduce redispatch costs, and optimize energy procurement for manufacturers by shifting consumption to periods of lower electricity prices or higher renewable generation. These strategies gain further significance as renewable penetration rises, indicating that flexible industrial processes will become essential to energy policy and industry decision-making. Thus, developing energy-flexible infrastructure, such as integrating bivalent heating systems and energy storage, should be further supported through regulatory and market frameworks that encourage coordinated demand-side management.

This paper provides a transparent and replicable framework for evaluating industrial energy flexibility, relying on a combination of literature review and process-level data. While doing so, the assumption is that modulating or shifting energy use does not adversely affect output or product quality. Future research could test this assumption in real-world pilot projects, considering process constraints, throughput requirements, and the potential impacts on product characteristics. The study likewise does not account for the influence of workforce models, material usage, and inventory management, factors that can affect load-shifting strategies in large-scale production environments. A more detailed assessment of these operational elements would provide insights into the viability of practical implementation.

The scenarios examined here rely on high-level projections, and further refinements could involve more granular scenario-building, considering regional grid conditions, economic incentives, and varying technology adoption rates. Such an approach would yield a more detailed perspective on how flexible load might evolve under different policy or market conditions. Nevertheless, the theoretical flexibility potentials

identified for battery cell and EV manufacturing strengthen the argument that industrial processes can be substantial enablers of a renewable-centric energy system. By adopting demand-side management techniques on a large scale, Europe can better balance supply and demand, maintain a stable grid, and move closer to achieving its carbon neutrality goals by 2050.

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