Energy Scheduling for Industries under Real-Time Tariffs: Effects of On-Site PV and Battery Storage

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Abstract

Manufacturing often relies on power-intensive equipment, driving high electricity demand. The manufacturing sector accounts for 30% of global energy use today [1], and its energy consumption is expected to be growing to 50% by 2050 [2]. In response, manufacturers increasingly deploy energy-aware production scheduling to improve energy efficiency, reduce costs, and enhance sustainability, often in the context of Demand Response (DR) programs [3]. Numerous studies examine energy-aware scheduling with on-site renewables and battery storage systems (BSS) across single-machine, parallel-machine, flow-shop, and job-shop settings [3]. However, most studies adopt fixed tariffs or Time-of-Use (TOU) pricing and do not fully capture Real-Time Pricing (RTP) dynamics. A further challenge arises in continuous-process manufacturing, where strict industrial production requirements lead to complex scheduling models that are difficult to adapt, limit freedom to adjust assumptions, and can compromise computational tractability (larger gaps, longer runtimes). This complexity makes it difficult to quantify the technical and economic potential of future investments in renewables and storage and to support timely operational decisions.

Consequently, different system configurations (process setup, shift plans, on-site PV, BSS) can produce very different performance outcomes. There is therefore a need for a simple, systematic approach that can analyze and compare alternative industrial configurations under RTP, while remaining adaptable to process changes and providing actionable insights for strategy and operations.

To address this need, the paper aims to comprehensively and systematically compare and analyze energy efficiency, CO_2 impacts, and time-related system performance for manufacturing process across various scenarios of energy-aware scheduling, on-site generation, and battery storage. The approach is designed to support strategic and operational decision-making from both an industrial and market perspective, guiding progress toward sustainable production scheduling. Therefore, an energy-flexibility-aware scheduling model is proposed to minimize energy costs, produce an executable production plan, and expose daily flexibility, as depicted in the figure below. The optimization model follows a two-stage mixed-integer quadratically constrained programming (MIQCP) framework.

- Stage 1: A Baseline model computes an optimal production schedule over a specified horizon to meet targeted units, operating on production and energy inputs with a consistent shift plan. Per-line energy use is modeled as average energy per produced unit (estimated from historical energy and production data) plus standby consumption that maintains equipment readiness during idle periods. This formulation captures continuous-flow constraints (e.g., equipment cannot be fully shut down between intervals). The baseline also accounts for wage costs and facility costs, and adapts to dynamic electricity tariffs, on-site generation volatility, and the BSS charge/discharge model.
- Stage 2: An Internal optimization model generates daily flexibility by creating multiple Alternative Production Plans (APPs) and shifting production forward or delaying it within the

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day-ahead window, while keeping the same production plan as the baseline for the rest of the horizon. Each APP obeys the same feasibility constraints as the baseline. Flexibility activation costs are defined as the cost difference between the baseline schedule and the corresponding APP over the day-ahead window. The resulting profiles and their costs are exported to a cluster platform (or alternatively directly to the wholesale market), where multiple companies exchange energy with each other and interface with the market.

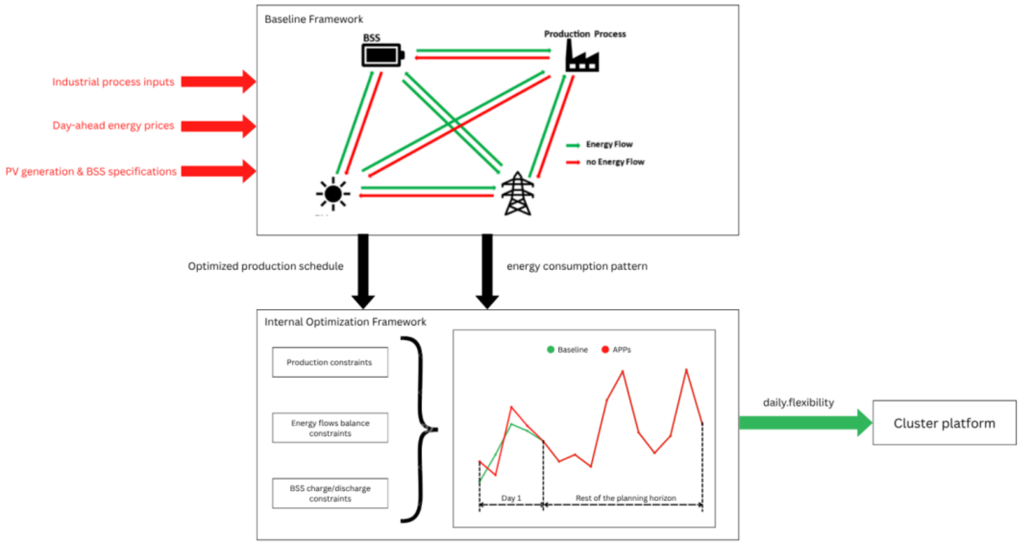

Figure 1: Energy-Flex Model concept and input/output interactions.

The methodology is validated on a real-world German manufacturer specializing in electromotive elevator technology and smart metering systems with on-site PV generation. Simulations cover multiple 7-day horizons across seasons and production volumes, considering scenarios without storage and with multiple BSS sizes. Performance is assessed using three KPIs: average daily energy-cost reduction over the planning horizon, CO_2 reduction versus the current (as-is) plan, and the energy flexibility offered by the factory to the aggregator (from internal-optimization results).

The simulations show that the Energy-Flex algorithms achieve significant energy-cost reductions and reliable flexibility across seasons and production profiles. Cost savings occur both with and without BSS, while flexibility increases further when storage is available, with most benefits already captured by small to medium BSS sizes and diminishing returns for larger capacities. Savings and flexibility are strongest when PV availability and price spreads are high, whereas battery value is limited in winter. In contrast, CO_2 results differ. Optimized schedules without storage achieve average emission reductions, while increasing BSS capacity does not improve emissions under the current charging hour accounting. This highlights the need for CO_2-aware charging strategies to align economic and flexibility benefits with environmental performance.

References

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