Energy-Aware Production Scheduling with Rooftop Solar, Battery Storage and Time-of-Day Tariffs: A Critical Review and Research Framework

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***Abstract*—Manufacturing schedules increasingly determine how effectively local solar generation, battery storage and electricity tariffs can be used. Yet the apparent benefit of coordination depends on production restrictions, the electrical boundary, the cost components represented and the information available when a decision is issued. This article critically synthesises selected literature on energy-aware scheduling, distributed energy resources, storage economics and dynamic rescheduling. It develops a comparison framework organised around physical feasibility, economic accounting, information timing and evaluation credibility. The synthesis distinguishes lower energy consumption from lower grid expenditure, solar retention from useful delivered solar, and a projected demand peak from an actual billing liability. Closely related studies establish that combining scheduling, renewables and storage is already an established research direction; the remaining contribution must concern a precisely defined operational improvement. The article proposes a research framework linking validated inputs to delivery-constrained joint scheduling, stateful updates and independent outcome reconstruction. It also identifies a staged route from constructed verification cases to industrial replay and advisory validation.**

***Index Terms*—Energy-Aware Scheduling; Flexible Job Shop; Photovoltaic Generation; Battery Storage; Time-Of-Use Tariffs; Demand Charges; Critical Review**

I. INTRODUCTION:

A factory's electricity demand is partly the consequence of its schedule. Two plans completing the same orders can differ in their coincidence with solar output, their purchases during expensive periods and the maximum import registered by the utility. Storage introduces another timing decision: electricity can be acquired earlier and delivered later, with losses and ageing exposure. The useful question is therefore not simply whether a factory owns solar panels or a battery, but how feasible production choices interact with those resources.

Energy-aware scheduling has a substantial literature. Gahm et al. (2016) organise manufacturing scheduling around energy considerations, while Biel and Glock (2016) examine decision-support modelling choices for energy-efficient production planning. Catanzaro et al. (2023) focus specifically on scheduling under time-of-use tariffs. These contributions show why a new study needs a narrower claim than the general proposition that electricity prices can influence operation timing.

The challenge is that published percentage savings answer different questions. Some comparisons change hardware, others change the production policy, and still others relax the service requirement. A battery may begin with more usable energy in one treatment or finish more depleted. A daily optimisation may omit a monthly demand liability. Without these distinctions, a numerically impressive result can be difficult to interpret.

This article asks three connected questions. Which modelling decisions determine the meaning of an integrated scheduling result? How should established technical combinations be distinguished from a specific operational contribution? What evaluation structure can connect a verified optimisation model to

credible adoption evidence? The article answers through a selective literature synthesis and a conceptual research framework, without claiming new industrial observations.

II. REVIEW METHOD AND ANALYTICAL SCOPE:

2.1 Source selection:

The review uses a purposive set of primary research papers, established surveys and technical modelling reports relevant to four interfaces: production and electricity demand; scheduling and tariffs; solar and storage; and decisions and operational feedback. Publisher records and DOI metadata were checked during manuscript preparation. Foundational studies were retained where they explain a modelling mechanism still relevant to current systems.

The selection includes flexible job-shop formulations, factory-level photovoltaic and storage coordination, renewable-aware scheduling frameworks, battery-performance modelling and rescheduling methods. It is not presented as a complete Scopus or Web of Science extraction. No screening counts, inter-reviewer agreement or PRISMA flow numbers are invented. Page et al. (2021) provide reporting guidance for a systematic review, but invoking that guidance alone would not turn this selective synthesis into one.

2.2 Comparison dimensions:

Each study is examined in terms of decision scope, physical representation, economic boundary, information structure and evidence type. The comparison records what the source establishes and which additional question a new study must answer. An omission is not inferred merely because a feature is absent from an abstract.

The resulting framework supports analytical comparison rather than a numerical league table. Savings from different papers are not pooled because their baselines, assets and delivery conditions are not exchangeable.

Table 1 Literature strands and analytical questions

Literature strand	Decision represented	Critical comparison question
Classical scheduling	Assignment, order and capacity	Are routes, eligibility and delivery obligations equal?
Energy-aware machines	Processing, idle and state changes	Are power states and transition obligations represented?
Tariff-aware timing	When grid energy is acquired	Does the full bill differ from the optimised term?
Solar and storage	Supply allocation and inventory	Are losses, origins and boundary energy consistent?
Dynamic decisions	Update timing and recourse	What information was available when action was issued?
Empirical evaluation	Replay or executed operation	Which claims are verified, validated or still proposed?

III. PRODUCTION SCHEDULING AS AN ENERGY DECISION

3.1 Timing and assignment:

In a job shop, technological precedence and machine capacity determine when an operation can occur. In a flexible job shop, qualified alternatives also determine processing duration and power. Pinedo (2022) provides the scheduling foundation, while Meng et al. (2019) formulate energy-aware flexible job-shop models. The relationship between duration and power makes a local low-power rule insufficient: a slower machine may consume more energy, occupy a bottleneck longer or move a successor into a costly interval.

A credible model must identify whether the material unit is a job, a batch or an operation quantity. It must also distinguish waiting between operations from interruption during processing. Permitting a machining operation to pause across an expensive tariff band can create flexibility that the real process does not possess.

3.2 Operating states and shared demand:

Mouzon et al. (2007) establish a basis for examining equipment operating practices in energy reduction. Processing, ready idle, standby and off states have different power levels and return-to-service requirements. An idle period is not automatically a zero-load interval, and a shutdown is not automatically free.

Machine demand is only part of the electrical boundary. Lighting, ventilation, cooling and compressed air can influence whether solar is surplus

and whether a battery can shave an import peak. If a machine meter already includes a dedicated auxiliary, adding that auxiliary again as a common load double counts demand. Conversely, comparing machine-only prediction with a whole-site meter creates an unexplained boundary mismatch.

The modelling resolution should follow the available observations and the decision being supported. A detailed state diagram with unmeasurable transition parameters can be less credible than a transparent fixed-state approximation. Studies should state which state choices are active and which are fixed, then test the consequences of simplification.

IV. ECONOMIC ACCOUNTING UNDER TIME-DEPENDENT TARIFFS:

4.1 Energy quantity and expenditure:

Electricity-cost minimisation and electricity-consumption minimisation are different objectives. A schedule may purchase the same kWh in cheaper periods. It may also increase charging losses while reducing expensive purchases or demand exposure. The total monetary effect cannot be interpreted as physical energy conservation without a quantity analysis.

Catanzaro et al. (2023) review time-of-use scheduling models, and Hall and Posner (2026) examine optimal scheduling under such tariffs. These works motivate explicit time-band mapping. Prices should be matched to interval boundaries and day types; a tariff change inside a coarse slot requires overlap accounting or a disclosed approximation.

4.2 Demand intervals and historical state:

A demand charge concerns the utility's defined electrical quantity and aggregation rule. It need not equal instantaneous production power or the largest scheduling-slot import. For a fixed interval, imported energy divided by duration gives me an active-power demand. Apparent-power tariffs require reactive-power information or a validated approximation.

Billing history also changes the marginal consequence of a decision. If a 50-kW peak is already established, reducing the next interval from 40 to 35 kW creates no additional saving under a simple maximum-demand charge. Raising it to 60 kW does create exposure. Repeatedly charging the full predicted peak in each planning window confuses an optimisation estimate with the realised monthly bill.

This accounting requirement does not imply that a short horizon predicts the remainder of a billing period accurately. A controller can represent known history correctly while anticipating future peaks poorly. Billing correctness and forecast quality should therefore be evaluated separately.

V. SOLAR GENERATION AND STORAGE INTEGRATION

5.1 Established combinations and remaining questions:

Moon and Park (2014) study production scheduling with distributed resources and storage. Zhang et al. (2017) explicitly address a grid-connected factory with photovoltaic generation and batteries. Karimi and Kwon (2021) compare scheduling, renewable generation and storage configurations. These precedents rule out treating the simple presence of all three technologies as a sufficient novelty claim.

Zahid et al. (2026) integrate flexible routing, time-of-use prices, photovoltaic generation, storage and fixed preventive-maintenance availability, using exact and scalable solution approaches. The relevant question for a new framework is therefore what operational relationship is represented differently, how that difference changes decisions and whether the comparison demonstrates useful consequences.

Table 2 Selected studies and the questions they inform:

Study	Relevant scope	Implication for the present framework
Gahm et al. (2016)	Review of energy-efficient scheduling	General energy-aware scheduling is established.
Biel & Glock (2016)	Production-planning decision models	Identify the production and economic boundary.
Moon & Park (2014)	Scheduling with distributed resources and storage	Integration alone is not a sufficient novelty claim.
Zhang et al. (2017)	Grid-connected factory with PV and battery	Compare dispatch assumptions and production choices.

Karimi & Kwon (2021)	Comparative scheduling/resource analysis	Separate coordination from hardware changes.
Catanzaro et al. (2023)	Time-of-use scheduling survey	State price structure and service constraints.
Shao et al. (2024)	Renewable-aware hybrid scheduling	Explain update rules and execution evidence.
Zahid et al. (2026)	Flexible job shop, renewables, storage and maintenance	Position the specific operating improvement carefully.

5.2 Battery boundaries and ageing

AC charging power and internal stored energy are not the same quantity. Charge efficiency maps purchased or solar electricity into inventory; discharge efficiency maps internal withdrawal into delivered electricity. DiOrio et al. (2015) provide a detailed storage-modelling foundation. A simpler scheduling model may use constant efficiencies, but its convention must be explicit and consistent with inverter and auxiliary boundaries.

Ageing also affects whether an attractive utility-bill saving is an attractive operating decision. Cai et al. (2019) examine ageing-aware predictive control in buildings. This is relevant methodological evidence about storage control, not direct proof of manufacturing performance. A factory model using a linear throughput allocation should identify its replacement-cost and lifetime-throughput convention, then test the coefficient rather than treating it as a measured cash charge.

5.3 Useful solar and source attribution

Solar sent into a battery has not yet served production. Some is lost in conversion and some can remain in terminal inventory. If grid charging is permitted, later discharge can have mixed origins. Labelling every discharged kWh as solar would overstate renewable delivery.

A practical reporting convention assigns utilised solar first to contemporaneous load and then to charging, and tracks source composition through the store. Initial energy of unknown origin remains separate. Proportional mixing is an accounting rule rather than physical electron tracing, but it prevents double counting and allows direct solar, delivered solar-origin discharge, losses and terminal inventory to be reported together.

VI. UNCERTAINTY AND ROLLING DECISIONS

A deterministic schedule can become unsuitable as solar forecasts, processing estimates and machine availability change. Ouelhadj and Petrovic (2009) review dynamic manufacturing scheduling, while Vieira et al. (2003) organise rescheduling strategies and policies. These foundations show that repeated decision-making is an established topic, with important choices about when to revise a plan and what remains committed.

Shao et al. (2024) develop an event-triggered hybrid scheduling framework for manufacturing integrated with renewables and include industrial case evidence. A new rolling procedure therefore needs to explain its own information boundary, state transfer and computational trade-off rather than claiming novelty from the word “rolling”.

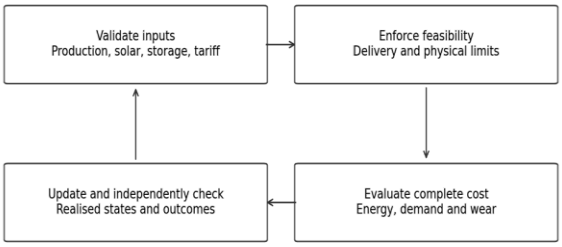
At each update, completed and in-progress work must persist. Battery state and actual peak history must also persist. Forecast vintages should correspond to issue times, while realised future data belong to the evaluator. A controller granted exact short-term future output can be useful as an information experiment, but should not be described as a validated forecasting service.

Schedule stability deserves a separate definition. A fixed-production dispatch replay has zero operation changes by design; that is not evidence that free production rescheduling is stable. Useful stability indicators include start-time revisions, machine changes and proximity of the changed instruction to execution.

VII. PROPOSED RESEARCH FRAMEWORK

The proposed framework has four linked layers. The input layer validates production routes, state-power observations, solar forecasts, storage specifications and tariff evidence. The feasibility layer enforces qualified assignment, non-preemption, physical supply limits and the declared service condition. The economic layer evaluates energy, avoidable demand exposure and wear using common boundary states.

Figure 1 Proposed research framework linking input credibility, feasible decisions and independently evaluated outcomes.



Its operating cycle begins with a current state and issued forecasts. A candidate plan is generated, checked and released only for the approved near-term window. The evaluator advances using realised conditions, records permitted recourse and passes actual state to the next run. An invalid or late candidate is retained as an unsuccessful outcome, not assigned an invented cost.

VIII. VERIFICATION AND INDUSTRIAL VALIDATION

Sargent (2013) distinguishes implementation verification from validity for an intended application. A solver's successful status addresses neither automatically. Small cases should test unique assignment, precedence, occupancy, storage loss, terminal energy and tariff aggregation. Deliberately corrupted traces test whether the independent checker can reject a plausible-looking invalid output. Industrial validation then asks whether measured power and actual restrictions support the abstraction. It should compare predictions and observations at the same boundary, retain chronological calibration separation and reconstruct actual billing. Historical replay supplies counterfactual evidence; planner review supplies feasibility knowledge; an advisory pilot supplies adoption and executed-action evidence. These stages answer different questions.

Table 3 Minimum evidence for defensible performance claims:

Claim	Minimum supporting evidence	What remains insufficient
Correct mathematical implementation	Unit checks, feasible traces, rejection tests	Solver success alone
Lower policy cost	Matched resources, service and independent scoring	Different batteries or depleted terminal inventory
Forecast/control benefit	Issue-time information and realised replay	Actual future data silently used as forecasts
Industrial feasibility	Measured constraints and planner review	A small constructed schedule
Investment value	Annual cash flows, capital and replacement costs	One-shift operating savings

A stronger method is not required to improve every indicator. It may lower complete cost while extending makespan within permitted slack. Reporting an unfavourable or negligible outcome strengthens the explanation because it identifies which trade-off or constraint governs the decision.

IX. RESEARCH AGENDA AND LIMITATIONS

The priority is not indiscriminate addition of model features. It is to identify a decision-relevant limitation, obtain the necessary data and test whether the extension changes feasible outcomes. Examples include a demand interval different from the scheduling grid, an actual reserve restriction, or a preparation process that prevents a nominal machine switch.

Future studies should combine multi-season solar with matched production records, compare strong simple rules and assess full data-to-release runtime. More detailed ageing, shared resources and uncertainty models should be evaluated against a common reduced reference, including cases where their extra complexity offers little practical value.

This synthesis is selective and cannot estimate the prevalence of a modelling practice across all published studies. It also contains no meta-analysis or industrial experiment. Its comparisons are intended to structure research questions and reporting, not rank the reviewed algorithms universally.

X. CONCLUSION

Energy-aware production scheduling is most interpretable when physical feasibility, complete cost, information timing and evaluation evidence are aligned. Existing studies already establish the integration of scheduling, renewables and storage. A defensible new contribution therefore identifies a specific operational improvement and demonstrates its consequence under matched conditions. The framework proposed here provides a route from reliable inputs and explicit boundaries to checked decisions, stateful updates and staged industrial validation. Its practical value remains a question to be tested rather than an assumption attached to technological complexity.

Declarations:
This manuscript is a thesis-derived draft prepared for author review. The literature synthesis is selective and does not claim an exhaustive systematic search.
Data availability: This review analyses published literature and introduces no primary industrial dataset. Source details are provided in the reference list.

REFERENCES

[1] K. Biel and C. H. Glock, "Systematic literature review of decision support models for energy-efficient production planning," *Computers & Industrial Engineering*, vol. 101, pp. 243–259, 2016, doi: 10.1016/j.cie.2016.08.021.

[2] J. Cai, H. Zhang, and X. Jin, "Aging-aware predictive control of PV-battery assets in buildings," *Applied Energy*, vol. 236, pp. 478–488, 2019, doi: 10.1016/j.apenergy.2018.12.003.

[3] D. Catanzaro, R. Pesenti, and R. Ronco, "Job scheduling under time-of-use energy tariffs for sustainable manufacturing: A survey," *European Journal of Operational Research*, vol. 308, no. 3, pp. 1091–1109, 2023, doi: 10.1016/j.ejor.2023.01.029.

[4] N. DiOrio, A. Dobos, S. Janzou, A. Nelson, and B. Lundstrom, "Technoeconomic modeling of battery energy storage in SAM," National Renewable Energy Laboratory, Tech. Rep. NREL/TP-6A20-64641, 2015, doi: 10.2172/1225314.

[5] C. Gahm, F. Denz, M. Dirr, and A. Tuma, "Energy-efficient scheduling in manufacturing companies: A review and research framework," *European Journal of Operational Research*, vol. 248, no. 3, pp. 744–757, 2016, doi: 10.1016/j.ejor.2015.07.017.

[6] N. G. Hall and M. E. Posner, "Optimal energy scheduling under time-of-use tariffs," *Journal of Scheduling*, vol. 29, no. 2, pp. 157–171, 2026, doi: 10.1007/s10951-026-00872-5.

[7] S. Karimi and S. Kwon, "Comparative analysis of the impact of energy-aware scheduling, renewable energy generation, and battery energy storage on production scheduling," *International Journal of Energy Research*, vol. 45, no. 13, pp. 18981–18998, 2021, doi: 10.1002/er.6999.

[8] J.-Y. Moon and J. Park, "Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage," *International Journal of Production Research*, vol. 52, no. 13, pp. 3922–3939, 2014, doi: 10.1080/00207543.2013.860251.

[9] G. Mouzon, M. B. Yildirim, and J. Twomey, "Operational methods for minimization of energy consumption of manufacturing equipment," *International Journal of Production Research*, vol. 45, nos. 18–19, pp. 4247–4271, 2007, doi: 10.1080/00207540701450013.

[10] D. Ouelhadj and S. Petrovic, "A survey of dynamic scheduling in manufacturing systems," *Journal of Scheduling*, vol. 12, no. 4, pp. 417–431, 2009, doi: 10.1007/s10951-008-0090-8.

[11] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, S. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, S. Mayo-Wilson, S. McDonald, *et al*., "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *BMJ*, vol. 372, Art. no. n71, 2021, doi: 10.1136/bmj. n71.

[12] M. L. Pinedo, *Scheduling: Theory, Algorithms, and Systems*, 6th ed. Cham, Switzerland:

Springer International Publishing, 2022, doi: 10.1007/978-3-031-05921-6.

[13] R. G. Sargent, "Verification and validation of simulation models," *Journal of Simulation*, vol. 7, no. 1, pp. 12–24, 2013, doi: 10.1057/jos.2012.20.

[14] Z. Shao, W. Li, Y. Tan, and K. Otto, "A systematic energy-aware scheduling framework for manufacturing factories integrated with renewables," *International Journal of Production Research*, vol. 62, no. 21, pp. 7644–7659, 2024, doi: 10.1080/00207543.2024.2323067.

[15] G. E. Vieira, J. W. Herrmann, and E. Lin, "Rescheduling manufacturing systems: A framework of strategies, policies, and methods," *Journal of Scheduling*, vol. 6, no. 1, pp. 39–62, 2003, doi: 10.1023/A:1022235519958.

[16] Zahid, P. Leclaire, L. Hammadi, R. Costa Affonso, and A. El Ballouti, "Energy-aware flexible job shop scheduling under time-of-use pricing with renewable, battery storage and preventive maintenance," *Scientific Reports*, vol. 16, no. 1, Art. no. 25007, 2026, doi: 10.1038/s41598-026-54904-3.

[17] H. Zhang, J. Cai, K. Fang, F. Zhao, and J. W. Sutherland, "Operational optimization of a grid-connected factory with onsite photovoltaic and battery storage systems," *Applied Energy*, vol. 205, pp. 1538–1547, 2017, doi: 10.1016/j.apenergy.2017.08.140.