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A Controlled Comparison with Sequential Scheduling

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Integrated Day-Ahead Unit Commitment and Economic Dispatch in the Libyan Power System: A Controlled Comparison with Sequential Scheduling

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Abstract

Day-ahead thermal generation scheduling is an intertemporal decision problem because start-up, shut-down, ramping, and minimum-time decisions made in one hour affect the feasibility and cost of later hours. This study formulates a 24-hour mixed-integer linear programming model that jointly optimizes unit commitment (UC), start-up and shut-down decisions, and economic dispatch (ED), and compares it with a sequential one-hour benchmark under identical demand, unit limits, initial conditions, and cost coefficients. The analysis uses authorized operating records from the General Electricity Company of Libya (GECOL) for 19 selected operating days in 2025, represented by 25 plant-level generation blocks, with peak demand ranging from 4.665 to 8.166 GW and daily energy from 93.314 to 181.881 GWh. MATLAB Optimization Toolbox solves the primary models, while an independent SciPy/HiGHS implementation verifies objective values, integrality, hourly balance, ramping, and minimum up/down-time constraints.

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Across the complete sample, both methods serve 2,485.132 GWh. Integrated scheduling reduces the aggregate objective from 98.942 to 96.987 million comparative cost units (CU), a 1.976% reduction, and lowers the mean number of online blocks from 14.99 to 9.17. Daily objective reductions range from 1.019% on the peak day to 4.832% on the lowest-load day. Peak-demand-quartile analysis shows the mean objective reduction declining from 3.921% in the lowest quartile to 1.142% in the highest, while the mean online-block reduction declines from 52.96% to 24.99%. The results show that full-horizon UC-ED is most valuable when commitment flexibility is high and that objective value, online depth, and switching decisions should be assessed jointly. The workflow provides a practical foundation for advisory day-ahead scheduling and for future unit-level and network-aware development.

Keywords: Day-Ahead Scheduling; Economic Dispatch; Integrated Scheduling; Libyan Power System; Mixed-Integer Linear Programming; Unit Commitment.

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التكامل بين إلزام الوحدات والتوزيع الاقتصادي لجدولة اليوم التالي في منظومة القدرة الليبية :مقارنة منضبطة مع الجدولة المتتابعة

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الملخص

تُعد جدولة التوليد الحراري لليوم التالي مسألة مترابطة زمنيًا، لأن قرارات البدء والإيقاف والتدرج والحدود الدنيا لمدد التشغيل والتوقف في ساعة معينة تؤثر في جدوى الساعات اللاحقة وكلفتها .تصوغ هذه الدراسة نموذج برمجة خطية صحيحة مختلطة لمدة 24 ساعة يحسن بصورة مشتركة إلزام الوحدات وقرارات البدء والإيقاف والتوزيع الاقتصادي، وتقارنه بخط أساس متتابع لمدة ساعة واحدة مع استخدام الحمل وحدود الوحدات والحالات الابتدائية ومعاملات الكلفة نفسها .تعتمد الدراسة على سجلات تشغيلية مأذون باستخدامها من الشركة العامة للكهرباء في ليبيا (GECOL)لتسعة عشر يوم تشغيل خلال عام 2025، ممثلة في خمس وعشرين كتلة توليد على مستوى المحطات، وبذروات حمل تراوحت بين 4.665و 8.166جيجاواط وطاقة يومية بين 93.314و 181.881 جيجاواط ساعة .نُفذت النماذج الأساسية في MATLABباستخدام صندوق أدوات التحسين، وأُجري تحقق مستقل بواسطة SciPy/HiGHSلقيم دالة الهدف، وصحة المتغيرات الثنائية، وتوازن القدرة الساعي، وقيود التدرج، ومدد التشغيل والتوقف الدنيا . غطت الطريقتان طاقة متساوية مقدارها 2,485.132جيجاواط ساعة .وخفضت الجدولة المتكاملة دالة الهدف التجميعية من 98.942إلى 96.987مليون وحدة كلفة مقارنة، أي بنسبة 1.976%، كما خفضت متوسط عدد الكتل العاملة من 14.99إلى 9.17. وتراوح الانخفاض اليومي في دالة الهدف بين 1.019%في يوم الذروة و 4.832%في اليوم الأقل حملًا .وأظهر تحليل أرباع حمل الذروة انخفاض متوسط التحسن من

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3.921%في الربع الأدنى إلى 1.142%في الربع الأعلى، وانخفاض متوسط تقليل عدد الكتل العاملة من 52.96%إلى 24.99%. وتبين النتائج أن قيمة التكامل تكون أكبر عندما تمتلك المنظومة مرونة أوسع في الالتزام، وأن تقييم الجدول ينبغي أن يجمع بين دالة الهدف وعمق الالتزام وقرارات التبديل .ويوفر الإطار المقترح أساسًا عمليًا للجدولة الاستشارية لليوم التالي والتطوير المستقبلي نحو تمثيل تفصيلي للوحدات والشبكة.

الكلمات المفتاحية: جدولة اليوم التالي؛ التوزيع الاقتصادي؛ الجدولة المتكاملة؛ منظومة القدرة الليبية؛ البرمجة الخطية الصحيحة المختلطة؛ إلزام الوحدات.

1. Introduction

The Libyan power system is supplied mainly by geographically dispersed thermal stations and experiences pronounced daily and seasonal demand variation. The 2025 GECOL operating records selected for this study contain daily peaks between 4.665 and 8.166 GW. In this operating range, excessive commitment increases production and no-load cost, whereas delayed commitment can require steeper ramping or additional start-up actions later in the day. Unit commitment (UC) selects the generating blocks that should be online, determines their start-up and shut-down events, and preserves the duration of each operating state. Economic dispatch (ED) then allocates the required active power among the committed blocks. These decisions must be optimized together because every commitment decision changes the available capacity, stable minimum output, ramping capability, no-load cost, and future flexibility, while the expected dispatch trajectory determines whether a start or stop is economically justified. Strong mixed-integer linear programming formulations retain these binary and continuous interactions in one auditable model [1]-[8].

Libya-focused forecasting research confirms that peak demand changes materially with operating period and season [9], and the GECOL records provide the plant and demand evidence used to construct the comparative cases [10].

The research question is therefore precise: when identical Libyan demand, unit limits, initial conditions, and model cost coefficients are used, how does a 24-hour integrated UC-ED solution differ from

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a sequential one-hour solution that carries only the current state forward? The paper contributes four elements: (1) a transparent thermal UC-ED formulation; (2) a controlled integrated-versus-sequential experiment; (3) a complete engineering interpretation of commitment depth, cycling, dispatch, and cost composition; and (4) a demand-level sensitivity analysis across the full operating sample. Figure 1 summarizes the study workflow and establishes the common input layer used by both methods.

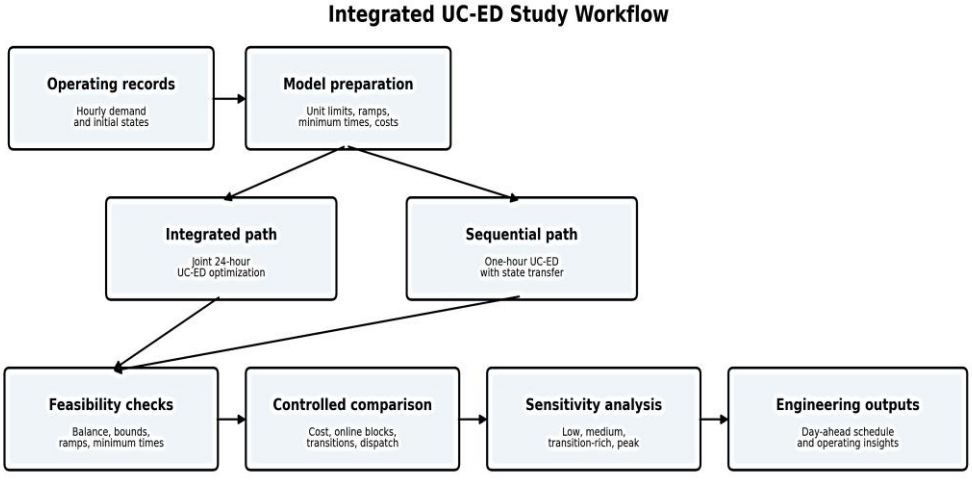


Fig. 1. Study workflow and controlled comparison between integrated and sequential UC-ED.

Figure 1 should be read from top to bottom. GECOL hourly demand and initial unit states enter a common model-preparation layer. The two solution paths then use exactly the same unit limits and cost coefficients: the integrated path optimizes the complete 24-hour trajectory, whereas the sequential path solves one hour and transfers the resulting status and output to the next hour. Both paths pass through the same feasibility checks, controlled comparison, and demand-level sensitivity analysis. Consequently, every reported difference is caused by temporal foresight rather than by different inputs or operating equations.

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2. Related Work and Research Gap

Priority lists and dynamic programming provided early commitment rules, while Lagrangian relaxation decomposed large thermal systems [1], [2]. Modern MILP formulations strengthened transition logic, output bounds, start-up and shut-down ramps, and minimum-time representation [3]-[7]. Comparative studies show that seemingly small modeling choices can materially alter cost, feasibility, and solver performance [8], while recent UC surveys emphasize the need to preserve the physical and temporal constraints represented by the scheduling model [11].

Recent research has proposed learning-assisted warm starts, constraint screening, graph neural networks, and spatio-temporal model reduction to accelerate large UC instances [12]-[15]. These developments confirm the value of computational assistance, but the governing optimization equations and feasibility checks remain essential. The gap addressed in this paper is different: a controlled Libya-focused comparison in which the integrated and sequential methods use exactly the same operating records, unit representation, initial state, and coefficients. This design makes the value of temporal foresight directly observable and prevents data or model changes from being mistaken for an algorithmic advantage.

The paper therefore evaluates the scheduling architecture itself rather than conducting a broad competition among unrelated solvers. The full-day model and the sequential benchmark are judged by the same objective components, the same operating constraints, the same feasibility tests, and the same output metrics. This controlled structure also supports the sensitivity analysis presented later, because changes in saving can be traced to the operating condition rather than to a change in formulation.

3. Operating Data and Model Preparation

The study uses authorized GECOL operating records for 19 selected dates between 5 January and 5 December 2025 [10]. For each operating day, the retained information includes 24 hourly national-demand values, the initial status and output of the generation fleet, and station-level generation observations. Twenty-five plant-level blocks form the thermal generation portfolio. Each generation block

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is treated as an aggregated scheduling entity rather than an explicit representation of every individual generating unit within a power station. Consequently, the reported commitment, start-up, and shut-down decisions should be interpreted at the modeled block level. The selected days cover low-load, medium-load, transition-rich, and peak-load conditions, which allows the two scheduling methods to be evaluated over a broad range of operating patterns.

Data preparation reconstructs the operating date and hour, checks blank and nonnumeric entries, aligns station names, and maps plant observations to the common generation-block representation. Positive station output is used to support the initial online state, while unit limits, ramp capability, minimum up/down time, and relative cost coefficients are derived through one consistent engineering procedure and then applied identically to the integrated and sequential models. Objective values are reported in comparative cost units (CU), providing a uniform basis for evaluating all cases.

The primary optimization model is implemented in MATLAB using Optimization Toolbox and the intlinprog solver. An independent Python reconstruction based on SciPy and HiGHS checks the objective value, integrality, hourly power balance, generation bounds, ramping, and minimum-time residuals [16], [17]. Using two computational paths strengthens the numerical review because the main scheduling conclusions must be reproduced from the same case definition rather than inferred from a single software output.

Figure 2 presents three representative demand trajectories from the GECOL records: 5 May 2025 for the low-load condition, 5 January 2025 for the medium-load condition, and 5 August 2025 for the peak-load condition [10]. The curves differ in both magnitude and duration. UC responds to how long additional capacity is required, whereas ED responds to the hourly MW level. The complete evaluation uses all 19 operating dates listed later in Table 6; the three trajectories are displayed to explain the operating regimes used in the sensitivity analysis.

Table 1 summarizes the complete translation from operating records to optimization inputs and from optimized decisions to evaluation metrics. It provides a compact map of the data, the mathematical

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decisions, the operating constraints, and the numerical outputs used throughout the paper.

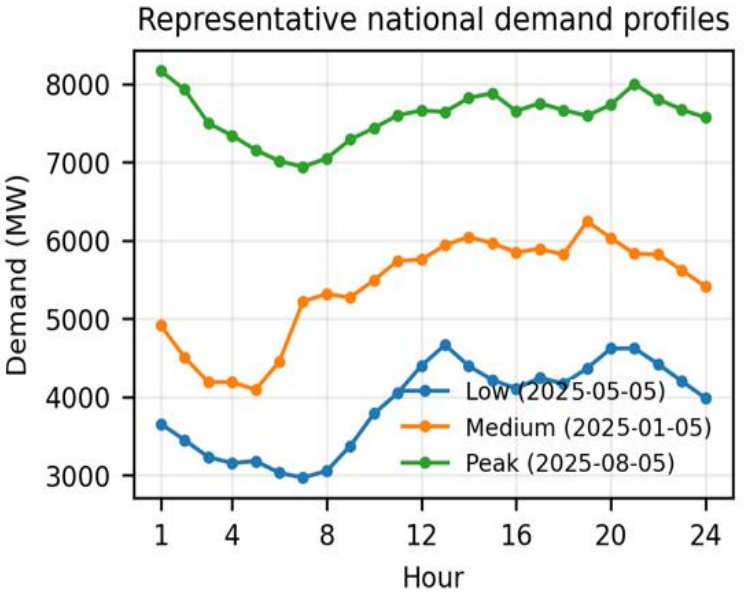


Fig. 2. Representative 2025 low-, medium-, and peak-demand trajectories used to interpret operating-condition sensitivity.

Table 1. Operating Data, Model Decisions, And Evaluation Outputs

Item	Representation
Operating records	**Hourly demand, initial state/output, and station-generation observations**
Generation representation	**Twenty-five plant-level thermal generation blocks**
Decision variables	**Online state, start-up, shut-down, and hourly active-power output**
Objective components	**Production, no-load, start-up, and shut-down cost**
Operating constraints	**Power balance, output limits, ramping, and minimum up/down time**
Evaluated conditions	**Nineteen low-, medium-, transition-rich, and peak-load operating days**

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Item	Representation
Reported outputs	**Objective value, online blocks, transitions, technology energy, and feasibility residuals**

Table 1 shows that both solution paths are built from one common information base. The comparison therefore measures the effect of optimizing the complete 24-hour trajectory rather than the effect of changing the data, the generation portfolio, or the objective coefficients. The same structure is retained for every operating day and for all sensitivity calculations.

4. Mathematical UC-ED Formulation

Let G denote the set of generation blocks and T the set of 24 hourly intervals. For block g and hour t, u_g,t is the binary online state, y_g,t and z_g,t are the start-up and shut-down indicators, and p_g,t is the dispatched active power in MW. The parameters C_g(.), C_g^NL, C_g^SU, and C_g^SD represent the production, no-load, start-up, and shut-down cost terms used consistently in both scheduling methods. The integrated objective in Eq. (1) follows standard thermal UC practice [1], [3]-[8].

$$\min J = \sum_{t\in\mathcal{T}} \sum_{g\in\mathcal{G}} \left[C_g(p_{g,t}) + C_g^{NL} u_{g,t} + C_g^{SU} y_{g,t} + C_g^{SD} z_{g,t}\right] \quad \textbf{(1)}$$

The remaining symbols are P_g^min and P_g^max for stable minimum and maximum output; RU_g and RD_g for normal upward and downward ramp limits; SU_g and SD_g for start-up and shut-down ramp allowances; UT_g and DT_g for minimum up and down times; D_t for demand; J_int and J_seq for the integrated and sequential objective values; and N_online,t for the number of online blocks. These definitions are used throughout the formulation and the result tables.

Equation (2) identifies every change in online status as either a start or a stop. Equation (3) forces an offline block to produce zero and constrains an online block between its study minimum and

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maximum output. Together, the equations connect the binary commitment decision to the continuous dispatch variable using the logical structure reported in [3]-[8].

$$u_{g,t} - u_{g,t-1} = y_{g,t} - z_{g,t} \quad \textbf{(2)}$$

$$P_g^{\min} u_{g,t} \le p_{g,t} \le P_g^{\max} u_{g,t} \quad (3)$$

Equations (4) and (5) distinguish normal hour-to-hour ramping from the larger changes permitted during start-up and shut-down. Equation (6) accumulates recent start and stop decisions so that a block cannot be released before satisfying its minimum up-time or restarted before satisfying its minimum down-time. This representation preserves intertemporal feasibility and follows the compact ramping and minimum-time formulations in [5]-[8].

$$p_{g,t} - p_{g,t-1} \le RU_g u_{g,t-1} + SU_g y_{g,t} \quad \textbf{(4)}$$

$$p_{g,t-1} - p_{g,t} \le RD_g u_{g,t} + SD_g z_{g,t} \quad (5)$$

$$\sum_{\tau=t-UT_g+1}^{t} y_{g,\tau} \le u_{g,t}, \qquad \sum_{\tau=t-DT_g+1}^{t} z_{g,\tau} \le 1 - u_{g,t} \quad (6)$$

Equation (7) is the direct integration point between UC and ED: the binary variables determine which blocks are available, and the continuous dispatch variables allocate the full hourly demand among those blocks. The equality is enforced for every hour [1], [3]. Equation (8) defines the two reporting metrics used in the comparison: relative saving and the hourly number of online blocks. Both metrics are calculated directly from the optimized schedules.

$$\sum_{g \in \mathcal{G}} p_{g,t} = D_t, \qquad \forall t \in \mathcal{T} \quad \textbf{(7)}$$

The integrated method solves Eqs. (1)-(7) simultaneously for the complete 24-hour trajectory. The sequential benchmark solves the same equations for one hour, transfers the resulting state and output

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to the next hour, and proceeds without access to the remaining demand trajectory. Thus, the sequential path retains physical feasibility while using one-step visibility, whereas the integrated path can coordinate present decisions with future demand, start-up cost, ramping, and minimum-time obligations.

$$\text{Saving}(\%) = 100\frac{J_{seq} - J_{int}}{J_{seq}}, \qquad N_{online,t} = \sum_{g \in \mathcal{G}} u_{g,t} \tag{8}$$

5. Experimental Design

Table 2 summarizes the controlled experiment. Both approaches use the same 25 generation blocks, the same hourly demand, the same model parameters, the same initial state and output, and the same feasibility checks. The structural difference is the optimization horizon and the amount of future demand information available when a binary start or stop decision is made.

Table 2. Controlled Methodological Comparison

Feature	Integrated 24-h UC-ED	Sequential Benchmark
Optimization horizon	24 hours optimized jointly	1 hour optimized at a time
Future-demand visibility	Complete 24-h trajectory	Current hour only
Demand, units, and costs	Identical	Identical
Initial state and output	Identical	Identical
Physical constraints	Eqs. (2)-(7)	Same equations
State transfer	Internal to one 24-h model	Status and output passed to next hour
Decision characteristic	Joint intertemporal optimization	One-step receding decision

The evaluation reports objective value, relative saving, mean online blocks, explicit start/stop transitions, technology-level energy, and constraint residuals. MATLAB and the independent SciPy/HiGHS

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reconstruction must agree on served energy, objective value, and all feasibility checks [16], [17]. Peak-day results are examined at block and technology levels, while sensitivity is evaluated by grouping the 19 operating dates into peak-demand quartiles. A result is accepted only after power balance, output limits, ramping, binary transitions, and minimum-time logic have passed the verification routine.

6. Results

6.1 Selected Operating Conditions

Four cases are highlighted in Table 3 to demonstrate how the integration benefit changes with the operating regime. The dates and load values are taken from the 2025 GECOL records [10]. Low-load, medium-load, transition-rich, and peak-load conditions are compared using the same model, the same coefficients, and the same feasibility tests.

Table 3. Selected Operating Conditions, Source Dates, And Comparative Objectives

Operating Case and Source Date	Peak (MW)	Energy (GWh)	Integrated / Sequential (M CU)	Objective Reduction (%)
Low load 2025-05-05	4,665	93.314	3.493 / 3.670	4.832
Medium load 2025-01-05	6,243	129.585	5.046 / 5.151	2.025
Transition-rich 2025-04-06	5,510	105.970	4.032 / 4.205	4.102
Peak load 2025-08-05	8,166	181.881	7.327 / 7.403	1.019

Table 3 reports a positive saving in every selected condition. The low-load case provides the largest relative improvement because the integrated model can decommit initially online blocks that are not required later in the day. The transition-rich case also benefits from foresight because the optimizer coordinates an extended low-load interval with the subsequent evening recovery. On the peak day, most low-cost capacity is needed in both methods, so the schedules

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approach one another and the percentage improvement becomes 1.019%.

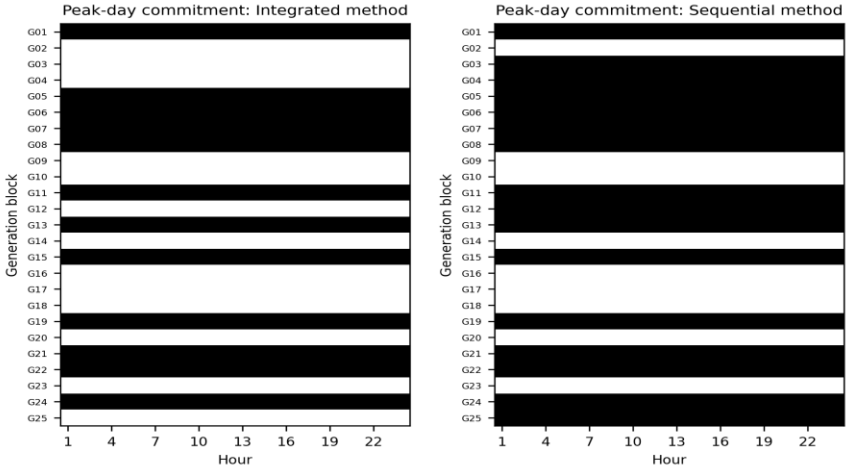


Fig. 3. Peak-day commitment matrices for the integrated and sequential methods.

Figure 3 compares the binary commitment matrices for the 8,166-MW peak day. Each row represents a generation block, each column an hour, black indicates online, and white indicates offline. The integrated solution averages 12 online blocks, compared with 16 for the sequential benchmark. Both schedules serve the same demand; the difference is the number of blocks retained online across the complete day.

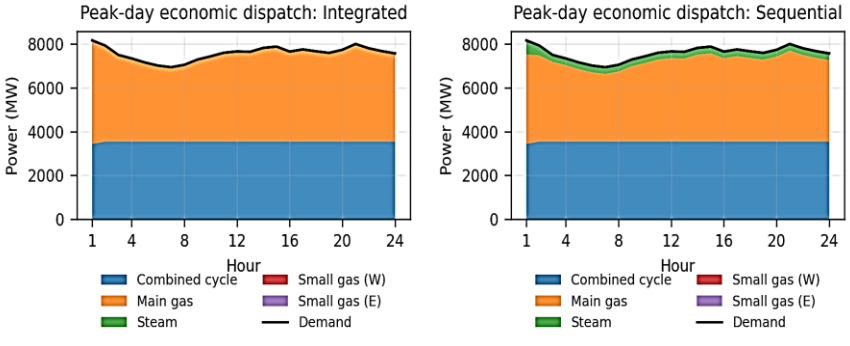


Fig. 4. Peak-day economic dispatch under integrated and sequential scheduling.

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Figure 4 converts the binary decisions in Figure 3 into continuous ED trajectories. The upper boundary of each stacked area follows the same hourly demand in both panels, confirming equal energy service. Relative to the sequential schedule, the integrated case reallocates 7.890 GWh from steam generation to main-gas blocks while preserving the combined-cycle contribution. This redistribution explains part of the objective reduction and shows how commitment and dispatch interact within the complete daily trajectory.

6.2 Aggregate Results

The aggregate comparison is reported in Table 4. In addition to cost and online depth, the table now reports explicit transitions and feasibility checks so that a lower commitment level is not interpreted as an unverified simplification.

Table 4. Complete Aggregate Comparison Over The Evaluated Operating Days

Metric	Integrated	Sequential
Energy served (GWh)	2,485.132	2,485.132
Aggregate objective (million CU)	96.987	98.942
Objective reduction	1.976%	Reference
Mean online blocks	9.17	14.99
Mean online-block reduction	38.81%	Reference
Recorded binary transitions	198	85
Verified balance/ramp/min-time violations	0	0

Table 4 confirms equal served energy and zero verified power-balance, ramp, and minimum-time violations in both approaches. Integrated scheduling reduces the aggregate objective by 1.955 million CU and the mean online-block count by 38.81%. It also records more explicit binary transitions, 198 compared with 85, because it actively removes excessive initial commitment and later restores only the capacity required by the complete trajectory. This

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result demonstrates that the integrated objective balances production, no-load, and transition cost rather than minimizing any single indicator in isolation. The increase in switching events is an important operational trade-off, particularly because frequent cycling may introduce additional maintenance and equipment-wear implications. Consequently, the economic advantage reported here remains conditional on the assumed start-up and shut-down cost coefficients, and its practical magnitude would require reassessment using validated plant-specific transition costs.

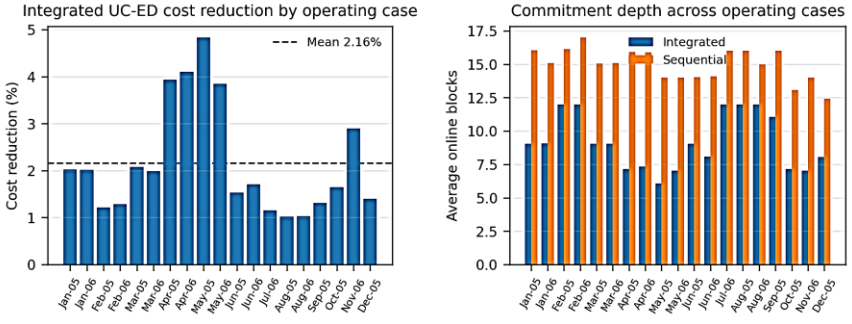


Fig. 5. Objective reduction and average commitment depth across operating cases.

Figure 5 contains two complementary panels. The left panel reports the saving for each operating date and shows that the integrated result is lower in all 19 cases. The right panel compares the mean number of online blocks and demonstrates that the integrated schedule consistently uses a shallower commitment. Reading the panels together confirms that the objective improvement is accompanied by a systematic reduction in unnecessary online capacity while the same demand and operating constraints remain satisfied.

6.3 Sensitivity to Demand Level

Table 5 groups the complete operating sample by peak-demand quartile. Figure 6 visualizes the same values so that the decline in both saving and commitment flexibility can be read directly.

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TABLE 5. OPERATING-CONDITION SENSITIVITY BY PEAK-DEMAND QUARTILE

Quartile	Cases	Mean Peak (MW)	Mean Objective Reduction (%)	Mean Online-Block Reduction (%)
Q1 - low	5	5,285	3.921	52.96
Q2	5	5,910	1.753	41.35
Q3	4	6,465	1.734	36.57
Q4 - high	5	7,726	1.142	24.99

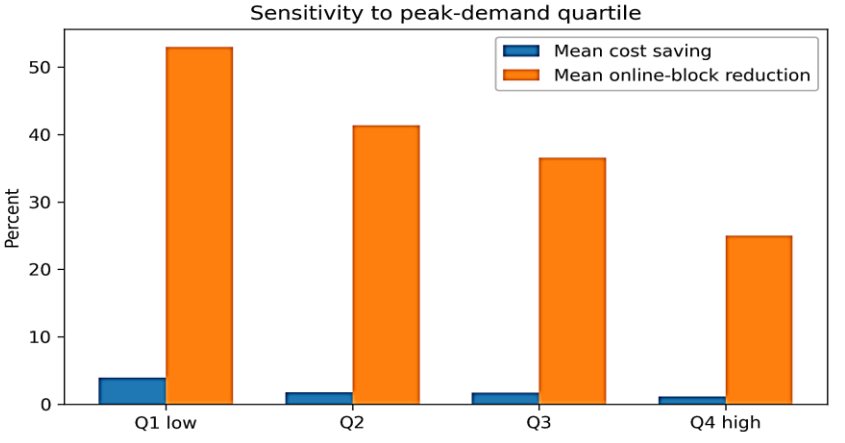


Fig. 6. Sensitivity of objective reduction and commitment-depth reduction to peak-demand quartile.

Table 5 and Figure 6 show a monotonic reduction in integration benefit as peak demand increases. Mean saving decreases from 3.921% in Q1 to 1.142% in Q4, while mean online-block reduction decreases from 52.96% to 24.99%. The observed correlation between peak demand and saving is -0.796, and the correlation between peak demand and online-block reduction is -0.932. The engineering interpretation is direct: at high demand both methods must use much of the fleet, whereas at lower demand the integrated model has more freedom to remove unnecessary commitment and coordinate later starts.

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6.4 Transition-Rich Operation and Cost Composition

The transition-rich case is 6 April 2025, when demand falls from approximately 4.47 GW to 3.41 GW before rising to 5.51 GW [10]. This case tests whether full-day foresight changes not only the objective value but also the type and timing of binary decisions. The integrated model schedules two starts and twelve stops, while the sequential benchmark schedules no starts and two stops. The integrated events release excessive initial commitment during the long low-load interval and restore only the capacity required for the later demand increase.

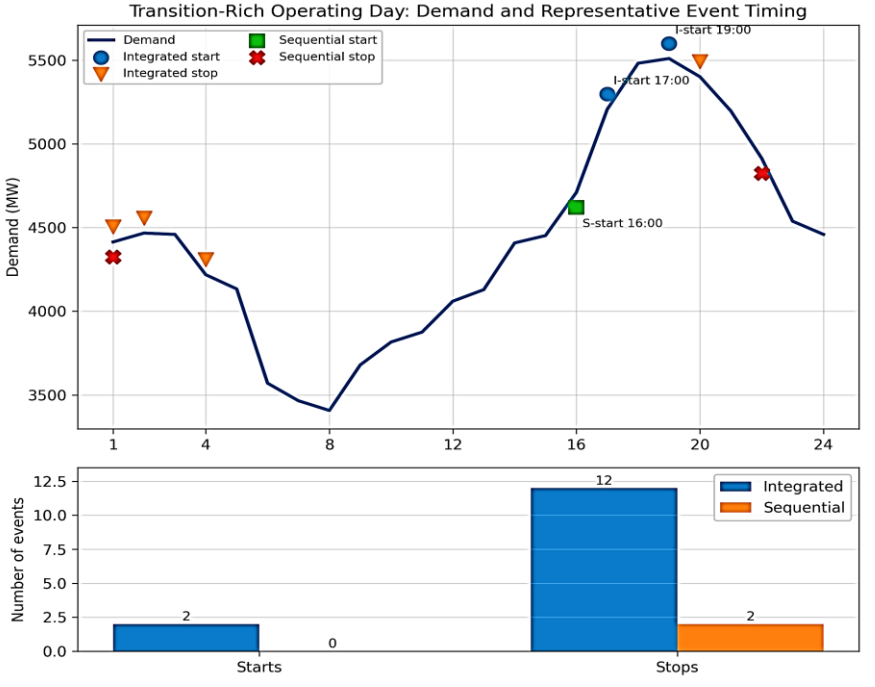


Fig. 7. Transition-rich case: representative event timing and complete start/stop counts.

Figure 7 has two panels. The upper panel places representative start and stop events on the measured demand trajectory using distinct marker shapes; integrated stops occur during the sustained low-load interval, and integrated starts are scheduled before the evening rise.

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The lower panel reports the complete event counts: two starts and twelve stops for the integrated solution, compared with zero starts and two stops for the sequential benchmark. Multiple blocks can change state at the same hour, which explains why the total count exceeds the number of visible event times in the upper panel.

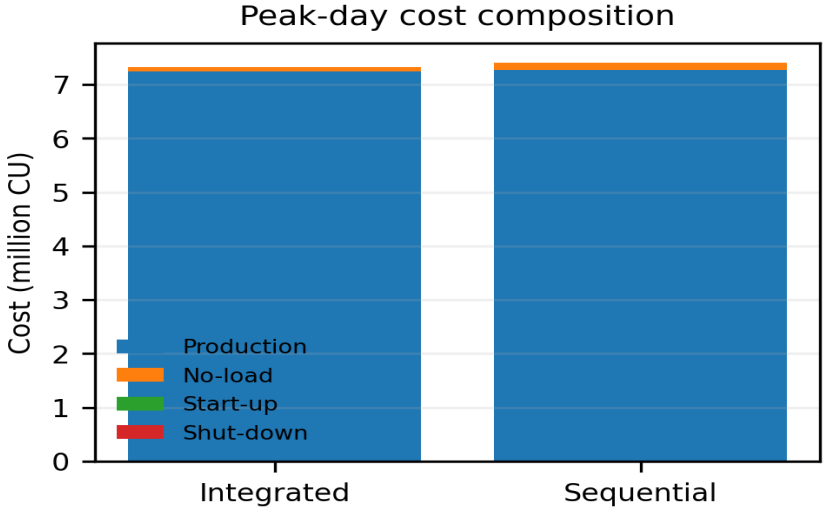


Fig. 8. Peak-day objective composition for the integrated and sequential schedules.

Figure 8 decomposes the peak-day objective into production, no-load, start-up, and shut-down components. Production cost dominates both bars because 181.881 GWh must be supplied in either case. The integrated bar is lower because the model carries fewer unnecessary online blocks and selects the technology allocation shown in Figure 4. Start-up and shut-down components are smaller, but their inclusion is essential because they prevent unrealistic cycling motivated only by short-term production cost.

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6.5 Full Operating-Sample Evidence

TABLE 6. COMPLETE OPERATING-DAY EVIDENCE USED IN THE SENSITIVITY ANALYSIS

Operating Date	Peak (MW)	Objective Reduction (%)	Online Reduction (%)	Transitions Int./Seq.
Jan-05	6,243	2.025	43.6	12/5
Jan-06	6,440	2.012	39.8	13/7
Feb-05	7,550	1.218	25.6	8/4
Feb-06	7,400	1.288	29.4	8/3
Mar-05	6,299	2.080	39.9	10/4
Mar-06	6,075	1.988	40.1	10/4
Apr-05	5,535	3.931	55.0	11/3
Apr-06	5,510	4.102	53.8	14/2
May-05	4,665	4.832	56.6	14/6
May-06	5,115	3.848	49.7	12/5
Jun-05	6,480	1.530	35.6	10/5
Jun-06	5,808	1.704	42.6	10/4
Jul-06	7,645	1.152	25.0	7/3
Aug-05	8,166	1.019	25.0	11/7
Aug-06	7,870	1.034	20.0	9/6
Sep-05	6,640	1.314	31.0	10/5
Oct-05	5,635	1.647	45.2	11/5
Nov-06	5,600	2.894	49.7	10/3
Dec-05	5,787	1.403	35.3	8/4

Table 6 provides the date, peak demand, saving, online-block reduction, and integrated/sequential transition counts for every evaluated operating day. It is the complete numerical basis of Table 5 and Figure 6. Positive improvement occurs on all dates, while transition count and saving vary with the initial commitment and the shape of the daily demand curve. The table therefore supports a joint interpretation of cost, commitment depth, and cycling rather than a conclusion based on one metric alone.

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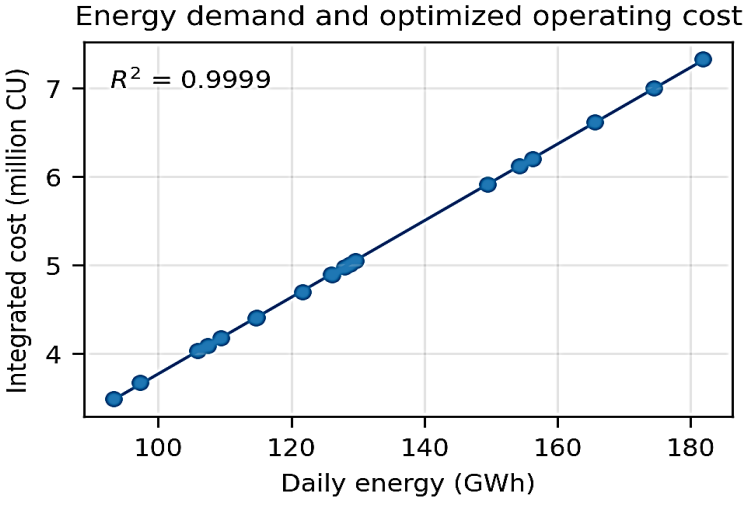


Fig. 9. Relationship between daily energy and the integrated operating objective; each point represents one operating date.

Each point in Figure 9 represents one of the 19 operating dates listed in Table 6. The horizontal coordinate is daily energy in GWh, and the vertical coordinate is the integrated objective in million CU. The fitted line yields $R^2 = 0.9999$, indicating a strong association between daily energy production and the modeled operating objective. This relationship is expected because production cost constitutes the dominant component of the objective and should not be interpreted as independent evidence of the superiority of integrated scheduling. The benefits of temporal integration are instead quantified through the direct comparison with the sequential benchmark presented in Table 6 and Figure 5.

7. Engineering Discussion and Practical Implications

The results establish that integrated UC-ED improves day-ahead scheduling through temporal foresight rather than through a different cost function. It can release initially online but uneconomic blocks, postpone start-up until capacity is actually required, and select a lower-cost technology combination while satisfying the same hourly demand. This operating mechanism is consistent with

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the intertemporal logic emphasized in standard UC formulations [1], [3]-[11].

The sensitivity analysis explains why one headline percentage cannot represent all operating conditions. During high-demand days, both methods require a large part of the available fleet and their commitment patterns converge. During low-demand days, the integrated model has greater freedom to remove excess online capacity. The transition-rich case adds a second insight: the lower-cost solution may intentionally use more start and stop events when the resulting reduction in production and no-load cost is larger than the modeled transition cost. Cost, online depth, transition timing, and feasibility margins should therefore be reviewed together. Since the objective uses calibrated comparative cost coefficients rather than audited plant-level expenditure data, the reported savings should be interpreted as reductions in the modeled operating objective, not as verified monetary or fuel savings.

For system operators, the most useful output is not the objective value alone but the full schedule: the online state of every block, the start and stop time, the dispatched MW, and the remaining flexibility in each hour. The controlled comparison shows that these decisions can change materially even when the demand and unit data are identical. An integrated day-ahead schedule therefore provides a clearer basis for dispatch preparation, fuel coordination, and operator review than a sequence of isolated hourly decisions.

7.1 Numerical Verification

Every integrated and sequential solution was checked for hourly power balance, binary consistency, generation bounds, ramp feasibility, and minimum up/down obligations. The same case builder and the same coefficient set were used for both methods. MATLAB provides the primary solution, while the independent SciPy/HiGHS reconstruction provides a second computational path [16], [17]. Agreement in served energy, objective value, integer status, and constraint residuals confirms that the reported differences are scheduling effects rather than software-specific artifacts.

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8. Implementation Recommendations

A practical day-ahead workflow can be organized into five auditable steps. First, update the hourly demand forecast, current unit status, and starting output. Second, refresh unit availability and the approved scheduling parameters. Third, solve the complete 24-hour UC-ED model and verify power balance, generation limits, ramping, and minimum-time conditions. Fourth, compare the optimized schedule with the current operating plan and identify every change in commitment or dispatch. Fifth, submit the proposed schedule for operator review and use the approved terminal states and outputs as the initial condition for the next scheduling cycle.

The sensitivity procedure used in this paper should be retained as a routine operating study. Re-solving the model for low, medium, transition-rich, and peak conditions shows how the economic value of integration changes with commitment flexibility. The same framework can be extended to additional operating days, detailed unit representations, and longer horizons while preserving the controlled comparison between full-horizon and sequential scheduling.

A progressive implementation is recommended: historical replay, comparison with recorded operating decisions, parameter refinement from observed plant performance, and then advisory day-ahead use alongside the existing dispatch process. This sequence preserves engineering oversight while building a traceable evidence base for wider deployment.

9. Conclusion

This paper compared integrated 24-hour UC-ED with a sequential one-hour benchmark using identical Libyan demand, generation blocks, initial conditions, and cost inputs. Both methods supplied 2,485.132 GWh and satisfied the stated feasibility checks. Integrated scheduling reduced the aggregate objective from 98.942 to 96.987 million CU, a 1.976% reduction, and decreased the mean online commitment from 14.99 to 9.17 blocks.

The principal technical result is that the value of integration depends on commitment flexibility. Full-day foresight releases excessive online capacity and coordinates future starts, whereas peak

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conditions naturally reduce the difference between the methods because much of the fleet is required in either case. The quartile analysis quantified this effect: mean objective reduction declined from 3.921% in the lowest peak-demand quartile to 1.142% in the highest, while mean online-block reduction declined from 52.96% to 24.99%.

The transition-rich case further showed that a lower-objective integrated schedule can use more explicit state changes when those actions release unnecessary initial commitment and reduce production and no-load costs over the full day. The engineering conclusion is therefore not to minimize switching events in isolation, but to evaluate objective value, commitment depth, transition timing, and feasibility together. The resulting framework provides a transparent basis for advisory day-ahead scheduling and can be extended to unit-level and network-aware formulations.

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