Monetizing Data-Centre Flexibility Across French Day-Ahead and Intraday Continuous Markets

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***Abstract*—The rapid growth of AI and digital/cloud services, coupled with the spatial concentration of data centers (DCs), is placing increasing stress on the power systems. Fortunately, in most cases, DCs combine deferrable computing, cooling inertia, battery energy storage systems (BESSs), and uninterruptible power supplies (UPSs) that allow DC operation as a flexible load, within operational limits. This paper is an attempt at coordinating these resources across the day-ahead (DA) and intraday continuous (IDC) markets to identify trading opportunities that minimize energy cost over a single day while also allowing for arbitrage and virtual/speculative bids in the IDC. A quarter-hour mixed-integer linear program (MILP) selects a risk-averse DA bidding schedule considering 100 price scenarios while over 130 causal IDC updates revise physical and virtual positions. A 15-min IDC price signal is refined using Ornstein–Uhlenbeck interpolation every 10s, while requested orders/bids are executed through gated time-weighted average price (TWAP) execution under adverse stochastic slippage and controller-induced non-execution. The power-balance dual is converted into a slippage budget which acts as a hard constraint at each execution step. Three one-day French-market cases compare import-only operation, allowed BESS export, and risk-neutral DA bidding with allowed export. The gated bid execution yields 20.14–20.80% savings against the DA-only comparator, versus 33.88–42.04% under guaranteed fill, while reducing implementation loss by €356.07–€367.89. The simulation results present a realistic (although limited) market participation scenario for a DC under asset flexibility, and make a strong case for pursuing operational flexibility via software layers.**

***Index Terms*—Data-centre flexibility, day-ahead market, intraday continuous market, CVaR, mixed-integer linear programming, shadow price, TWAP**

I. Introduction

The rapid expansion of cloud computing, artificial intelligence, and digital services is concentrating large electrical loads in regions where grid capacity is already scarce. ENTSO-E estimates that Europe hosts more than 10,000 data centres (DCs) above 50 kW IT load, representing approximately 12.7 GW of installed IT capacity, and projects that their electricity demand will increase by more than 50% between 2025 and 2030 [1]. Grid availability and connection delays are therefore becoming material constraints on further DC development [2], [3]. In addition to their annual energy demand, the size and spatial concentration of new DC connections can create local adequacy, congestion, and operational challenges for the power system. A DC is nevertheless not a completely inflexible consumer. Selected computing tasks can be deferred within service-level-agreement (SLA) deadlines, cooling systems can exploit thermal inertia, and uninterruptible power supply (UPS) batteries can respond rapidly while retaining the energy reserve required for emergency operation. A dedicated battery energy storage system (BESS) adds a resource that is better suited to repeated cycling and, where permitted, grid export. These resources differ in response speed, duration, recovery requirements, degradation, and operational criticality. Their market value must therefore be assessed through an integrated model that preserves workload completion, thermal safety, storage dynamics, UPS resilience, and the point-of-connection limit [4]–[7].

Most DC energy-management studies optimize electricity cost under a single price or tariff signal, or examine demand response and frequency support using selected facility resources [8]–[13]. These studies establish that computing, cooling, UPS capacity, and local storage can provide technically useful flexibility. However, technical flexibility alone does not establish its economic value to a DC operator who must recover the cost of control integration, storage degradation, additional equipment, and any contractual arrangements required to make tenant workloads schedulable, while continuing to satisfy availability and resilience requirements.

A related but largely separate literature considers sequential day-ahead (DA) and intraday market participation by storage and other flexible assets. These studies address stochastic recourse, virtual positions, intraday forecasting, transaction costs, and repeated market updates [14]–[20]. They generally omit the deadline-constrained computing, multistate thermal dynamics, and protected UPS reserve that determine the opportunity cost of changing a DC power trajectory. Conversely, the DC literature rarely evaluates the combined economic potential of DA procurement, causal intraday continuous (IDC) repositioning, asset-backed arbitrage, and bounded virtual trading while representing the friction encountered during order execution due to liquidity constraints and competing bidding parties for the same opportunities.

A further gap arises between an order selected by an optimization model and the value that can actually be realized when that order is executed in continuously evolving IDC

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markets having limited liquidity and competing agents. In an IDC market, a parent order may be split up into multiple child orders to limit exposure to adverse price movement, limited bid–ask depth, slippage, competing orders, and possible non-execution before delivery [21], [22]. This paper develops an execution-aware, sequential DA–IDC framework for an integrated IT–cooling–BESS–UPS system. A quarter-hour risk-averse mixed-integer linear program (MILP) determines a common DA schedule from stochastic price scenarios using conditional value-at-risk. Causal rolling optimization subsequently updates physical and bounded virtual IDC positions as new price information becomes available. Requested IDC quantities are evaluated on a 10-s price trajectory and settled through dual- or forecast-gated time-weighted average price (TWAP) execution under execution friction. A brief summary of our main contributions is given as follows:

1) An integrated quarter-hour DC model that co-optimises deferrable IT workload, cooling flexibility, BESS, and a reserve-constrained UPS under hard SLA, thermal, storage, resilience, and grid-connection limits.
2) A controlled comparison of risk-averse import-only, risk-averse BESS-export, and risk-neutral export cases within sequential DA procurement and causal IDC repositioning, with physical and virtual trading outcomes reported separately.
3) An execution-aware IDC layer that compares guaranteed full fill with partial dual-gated TWAP, and rolling position feedback.

II. Market Sequence and Position Accounting

The coupled DA auction applies uniform marginal (pay-as-cleared) pricing, whereas IDC orders are continuously matched at the resting order's limit price, i.e., trade-by-trade pay-as-bid settlement. Table I links the European/French timeline to the controller. Times are CET/CEST. EPEX reports a zero-minute French *local* IDC lead time, while cross-zonal closure is a separate constraint and RTE has a derogation from the 30-min rule through 2028. The simulation deliberately uses $T - 15$ min as its final actionable control instant; this is a conservative model cutoff, not the statutory local gate closure.

DA establishes the initial physical position. IDC asset-backed trades modify the intended net import/export, whereas a bounded virtual overlay opens and closes a financial position without changing the final dispatch. All signed positions use import-positive convention. Residual metered deviation is assigned to the BRP and is not treated as a free balancing resource.

III. Methodology

The delivery horizon is $\mathcal{T} = \{1, \ldots, 96\}$ with $\Delta t = 0.25$ h. Only DA prices are stochastic. IDC prices are revealed causally along one synthetic path; workload, equipment availability, and thermal parameters are deterministic.

A. Integrated data-centre model

Let $a_t = u_t^{\mathrm{arr}} \Delta t$ be flexible CPU-hours arriving in MTU t and f_{tr} the share assigned to deadline tranche r with delay d_r. With $A_t = \sum_{\tau \le t} a_\tau$, cumulative work due D_t, execution state $X_t = X_{t-1} + u_t^{\mathrm{flex}} \Delta t$, and backlog $b_t = A_t - X_t$, the queue model is

$$\begin{aligned} D_t \le X_t \le A_t, \qquad b_t = A_t - X_t, \\ P_t^{\mathrm{IT}} \simeq P_0 + (P_{\max} - P_0)(u_t^{\mathrm{inf}} + u_t^{\mathrm{flex}})^\gamma. \end{aligned} \tag{1}$$

Here D_t accumulates $a_\tau f_{\tau r}$ at $\min(\tau + d_r, 96)$. The linear holding rate is calibrated from the four deadline values c_r as

$$\begin{aligned} h &= \frac{\sum_{t,r} a_t f_{tr} c_r / (d_r \Delta t)}{\sum_{t,r} a_t f_{tr}} = 8.7324 \text{ EUR/(CPU-h h)}, \\ C^{\mathrm{IT}} &= h \Delta t \sum_t b_t. \end{aligned} \tag{2}$$

The 24-hour inflexible/flexible utilisation profile and the hourly shares of the four deferral classes are adopted without modification from Tables II–III of Takci et al. [5]. Each hourly entry is repeated over four quarter-hours; optimisation may then reschedule only the flexible component.

The four-state vector $\boldsymbol{\theta} = [T^{\mathrm{IT}}, T^{\mathrm{rack}}, T^{\mathrm{cold}}, T^{\mathrm{hot}}]^\top$ obeys

$$\boldsymbol{\theta}_{t+1} = \mathbf{A}\boldsymbol{\theta}_t + \mathbf{B}[P_t^{\mathrm{IT}}, P_t^{\mathrm{ch}}]^\top + \mathbf{e}T^{\mathrm{out}}, \tag{3}$$

where $(\mathbf{A}, \mathbf{B}, \mathbf{e})$ are the zero-order-hold discretisation of the continuous RC network over 900 s. Initial and target terminal states are steady states evaluated at the first and last baseline utilisations. The supply temperature is $T_t^{\mathrm{sup}} = T_t^{\mathrm{hot}} - \mathrm{COP} P_t^{\mathrm{ch}} / (\dot{m} c_p)$ and is restricted to 18–30°C in the implemented model.

For $a \in \{\mathrm{BESS}, \mathrm{UPS}\}$,

$$E_{t+1}^a = E_t^a + \eta_{\mathrm{ch}}^a P_{t,\mathrm{ch}}^a \Delta t - P_{t,\mathrm{dis}}^a \Delta t / \eta_{\mathrm{dis}}^a, \tag{4}$$

$$\underline{E}^a \le E_t^a \le \bar{E}^a, \quad E_0^a = E_{96}^a = E_{\mathrm{ini}}^a, \tag{5}$$

$$0 \le P_{t,\mathrm{ch}}^a \le \bar{P}_{\mathrm{ch}}^a z_t^a, \quad 0 \le P_{t,\mathrm{dis}}^a \le \bar{P}_{\mathrm{dis}}^a (1 - z_t^a). \tag{6}$$

For the BESS, $E_{\mathrm{ini}}^{\mathrm{B}} = 0.5 \bar{E}^{\mathrm{B}}$ and the 10–90% SoC bounds apply. For the UPS, $E_{\mathrm{ini}}^{\mathrm{U}} = \bar{E}^{\mathrm{U}}$, $\underline{E}^{\mathrm{U}} = E^{\mathrm{res}} = \bar{P}^{\mathrm{U}}(20/60)/\eta_{\mathrm{dis}}^{\mathrm{U}}$, and $P_{t,\mathrm{dis}}^{\mathrm{U}} \le P_t^{\mathrm{IT}}$. Thus UPS discharge can offset only IT demand; together with the balance below, any negative grid exchange is necessarily backed by concurrent BESS discharge. BESS export is enabled only in S2–S3. The point-of-connection balance is

$$\begin{aligned} P_t^{\mathrm{g}} = P_t^{\mathrm{IT}} + P_t^{\mathrm{ch}} + P^{\mathrm{aux}} + P_{t,\mathrm{ch}}^{\mathrm{B}} - P_{t,\mathrm{dis}}^{\mathrm{B}} \\ + P_{t,\mathrm{ch}}^{\mathrm{U}} - P_{t,\mathrm{dis}}^{\mathrm{U}}. \end{aligned} \tag{7}$$

TABLE I
CHRONOLOGICAL DA–IDC ACTIONS FOR DELIVERY DAY D

Time	Market/system event	DC/BRP action	Position or information update
D−1, 09:30–10:30	Cross-zonal capacities published	Finalise scenarios and feasible DA bids	Capacity and 100 DA price scenarios available
D−1, 12:00	SDAC order-book closure	Submit non-anticipative physical nomination	DA order book fixed
D−1, about 12:57	Final coupled results normally published	Record cleared prices/volumes and initialise BRP position	DA schedule becomes the reference position
D−1, about 15:00	IDC continuous trading opens	Start causal rolling MILP for all 96 quarter-hour MTUs	Current IDC quotes replace DA anchors as revealed
D−1/D, every 15 min	IDC order-book update	Re-optimise; execute accepted physical/virtual parents through 10-s TWAP	Filled trades update physical and virtual positions
Until local T; model uses $T-15$	Product-specific closure	Close virtual position; stop discretionary execution at model cutoff	Final market position sent for nomination
At/after delivery	Metering and imbalance settlement	BRP reconciles realised injection/withdrawal	Residual deviation settled as imbalance

The complete non-energy operating cost implemented in the MILP is

$$C^{\text{flex}} = \frac{c_{\text{B}}\Delta t}{1000}\sum_t (P^{\text{B}}_{t,\text{ch}} + P^{\text{B}}_{t,\text{dis}}) + \frac{c_{\text{U}}\Delta t}{1000}\sum_t (P^{\text{U}}_{t,\text{ch}} + P^{\text{U}}_{t,\text{dis}}) + C^{\text{IT}} + c_{\text{R}}\Delta t\sum_t \delta_t^2 + c_\theta \Delta t \sum_t [T^{\text{cold}}_t - T^{\text{soft}}]^2_+ + \frac{c_\Delta}{1000}\sum_{t\in\mathcal{R}} |P^{\text{ch}}_t - P^{\text{ch}}_{t-2}| + c_T \sum_{j=1}^{4} |\theta_{96,j} - \theta^\star_j|, \tag{8}$$

where $\delta_t = (\bar{E}^{\text{U}} - E^{\text{U}}_t)/(\bar{E}^{\text{U}} - E^{\text{res}})$, $\mathcal{R} = \{2, 4, \ldots, 94\}$, and the squared terms use the tabulated PWL approximations. During rolling IDC re-optimisation only, the objective also contains the physical-repositioning regulariser $C^{\text{rep}}_k = \bar{s}\Delta t \sum_t |P^{\text{g}}_{k,t} - q^{\text{phys}}_{k,t}|/1000$; it represents expected execution slippage and is excluded from reported physical-flexibility cost.

B. Risk-averse DA schedule and IDC recourse

For DA scenario $s \in \mathcal{S}$, the common schedule $\boldsymbol{y} \in \mathcal{Y}$ has cost

$$L_s(\boldsymbol{y}) = \sum_t \lambda^{\text{DA}}_{s,t} P^{\text{g}}_t \Delta t/1000 + C^{\text{flex}}(\boldsymbol{y}). \tag{9}$$

The non-anticipative DA schedule solves

$$\min_{\boldsymbol{y},\eta,\xi} (1-\beta)\sum_s \pi_s L_s + \beta\left(\eta + \frac{\sum_s \pi_s \xi_s}{1-\alpha}\right), \quad \text{s.t. } \boldsymbol{y}\in\mathcal{Y}, \quad \xi_s \ge L_s - \eta, \quad \xi_s \ge 0. \tag{10}$$

S1–S2 use $(\alpha, \beta) = (0.9, 0.5)$; S3 uses $\beta = 0$.

IDC prices are initialised by the cleared DA curve and replaced, product by product, as observations arrive. At decision k, delivered dispatch is fixed, the remaining 96-MTU physical MILP is re-solved using the hybrid price curve, and previous fills define $q^{\text{phys}}_{k,t}$. The parent adjustment is $\Delta q^{\text{phys}}_{k,t} = P^{\text{g}}_{k,t} - q^{\text{phys}}_{k,t}$; the rolling objective contains C^{rep}_k from (8). Filled parents update the position before the next solve.

For the separate virtual overlay, the exponential moving average and causal forecast are

$$m_{k,t} = 0.30 p_{k,t} + 0.70 m_{k-1,t}, \quad \hat{p}_{k,t} = 0.25 p^{\text{DA}}_t + 0.75 m_{k,t}, \qquad m_{0,t} = p^{\text{DA}}_t. \tag{11}$$

Let $v_{k,t} = v^+_{k,t} - v^-_{k,t}$ be the target, $v^{\text{old}}_{k,t}$ the open position, and $w_{k,t} \ge |v_{k,t} - v^{\text{old}}_{k,t}|$. Up to the common positive energy-conversion factor, all currently tradable products solve

$$\min \sum_t \{p_{k,t}(v_{k,t} - v^{\text{old}}_{k,t}) + \bar{s} w_{k,t} - \hat{p}_{k,t} v_{k,t} + (\bar{s} + c_v)(v^+_{k,t} + v^-_{k,t})\}, \tag{12}$$

subject to $0 \le v^\pm_{k,t} \le \bar{v}$, a binary selector preventing simultaneous long and short positions, and $v_{k,t} = 0$ at the final actionable decision. Here $\bar{s} = 1.5$ EUR/MWh and $c_v = 1$ EUR/MWh. Physical and virtual parents below 1 kW are suppressed except for mandatory final reconciliation.

C. Fixed-LP dual and execution gate

Constraint duals are undefined for the MILP itself. After obtaining incumbent integer modes $\boldsymbol{z}^\star_k$, a continuous fixed model is formed:

$$\min_{\boldsymbol{x}} \; c_k^\top \boldsymbol{x} \quad \text{s.t. } A\boldsymbol{x} = b, \; G\boldsymbol{x} \le h, \; \boldsymbol{z} = \boldsymbol{z}^\star_k. \tag{13}$$

The fixed LP is solved to optimality and the dual $\pi^{\text{bal}}_{k,t}$ of (7) is read. Because the balance is expressed in kW while the objective is in EUR, its energy-value form is

$$\mu_{k,t} = \frac{1000}{\Delta t}\pi^{\text{bal}}_{k,t} \quad [\text{EUR/MWh}]. \tag{14}$$

$\mu_{k,t}$ is the local value of one additional MWh conditional on the chosen binary modes and active PWL segment. For a physical parent with direction $d_i = \text{sgn}(\Delta q_i)$ and submission price p^0_i, the maximum accepted execution-cost headroom is

$$B_i = \left[d_i(\mu_{k,t} - p^0_i) - \kappa\right]_0^{B_{\max}}, \qquad g_{i,n} = d_i(p_{i,n} - p^0_i) + \bar{s}, \tag{15}$$

where κ is a safety haircut and $[\cdot]_0^{B_{\max}}$ clips the budget. Child n is released only if $g_{i,n} \le B_i$. Thus the decision uses the observed reference price $p_{i,n}$ and expected slippage $\bar{s}$; realised slippage is sampled only after release and cannot leak into the

TABLE II
DUAL-GATED EXECUTION AND FALLBACK LOGIC

Condition	Execution action
Physical dual valid	Use (15); release while $g_{i,n} \le B_i$
Physical dual unavailable	Use $B^{\text{fb}} = 1.5$ EUR/MWh; log fallback
Virtual parent	Use forecast-edge budget (16)
First budget breach	Stop parent; defer unfilled residual
Final actionable decision	Force residual at 2.5 EUR/MWh slippage

gate. For a virtual parent, the corresponding budget is based on its causal forecast,

$$B_i^{\text{v}} = \left[d_i(\hat{p}_{k,t} - p_i^0) - c_v - \kappa\right]_0^{B_{\max}}, \tag{16}$$

rather than the physical power-balance dual.

The physical dual is rejected when the rolling MILP is not optimal, the fixed model is not an optimal continuous LP, a dual is missing/non-finite, or a ± 1 kW finite-difference check at the largest planned adjustment differs by more than 0.25 EUR/MWh. The implemented parameters are $\kappa = 0$, $B_{\max} = 2.5$ EUR/MWh, and a fixed physical fallback budget $B^{\text{fb}} = 1.5$ EUR/MWh. A first breach stops that parent and returns its unfilled quantity to the next rolling solve. At the final actionable decision, the simulator forces any remaining physical or virtual mismatch at the last reference price and the worst configured slippage, 2.5 EUR/MWh.

D. Nested IDC path and TWAP settlement

The causal 15-min IDC trajectory is read from the optimizer feed; the published ID Full, ID3, ID1, and Last series are used for plotting and alignment checks, not directly by the 10-s generator. Between consecutive feed anchors P_j and P_{j+1}, first generate $y_0 = 0$ and $y_n = \phi_r y_{n-1} + \sigma_r \varepsilon_n$. The exact Gaussian AR(1)/OU bridge is

$$\begin{aligned} x_n &= y_n - \frac{\phi_r^{N-n} V_n}{V_N} y_N, \quad V_n = \sigma_r^2 \frac{1 - \phi_r^{2n}}{1 - \phi_r^2}, \\ p_n &= (1 - n/N) P_j + (n/N) P_{j+1} + x_n, \qquad N = 90, \end{aligned} \tag{17}$$

which enforces $x_0 = x_N = 0$. For regime r, the robust 15-min change scale is $s_r = \max\{0.5, 1.4826\,\text{MAD}(\Delta P)\}$, $\sigma_r = s_r/\sqrt{90}$, and $\phi_r = \exp[-(\ln 2)10/h_r]$ with $h_r = 240/150/90$ s for early/ID3/ID1. Cross-product dependence is imposed by $\varepsilon_{j,n} = \sqrt{0.35}\varepsilon_n^c + \sqrt{0.65}\varepsilon_{j,n}^s$. Only the offline simulator sees P_{j+1}.

Each parent is split into 90 equal scheduled children, $q_{i,n} = \Delta q_i / 90$, with signed energy $e_{i,n} = q_{i,n}\Delta t/1000$, and

$$p_{i,n}^{\text{ex}} = p_{i,n} + d_i s_{i,n}, \qquad s_{i,n} \sim \mathcal{U}(0.5, 2.5) \text{ EUR/MWh}. \tag{18}$$

Equation (18) is evaluated only for a released child. Once the gate stops, later scheduled children remain rejected even if the reference price subsequently improves; only executed volume updates the market position. A forced final residual is recorded separately. The full-fill comparator uses the same OU paths and slippage seed with the gate disabled. Market impact, queue priority, empirical fill probability, and the 0.1-MW market-volume increment remain outside the settlement model.

E. Settlement and performance accounting

With import/buy positive, the implemented market costs are

$$\begin{aligned} C^{\text{DA}} &= \frac{\Delta t}{1000} \sum_t p_t^{\text{DA}} q_t^{\text{DA}}, \quad C^{\text{IDC}} = \sum_{i,n} p_{i,n} e_{i,n}, \\ C^{\text{slip}} &= \sum_{i,n} s_{i,n} |e_{i,n}|, \qquad\qquad r_t = P_t^{\text{g}} - (q_t^{\text{phys}} + v_t). \end{aligned} \tag{19}$$

The IDC and slippage sums include released children and forced final rows only; rejected children have zero energy and do not update either position. For residual volume $x_t = |r_t|\Delta t/1000$, the post-settlement progressive imbalance charge is

$$C^{\text{imb}} = \sum_t \sum_{m \ge 0} (c_0 + m\Delta c) \min\{[x_t - mW]_+, W\}, \tag{20}$$

where $(W, c_0, \Delta c) = (10, 5, 5)$ in MWh and EUR/MWh. It is not anticipated by the optimiser. The realised and ideal costs, benefit, and execution loss are

$$\begin{aligned} C^{\text{real}} &= C^{\text{DA}} + C^{\text{IDC}} + C^{\text{slip}} + C^{\text{flex}} + C^{\text{imb}}, \\ C^{\text{ideal}} &= C^{\text{DA}} + \sum_i p_i^0 e_i + C^{\text{flex}} + C^{\text{imb}}, \\ V &= C^{\text{ref}} - C^{\text{real}}, \\ L^{\text{impl}} &= C^{\text{real}} - C^{\text{ideal}} = L^{\text{move}} + C^{\text{slip}}. \end{aligned} \tag{21}$$

Virtual margin is reported separately as the negative of its IDC cash flow plus slippage; final virtual positions are zero.

IV. CASE STUDY AND RESULTS

A. Setup

The study day is 28 July 2026 in the French bidding zone. The realised DA price and ID Full, ID3, ID1, and Last series are the actual published indices for delivery on 28 July 2026 [23]. The 100 DA planning scenarios are loaded from the 30 July 2026 source-date block and mapped to the 28 July horizon by quarter-hour slot. The separate 28 July optimizer feed provides the causal 15-min IDC anchors. Gurobi 12.0.3 solves the MILPs. Table III reports the scalar inputs used in every run; the time-series price inputs are shown in Fig. 1.

Figure 1(a) compares the realised DA price with the mean of the 100 input scenarios for each MTU. The CVaR cases use the full scenario set, whereas the mean drives S3's expected-cost objective. Figure 1(b) shows the four EPEX IDC indices used to characterise and validate the study day; the separate causal optimizer feed supplies the OU-bridge anchors.

The reference fixes IT utilisation to the baseline profile and disables BESS and UPS operation, while retaining optimised cooling under realised DA prices. It is therefore a DA-only, no-dispatchable-flexibility comparator rather than a completely rigid facility.

TABLE III
DATA-CENTRE AND MARKET SIMULATION SPECIFICATIONS (ALL CASES UNLESS STATED)

Group	Parameters	Values
Horizon and site	MTUs; duration; auxiliary demand; grid import/export limits	96; 0.25 h; 53.095 kW; 1.50/1.25 MW
IT demand	Idle/rated power; power exponent; PWL points	166.7/1000 kW; 1.32; 6
Flexible IT	Deadline tranches; delay values; calibrated linear holding rate	0.5/1/2/3 h; 12/8/4/2 EUR/(CPU h); 8.7324 EUR/(CPU-h h)
BESS rating	Charge/discharge power; AC-deliverable/internal nominal energy	1.25/1.25 MW; 2.50/3.289 MWh
BESS operation	Charge/discharge efficiency; SoC min/max/initial; throughput cost	0.95/0.95; 10/90/50%; 5 EUR/MWh
UPS rating	Installed/critical power; runtime; nominal/reserve energy	1.25/1.00 MW; 20 min; 0.906/0.453 MWh
UPS operation	Charge limit; charge/discharge efficiency; energy multiplier; throughput/readiness cost; PWL points	270 kW; 0.82/0.92; 2; 3 EUR/MWh; 15 EUR/h; 9
Cooling plant	COP; chiller limit; air flow; air heat capacity; flow effectiveness	5; 400 kW; 100 kg/s; 1.005 kJ/(kg K); 0.766
Thermal masses	IT/rack/cold-aisle/hot-aisle capacitance	17880/18020/2330/1170 kJ/K
Thermal coupling	IT–rack/cold–ambient conductance; ambient/initial cold temperature	109/4.484 kW/K; 22/22°C
Temperature limits	Implemented supply; cold min/soft/hard; rack/hot; IT	18–30; 18/22.5/23; 18–40; 18–60°C
Thermal costs	Buffer; terminal; chiller ramp penalty; buffer PWL points	80 EUR/(K^{2}h); 100 EUR/K; 2 EUR/MW-change; 9
DA cases	Scenarios/source date; α; β; BESS export	100/30 Jul. 2026; 0.9; S1/S2: 0.5, S3: 0; no/yes/yes
IDC control	Opening; decision interval; simulated gate lead; virtual limit	15:00 D–1; 15 min; $T - 15$ min; 1.25 MW
Execution	TWAP window/step; slippage min/max/mean	15 min/10 s; 0.5/2.5/1.5 EUR/MWh
Gate	κ; budget cap; fallback; finite-difference step/tolerance	0; 2.5; 1.5 EUR/MWh; 1 kW/0.25 EUR/MWh
OU bridge	Common-shock correlation; volatility scale; half-lives early/ID3/ID1; 10-s sigmas	0.35; 1; 240/150/90 s; 0.084/0.321/0.780 EUR/MWh
Virtual signal	DA weight; EMA factor; risk charge; minimum trade	0.25; 0.30; 1 EUR/MWh; 1 kW
Imbalance curve	Band width; first-band rate; rate increment	10 MWh; 5 EUR/MWh; 5 EUR/MWh
Solver and seed	Time limit; MIP gap; feasibility tolerance; full rolling solve; sampling^a; seed	20 s; 10^{-4}; 10^{-7}; yes; 1/1/2/1 slots; 20260728

^{a}UPS readiness, thermal buffer, chiller ramp, and physical-trade regularizer, respectively.

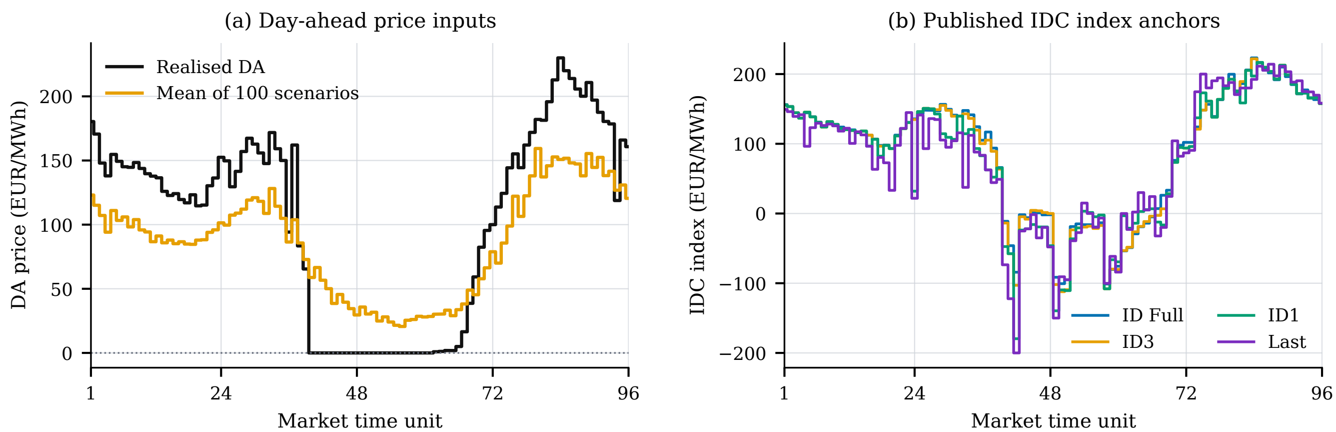

Fig. 1. Price inputs for delivery on 28 July 2026: (a) actual realised DA price and the mean of 100 planning scenarios; (b) actual ID Full, ID3, ID1, and Last indices used for study-day characterisation and alignment checks.

B. Risk, export, and feasibility

Figure 2(a) shows independently ranked scenario costs. Negative low-rank values arise from negative DA prices, not from an accounting error. Export reduces expected DA cost from €1369.10 (S1) to €1342.01 (S2) and its 90% CVaR from €2450.92 to €2416.91. S3 reduces expected DA cost by a further €6.82, but its diagnostic tail mean rises by €31.51 relative to S2. Moderate risk aversion therefore has little realised one-day cost but retains tail protection.

Figure 2(b) shows the irreversible within-parent stop. The gate uses expected, not realised, slippage; execution-price dots therefore appear only after release. A later recovery of the reference path does not reopen the stopped parent, although its unfilled volume may be reconsidered at the next 15-min optimisation.

The physical audit in Table IV confirms that S2–S3 export is backed by BESS discharge while S1 grid exchange remains nonnegative. The 1.5-MW import limit, 1.25-MW export limit, storage reserves, 22.5°C soft thermal limit, and every workload deadline are respected. S2 increases BESS use from 1.76 to 2.30 equivalent cycles, so degradation and warranty sensitivity are necessary before investment conclusions.

TABLE IV
OPERATIONAL FEASIBILITY

Metric	S1	S2	S3
Maximum import (MW)	1.500	1.500	1.500
Maximum export (MW)	0	1.121	1.121
Minimum BESS SoC (%)	10.00	10.00	10.00
Minimum UPS SoC (%)	70.88	70.79	70.79
Maximum cold aisle (°C)	22.50	22.50	22.50
Work completed (%)	100	100	100
BESS equivalent cycles	1.76	2.30	2.30
Balance error (kW)	0	0	0

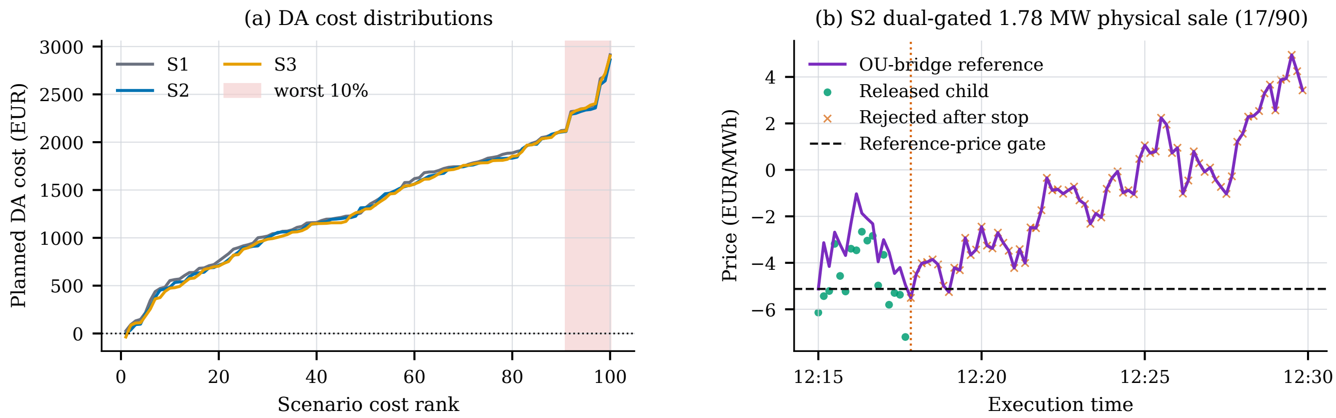

Fig. 2. DA risk and execution example: (a) independently ranked S1–S3 scenario costs with the worst 10% marked; (b) a representative S2 physical sale of 1.78 MW. Seventeen of 90 children are released before the first gate breach; the remaining scheduled children are rejected for that parent.

C. Economic value and execution loss

Table V gives the one-day accounting against the €1946.85 DA-only reference. The earlier guaranteed-full-fill comparator is retained to isolate the effect of activating the gate: it gives the €659.59–€818.50 benefits and €484.80–€554.19 implementation losses. With the implemented gate and position feedback, realised benefits are instead €404.91, €392.09, and €399.45. Thus S1 is best on this realisation; S2 earns €396.89 of DA export revenue but is €12.82 below S1 after IDC execution, while S3 recovers €7.36 relative to S2.

Average realised slippage rises to 1.78–1.79 EUR/MWh because forced closures use 2.5 EUR/MWh rather than a uniform draw. Figure 3 shows the gated policy's cumulative price-movement and slippage costs. The gate reduces implementation loss by €356.07–€367.89 relative to full fill, but total benefit falls by €254.69–€424.74 because rejected quantities alter later plans and large final closures remain. The 18.7–20.0% release ratios refer to repeatedly requested turnover, not permanently unmet energy. Virtual turnover falls to 71.22 MWh but loses about €241 in each case.

All three runs pass checks for balance, storage dynamics, exclusive modes, terminal states, workload conservation, market-position reconciliation, and virtual closure; final position error and residual imbalance are zero. The fixed-LP dual passes at 84/105/106 of the 131 decisions in S1/S2/S3. One rolling MILP in each of S2 and S3 reaches the 20-s limit with an incumbent; those decisions use the logged fallback rather than a claimed dual.

D. Limitations

This is a one-day operational comparison, not an investment appraisal. The DA scenario block is sourced for 30 July and mapped to 28 July, so this DA experiment is not a strictly causal D–1 historical forecast. IDC anchors are calibrated ex post from completed-session indices and the 10-s bridge is synthetic; CVaR covers DA prices only. Gate rejections are controller-induced cancellations, not empirical queue-competition non-fills. The forced final order is assumed accepted at worst configured slippage, while order-book depth, spread, priority, impact, and minimum-volume rounding are omitted. Capital cost, tariffs, taxes, tenant benefit sharing, and reserve stacking are also excluded.

V. Conclusion

This work considers energy market participation of a flexible DC and investigates the economic incentives possible under different bidding strategies and under various degrees of realistic market considerations. The model coordinates the exact IT workload and deferred SLA class considered in [5], while retaining most of the setup except thermal storage, which is replaced by an appropriately sized BESS unit. The full-fill comparator suggests a 33.88–42.04% gross operating benefit, whereas the implemented gated execution gives 20.14–20.80% on this synthetic one-day bidding. It reduces implementation loss but creates conservative deferral and large final closures; consequently, BESS export does not improve gated benefit on this realisation. The implementation is a useful baseline for future studies with real shared order book data and validation over extended periods. Value stacking by considering balancing capacity/energy market participation, such as automatic/manual frequency restoration reserve and frequency containment reserve, would provide a more holistic revenue potential and will be considered in future scope of work.

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TABLE V
FULL-FILL COMPARATOR AND IMPLEMENTED DUAL-GATED RESULTS

Metric	S1: CVaR, no export	S2: CVaR, export	S3: risk-neutral, export
Expected DA planned cost (EUR)	1369.10	1342.01	**1335.19**
90% DA CVaR / diagnostic tail (EUR)	2450.92	**2416.91**	2448.42[a]
Full-fill saving (EUR; %)	659.59; 33.88	816.83; 41.96	**818.50; 42.04**
Full-fill implementation loss (EUR)	484.80	554.19	553.45
Gated realised total cost (EUR)	**1541.94**	1554.76	1547.40
Gated saving (EUR; %)	**404.91; 20.80**	392.09; 20.14	399.45; 20.52
Gated-path frictionless / realised benefit (EUR)	533.64 / 404.91	583.98 / 392.09	585.01 / 399.45
Price movement / slippage loss (EUR)	−27.32 / 156.05	25.78 / 166.11	21.20 / 164.36
Gated implementation loss (EUR)	128.73	191.89	185.56
Released before forced close (%)	20.0	18.7	18.8
Forced reconciliation (MWh)	24.42	26.80	26.57
Physical / virtual turnover (MWh)	16.36 / 71.22	21.45 / 71.22	20.50 / 71.22
Virtual realised margin (EUR)	−241.26	−241.20	−241.04
Dual-valid decisions / fallback parents	84 / 1064	105 / 502	106 / 565

[a] Diagnostic only; CVaR is inactive in the S3 objective.

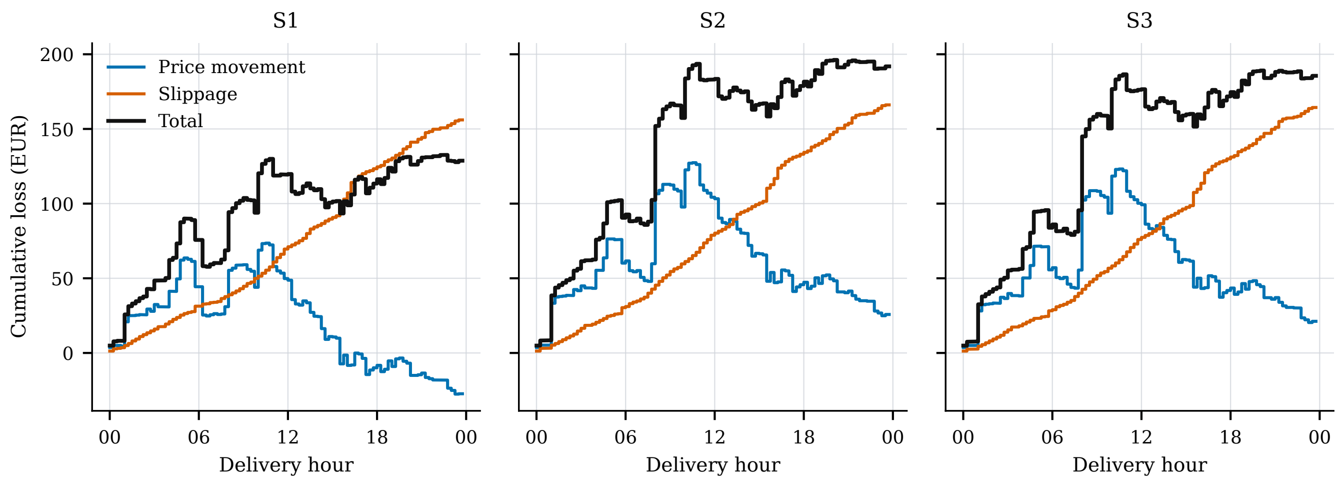

Fig. 3. Cumulative gated price-movement, slippage, and total implementation loss. Final values reconcile with Table V; negative movement cost in S1 denotes favourable execution relative to submission prices.

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