DIGITAL TWIN FOR DAY-AHEAD AND INTRADAY MARKET CO-OPTIMISATION USING DYNAMIC LINE RATING

Bálint Hartmann*, Bence Bereczki, Péter M. Sőrés, István Vokony

Department of Electric Power Engineering
Faculty of Electrical Engineering and Informatics
Budapest University of Technology and Economics
Műegyetem rkp. 3., H-1111 Budapest, Hungary
**hartmann.balint@vik.bme.hu*

Keywords: TWINEU, DIGITAL TWIN, MARKET CO-OPTIMISATION, DLR

Abstract

Static line ratings and sequential, non-co-optimised energy and balancing market clearing increasingly constrain transmission system utilisation under growing renewable penetration. This paper addresses both limitations by proposing a unified methodological framework that integrates Dynamic Line Rating (DLR) into flow-based capacity calculation and multi-timeframe market co-optimisation, implemented as a modular digital twin. The framework is demonstrated in a controlled, regulatory-consistent Hungarian pilot environment within the TwinEU Horizon Europe project. Parallel static and dynamic rating datasets enable benchmarking, while sequential gate-closure alignment ensures temporal consistency. A structured scenario framework is applied to assess separated versus co-optimised market designs under multiple DLR assumptions. Results indicate that DLR primarily expands the feasible operational boundary of the transmission system, while co-optimisation fundamentally alters the allocation of scarce cross-zonal capacity across market products. The digital twin framework enables reproducible experimentation without structural modification of the existing flow-based methodology. Key implementation challenges include forecast uncertainty, welfare redistribution, computational scalability, data governance, and regulatory alignment with current and future EU regulations on capacity allocation and electricity balancing market frameworks. DLR-enabled co-optimisation emerges as a viable evolutionary pathway for European market operation but current project experiences are suggesting institutional barriers may exceed technical ones in delivering new solutions.

1 Introduction

Power systems face growing operational stress as renewable penetration rises, demanding more flexible network operation. Utilisation of power lines remains constrained by conservative static line ratings, even when real thermal conditions would permit higher flows. Meanwhile, energy and balancing products are cleared sequentially – fragmenting network capacity and reducing welfare. This inefficiency deepens as intraday trading grows [1], since shorter gate-closure lead times and higher temporal resolution create natural alignment with weather-dependent margins such as dynamic line rating (DLR) [2].

Static thermal limits do not necessarily reflect the real state of the grid, because ampacity depends on conductor temperature and ambient conditions [3], [4]. Therefore, fixed constraints may leave power flow margins unused and keep bottlenecks higher than necessary. Current flow-based optimisation relies on network capacity datasets where parameters are static (even if hourly changing), while DLR enables line-by-line, continuously updated additional transmission capability. In parallel, the flexibility service of balancing still does not have a unified market: balancing energy integration is progressing, but reserve capacity procurement is still mainly done on a national or per-TSO basis. As a result, capacity is allocated independently across products, and transparency of cross-product interactions remains limited [5].

To bridge this gap, the Hungarian demonstration of the TwinEU project implements a digital twin platform that represents both the grid and key market processes. The essence of a digital twin is to create a digital representation with the same parameters as a physical system; thus, tests and simulations can be carried out without breaking or endangering the physical system and without interfering with real-time operation [6]. The demonstration is designed as a controlled, auditable and regulatory-consistent simulation environment, where alternative assumptions can be tested repeatably. This is especially important in market-related use-cases, where the sensitivity of the data does not allow actual interference with business-as-usual processes.

The Hungarian demonstration integrates DLR into capacity calculation and couples it with a co-optimisation framework jointly clearing energy and balancing capacity products [7], [8]. Weather- and load-dependent ampacity forecasts are produced by a hybrid ANN-based approach that combines real sensor measurements with digital twin extensions, reducing sensor deployment costs while maintaining accuracy. These dynamic ampacity outputs extend network constraint quantification and enable flow-based market simulations with increased transmission capacity, so the market value of temporarily added margins on congested lines can be quantified. On top of this, an implemented co-optimisation auction algorithm as the market animation tool clears energy together with balancing capacity products, extended with intraday specific timings and products (15-min and hourly) while realizing implicit auction of transmission capabilities. The structured testing environment also helps identify implementation challenges [9], such as data exchange between the digital twin and the market platform (market bids and network capacity datasets), protection of business sensitive datasets, tight intraday sequencing (gate logic) and auction scheduling, forecast uncertainty, and the need to keep TSO security margins.

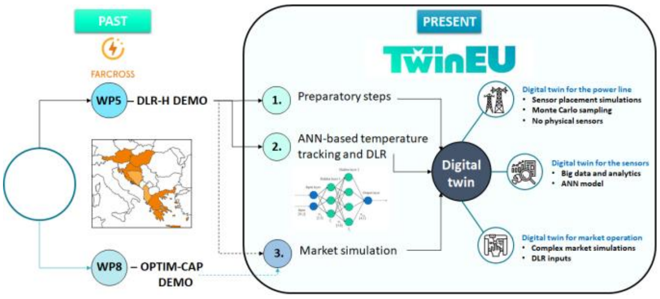

Fig. 1: Concept of the co-optimisation digital twin in TwinEU

2 Digital Twin Architecture and Workflow

The Hungarian demonstration is implemented as a modular digital twin that integrates transmission capacity calculation and electricity market clearing into a unified simulation From a process perspective, the workflow reproduces the logical phases of auction-based market coupling:

- Pre-coupling phase, including capacity calculation and order book preparation,
- Coupling phase, where the market clearing algorithm determines prices and cross-zonal exchanges,
- Post-coupling phase, involving validation and publication of results.

Overall, the proposed architecture, displayed on **Error! Reference source not found.** enables systematic experimentation with alternative capacity calculation and market design assumptions while preserving alignment with real operational workflows. The modular structure also facilitates scalability and supports integration with external data sources and digital twin components developed in other project work packages.

environment. The design replicates the operational workflows of the European market coupling process and allows for controlled experimentation in selected bidding zones using alternative network and market prerequisites. The system is composed of three primary modules:

- Capacity Calculation (CC) module, responsible for generating flow-based transmission constraints,
- Market Coupling and Co-Optimisation (MC) module, performing joint market clearing,
- Scenario and Data Management layer, coordinating sequential execution and dataset handling.

The overall workflow mirrors the operational timeline of the single day-ahead coupling (SDAC) and single intraday coupling (SIDC) processes [10]. Four coordinated capacity calculations are executed sequentially before the respective market gate closures. All capacity calculations utilise line rating forecasts obtained via an ANN-based tool trained using real DLR sensor data. Each run incorporates updated grid information, including revised net positions and remedial action assumptions. This progressively improves the representation of the system state as the delivery time approaches. This multi-stage approach ensures temporal consistency between the capacity calculation and market clearing processes.

The digital twin of the market algorithm interacts with the HUPX Labs data platform, which serves as the primary data exchange interface for Hungarian energy and balancing capacity bids. Bid data and network constraints for the participating bidding zones are acquired through NEMO and TSO transparency platforms or through TwinEU's federated data space via APIs, using standardised data formats.

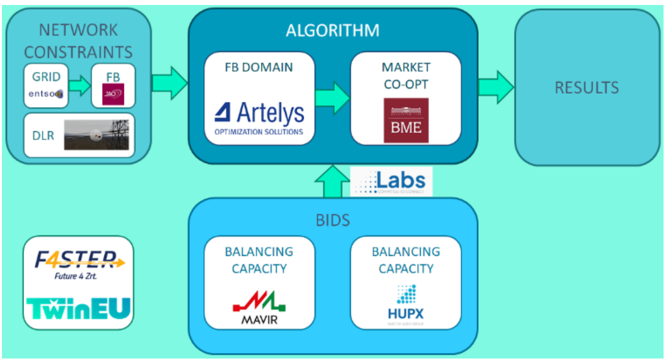

Fig. 2: Demonstration Workflow and Conceptual Overview

3 Capacity Calculation and Dynamic Line Rating Integration in Flow-based Methodology

The capacity calculation module implements the flow-based transmission capacity calculation methodology consistent with Core region practice. The core constraint requires that the product of the Power Transfer Distribution Factor (PTDF) matrix and the net position (NP) vector does not exceed the Remaining Available Margin (RAM) on Critical Network

Elements and Contingencies (CNECs). CNECs are selected by TSO operational security assessments, and the effects of operational (ex-post market-based capacity allocation) remedial actions are incorporated prior to constraint finalisation.

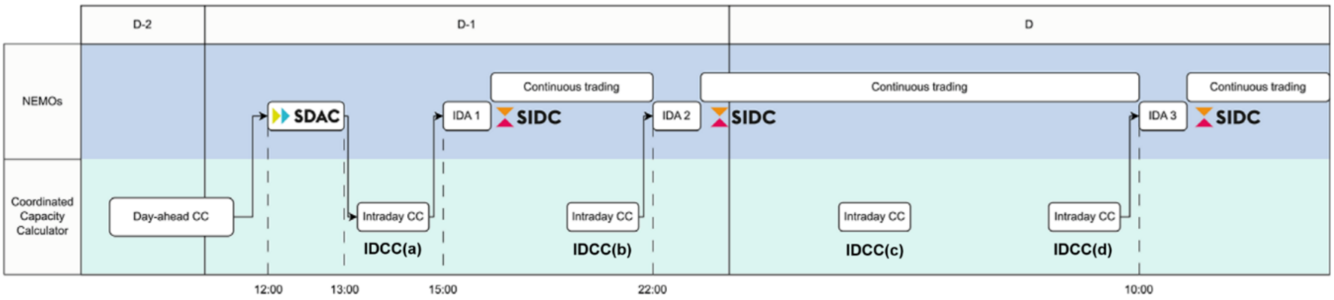

Fig. 3: Capacity calculation timeline [11]

For the TwinEU demonstration, the 14-zone Core representation is reduced to a 4-zone model to reduce computational complexity while preserving accuracy (presolve), with zonal RAM values corrected for net exchange:

$$RAM_4zones = RAM_{14}zones - \Sigma(PTDF_z \cdot NEX_z) \quad (1)$$

DLR integration is implemented through a dynamic ampacity-improvement ratio approach. For each monitored line, for a given delivery period, the ratio of dynamic to static rating is computed, and the effective maximum flow limit is linearly scaled accordingly, while RAMs are updated:

$$F_{max,new} = F_{max} \cdot ratio_{DLR/SLR} \quad (2)$$

Dynamic ampacity forecasts are produced by an ANN trained Hungarian TSO's (MAVIR's) meter and DLR infrastructure, replacing fixed physical thermal models and enabling cost-effective distributed sensor placement. Parallel SLR and DLR time series are maintained throughout all simulation runs to enable systematic benchmarking. DLR is treated as applicable within the 24-hour forecast horizon to reflect realistic operational constraints on ampacity prediction accuracy.

This integration demonstrates that DLR can be embedded into the existing Core flow-based methodology without structural modification, extending the feasible RAM envelope on congested lines and making temporarily available transmission margins accessible to the market.

4 Market Co-Optimisation and Scenario Framework

The market module implements a co-optimised auction clearing framework that jointly allocates cross-zonal transmission capacity across energy and balancing capacity products in a single optimisation run. Current European practice clears these sequentially and independently, implicitly partitioning transmission capacity between products and reducing overall welfare. The proposed framework allocates capacity according to marginal economic value across competing uses simultaneously.

The clearing problem is formulated as welfare maximisation subject to flow-based network constraints and market pricing rules. The objective function combines the social welfare contribution of the energy market with the procurement efficiency of balancing capacity services, while respecting flow-based transmission limits provided by the capacity calculation module. Decision variables cover bid acceptance levels for both energy and balancing capacity products, including integer variables for block and complex order types.

A realistic representation of market behaviour is ensured through multiple bid formats derived from operational market rules, including linear bids, block bids with minimum acceptance ratios, exclusive block groups, parent-child linked structures and loop blocks. Balancing capacity bids are derived from historical procurement datasets and transformed into piecewise linear supply curves, preserving economic characteristics while avoiding dependence on confidential participant-level data. The modelling framework therefore captures essential price formation mechanisms and cross-product interactions across both energy and balancing segments.

To ensure numerical robustness and reproducibility, a unit-testing framework was implemented covering both individual modules and the end-to-end workflow. These tests verify consistency of optimisation results, correct handling of complex bid types, and solver stability across scenarios.

The scenario framework evaluates the interaction between transmission capacity modelling and market design choices. Transmission scenarios span a static rating reference case and multiple DLR configurations, including sensitivity variants and a historical data-driven case (DLR Light) using ANN forecasts. Market scenarios compare separated and co-optimised clearing in both day-ahead and intraday timeframes [12], [13], also considering cascading effect of subsequent market auction outcomes. The full scenario matrix is shown in Fig. 4.

The scenario classes, matching the designations in Fig. 4, are as follows. Configuration (a) is a basic reference using detailed datasets for a single delivery day without cascading: all capacity calculations share the same base grid state, enabling isolated evaluation of co-optimisation effects free of temporal feedback. Configuration (b) introduces bid forwarding within the same delivery day: unaccepted day-ahead bids are carried forward to subsequent intraday auctions, preserving liquidity and enabling assessment of price discovery improvements under sequential market design. Configuration (c) is an intraday-intensive cascade combining day-ahead and multiple intraday stages, where net positions from each stage feed back into the capacity calculation of the next, reflecting the increasing operational relevance of short-term forecasting and tighter gate-closure scheduling under high renewable penetration.

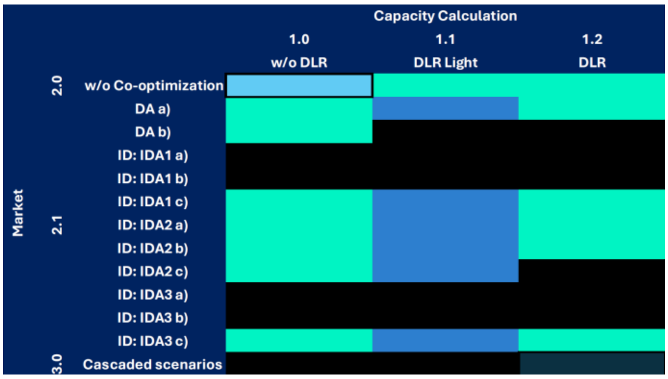

Fig. 4: Scenario Matrix of DLR enhanced Co-optimisation

The scenario design incorporates market structure considerations such as bid forwarding between successive intraday auctions. Uncleared bids from earlier auctions can be transferred to subsequent ones, representing realistic trader participation across multiple market sessions and preserving liquidity across timeframes. This feature allows assessment of liquidity effects, price discovery improvements, and efficiency gains associated with more dynamic intraday market participation, particularly under cascaded capacity recalculation conditions.

Verification procedures are embedded in the scenario execution to ensure methodological robustness, including consistency checks for cross-zonal capacity sharing, validation of price formation under complex bid interactions, and solver stress-testing under large constraint sets. This is particularly important given the use of anonymised and partially synthetic datasets required by confidentiality constraints on operational market data.

The scenario framework as a whole enables systematic evaluation of the combined impact of DLR and market co-optimisation across multiple timeframes. DLR primarily expands the feasible transmission boundary, while co-optimisation determines how that boundary is allocated across competing market products, together providing insight into both efficiency gains and structural market outcome changes within a realistic operational context.

5 Implementation and Governance Challenges

Several technical and institutional challenges arise from integrating DLR and co-optimisation into the operational European market structure. On the technical side, DLR introduces a dependency on short-term weather and loading forecasts: errors in these inputs propagate directly into RAM values, and the resulting uncertainty requires conservative headroom in RAM determination to preserve TSO security margins, partially offsetting the transmission capacity gains that dynamic rating can deliver. Computational scalability is a parallel concern: the co-optimised clearing problem combines large CNEC constraint sets with mixed-integer bid logic, and solver performance must be validated under realistic problem scales before any operational deployment.

Data governance poses equally significant constraints. Despite regulatory harmonisation, data sharing outside operational workflows remains limited, restricting third-party validation and research access. Addressing this is a core objective of TwinEU's federated data space development. For the co-optimisation demonstrator specifically, transmission capacity and energy bids from non-participant market zones remain restricted despite strong physical coupling between bidding areas, requiring the use of anonymised and partially synthetic inputs. These restrictions do not affect methodological validity but constrain the scope of quantitative benchmarking achievable within the demonstration.

At the regulatory level, the proposed framework is already aligned with the Regulation (EU) 2015/1222 on Capacity Allocation and Congestion Management, and Regulation (EU) 2017/2195 Electricity Balancing Guideline (EBGL) [14], and the operational procedures of single day-ahead and intraday market couplings. Co-optimisation across gate closures requires modifications to auction sequencing and capacity reservation logic that have no direct precedent in current EU market design. Welfare redistribution between energy traders and balancing service providers is a likely source of stakeholder friction that may prove harder to resolve than the technical implementation challenges. Regulatory alignment and governance design are therefore critical enablers for any pathway from demonstration to operational deployment.

6 Conclusions

This paper presented how the Hungarian pilot of the TwinEU project facilitates the inclusion of Dynamic Line Rating into flow-based capacity calculation and co-optimised multi-timeframe market clearing, demonstrated in a regulatory-consistent pilot environment. The architecture replicates the operational logic of SDAC and SIDC processes and supports controlled experimentation across a structured scenario matrix spanning separated and co-optimised market designs under both static and dynamic line rating conditions. The framework demonstrates that DLR-enhanced flow-based capacity calculation is architecturally compatible with existing Core methodology without structural redesign, while co-optimisation fundamentally alters the allocation of scarce cross-zonal transmission capacity across competing market products.

The demonstration establishes a reproducible environment for evaluating efficiency improvements and structural market changes under realistic operational conditions. DLR primarily expands the feasible transmission boundary; co-optimisation determines how that boundary is allocated across products and timeframes. Their combined application represents a viable evolutionary pathway toward more efficient and transparent European market operation, provided that the identified challenges – forecast uncertainty, data governance, computational scalability, and regulatory alignment – are addressed systematically. Next steps include quantitative performance assessment across the full scenario matrix, scalability stress-testing under full Core constraint sets, and policy pathway analysis in the context of evolving regulatory frameworks and TSO-market operator practices.

7 Acknowledgements

This research has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101136119 (TwinEU). István Vokony acknowledges the support of the Bolyai János Research Scholarship of the Hungarian Academy of Sciences (BO/50/24)

7 References

[1] Shinde, P., Gamberi, G., Amelin, M.: 'A multi-agent model for cross-border trading in the continuous intraday electricity market', Energy Reports, 2023, 9, pp. 6227–6240

[2] Ovaere, M., Kenis, M., Van den Bergh, K., Bruninx, K., Delarue, E.: 'The effect of flow-based market coupling on cross-border exchange volumes and price convergence in Central Western European electricity markets', Energy Economics, 2023, 118, pp. 106519

[3] Rácz, L., Németh, B.: 'Dynamic line rating - An effective method to increase the safety of power lines', Applied Sciences, 2021, 11, (2), pp. 492

[4] Hajeforosh, S.F., Bollen, M.H.J., Abrahamsson, L.: 'Dynamic line rating operational planning: Issues and challenges'. Proc. 25th Int. Conf. Electricity Distribution (CIRED), Madrid, Spain, June 2019, paper 1957

[5] Ihlemann, M., van Stiphout, A., Poncelet, K., Delarue, E.: 'Benefits of regional coordination of balancing capacity markets in future European electricity markets', Applied Energy, 2022, 314, pp. 118874

[6] Lombardi, M., Cammarota, A., Refoyo, J.: 'Development, applications and benefits of the network digital twin'. Proc. 25th Int. Conf. Electricity Distribution (CIRED), Madrid, Spain, June 2019, paper 2149

[7] Vokony, I., Sőrés, P.M., Németh, B., Hartmann, B.: 'Market design for cross border co optimised energy reserve allocation', Renewable Energy and Power Quality Journal, 2023, 21, (3)

[8] Divényi, D.D., Sleisz, Á., Sőrés, P., Csercsik, D., Hartmann, B.: 'A potential framework for cross-zonal reserve procurement on European power exchanges based on robust optimization', Sustainable Energy, Grids and Networks, 2024, 37, pp. 101267

[9] Rácz, L., Németh, B., Göcsei, G., Zarchev, D., Mladenov, V.: 'Performance analysis of a dynamic line rating system based on project experiences', Energies, 2022, 15, (3), pp. 1003

[10] Regulation (EU) 2015/1222: 'Establishing a guideline on capacity allocation and congestion management', 2015

[11] Estermann, A., Schrade, M. (Eds.): *'European electricity market coupling: A practitioner's guide'* (Springer, 2025)

[12] Polgári, B., Divényi, D., Sőrés, P., Sleisz, Á., Hartmann, B., Vokony, I.: 'Increasing the flexibility of continuous intraday markets in Europe'. In: Németh, B., Ekonomou, L. (Eds.): International Symposium on High Voltage Engineering (ISH) (Springer, 2020), pp. 23–34

[13] Divényi, D., Polgári, B., Sőrés, P., Vokony, I., Hartmann, B.: 'Improving the flexibility of intraday markets by introducing special products'. European Energy Market (EEM), 2019

[14] Regulation (EU) 2017/2195: 'Establishing a guideline on electricity balancing (EBGL)', 2017