



HAL
open science

Improving cross-border capacity for near real-time balancing

Marie Girod, Efthymios Karangelos, Emily Little, Viktor Terrier, Jean-Yves Bourmaud, Virginie Dussartre, Oualid Jouini, Yannick Perez

► **To cite this version:**

Marie Girod, Efthymios Karangelos, Emily Little, Viktor Terrier, Jean-Yves Bourmaud, et al.. Improving cross-border capacity for near real-time balancing. 2022 18th International Conference on the European Energy Market (EEM), Sep 2022, Ljubljana, Slovenia. pp.1-6, 10.1109/EEM54602.2022.9921034 . hal-03894205

HAL Id: hal-03894205

<https://hal.science/hal-03894205v1>

Submitted on 28 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Improving cross-border capacity for near real-time balancing

Marie Girod
Laboratoire de Génie
Industriel, CentraleSupélec
and RTE
Paris, France
marie.girod@rte-france.com

Efthymios Karangelos
Montefiore Institute,
Université de Liège
Liège, Belgium
e.karangelos@uliege.be

Emily Little
Laboratoire de Génie
Industriel,
CentraleSupélec and RTE
Paris, France
emily.little@rte-france.com

Viktor Terrier
RTE
Paris, France
viktor.terrier@rte-france.com

Jean-Yves Bourmaud
RTE
Paris, France
jean-yves.bourmaud@rte-france.com

Virginie Dussartre
RTE
Paris, France
virginie.dussartre@rte-france.com

Oualid Jouini
LGI, CentraleSupélec
Paris, France
oualid.jouini@centralesupelec.fr

Yannick Perez
LGI, CentraleSupélec
Paris, France
yannick.perez@centralesupelec.fr

Abstract— European markets continue to integrate with two ongoing projects for common markets of manually activated balancing reserve. In the design of these balancing markets, the method for computing cross-border capacity has several limitations: it uses a network representation forecasted too early, uses a methodology that does not represent well meshed grid physics and does not properly account for remedial actions put in place by the grid operator to mitigate congestion. In this paper, we provide an improved capacity computation process for manually activated balancing reserve using a flow-based methodology and a network representation forecast one hour before real-time. We assess the impact of the current and the proposed capacity computation processes on market prices and network security configurations on an updated IEEE-96 network. Results show an increase in social welfare with the proposed methodology.

Index Terms-- Balancing, congestion management, cross-border capacity, flow-based, market integration

I. INTRODUCTION

Regional power systems around the world are integrating with different levels of unification [1]. Among them, European markets are undergoing a new phase with the integration of manually activated balancing markets. TERRE and MARI are the two reference projects respectively for the Replacement Reserve (RR) and the manual Frequency Restoration Reserve (mFRR). Until now, each Transmission System Operator (TSO) was responsible for selecting balancing activation offers in its own area. Bids and TSO needs from all participating zones will now be shared in the platform and selected for activation according to a Common Merit Order List. The motivation for these projects is to reduce European electricity balancing costs [2]–[5] and facilitate greater renewable integration [2], [5], [6]. In the design of these balancing markets, cross-border capacity

represents in a synthetic manner how much power can be exchanged on a specific border without causing congestion. Currently, the method applied to compute it has several limitations.

A. Weaknesses in current cross-border capacity computation

The cross-border capacity for manually activated balancing markets is the capacity remaining after the intraday market. Capacity for intraday market is computed at 13:00 the day before with the Available Transfer Capacity (ATC) method (described in [7]). It is based on a network representation forecast two days ahead for the day-ahead market. The intraday capacity is computed by subtracting from the total capacity the netted exchanges resulting from the Long Term and the Day Ahead markets. There are two main issues with this methodology. First, the network representation is not fully refreshed between the moment it is computed two days before and balancing markets so it holds strong uncertainty. Second, remedial actions are not properly taken into account. There is a limited number of remedial actions that can be activated in a short amount of time by an operator (around 3 in 20 minutes at RTE, the French TSO). When the network situation is forecast, this is not an issue and no limit to the simultaneous activation of remedial action is set. When MARI results are issued, 8 minutes ahead of real-time, there may not be enough time to apply all the forecast remedial actions.

To the best of our knowledge, a single paper discusses the issue of TERRE and MARI's cross-border capacity computation and offers a solution [8]. The authors propose a methodology where each TSO groups orders into a residual supply function using Optimal Power Flows over its zone. However, they do not explicitly state how a change in net position is allocated in the neighboring zones, which would have a big impact on flows. Furthermore, they acknowledge that the disaggregation of clearing results may cause problems

outside of the zone, which means that the method does not completely meet its objectives. Finally, the method would be very complex to set up.

B. Paper contribution

The contribution of this paper is three-fold. First, we propose an improved capacity computation process for manually activated balancing markets. It aims to improve the existing process in a manner achievable in the short term rather than put forward a completely new method. It uses a flow-based methodology and a network representation forecast one hour before real-time, which is compatible with TERRE and MARI timelines. Unlike ATC, the flow-based methodology takes into account the interdependency of power flows in a meshed grid in order to better represent physical limitations of the grid. It has been used in the Central Western Europe (CWE) day-ahead market since May 2015. It was designated by the European Commission as the reference methodology for “highly interdependent” bidding zones [9]. Second, we establish a model that simulates a manual balancing process and evaluates its impact on network congestion. Third, using this model, we estimate the impact of the current and the proposed cross-border capacity computations on both market welfare and network congestion. The study is run on an updated IEEE-96 network [10] over six winter days. Results show a 26% increase in social welfare between the proposed and the current methodology.

Although the developed model is applied to a European manual balancing platform, it could also be used for other regional markets, especially those classified as less integrated than European markets by the International Energy Agency [1].

II. METHODOLOGY

The manual balancing process is simulated in five steps (Figure 1.): a day-ahead flow-based domain computation, a day-ahead market, a balancing cross-border capacity computation, a market of manually activated balancing reserve and a security analysis. Two scenarios, summarized in TABLE I. are simulated with this process.

TABLE I. STUDIED SCENARIOS

	<i>Scenario 1 – current methodology</i>	<i>Scenario 2 – proposed methodology</i>
Methodology	ATC	Flow-based
Network forecast	H-24	H-1
Limit number of topological actions	No	Yes

Both scenarios go through the same five steps, except for the balancing capacity computation. These steps can be grouped in four different models (represented by different colors on Figure 1.): flow-based computation, ATC computation, market coupling and security analysis.

The day-ahead market in this study is a mix between the actual day-ahead market and the intraday market to avoid having too many steps in the model. It acts as the first daily market but takes place two hours before real-time like an

intraday market. In this step, the capacity computation uses a flow-based method, as is currently the case in CWE day-ahead markets.

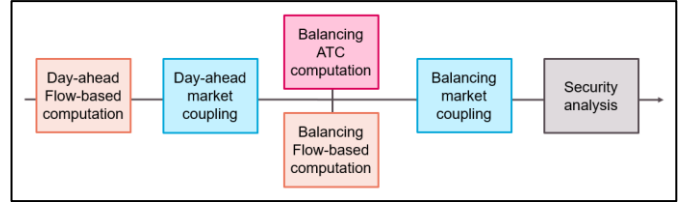


Figure 1. Model Overview

A security-constrained DC optimal power flow (SCOPF) is used in three different steps of the model: the base case computation for day-ahead and balancing flow-based domains and the security analysis. It is an optimization of economic dispatch considering N and $N-1$ network constraints (see [11] for more details on different SCOPF formulations). This SCOPF is composed of three stages: a preventive mode (N state), an intermediate post-contingency mode with a set of less restrictive constraints that simulates the short moment following a contingency before the operator has taken any action, and a curative mode ($N-1$ state). The SCOPF includes optimal topology control: it optimizes the use of preventive and corrective topological remedial actions. These include node breakers and switchable parallel lines. The problem is linearized with a BigM method, with the equations described in [12]. Different objective functions and features (see TABLE II.) are implemented in the three different steps, to match real conditions.

TABLE II. SCOPF FEATURES

	<i>Day-ahead base case</i>	<i>Balancing base case</i>	<i>Security Analysis</i>
Curative redispatch	No	No	Yes
Load shedding	No	No	Yes
Limit preventive topological actions	No	Yes	Yes

A. Flow-based computation

The flow-based methodology starts from a base case, and finds all the net positions where, for all critical branches, the flow does not overcome the maximum flow of the line in N and $N-1$ states, given curative topological actions. Generation Shift Keys (GSK) are used in order to distribute the change of generation linked to a shift in net position over the zone. As is done in the ATC computation, the day-ahead market position is included in the final flow-based domain.

1) Base case

The base case represents the most likely dispatch, as anticipated by the TSO. In this model, it is computed using the SCOPF mentioned above. No curative redispatch is allowed, to match the conditions of the flow-based curative state. Different objective functions are used for the day-ahead base case and the balancing base case. For the day-ahead base case, the objective is to optimize dispatch costs whereas for balancing, the objective is to minimize necessary redispatch

costs. The day-ahead objective function is formulated as follows:

$$\min\left(\sum_{g \in G} c_g * P_g + \sum_{t \in T} c_t * TA_t\right)$$

where G is the set of generators of price c_g and production P_g . T is the set of topological actions with the wear-and-tear cost of c_t and TA is the binary variable representing a change in activation status.

The balancing objective function can be written as

$$\min\left(\sum_{g \in G} c_g * \Delta P_{up,g} - (MP - c_g) * \Delta P_{down,g} + \sum_{t \in T} c_t * TA_t\right)$$

where $\Delta P_{up,g}$ and $\Delta P_{down,g}$ are respectively positive upward and negative downward redispatch. MP is the maximum price of all generators. The negative inversed price for downward redispatch serves to prioritize redispatching the most expensive generator.

For day-ahead, there is no limit to the number of preventive topological actions. For balancing, they are limited to four topological changes regarding the previous hour (which would be approximately what an operator could apply after the TERRE market).

2) Generation Shift Keys

GSKs give the contribution of a node in case of change in zonal balance. In this model, they are computed as the proportion of production capacity installed in the node over total capacity installed in the zone, as they are currently computed in Belgium and the Netherlands [13]. The same GSKs are used for day-ahead and balancing.

3) Remedial Action Optimization

In the load flow stage of the flow-based computation, a Remedial Action Optimizer (RAO) is applied to select the most efficient curative topological actions for each outage. The CASTOR [14] RAO is used here, which is the one used operationally for the CORE day-ahead flow-based parallel run.

B. ATC computation

The ATC is not fully recomputed, but deduced from the day-ahead flow-based domain as described in the operational methodology used to compute the balancing ATC [15].

C. Market coupling

Market simulation is performed with the ATLAS model, an agent-based modeling tool designed to simulate a sequence of electricity markets considering the evolution of forecasting uncertainties. The ATLAS model is described in [15]. In this model, two phases are included for each market: formulation of offers and clearing. Offers are determined with different modules for day-ahead and balancing. A similar market clearing works for both.

1) Day-ahead offers

Each generator formulates buy or sell orders with the aim of maximizing its profit given a price forecast. Different equipment constraints are taken into account depending on the equipment type, such as maximum and minimum power, maximum gradient, minimum off and on times, startup and shutdown durations. Links between offers are formulated to better reflect generator constraints in the market.

2) Balancing offers

This module is developed as part of Florent Cogen's PhD "Balancing power systems in 2025 - 2050: Impacts of energy transition on architectures and economic underlyings of European balancing markets"¹. In this module, equipments offer all their remaining available capacity given their operational constraints (same as mentioned above). They bid at marginal cost. They can formulate links between their offers. TSOs also formulate offers : they request the difference between total forecast production minus load and the power level sold on previous markets. They bid at the price of demand utility.

3) Clearing

The market clearing accepts or rejects bids taking into account cross-border capacity and sets the market price. The algorithm used in the ATLAS model resembles the EUPHEMIA algorithm currently used in the European day ahead market.

D. Security analysis

The security analysis checks network security at the output of the balancing market and prices congestion management. The SCOPF described above is also used for the security analysis with some changes. It includes preventive and curative topological actions, as well as redispatch. The nuclear power plant is not allowed to take part in N and $N-1$ redispatch, as it would be too slow. Load shedding is also allowed at the cost of demand utility. The redispatch and load shedding costs in N states represent the cost of congestion management. The objective function is slightly different from that of the balancing base case computation. It is given by

$$\min\left(\sum_{g \in G} c_g * \Delta P_{up,g} - (MP - c_g) * \Delta P_{down,g} + \sum_{t \in T} c_t * TA_t + c_{DU} * (P_N^{LS} + \delta_{N-1} * P_{N-1}^{LS})\right)$$

where c_{DU} is the demand utility, δ_{N-1} the probability of an outage occurrence and P_N^{LS} and P_{N-1}^{LS} the quantity of load shedding in preventive and curative states, respectively.

Curative redispatch cost is neglected as the probability of each contingency happening is very low. However, curative load shedding is penalized as $c_{DU} * \delta_{N-1}$ is not negligible.

III. CASE STUDY

Using the model described previously, a market of manually activated balancing reserve is simulated. It takes place hourly, 45 minutes ahead of real-time. The model is run

¹ It is still a work in progress, and no paper has yet been submitted on the subject, but it will shortly be the case.

over the first six days of January on the RTS GMLC network [10]. This network is an updated version of the original IEEE-96 system with a higher share of renewable production. It has 3 zones and 73 nodes. A few simplifications were made to the RTS GMLC: minimum power for thermal generators were not taken into account, only the marginal price was considered and storage was not included. Topological remedial actions – bus breakers and switchable lines- were added to the network with the methodology described in [12]. Demand utility was set at 200€/MWh, slightly higher than the maximum generator price at 180€/MWh.

A. Forecasting data

Forecasts for load and renewable production were updated during the process. This is a first attempt to model the update in the forecast quality. In the operational process, the day-ahead flow-based base case is forecast two days ahead; offers and market clearing are formulated one day ahead. To mimic this, in this model, the day-ahead flow-based base case was computed with an $H-24$ network forecast. The day-ahead offers and market coupling are formulated two hours ahead with an $H-2$ network forecast – so as to fill both the roles of the day-ahead and the intraday. The forecast is updated for the balancing flow-based computation but not for the balancing ATC computation (as per the operational methodology). The balancing market takes place with the same $H-1$ forecast as for the flow-based computation. Finally, the security analysis is performed with real-time data to evaluate actual network costs.

As the RMSE for the $H-24$ load forecast provided in the initial RTS GMLC network was low, the forecast was rescaled to have a zonal RMSE of 5.4% over the whole year. The $H-1$ and $H-2$ forecasts for load and renewable production were then derived using the following formula:

$$y_{h-x} = y_h + (y_{h-24} - y_h) * \frac{RMSE_{h-2}}{RMSE_{h-24}}$$

with y_x the value forecast at x and $RMSE_x$ a generic RMSE value for a forecast at x .

B. Critical branches selection

Critical branches were selected for the flow-based computation using a sensitivity analysis over a winter and a summer week. All branches with a sensitivity of at least 15% on at least one of the hours were selected. Critical branches are used in flow-based computations as outages and monitored elements. They remain the same for day-ahead and balancing flow-based. In the SCOPF, all branches are used as outages and monitored elements.

IV. RESULTS

A. Market price

We first observe the impact of each scenario on market prices. Figure 2. shows balancing market prices with the current cross-border capacity computation and Figure 3. with the proposed cross-border capacity computation. Prices converge more often between zones with the proposed capacity computation (price converges on all three zones 76%

of the time) than with the current capacity computation (price converges 40% of the time), which suggests that the proposed method allows more exchanges between zones.

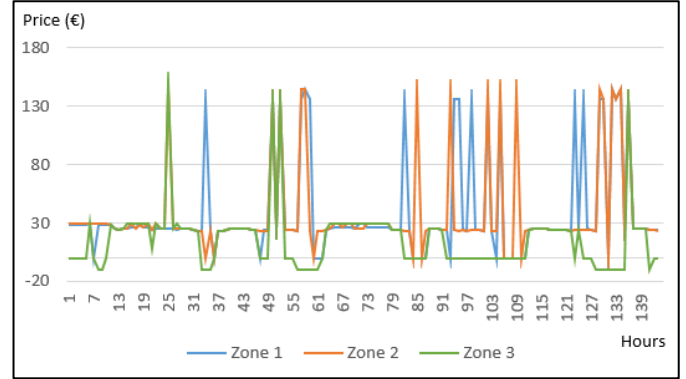


Figure 2. Market coupling prices with current cross-border capacity computation methodology

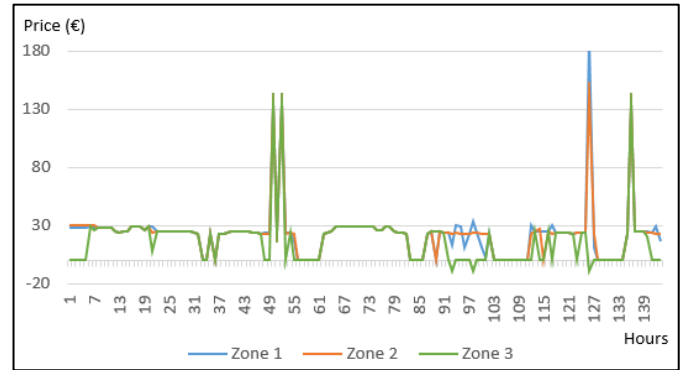


Figure 3. Market coupling prices with proposed cross-border capacity computation methodology

B. Net Social Welfare

In order to compare both capacity computation methodologies, we compute the net social welfare (SW) linked to each method. Congestion management costs are included in net social welfare to reflect the balance between market value and network operation costs. Since the day-ahead market welfare is kept constant between the two variants, it may be omitted from the comparison. We have

$$SW = PS + CS + CR - CM$$

where PS, CS, CR and CM denote the production surplus, the consumer surplus, the congestion rent and congestion management costs, respectively. They are given by

$$PS = \sum_{z \in Z} \sum_{g \in G_z} (C_z^* - c_g) * P_g$$

$$CS = \sum_{z \in Z} (C_{DU} - C_z^*) * D_z$$

$$CR = \sum_{z \in Z} \left(D_z - \sum_{g \in G_z} P_g \right) * C_z^*$$

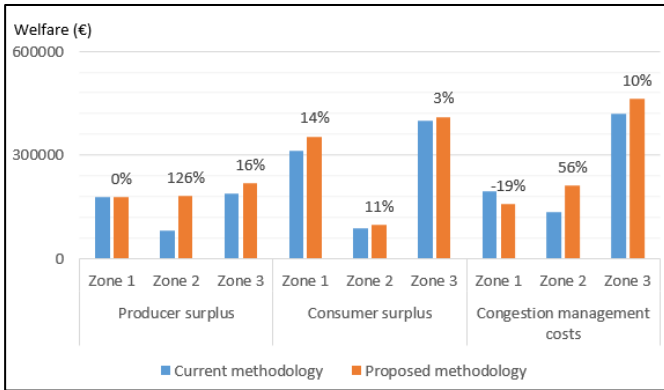
$$CM = \sum_{g \in G, z \in Z} c_g * (\Delta P_{up,g} + \Delta P_{down,g}) + c_{DU} * P_N^{LS}$$

with C_z^* the market coupling price in zone z and c_{DU} the demand utility. G_z is the set of generators in zone z of price c_g and production P_g . The quantities $\Delta P_{up,g}$ and $\Delta P_{down,g}$ are the positive upward and negative downward redispatch, respectively. D is the set of loads of power D_z in zone z . P_N^{LS} is the quantity of load shedding in preventive state.

TABLE III. SOCIAL WELFARE RESULTS

	<i>Current methodology</i>	<i>Proposed methodology</i>	<i>Change</i>
Producer surplus (€)	446 781	577 003	+29%
Consumer surplus (€)	800 350	863 624	+8%
Congestion rent (€)	16 495	36 383	+121%
Congestion management costs (€)	751 244	833 122	+11%
Social Welfare (€)	512 382	643 888	+26%
TSO final position (€)	-495 887	-607 505	-23%

TABLE III. summarizes the results. We find the total social welfare over six days is 26% higher with the proposed methodology than with the current one. As expected from the market prices, the proposed methodology achieves a higher market welfare. Although the absolute increase is not as high



as for market welfare, congestion management costs are also higher than in the current methodology. Overall the TSO final position ($CR - CM$) decreases.

Figure 4. Sum of social welfare components over six days with % change between the two methodologies

Not all zones are affected in the same way. Figure 4. presents the distribution of welfare over the different components for each zone (congestion rent is not included as it concerns flows between zones). Despite the rise in congestion management costs, zone 1 and zone 2 benefit from a strong increase in welfare. Zone 3 remains stable.

V. DISCUSSION

A. Limits in base case computation

The SCOPF for flow-based base cases doesn't include curative redispatch, which makes the problem much longer to solve. A maximum time limit of 1000 seconds was added to the optimization and the optimal dispatch was not found for all hours. For the day-ahead base case, 16% of hours had a duality gap larger than 10%. For the balancing base case, it concerns 20% of hours. It is a limit to the case study and resolving this issue is a next step.

B. Further improvements

The proposed methodology is supposed to better represent network constraints, especially since the network forecast is updated one hour ahead. The fact that congestion management costs are higher with the proposed methodology than with the current one could be an indication that the flow-based method can still be improved. There is a right balance to find between market welfare and congestion management costs and social welfare may be further increased if the flow-based parameters were refined. Many studies, among which [16]–[18], suggest that these have a major impact on the performance of the flow-based methodology. In particular, the GSKs used could better reflect participation in TERRE and MARI markets. The SCOPF limitations discussed above impact the base case, and finding the optimum may also improve the quality of the flow-based domains.

VI. CONCLUSION

In this paper, we have proposed an improved methodology for computing the cross-border capacity for manual balancing markets. It uses a flow-based method, is computed on a network forecast updated one hour before real-time and takes into account the limit of topological actions that are applicable at the outcome of balancing markets. We simulated the process of manual balancing markets in five steps: a day-ahead capacity computation, a day-ahead market, a balancing capacity computation, a balancing market, and a security analysis. We ran this model on a 73-node network with the current cross-border capacity and the proposed one and compared their impacts on market welfare and congestion management costs. We found that the proposed cross-border capacity computation increases social welfare by 26% over six days. The gains are mostly in market welfare and overall congestion management costs increase, indicating social welfare may be further increased by refining flow-based parameters. The case study should be run on more days to confirm this first result.

VII. FUTURE WORK

Cross-border capacity computations aim to limit congestion mainly linked to cross-border flows. Other processes are included in the market design of TERRE and MARI to secure internal flows: bid filtering and bid blocking. With filtering, a TSO can choose not to transfer to the market bids that are likely to create congestion. With blocking, a TSO is allowed not to activate a bid that was accepted by the market. It would be interesting to add these processes to the

model described in this paper to understand how they could best complement cross-border capacity management.

REFERENCES

- [1] International Energy Agency, *Integrating Power Systems across Borders*. OECD, 2019. doi: 10.1787/6c1b3f61-en.
- [2] H. Farahmand, T. Aigner, G. L. Doorman, M. Korpas, and D. Huertas-Hernando, "Balancing Market Integration in the Northern European Continent: A 2030 Case Study," *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 918–930, Oct. 2012, doi: 10.1109/TSTE.2012.2201185.
- [3] L. Meeus, K. Purchala, and R. Belmans, "Development of the Internal Electricity Market in Europe," *Electr. J.*, vol. 18, no. 6, pp. 25–35, Jul. 2005, doi: 10.1016/j.tej.2005.06.008.
- [4] L. Vandezande, M. Saguan, L. Meeus, J. Glachant, and R. Belmans, "Assessment of the implementation of cross-border balancing trade between Belgium and the Netherlands," in *2009 6th International Conference on the European Energy Market*, May 2009, pp. 1–6. doi: 10.1109/EEM.2009.5207126.
- [5] L. Vandezande, L. Meeus, R. Belmans, M. Saguan, and J.-M. Glachant, "Well-functioning balancing markets: A prerequisite for wind power integration," *Energy Policy*, vol. 38, no. 7, pp. 3146–3154, Jul. 2010, doi: 10.1016/j.enpol.2009.07.034.
- [6] H. Holtinen *et al.*, "Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration," *Wind Energy*, vol. 14, no. 2, pp. 179–192, 2011, doi: <https://doi.org/10.1002/we.410>.
- [7] ENTSO-E, "Network code on Capacity Allocation & Congestion Management (CACM) - Supporting document." 2012.
- [8] A. Papavasiliou, M. Bjorndal, G. Doorman, and N. Stevens, "Hierarchical Balancing in Zonal Markets," in *2020 17th International Conference on the European Energy Market (EEM)*, Stockholm, Sweden, Sep. 2020, pp. 1–6. doi: 10.1109/EEM49802.2020.9221883.
- [9] European Commission, "Guideline on Capacity Allocation and Congestion Management," p. 49, 2015.
- [10] C. Barrows *et al.*, "The IEEE Reliability Test System: A Proposed 2019 Update," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 119–127, Jan. 2020, doi: 10.1109/TPWRS.2019.2925557.
- [11] F. Capitanescu *et al.*, "State-of-the-art, challenges, and future trends in security constrained optimal power flow," *Electr. Power Syst. Res.*, vol. 81, no. 8, pp. 1731–1741, Aug. 2011, doi: 10.1016/j.epsr.2011.04.003.
- [12] E. Little, S. Bortolotti, J.-Y. Bourmaud, E. Karangelos, and Y. Perez, "Optimal Transmission Topology for Facilitating the Growth of Renewable Power Generation," in *2021 IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6. doi: 10.1109/PowerTech46648.2021.9495032.
- [13] C. Dierstein, "Impact of Generation Shift Key determination on flow based market coupling," in *2017 14th International Conference on the European Energy Market (EEM)*, Dresden, Germany, Jun. 2017, pp. 1–7. doi: 10.1109/EEM.2017.7981901.
- [14] "CASTOR," *FARAO*. <http://farao-community.github.io/docs/engine/ra-optimisation/search-tree-rao> (accessed Mar. 17, 2022).
- [15] OSMOSE, "Models for market mechanisms simulation taking into account space-time downscaling and novel flexibility technologies." 2022.
- [16] D. Schönheit, M. Kenis, L. Lorenz, D. Möst, E. Delarue, and K. Bruninx, "Toward a fundamental understanding of flow-based market coupling for cross-border electricity trading," *Adv. Appl. Energy*, vol. 2, p. 100027, May 2021, doi: 10.1016/j.adapen.2021.100027.
- [17] D. Schönheit, R. Weinhold, and C. Dierstein, "The impact of different strategies for generation shift keys (GSKs) on the flow-based market coupling domain: A model-based analysis of Central Western Europe," *Appl. Energy*, vol. 258, p. 114067, Jan. 2020, doi: 10.1016/j.apenergy.2019.114067.
- [18] M. Sebestyen, D. Divenyi, and P. Sores, "An Enhanced Calculation Method of Generation Shift Keys in Flow Based Market Coupling," in *2018 15th International Conference on the European Energy Market (EEM)*, Lodz, Jun. 2018, pp. 1–5. doi: 10.1109/EEM.2018.8469923.