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Model-based Approaches to Demand Curtailment Allocation

Tamás Borbáth
Department of Electrical Engineering
KU Leuven
Leuven, Belgium
tamas.borbath@kuleuven.be

Dirk Van Hertem
Department of Electrical Engineering
KU Leuven
Leuven, Belgium
dirk.vanhertem@esat.kuleuven.be

***Abstract*—Demand curtailment is a last resort option to maintain the balance between generation and load in a power system. During these rare events, operators need to decide the magnitude and location of curtailed demand. In the context of the large European power system, this raises multiple questions related to the use of the network, the resulting welfare, and fairness towards all consumers. Currently, the market coupling algorithm allocates demand curtailment between affected zones pro-rata based on their willingness to buy at the maximum price while minimizing overall curtailment and guaranteeing that no affected zone has to export simultaneously. However, using the flow-based approach to cross zonal capacity representation exposes the complexities of the power network, resulting in the location of demand curtailment affecting the necessary magnitude.**

In this paper, we propose models that can accurately portray these rules, discuss the design challenges and quantify their impact on an illustrative example system. We found that a minimal amount of total curtailment can be achieved if the location is selected based on the zone's impact on network congestion. This method, however, disproportionately allocates the burden to often smaller zones, resulting in hard-to-manage high curtailment ratios. Aiming for equal curtailment ratios between the affected zones results in significantly larger overall volumes and curtailment events spreading to neighbouring zones more easily.

***Index Terms*—Demand Curtailment, Resource Adequacy, Flow-Based approach, Net Transfer Capacities**

I. INTRODUCTION

Involuntary demand curtailment is a contentious topic, directly linked to the reliability of a power system. Marginal cost theory suggests that the optimal reliability level is achieved once the marginal cost of increasing reliability equals the marginal decrees in the lost benefit of demand. This basic principle is used to guide the reliability standard in EU countries that is quantified in thresholds values for zonal Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS) [1].

While based on the cost estimates the threshold values - what is socially acceptable - can differ between member states the reliability standard usually is in the range of 3 to 9 hours per year of LOLE [2], [3]. This does not mean hours with black-out, rather during these hours, it is expected that the system would not be able to serve *part*[1] of its price inelastic demand.

In the electricity system of Europe, increasingly reliant on weather-dependent generation resources, it is reasonable to expect that - at least some of these - supply shortages would affect more than just one zone simultaneously [4]. This requires a *decision-making mechanism* to allocate the necessary demand curtailment volumes between zones already during the day-ahead market clearing stage. These allocated volumes would be managed by the system operators responsible for the affected zones and ultimately *could* lead to load shedding. In this paper, we investigate the importance of these rules on several key aspects of power system adequacy. To do this we propose mathematical optimization models and perform a numerical simulation on an illustrative example.

II. BACKGROUND

A. Current design

Currently, the Single Day-ahead Coupling (SDAC) of Europe is using an algorithm called: Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA) [5]. This algorithm matches bids of the market participants, and already has rules for the allocation of curtailment.

If the cross zonal capacity is represented through net transfer capacities (NTC), allocation of demand curtailment between the affected zones does not affect the overall volumes nor the welfare, subject to the available transfer capacity between the zones. To solve this indeterminacy the algorithm runs a second optimization, outside the welfare maximization framework that aims to equalize the share of curtailed demand orders compared to the total of price-taking demand orders submitted in each zone.

The flow-based approach to the capacity calculation aims to allocate transmission capacity to trades that maximize welfare. This behaviour often referred to as flow-factor competition, means that trades compete not just based on price but also based on their impact on congestion. A direct consequence

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[1] However small this part may be.

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is that price-taking demand orders (PTDOs) submitted at the technical price cap - unable to express their true willingness to pay - can be outbid by lower-priced bids from other zones. To avoid this, a penalty is applied to the welfare function if PTDOs are curtailed. This penalty is proportional to the ratio[2] of curtailed demand. This method aims for an equal share or curtailed PTDOs between the affected zones. [6]

There is an additional consideration called a "local matching" constraint introduced, aiming at locally matching the hourly PTDOs with supply from the same zone. This guarantees that a zone will not have to simultaneously export and face demand curtailment.

B. Resource Adequacy

The EU legal framework mandates the use of probabilistic indicators for the reliability standard [7]. These are the Expected Energy Not Served (EENS) and Loss of Load Expectation (LOLE). As their name suggests these indicators are expected values, namely of the yearly Energy Not Served (ENS) and of the yearly Loss of Load Hours (LOLH) in each zone. Given their probabilistic nature, they represent sample averages over a large number of simulated future operational years.

To assess if the standards are met, and to justify last resort intervention through capacity remuneration mechanisms (CRMs), a pan-European study is mandated. The methodology for the European Resource Adequacy Assessment calls for the use of the Mone-Carlo method [8]. Monte-Carlo years - year-long samples with an hourly resolution of the uncertain future state of the system - are fed into a simulation, aiming at computing the ENS and LOLH for each MC year. Convergence is tested on the value of EENS. The simulation model used has to consider the flow-based approach to capacity calculation where applicable. Clearly, for these studies, it is crucial to accurately model the demand curtailment allocation rules of the market coupling.

C. Transmission constraints

The CACM[3] network code [9] of Europe mandates the use of the flow-based approach for most European borders. While this method is currently only used for a small subset of borders located in Central-Western Europe (CWE region) and only for the day-ahead market, it is expected to be operational in the coming years over most of the continent.

This method aims at a closer representation of the reality of the power network for the market algorithm enabling more efficient use of the underlying physical assets. Through a well-defined method Critical Network Element - Contingency pairs are directly translated into affine constraints for the market coupling algorithm, the variables being the net positions of the zones. This way the amount of transmission capacity allocated for trade between two zones is interlinked with all other transactions, the algorithm can allocate the scarce capacity to transactions bringing the most benefits.

Crucially, demand curtailment allocation between zones affects the net position of these zones, and consequently the available transmission capacity between the affected zones and zones with available supply. As described, in the previous section, the current algorithm aims at finding a market solution that equalizes the ratio of curtailed price-taking demand between the affected zones. Since the redistribution of demand curtailment volumes among the affected zones influences the available transmission capacity from supply towards zones in scarcity, this solution does not guarantee a minimal amount of curtailment. The main idea of this paper is to propose and analyze methods that can directly consider sharing and minimization objectives in a single stage.

III. MODELLING APPROACH

A. Minimizing ENS

One clear objective of welfare maximization is to minimize the amount of demand curtailment.

For the traditional models, using NTCs to represent the transmission gird, the available imports to a zone do not depend on the position of the other zones. There is no competition for the transmission capacity, a social welfare maximization objective guarantees that the amount of curtailment will be minimized.

For markets using the flow-based approach to represent the transmission grid, this is not true. There is a competition between bidding zones for transmission capacity, demand orders submitted below the market cap can outbid demand orders submitted at the market cap. This is counterintuitive as the price for the latter is by definition higher, however, the competition for import capacity considers also the flow factors on the congested network elements. Since price-taking orders are limited in expressing their utility by the technical price limits there is a need to apply a special treatment for them. One way to do this is to completely disregard any bids that are not price-taking and allocate demand curtailment in a separate stage.

This can be mathematically modelled using the following minimization model:

$$\underset{e}{Minimize} \quad \frac{1}{\mid \mathcal{Y} \mid} \sum_{y}^{\mathcal{Y}} \sum_{t}^{\mathcal{T}} \sum_{z}^{\mathcal{Z}} (e_{z,y,t}) \tag{1}$$

Subject to:

$$D_{z,t,y} - p_{z,t,y} + n_{z,t,y} - e_{z,t,y} = 0 \quad \forall z,t,y : \lambda_z \tag{2}$$

$$\sum_{z}^{\mathcal{Z}} n_{z,t,y} = 0 \quad \forall t,y : \quad \lambda_n \tag{3}$$

$$p_{z,t,y} - P_{z,t,y} \leq 0 \quad \forall z,t,y : \lambda_p \tag{4}$$

$$\sum_{z}^{\mathcal{Z}} (F_{k,z,t,y} \times n_{z,t,y}) - R_{k,t,y} \leq 0 \quad \forall k,t,y : \lambda_f \tag{5}$$

The variable $e_{z,t,y}$ represents the amount of curtailment in zone z at time-step t of Monte-Carlo year y. Similarly, n represents the net position of the zone z, while p represents

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[2] 1 - (accepted price taking volume / submitted price taking volume)

[3] Capacity Allocation and Congestion Management Guideline

the supply located in the zone. The objective is to minimize the expected value of demand curtailment. The input parameters are $P_{z,t,y}$ the available production, the amount of PTDOs $D_{z,t,y}$, and the transmission constraints. The transmission constraints for each CNEC k are represented by the zone-to-slack PTDF $F_{k,z,t,y}$ and the available margin for trade RAM $R_{k,t,y}$

This is not a welfare maximization model, instead, it looks for a solution with minimal curtailment, justified by the assumption that curtailment should be the last resort option. Since no costs are considered prices can not be derived from this model. Furthermore, if there is no ENS present in a zone the values are undetermined and should not form the basis for any further computation.

B. Local Matching

One observation we can make with the previous model (1)-(5) is that zones can be forced to curtail demand and simultaneously export generation. In this situation the zone would be better without the market coupling, a politically sensitive topic. To counter this an additional constraint has been added, called local matching, that restricts zones from simultaneously exporting and being in scarcity. This effectively sets an upper bound on the curtailment volumes.

Arguably this forces countries to prefer to have generators physically located in their territory, gaining priority access to their production during scarcity, promoting not only an inefficient use of the network but also creating strong incentives for intervention.

Local matching as described can be added as an additional constraint.

$$n_{z,t,y} - \max(P_{z,t,y} - D_{z,t,y}; 0) \leq 0 \quad \forall z, t, y : \lambda_l \tag{6}$$

Since this is a constraint of the previous model, by definition will lead to higher curtailment volumes, and directly affect the value of the transmission.

C. Curtailment Sharing

If more than one zone is affected, and there is still transmission capacity available between the zone, NTC models face indeterminacy. To solve this a sharing rule was introduced aiming for an equal share of curtailment among the affected zones. This indeterminacy could be solved in a post-processing step for NTC-based models.

Modelling these rules for flow-based constraints requires updating the objective of the base model to a quadratic function:

$$\underset{e}{Minimize} \quad \frac{1}{\mid \mathcal{Y} \mid} \sum_{y}^{\mathcal{Y}} \sum_{t}^{\mathcal{T}} \sum_{z}^{\mathcal{Z}} (M \times (\frac{e_{z,y,t}}{D_{z,y,t}})^2) \tag{7}$$

The constraints of the problem remain the same.

M is a large constant. If the curtailment minimization and sharing objectives would be combined this value can be tuned to represent a trade-off between the two objectives.

Interestingly this rule, aiming for equal shares, overwrites the model's ability to optimize the location of the curtailed demand, leading to higher volumes.

IV. NUMERICAL EXAMPLE

The above-mentioned models are demonstrated in this section using a numerical example. The scope is to compute the EENS and LOLE adequacy indicators using the same inputs but with the different models described in section III.

The complete code and input data, described here, are publicly available at a GitHub repository [10]. The code is implemented using the Julia programming language, with the JuMP solver-independent abstraction layer. The results presented here are computed with Gurobi[4], a high-performance commercial mathematical optimization solver, that offers free licenses for academic use.

A. Modeled Areas

We consider the European bidding zones that have at least a border part of the Core Capacity Calculation Region. The region is expected to use the Flow-Based approach to capacity calculation starting in June 2022. For the purpose of this example, we considered this region in isolation. No imports are available from other bidding zones, and trade between the other zones in the market coupling does not influence the available transmission capacities between the zones.

B. Transmission constraints

Computing accurately the cross zonal capacities, using the flow-based approach for adequacy studies is subject to active research [11]–[13]. For this demonstration, we used real data from a randomly selected operational hour. The data is gathered from the External Parallel run of the Core Flow-Based capacity calculation region [14]. This data is published by the Joint Allocation Office (JAO) on their publication platform[5].

The Evolved Flow-Based method is used to represent trade on the ALEGrO HVDC link between Belgium and Germany. Using this method we can account for the effects of the flows on this HVDC link on the AC parts of the network. To model this we rely on two virtual areas (AlegroBE, and AlegroDE) with no demand or generation attached to them. The net positions of these zones are linked with opposite signs.

C. Electricity Demand

The 2019 actual total load from the European Market Information Transparency Platform [15] is used for each zone. The whole demand is considered non-price responsive, any shortfall in serving it is involuntarily curtailment - for our demonstration ENS.

Power system operation requires significant volumes of different types of operational reserves to guarantee the resilience of the system to disturbances. In this example, we consider that system operators have the necessary reserves secured outside of the described framework and these do not affect the curtailment allocation process during the day-ahead time frame.

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[4] https://www.gurobi.com/products/gurobi-optimizer/

[5] https://core-parallelrun-publicationtool.jao.eu/

TABLE I
EXPECTED ENERGY NOT SERVED (GWH/YEAR)

	Minimization		Sharing	
		w. Local		w. Local
Belgium	3.0	3.5	2.2	2.1
Czechia	0.0	0.0	0.1	0.0
Germany	16.7	17.6	44.7	44.8
Netherlands	23.0	21.6	6.3	6.3
Total	42.7	42.7	53.3	53.2

* Zones without ENS are omitted.

TABLE II
LOSS OF LOAD EXPECTATION (HR/YEAR)

	Minimization		Sharing	
		w. Local		w. Local
Belgium	7.40	8.90	19.20	16.73
Czechia	0.00	0.00	9.40	0.00
Germany	12.23	12.57	23.57	23.57
Netherlands	20.60	20.57	25.07	24.77

* Zones without LOLE are omitted.

D. Generation Capacities

Fleet level power generation capacities are used from the EU reference scenario for 2030 [16]. This is given as generation by type for each member state. In an effort to speed up the time to convergence of this example we used derated capacities for all conventional power plants instead of relying on samples of outages. Energy storage systems are not considered.

We rely on the synthetic capacity factors created by the EMHIRES study [17], [18] for 30 years of wind and solar generators on a country level, corresponding to climate years (1986-2015). Each climate year consists of 8760 hourly capacity values, for each member state for solar and for wind resources.

V. RESULTS AND DISCUSSION

A. Adequacy Indicators

The main indicators used today in Europe are the EENS and LOLE, these can be directly computed from the results of the optimization model. Hourly ENS in each zone is one of the decision variables of the optimization problem. These have been rounded to the nearest MW value and the yearly expectancy was computed, see table I. Hours, when the zonal hourly ENS is not null, are considered Loss of Load Hours, the yearly expectancy of these values (LOLE) is summarized in table II

Clearly, the choice of model has a great influence on these indicators. The cell background shading in the table is based on the relative values compared to the indicators achieved for the same zone.

As expected, the ENS minimization algorithm allocated ENS based on the impact of a zone's net position on the transmission network. The disadvantaged zones contribute to congestion on the most constraining transmission elements. In this example, the most striking difference can be seen in the Netherlands.

TABLE III
LOCAL MATCHING CONSTRAINT ACTIVE (HR/YEAR)

	Minimization	Sharing
Belgium	2.23	3.10
Czechia	9.93	10.57
Croatia	6.67	7.67
Hungary	0.27	0.77
Netherlands	2.27	0.30
Slovenia	1.03	2.03

* Zones with only zero values are omitted.

Models that aim for an equal share of curtailment among affected zones, lead to overall higher amounts of ENS. These models can not prioritize to curtail only in zones that would free up import capacity for others. The differences in overall EENS are striking, rising by close to 25%. Zones with larger demand, in the scope of achieving the same curtailment ratios, are allocated much larger ENS values. This is best seen in the case of Germany - being the zone with the largest demand attached - it is allocated about 2.5 times larger ENS.

A particular case is seen for Czechia, since it has little impact on the import potential of other zones it has no ENS allocated in the Minimization cases. Similarly, if the local matching constraint is considered the allocated ENS is null, indicating that in the hours with curtailment it would be self-sufficient. However, if the algorithm aims for an equal share among affected zones, in some hours it would choose to have Czechia export electricity while also having to curtail demand. This is counter-intuitive, but this way transmission capacity can be freed up for impacted zones.

The impact on the LOLE indicators of curtailment sharing is clear. Curtailment is spread out, all zones seeing more frequent curtailment events, but with smaller magnitudes. The Netherlands is an interesting case to investigate, because of the curtailment sharing rules it has a much smaller amount of ENS allocated, but the loss of load hours are increased significantly. This again indicates the prevalence of more frequent but smaller magnitude loss of load events, when curtailment sharing rules are implemented.

Local matching rules help zones where available generation is located. This essentially gives priority access to consumers in the same bidding zones, against EU free trade principles.

B. Local Matching constraints

The local matching constraints (6) are active if a zone would face scarcity simultaneously with exporting electricity (Summarized in Table III). During these hours the electricity generated in the zone is needed to match local inflexible demand. But as a negative effect of this priority access during these hours the import potential of other affected zones is jeopardized.

TABLE IV
TRANSMISSION CONSTRAINTS ACTIVE (HR/YEAR)

	Minimization		Sharing	
		Local		Local
Gyor [HU] - Neusiedl [AT]	25.30	25.30	25.30	25.30
Achene [BE] - Lonny [FR]	23.80	23.80	23.73	23.73
St. Peter [DE] - Pleinting [AT]	23.10	23.10	23.07	23.07
Gonyu [HU] - Gyor [HU]	21.27	21.40	23.30	23.27
Pasewalk [DE] - Vierraden [DE]	20.83	20.83	20.77	20.77
Hradec [CZ] - Rohrsdorf [DE]	19.70	19.70	19.00	18.93
ALEGrO Link [BE] - [DE]	12.73	14.37	22.00	22.03
Baru Mare [RO] - Hasdat [RO]	16.70	16.70	15.93	15.87

* Only showing the top 8 most active constraints.

TABLE V
POWER BALANCE CONSTRAINT ACTIVE (HR/YEAR)

	Minimization		Sharing	
		w. Local		w. Local
Belgium	19.07	16.83	19.63	16.83
Czechia	9.93	0.00	10.57	0.00
Germany	23.63	23.63	23.63	23.63
Croatia	6.70	0.00	7.60	0.00
Hungary	0.27	0.00	0.77	0.00
Netherlands	25.13	24.83	25.13	24.83
Slovenia	17.90	17.13	16.37	14.27

* Zones with only zero values are omitted.

C. *Transmission constraints*

An important facet of the flow-based approach is to connect the congestion to real assets (5). This way we gain an insight into where potential network expansion could help alleviate curtailment.

Importantly adding an extra MW of capacity to these lines oftentimes helps reduce the overall amount of demand curtailment by multiple MWh. This is because only part of the new trade potential would have to flow through these congested elements. It also underlines the importance of accuracy in cross zonal capacity computations.

Aiming for overall minimized curtailment versus for a logic based on equal shares presents a vastly different congestion pattern (Summarized in Table IV). While some elements seem to be constraining no matter the choice of model, others are highly dependent on the choice of algorithm.

We can see also elements located in zones that seemingly have no contribution to the scarcity situation such as (Baru Mare [RO] - Hasdat [RO][6]) show up among the most congested list. These elements limit imports from countries that have available power generation. In this particular case, we can observe that the CNE located deep inside Romania was often active, while the Power Balance constraint of Romania was never active, indicating that Romania had additional power that could not have been transported towards the zones needing it most.

D. *Power Balance constraints*

Another insight can be gained by looking at the number of hours the zonal power balance constraints (3) were active (Summarized in Table V). During these hours more power generation located in that zone could have helped lower the overall ENS. These hours include those when the zone itself faces scarcity, but also those when the additional generation could have been transported towards other zones facing scarcity.

In this context, we see that zones like Slovenia and Hungary could contribute significantly to the elimination of the scarcity situation in other parts of Europe. Given the use of marginal pricing, during the hours the power balance constraint is active, prices would reach the price cap also in these zones. This is an important aspect for analyzing the economic viability of generation assets and for generation expansion planning in general. We can also observe a clear impact of the local matching constraint on these zones' ability to contribute.

VI. CONCLUSIONS

The flow-based approach to capacity calculation brings markets closer to the reality of transmission networks. Linking the net position of all zones implies that the import capacity of any given zone is influenced by all others. This is particularly important during scarcity when an extra unit of imports could lower the magnitude of demand curtailment.

This presents a challenge, optimizing the grid to achieve overall minimum amounts of curtailment requires curtailing where the most congesting load is located. Contrary to this, the current practice is to curtail aiming for equal shares of curtailment. While these two objectives were easily reconciled using the traditional NTC-based network representation, it is not the case with the flow-base approach.

In this paper, we presented mathematical models for representing both systems and demonstrated the influence on an illustrative numerical example. While the setup is not a full adequacy study, the achieved results demonstrate a significant impact on zonal adequacy indicators - implicitly on investment needs.

In addition, the paper explores the impact of constraints restricting exports during scarcity. We showed that these constraints inhibit trades that could lower the problem's magnitude and distort the economic value of some units.

The flow-based approach also lets us explore the impact of individual network elements on the scarcity situation. Looking at the most constraining elements, we can gain insights into the congestion patterns, and gather information about how network expansion can contribute to alleviating the problems.

The models presented can guide practitioners in choosing the right methods for performing adequacy studies, and policymakers in understanding the impact of design rules. The two objectives can be ultimately balanced by tuning the parameter M in the objective (7).

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[6] https://www.openstreetmap.org/way/311569354

REFERENCES

[1] Agency for the Cooperation of Energy Regulators (ACER), "Decision 23/2020 - Annex I - Methodology for calculating the value of lost load, the cost of new entry and the reliability standard," May 2020.

[2] ——, "Market Monitoring Report 2019 - Electricity Wholesale Markets Volume," Feb. 2021. [Online]. Available: https://www.acer.europa.eu/electricity/market-monitoring-report

[3] L. Söder, E. Tómasson *et al.*, "Review of wind generation within adequacy calculations and capacity markets for different power systems," *Renewable and Sustainable Energy Reviews*, vol. 119, p. 109540, Mar. 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032119307488

[4] ELIA, "Adequacy and Flexibility Study for Belgium 2022-2032," Tech. Rep., Jun. 2021. [Online]. Available: https://www.elia.be/en/electricity-market-and-system/adequacy/adequacy-studies

[5] NEMO Committee, "EUPHEMIA Public Description - Single Price Coupling Algorithm," Tech. Rep., Dec. 2020. [Online]. Available: https://www.nordpoolgroup.com/globalassets/download-center/single-day-ahead-coupling/euphemia-public-description.pdf

[6] CWE TSOs and NEMOs, "Documentation of the CWE FB MC solution as basis for the formal approval-request - Annex 16.20 Mitigation to curtailment of price taking orders," Tech. Rep., Mar. 2015.

[7] European Union, "Regulation 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity." Jun. 2019, legislative Body: EP, CONSIL. [Online]. Available: http://data.europa.eu/eli/reg/2019/943/oj/eng

[8] Billinton and W. Li, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*. Springer US, 1994. [Online]. Available: https://www.springer.com/gp/book/9780306447815

[9] European Union, "Commission Regulation 2015/1222 of 24 July 2015 - Establishing a guideline on Capacity Allocation and Congestion Management (CACM GL)," Jul. 2015, legislative Body: COM. [Online]. Available: http://data.europa.eu/eli/reg/2015/1222/oj/eng

[10] T. Borbáth, "Demand curtailment allocation models," 2022. [Online]. Available: https://github.com/tamas-borbath/FB-models

[11] T. Borbáth and D. Van Hertem, "The Impact of Cross-Border Transmission Constraints on Resource Adequacy Assessment," in *2021 IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6.

[12] B. B. Zad, J.-F. Toubeau *et al.*, "Enhanced integration of flow-based market coupling in short-term adequacy assessment," *Electric Power Systems Research*, vol. 201, p. 107507, Dec. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779621004880

[13] M. Li and B. Seguinot, "Modelling of Flow-Based Domains in Antares for Adequacy Studies," Oct. 2017.

[14] Agency for the Cooperation of Energy Regulators (ACER), "Decision No 02/2019 on the Core CCR TSOs' proposal for the regional design of the day-ahead and intraday common capacity calculation methodologies," Feb. 2019.

[15] ENTSO-E Transparency Platform, "Actual Total Load [6.1.A]." [Online]. Available: https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show

[16] D.-G. for Climate Action, D.-G. for Energy *et al.*, *EU reference scenario 2020: energy, transport and GHG emissions : trends to 2050*. LU: Publications Office of the European Union, 2021. [Online]. Available: https://data.europa.eu/doi/10.2833/35750

[17] Joint Research Centre, "EMHIRES dataset Part I: Wind power generation," Tech. Rep., Jan. 2016. [Online]. Available: https://setis.ec.europa.eu/emhires-dataset-part-i-wind-power-generation_en

[18] ——, "EMHIRES dataset Part II: Solar power generation," Tech. Rep., Jan. 2017. [Online]. Available: https://setis.ec.europa.eu/emhires-dataset-part-ii-solar-power-generation_en