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What hourly net interchange hides at a multi-interface grid boundary

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Abstract

Net exchange combines electricity imports and exports over an area's boundaries into one signed value. The net amount across the area can be small even when its separately reported exchanges are large. We used U.S. Energy Information Administration observations for 26 balancing authorities in California and the Northwest, aligned on 4,294 common hours from January through June 2025. Across authorities, a median of 34.6% of bilateral exchange volume canceled before the hourly area net appeared. Summing those hourly net values over the period introduced a further median cancellation of 0.8% of bilateral volume. The first share exceeded 50% for ten areas. Most of the cancellation occurred within hourly area totals. Adding those values over the full observation period removed relatively little of the bilateral activity by comparison.

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Keywords: balancing authorities, electricity interchange, bidirectional exchange, aggregation, microgrid indicators

1. Introduction

A line on an electricity dashboard can show the exact net exchange for an area and still be a poor answer to the question of how much electricity the area exchanged. The problem arises when an area exports to one neighbor and imports from another during the same interval. Those flows enter the signed sum with opposite signs. Choosing an hourly interval is often an improvement over an annual average because it preserves reversal across hours. But higher time resolution cannot recover simultaneous opposing flows that were already lost in the spatial sum. An assessment that uses net interchange to report a system's energy balance can therefore disagree with one that uses the same number to characterize its external exchange.

Kan et al. (2024) propose an indicator system for evaluating low-carbon microgrids. We use their evaluation perspective to distinguish the boundary measurements that would be needed before combining technical measures with carbon or resource indicators. Hirsch et al. (2018) review the variety of technical and institutional settings in which microgrids interact with a surrounding grid. Olivares et al. (2014) distinguish operating and control requirements across different modes. Both issues make the system boundary consequential for evaluation. A site with a single point of exchange does not have multiple interfaces to add at that scale, while an assessment that combines electrically separate meters can make the issue immediate. We test the arithmetic with regional records because those records preserve separately identified counterparties, not because they measure the impact of any microgrid.

The research question is how much reported bilateral energy movement is absent from the signed area total because counterparties exchange power in different directions in the same hour, and how much more is lost when signed hourly totals are added across several months. We compare the two operations on an identical timestamp support for each of 26 reporting areas. An audit of values filed by counterparties separately measures how much the key findings depend on one side of the report. No pricing or dispatch intervention is used in the comparison.

2. Data and indicator design

2.1 Observations at the reporting boundary

Form EIA-930 provides separate hourly CSV archives for electricity balances and interchange with directly interconnected balancing authorities. The EIA describes bilateral interchange values as net metered tie-line exchanges with each connected authority, with negative values inward and positive values outward from the reporting area's perspective (U.S. Energy Information Administration, n.d.). We use the January–June 2025 bilateral file (U.S. Energy Information Administration, 2025). We calculate an area total by summing the bilateral file entries in the stated sign convention. The published total from the separate balancing file may have a different collection clock or discrepancies with the detailed fields, and is not needed for the arithmetic comparison. The analysis keeps the direction reported by the focal area.

We select every focal balancing authority (BA) identified with a California or Northwest reporting-region code in the source, yielding five California and 21 Northwest reporters. The neighbors of those focal areas remain in the calculation even if assigned to a different region. The region tags identify the agency's report group. A BA boundary follows the source's operating and reporting designation, so it cannot be interpreted as the geographic boundary of a city or state. The Federal Energy Regulatory Commission's market primer (Federal Energy Regulatory Commission, 2024) is helpful for understanding the distinction between electric operating roles and the organization of wholesale markets. Neither a transaction nor a price area is the measurement unit here.

We converted end-of-hour UTC timestamps to interval starts and used the requested window from 2 January 00:00 to 30 June 23:00 UTC, inclusive. UTC gives a common 24-hour calendar day across the focal authorities and avoids local clock complications. The partial first UTC date in the half-year file was outside the analysis window. The expected support was 4,320 hours. We identified each focal area's counterparties from the columns created by its directed hourly records. Every neighbor observed in the window contributed at least one numeric entry. For the main calculation an area-hour requires numeric values from all of that area's observed counterparties. A zero reported at a valid hour is retained. Duplicate reporting-area, counterparty and hour keys would stop the replay. We then use only hours satisfying the completeness condition for all areas. This intersection preserves the relationship between reported local clocks and a common sample without inventing values for missing observations.

2.2 Separating cancellation in space and time

Let (f_{ijt}) be interchange from the perspective of area (i) with counterparty (j) at hour (t). We compute inward exchange ($I_{it}=\sum_j \max(-f_{ijt},0)$) and outward exchange ($O_{it}=\sum_j \max(f_{ijt},0)$). The signed total is ($N_{it}=O_{it}-I_{it}$), and bilateral exchange volume is ($B_{it}=I_{it}+O_{it}$). The difference between bilateral volume and the magnitude of the area net in that same hour is ($C_{it}=B_{it}-|N_{it}|=2\min(I_{it},O_{it})$). An hour with 60 MW inward and 50 MW outward, for example, has 110 MWh of bilateral exchange volume and a 10 MWh inward area net. The 100 MWh difference is a consequence of applying the absolute value after combining the two signs. It is not a physical transmission loss.

For each area, the first component is ($\sum_t C_{it}$). The second is ($\sum_t |N_{it}|-|\sum_t N_{it}|$), which captures additional cancellation when combining net importing and net exporting hours. The third is ($|\sum_t N_{it}|$), the absolute net across the full window. These nonnegative components sum to ($\sum_t B_{it}$). A one-hour interval converts a reported hourly mean expressed in MW to the same numeric value in MWh. We report both signed period net and total bilateral volume in GWh and the three components as shares of the same area denominator. The quantity ($2\min(I,O)$) counts the two opposed

boundary crossings in the gross volume. It does not determine a common source of the electricity on the inward and outward sides.

A focal area may report two apparent directions because it has multiple neighbors, yet each bilateral value may in turn be the net of several physical tie lines. The decomposition cannot separate offsetting flows among those individual lines or reversals within an hour. Classical flow tracing uses line-level power-flow solutions and tracing assumptions to allocate sources and sinks. Bialek (1996) and Kirschen et al. (1997) establish examples of that different estimation task. Hörsch et al. (2018) show that a tracing approach can characterize the source composition of links under a network representation. Hoffmann and Krost (2017) use paths over a graph to recognize circular flows. Our aggregate records support a narrower scalar measurement. They do not identify a ring, provenance, or the physical path taken between any two reported interfaces.

2.3 Checking the paired readings

The EIA says a focal BA's reported exchange should be the sign reversal of its neighbor's report for the same hour, but it also describes reporting differences and missing agreement on directly connected neighbors (U.S. Energy Information Administration, n.d.). We looked for a numeric reverse-direction record in the archive by swapping the reporting and neighbor codes. Within the matched subset we recorded whether the numbers were exact negatives and whether their sum was within 10 MW of zero. We also calculated a stricter result on common hours where every focal interface had a numeric reverse observation within that tolerance. The choice of 10 MW is an absolute reporting agreement check, not a universal operational tolerance. An unmatched reverse report can result from different observation coverage and excludes that hour in this sensitivity, without converting the primary value to zero. This check preserves the focal area estimates rather than reconciling competing filings. We repeated the main shares on each area's own complete hours as a separate check on the common-window choice.

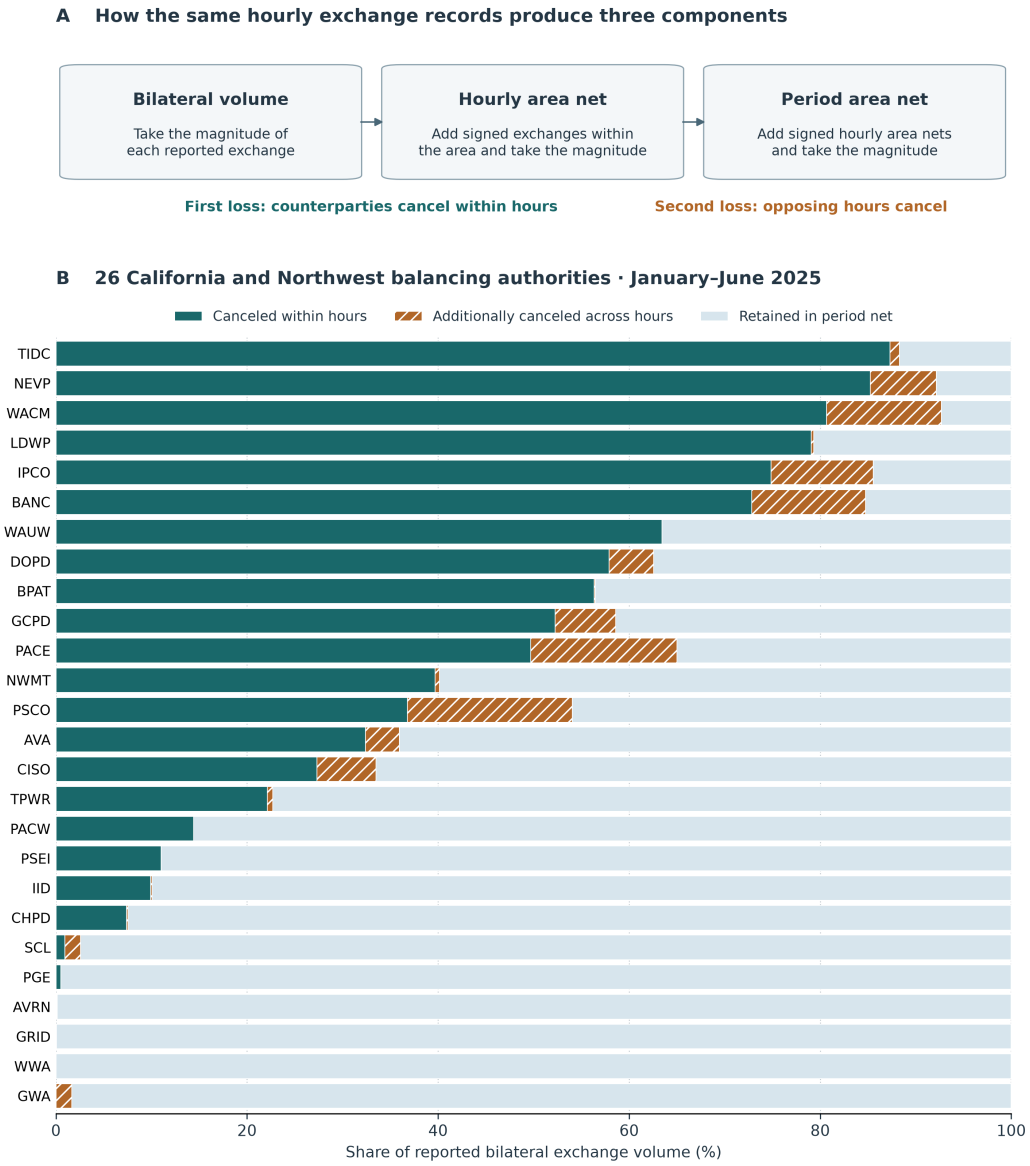

Figure 1. *Measurement design and results. The three components use each area's bilateral exchange volume as the denominator and sum to 100%. The two cancellation categories distinguish the addition of opposite signs across counterparties from the further addition of opposite signs across hours. All areas use the same 4,294 UTC hours.*

3. Results

3.1 How much interchange disappears from the hourly net?

The focal areas had between one and 18 observed counterparties. Twenty-three had all 4,320 candidate hours complete. California Independent System Operator (CISO) had 4,296, while CHPD and PSCO each had 4,319. The intersection of complete hours was 4,294, yielding 111,644 area-hours. Both an inward and an outward observation occurred in a median of 91.0% of common hours per area. This concurrence measure gives large and small exchange amounts equal weight. The decomposition shows the volume consequences. The median same-hour cancellation across authorities was 34.6% of each area's total bilateral exchange, and ten authorities lost more than half of their volume at this stage. In 23 areas, same-hour cancellation exceeded the additional cancellation from summing hourly area nets over all observed months.

The largest bilateral volume in the study was recorded by Bonneville Power Administration (BPAT), with 50,285 GWh. The hourly area net removed 56.3% of that volume, or 28,329 GWh. BPAT sent electricity

outward in net terms over the full period, with a signed balance of 21,899 GWh. Its across-hour cancellation was only 0.1% of gross volume. This pairing demonstrates that an area can maintain the same broad net direction over time while remaining highly active in both directions across different neighbors. CISO had 23,499 GWh of bilateral volume and was a net importer. Its within-hour and subsequent across-hour cancellation shares were 27.3% and 6.2%, respectively. The period sign and total alone conceal this difference in how each area exchanges power.

Table 1. *All five California reporters and the five Northwest reporters with the largest bilateral volume. A negative signed period net indicates net inward exchange. The percentages may not sum to 100 due to rounding. The results file reports every focal area.*

Area	Reporter group	Bilateral volume (GWh)	Signed period net (GWh)	Canceled within hours (%)	Additionally canceled across hours (%)	Retained as period net magnitude (%)
BANC	CAL	5,683	−867	72.8	11.9	15.3
CISO	CAL	23,499	−15,624	27.3	6.2	66.5
IID	CAL	1,696	+1,525	9.9	0.1	90.0
LDWP	CAL	16,088	−3,326	79.1	0.3	20.7
TIDC	CAL	2,572	−301	87.3	1.0	11.7
BPAT	NW	50,285	+21,899	56.3	0.1	43.5
PSEI	NW	10,713	−9,531	11.0	0.0	89.0
NEVP	NW	10,380	−814	85.2	6.9	7.8
PACW	NW	8,264	−7,073	14.4	0.0	85.6
PACE	NW	7,987	+2,796	49.7	15.3	35.0

Turlock Irrigation District (TIDC) showed the largest proportion of same-hour cancellation, 87.3%. The 2,572 GWh bilateral volume and 301 GWh net inward exchange describe different aspects of the area's boundary accounting. For the two single-counterparty reporters, GWA and WWA, the within-hour cancellation is zero by definition because only one signed value is present. This is a useful limiting case against which the results for multi-interface areas can be interpreted. In total there were 69 area-hours in which the area net equaled exactly zero despite both inward and outward exchanges. That count concerns exact zeros in the archived data. The substantive result does not depend on finding a sufficiently small threshold for calling an hourly net zero.

3.2 Sensitivity to coverage and which side reports the exchange

Replacing the common sample with all available complete hours for each area changes the first percentage by at most 0.16 percentage points. The check with opposite-side filings is more informative. All 4,294 common hours for Idaho Power (IPCO) satisfied the criterion that every observed interface was paired and within 10 MW. Its same-hour cancellation was 74.9% in both views. For Los Angeles Department of Water and Power (LDWP), the stricter sample contained 4,203 hours and the share was 79.1%, close to its full result. NV Energy (NEVP) had 4,271 such hours and a stricter share of 85.3%. These examples establish that high within-hour cancellation is present in many hours with closely corroborated directional readings.

Other results were based on far weaker counterpart coverage. None of the common hours in CISO or BPAT supported a complete reverse report within 10 MW on every observed interface. Some edges

lacked a reverse row, and some reverse values did not agree closely. That limits a claim of independent corroboration for those totals. It does not change the interpretation of the calculation as a comparison of aggregation methods applied to the focal reporter's own data. Table 2 shows areas with strong and incomplete corroboration so the difference is visible.

Table 2. *Selected corroboration checks. All 4,294 common hours enter the first column after the area name. In the strict column, the whole area-hour is omitted if any interface has no counterpart value or the reported signed values differ from exact opposites by more than 10 MW.*

Area	Full-window same-hour cancellation (%)	Common hours where every interface agrees within 10 MW	Cancellation in those hours (%)
BANC	72.85	4,279	72.86
BPAT	56.34	0	—
CISO	27.33	0	—
IPCO	74.85	4,294	74.85
LDWP	79.06	4,203	79.12
NEVP	85.23	4,271	85.27
PACW	14.41	4,060	14.39

4. Implications and limits

4.1 What an indicator can safely claim

The results suggest a reporting sequence. A net balance states the net dependence of an area on its surroundings over the chosen period. Displaying time-disaggregated area net adds information about switching net direction. Separately displaying import and export volume at the recorded boundaries adds information about contemporaneous activity that both net series omit. An area with nearly all of its exchange in one direction behaves very differently under this sequence from an area with nearby simultaneous sources and outlets. A gross total should be read at the focal area only because a transfer can count at both endpoints if the aggregates are combined. One study area may also include part of a flow already represented by another area's entries. There is no estimate here of how much power could flow if an observed interface were disconnected or available capacity changed.

The distinction is valuable in carbon accounting. Tranberg et al. (2019) model hourly electricity exchange to allocate emissions on a consumption basis in Europe. de Chalendar et al. (2019) use U.S. electricity data to trace embodied pollutants. Castrillo et al. (2026) consider joint carbon and water attributes. These are attribution exercises involving information beyond a signed boundary total. If the inward and outward sides have different sources or different accounting treatment, combining them before the attribution can remove information that a later emissions coefficient cannot reconstruct. This study neither attributes generation to individual consumers nor measures operational emissions. It shows why choosing a boundary interchange indicator precedes those tasks.

Physical exchange should also be distinguished from commercial schedules. Kunz (2018) decomposes scheduled and unscheduled European flows using a separate market and network model. The EU regulator's monitoring study (European Union Agency for the Cooperation of Energy Regulators, 2024) describes how some flows across zones originate in activity within another zone. Forbes and St. Cyr (2019) examine high-voltage exchanges for a different North American interface and specific

environmental question. Our opposing flows establish only the measured pattern across different reporters' neighbors. Although the published actual interchange is intended as a physical value, the comparison does not have contracts, scheduled flows or the complete network topology needed to diagnose telemetry discrepancies. Consequently no part of either cancellation share can be labeled an unscheduled transaction or used to infer trading inefficiency.

4.2 Fit to a planning question

An evaluation can document import and export separately at whatever interface resolution it can substantiate. Hu et al. (2021) emphasize that control models distinguish the internal system and its grid interaction. Ahmed et al. (2023) examine monitoring architectures for integrated distributed resources. This suggests a practical boundary question for a microgrid or a collection of microgrids. An evaluator can decide in advance whether reporting needs solely a net annual balance or directional measurements at distinct points. Once measurements are reduced to a net at the wrong stage, more frequent reporting of that net cannot restore the direction by interface. A site with one measured interface can instead study cancellation over time or compare different settlement and physical clocks. None of the BA findings establish how a particular microgrid should size storage or interconnection equipment.

A detailed network model is a further step. Caliskan and Tabuada (2014) study boundary-preserving reduction for a class of electrical networks. Hofmann et al. (2020) compare ways of allocating flows in modeled meshed grids. Xiong et al. (2025) describe representing high-voltage topology with public open geographic data, while Qu and Bang (2024) review European grid development models. Such work illustrates why operational claims need topology and physical constraints in addition to published transfer records. Wiese et al. (2019) also document the value of making the preparation of public electricity datasets reproducible. The current archive and output preserve the inputs for a transparent sum, not parameters for an equivalent network. A later effort could compare outcomes under a genuinely boundary-preserving representation after independently establishing the relevant topology.

Likewise, transport volumes alone do not tell us the value of transmission investment. Bloom et al. (2022) and MacDonald et al. (2016) simulate resource and transmission choices across large U.S. geographies. Brown et al. (2018) examine how other forms of flexibility change the modeled value of transmission reinforcement. Mertens et al. (2020) and Abrell and Rausch (2016) represent cross-border trade endogenously when assessing planning outcomes. Plancke et al. (2016) distinguish market capacity formulations, while Montoya et al. (2020) show why efficiency depends on additional market information. In each application the object of inference determines which data must be kept. A small net may be benign for the balance statement, but it is insufficient support for saying that an interface sees little use.

5. Conclusion

Across 26 California and Northwest balancing authorities, an hourly signed net canceled a median 34.6% of reported bilateral interchange volume before any across-hour netting took place. For ten authorities, this initial step removed more than half. The result is a property of the measured reports and the order of arithmetic at the chosen boundary. Net interchange remains the appropriate measure for a net balance. Interchange activity requires directional observations at the individual reporting interfaces and a clear account of missing or uncorroborated records.

Data and code availability

The official archive (U.S. Energy Information Administration, 2025) and the reproduction record provide source details, code, figure and results. This study used public area-level records and no customer measurements.

References

Plancke, G., De Vos, K., De Jonghe, C., & Belmans, R. (2016). Efficient use of transmission capacity for cross-border trading: Available Transfer Capacity versus flow-based approach. *2016 IEEE International Energy Conference (ENERGYCON)* (pp. 1–5). https://doi.org/10.1109/energycon.2016.7513974

Kirschen, D., Allan, R., & Strbac, G. (1997). Contributions of individual generators to loads and flows. *IEEE Transactions on Power Systems, 12*(1), 52–60. https://doi.org/10.1109/59.574923

Tranberg, B., Corradi, O., Lajoie, B., Gibon, T., Staffell, I., & Andresen, G. B. (2019). Real-time carbon accounting method for the European electricity markets. *Energy Strategy Reviews, 26*, 100367. https://doi.org/10.1016/j.esr.2019.100367

Montoya, L. G., Guo, B., Newbery, D., Dodds, P. E., Lipman, G., & Castagneto Gissey, G. (2020). Measuring inefficiency in international electricity trading. *Energy Policy, 143*, 111521. https://doi.org/10.1016/j.enpol.2020.111521

Bialek, J. (1996). Tracing the flow of electricity. *IEE Proceedings - Generation, Transmission and Distribution, 143*(4), 313. https://doi.org/10.1049/ip-gtd:19960461

Castrillo, M., Iglesias Blanco, J., Sáinz-Pardo Díaz, J., & López García, Á. (2026). Wattnet: Matching electricity consumption with low-carbon, low-water footprint energy supply. *Sustainable Computing: Informatics and Systems, 52*, 101473. https://doi.org/10.1016/j.suscom.2026.101473

Kunz, F. (2018). Quo Vadis? (Un)scheduled electricity flows under market splitting and network extension in central Europe. *Energy Policy, 116*, 198–209. https://doi.org/10.1016/j.enpol.2018.01.051

Federal Energy Regulatory Commission. (2024). *Energy Primer: A Handbook for Energy Market Basics*. https://www.ferc.gov/sites/default/files/2024-01/24_Energy-Markets-Primer_0117_DIGITAL_0.pdf

MacDonald, A. E., Clack, C. T. M., Alexander, A., Dunbar, A., Wilczak, J., & Xie, Y. (2016). Future cost-competitive electricity systems and their impact on US CO2 emissions. *Nature Climate Change, 6*(5), 526–531. https://doi.org/10.1038/nclimate2921

Kan, D., Jin, T., Zao, R., & Yin, S. (2024). A Low-carbon Microgrid Evaluation Index System Adapted to the New Power System. In *2024 IEEE International Conference on Electrical Energy Conversion Systems and Control (IEECSC)* (pp. 318–322). IEEE. https://doi.org/10.1109/IEECSC62814.2024.10913728

U.S. Energy Information Administration. (n.d.). *About the EIA-930 data*. https://www.eia.gov/electricity/930-content/about.html

U.S. Energy Information Administration. (2025). *Hourly Electric Grid Monitor interchange data, January–June 2025 [Data set]*. https://www.eia.gov/electricity/gridmonitor/sixMonthFiles/EIA930_INTERCHANGE_2025_Jan_Jun.csv

Wiese, F., Schlecht, I., Bunke, W. D., Gerbaulet, C., Hirth, L., Jahn, M., Kunz, F., Lorenz, C., Mühlenpfordt, J., Reimann, J., & Schill, W. P. (2019). Open Power System Data – Frictionless data for electricity system modelling. *Applied Energy, 236*, 401–409. https://doi.org/10.1016/j.apenergy.2018.11.097

Hu, J., Shan, Y., Guerrero, J. M., Ioinovici, A., Chan, K. W., & Rodriguez, J. (2021). Model predictive control of microgrids – An overview. *Renewable and Sustainable Energy Reviews, 136*, 110422. https://doi.org/10.1016/j.rser.2020.110422

Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., Canizares, C. A., Iravani, R., Kazerani, M., Hajimiragha, A. H., Gomis-Bellmunt, O., Saeedifard, M., Palma-Behnke, R., Jimenez-Estevez, G. A., & Hatziargyriou, N. D. (2014). Trends in Microgrid Control. *IEEE Transactions on Smart Grid, 5*(4), 1905–1919. https://doi.org/10.1109/tsg.2013.2295514

Mertens, T., Poncelet, K., Duerinck, J., & Delarue, E. (2020). Representing cross-border trade of electricity in long-term energy-system optimization models with a limited geographical scope. *Applied Energy, 261*, 114376. https://doi.org/10.1016/j.apenergy.2019.114376

Hörsch, J., Schäfer, M., Becker, S., Schramm, S., & Greiner, M. (2018). Flow tracing as a tool set for the analysis of networked large-scale renewable electricity systems. *International Journal of Electrical Power & Energy Systems, 96*, 390–397. https://doi.org/10.1016/j.ijepes.2017.10.024

Bloom, A., Novacheck, J., Brinkman, G., McCalley, J., Figueroa-Acevedo, A., Jahanbani-Ardakani, A., Nosair, H., Venkatraman, A., Caspary, J., Osborn, D., & Lau, J. (2022). The Value of Increased HVDC Capacity Between Eastern and Western U.S. Grids: The Interconnections Seam Study. *IEEE Transactions on Power Systems, 37*(3), 1760–1769. https://doi.org/10.1109/tpwrs.2021.3115092

European Union Agency for the Cooperation of Energy Regulators. (2024). *Transmission capacities for cross-zonal trade of electricity and congestion management in the EU*. https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_2024_MMR_Crosszonal_electricity_trade_capacities.pdf

Hoffmann, R., & Krost, G. (2017). Identification and visualisation of circular flows in a superior cluster-graph display for operational control. *IET Generation, Transmission & Distribution, 11*(5), 1251–1257. https://doi.org/10.1049/iet-gtd.2016.1169

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., & Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy, 160*, 720–739. https://doi.org/10.1016/j.energy.2018.06.222

Forbes, K. F., & St. Cyr, O. C. (2019). The Challenge Posed by Space Weather to High-Voltage Electricity Flows: Evidence From Ontario, Canada, and New York State, USA. *Space Weather, 17*(12), 1720–1747. https://doi.org/10.1029/2019sw002231

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews, 90*, 402–411. https://doi.org/10.1016/j.rser.2018.03.040

Hofmann, F., Schlott, M., Kies, A., & Stöcker, H. (2020). Flow Allocation in Meshed AC-DC Electricity Grids. *Energies, 13*(5), 1233. https://doi.org/10.3390/en13051233

Qu, C., & Bang, R. N. (2024). European grid development modeling and analysis: established frameworks, research trends, and future opportunities. *Discover Energy, 4*(1), 9. https://doi.org/10.1007/s43937-024-00033-9

Abrell, J., & Rausch, S. (2016). Cross-country electricity trade, renewable energy and European transmission infrastructure policy. *Journal of Environmental Economics and Management, 79*, 87–113. https://doi.org/10.1016/j.jeem.2016.04.001

Ahmed, I., Rehan, M., Basit, A., Ahmad, H., Ahmed, W., Ullah, N., Piecha, M., Blazek, V., & Prokop, L. (2023). Review on microgrids design and monitoring approaches for sustainable green energy networks. *Scientific Reports, 13*(1), 21663. https://doi.org/10.1038/s41598-023-48985-7

Caliskan, S. Y., & Tabuada, P. (2014). Towards Kron reduction of generalized electrical networks. *Automatica, 50*(10), 2586–2590. https://doi.org/10.1016/j.automatica.2014.08.017

de Chalendar, J. A., Taggart, J., & Benson, S. M. (2019). Tracking emissions in the US electricity system. *Proceedings of the National Academy of Sciences, 116*(51), 25497–25502. https://doi.org/10.1073/pnas.1912950116

Xiong, B., Fioriti, D., Neumann, F., Riepin, I., & Brown, T. (2025). Modelling the high-voltage grid using open data for Europe and beyond. *Scientific Data, 12*(1), 277. https://doi.org/10.1038/s41597-025-04550-7