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An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets: From Batteries to Insurance and Beyond

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
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Final Scientific/Technical Report

An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets: From Batteries to Insurance and Beyond

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Project Title:	An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets: From Batteries to Insurance and Beyond
Program Director:	Dr. Jon Glass
Principal Investigator:	Dr. Michael Blonsky
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Public Executive Summary

If power systems transition to integrate higher amounts of variable renewable energy sources, storage technologies, and distributed energy resources (DERs), new risk management frameworks are necessary to ensure cost-effective and reliable power system operations. Projects funded by the Advanced Research Projects Agency–Energy (ARPA-E) Performance-based Energy Resource Feedback, Optimization, and Risk Management (PERFORM) program aim to contribute new risk management frameworks by developing methods to quantify and manage risk at grid asset and system levels.

The National Renewable Energy Laboratory (NREL) led a PERFORM project in collaboration with the Johns Hopkins University, the Electric Power Research Institute (EPRI), kWh Analytics, Packetized Energy, and Imperial Consultants (ICON). The project addressed two challenges related to risk management in electricity markets:

- U.S. wholesale electricity markets typically manage net load imbalances (i.e., the difference in net load between sequential markets) through real-time markets, operator actions, and procurement of reserves. The imbalance is usually caused by net load forecast errors, changes in asset availability, and differences in the temporal resolution of sequential markets (e.g., hourly in day-ahead markets, or every 15 minutes in real-time markets). The project team developed the concept of Flexibility Options, a forward electricity (e.g., day-ahead) market product that would procure flexible capacity and address net load imbalances in subsequent markets. The analysis suggests that Flexibility Options offer distinct risk mitigation benefits to market participants compared to existing risk-hedging products and can support effective and reliable power system operations in a revenue neutral manner, while adhering to cost-causation principles.

- Flexibility from DERs—in particular, flexible loads—is underused in wholesale energy markets. Barriers to DER participation include a lack of perceived reliability, limited customer engagement, and regulatory challenges. The project team developed the concept of DER flexibility scores to quantify the flexible capacity of single and aggregated DERs. The team also developed bidding tools for DER aggregators that support aggregator participation in wholesale markets. The analysis suggests that the scoring effectively recognizes heterogeneity among devices and the bidding tool can help aggregators capture higher market revenues compared to heuristic approaches.

The project team has performed multiple sets of analyses to assess the impacts of these proposed concepts. This final technical report presents a list of project accomplishments, activities, and outputs.

Acknowledgements

The authors would like to thank the Advanced Research Projects Agency–Energy (ARPA-E) program directors and support staff who have provided feedback, direction, and support on this project. This includes Jonathan Glass, Richard O'Neill, Joseph King, Ashley Arigoni, Ricky Wilson, Syne Salem, and Kory Hedman.

We acknowledge the many partners, researchers, students, and interns who have contributed to this project's research, including Yingchen Zhang, Yajing Liu, and Li He (National Renewable Energy Laboratory [NREL]); Jairo Cervantes and Mohamed Kareem AlAshery (Johns Hopkins University); Erik Ela and Anwar Khan (Electric Power Research Institute [EPRI]); Jason Kaminsky (kWh Analytics); and Paul Hines and Mads Almassalkhi (Packetized Energy). We thank our data partners and collaborators, including Farnaz Safdarian (Texas A&M), Scott Greene (University of Wisconsin–Madison), Michal Grzadkowski and Xinshuo Yang (Princeton University), Cong Feng and Tarek Elgindy (NREL), and Azalfa Shafiq (Ecobee). We thank Jeff Maguire, Yonghong Chen, and Emily Horvath (NREL) for their review of this report.

Finally, we acknowledge the many industry stakeholders who have supported this project and provided support and feedback on this research. We thank Helen Lo (Sacramento Municipal Utility District) for her guidance as our industry advisor for the distributed energy resource aggregation and flexibility research. We thank the many stakeholders of EPRI's independent system operator and regional transmission operator Price Formation working group who provided their feedback. We thank many other industry stakeholders for their feedback through interviews and other discussions.

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Accomplishments and Objectives

This award allowed the National Renewable Energy Laboratory and its collaborators to accomplish a number of key objectives. The focus of the project was to design a wholesale electricity market product that would procure flexible capacity and address net load imbalances in subsequent markets and to develop concepts and tools that support the participation of distributed energy resource (DER) aggregators in these markets.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Phase 1: DER Risk Score Development 1.1 Develop and analyze DER datasets 1.2 Design baseline case for proposed DER risk scores and demonstrate DER heterogeneity.	Q1: M1.1.1: Provide information on the size, characteristics, and quality of the project's DER datasets. **Actual Performance:** (11/04/20) The project team documented information on the content and intended use of the data the team plans to access and use and submitted a supplemental DER report that describes and suggests DER types to include in the project. Q2: M1.1.2: Submit DER Data Plan **Actual Performance:** (01/31/21) We have submitted the DER Data Plan Report, which includes a summary table with our measurable targets about the DER portfolios we will include in future milestones and an outline of the procedure we will follow for bad and missing data. Q2: M1.1.3: Submit DER Evaluation Plan **Actual Performance:** (01/31/21) We have submitted the DER Evaluation Plan Report, which includes two flow charts summarizing our procedures for evaluation of the scoring and scheduling methods, respectively. Q3: M1.2.1: Summarize existing industry practice for DER scheduling and uncertainty management and provide spreadsheet detailing statistical properties of "BP1/2 dataset." **Actual Performance:** (04/30/21) We submitted a report that summarizes industry practice and that presents and briefly discusses scheduling error for the PE Dataset 1. Q3: M1.2.2: Choose Characteristic Days **Actual Performance:** (04/30/21) We presented our methodology for the selection of characteristic days and discuss in detail the six

Tasks	Milestones and Deliverables
	characteristic days we chose based on the high renewable scenario. Note that we might have to update the selection of characteristic days for M2.4. Q3: M1.2.3: Define DER risk score and quantitative metrics to assess DER risk score performance. **Actual Performance:** (04/30/21) We (a) discussed the definition and use of DER scores, (b) listed quantitative metric and show via illustrative examples how they could be applied, and (c) proposed risk measures that a DER portfolio manager could use to assess delivery of flexibility. Q4: M1.2.4: Demonstrate heterogeneity among DER assets that DER risk scores could capture. **Actual Performance:** (07/31/21) We completed the analysis and observe higher than 5% differences in the standard deviation of the "Grid" quality of service between two classes. We also observe significant differences in the average kWh/water heater among classes. It is worth noting that the classes have very different sizes.
Task 2: Phase 1: Wholesale flexibility auction	Q1: M2.1: Review the conceptual design of the counterfactual analysis conducted for at least two market enhancements adopted by a US ISO operator in the last decade. **Actual Performance:** (11/04/2020) We reviewed three studies and discussed the findings of our review. Q2: M2.2: Complete initial design of the baseline case. Complete initial flexibility auction market design. **Actual Performance:** (01/31/21) We have submitted two reports on the baseline design and the flexibility auction market design. Q3: M2.3: Using the Q3 2020 ARPA-E PERFORM Texas case study dataset, verify that the in-house software adequately simulates the baseline case by including a subset of existing features of U.S. ISOs' scheduling engines. In particular, features that influence the impact of forecast uncertainty for intermittent generators. **Actual Performance:** (09/08/21) All three cases (perfect forecast, imperfect forecast, imperfect forecast and reserve product that manages uncertainty) were simulated in our in-house software, FESTIV.

Tasks	Milestones and Deliverables
	Q4: M2.4: Design counterfactual analysis and estimate the magnitude of the gap our proposed modification aims to address through simulations on the ARPA-E PERFORM Texas case study. **Actual Performance:** (09/08/21) The team completed simulations for six characteristic days and compared the production cost and unserved energy of a reference case to a modified case that includes the flexibility auction.
Task 3: Phase 2: DER Risk score development	Q5: M3.1: Design counterfactual analysis and provide abstract schematic and mathematical formulation for the modifications related with the decisions involving DERs. **Actual Performance:** (01/31/21) For the reference case, we will model a DER aggregator offering its flexibility in the real-time market. For the modified case, we will model a DER aggregator participating as a price-taker in the DA flexibility auction. The input data will include historical timeseries of electricity consumption at the device level and the main performance metric will be the average value and standard deviation of the DER aggregator's bid surplus. We have formulated a DER offering module that we plan to test further prior to performing the work for our GNG milestone M3.4. Q6: M3.2: Initial demonstration of DER scoring methodology. **Actual Performance:** (03/17/22) A prototype scoring method has been developed. The proposed method yields scores that are equal to the monetary value of a volumetric option a DER portfolio manager can sell. The monetary value of the volumetric option includes both the expected value of flexibility and the expected penalty for non-delivery. Results including a penalty function in the analysis were presented on 03/17/2022 review meeting. Q7: M3.3: Demonstration of DER scoring methodology. **Actual Performance:** (06/22/22) We present and report additional results that show the sensitivity of the scoring methodology to prices and results that show the method's performance for a new dataset that includes run times for air conditioning systems in Texas. Q8: M3.4: Conduct counterfactual analysis to demonstrate improvement in DER portfolio scheduling / bidding through use of DER risk scores.

Tasks	Milestones and Deliverables
	Actual Performance: (10/31/22) This Go/No-go milestone was marked as complete on October 21, 2022, because the first portfolio of the milestone was fully met and the second portfolio required augmented data to complete. We discuss in detail the augmentation of the data in M5.1.1 and we plan to provide updates on the counterfactual analysis each quarter in preparation for Milestone 5.2.3.
Task 4: Phase 2: Wholesale flexibility auction 4.1 Gather/address industry feedback and estimate the value of the proposed flexibility auction. 4.2 Preliminary assessment on the value of novel insurance product	Q6: M4.1.1: Summarize feedback received from at least two US Independent System Operators. **Actual Performance:** (01/31/21) We had several feedback sessions with staff from all 7 US ISOs/RTOs and one company that manages portfolios of intermittent resources. Q7: M4.1.2: Model proposed modification i.e., flexibility auction in the in-house scheduling software. **Actual Performance:** (06/22/22) We report the computational performance of simulations that include the flexibility auction. The computational time requirements are within the target sets for simulations without the network and we aim to test the time including the network in the future. Q8: M4.1.3: Conduct counterfactual analysis to evaluate prototype on the ARPA-E PERFORM Texas case; study the value of the proposed flexibility auction. **Actual Performance:** (08/17/22) This Go/No-go milestone was marked as complete on 08/17/2022 because the team demonstrated that simulations with the flexibility options had ~15% and 2% lower system costs compared to uncertainty-ignorant and imbalance reserve-like simulations, respectively. Q7: M4.2.1: Develop methodology to estimate the benefits from risk aggregation and/or mitigation of risk aversion an insurer could leverage. **Actual Performance:** (06/22/22) We propose a methodology to assess the benefits of risk aggregation for participation in the flexibility auction as a buyer and illustrate the methodology by reporting results for one day.

Tasks	Milestones and Deliverables
Task 5: Phase 3: DER Risk score development 5.1 Create BP3 dataset 5.2 Gather industry feedback and test DER scores and their applications on scheduling/bidding using BP3 dataset	Q9: M5.1.1: Gather and analyze “BP3 dataset”. **Actual Performance:** (02/03/23) We completed two remaining tasks to mark this Milestone as fully complete. The first task was to finish adjusting model parameters (e.g., water heater deadband temperature) to better fit the field data. The second task was to collect additional data from the Ecobee Donate Your Data (DYD) dataset for more recent years. Q10: M5.2.1: Gather feedback from multiple stakeholders interested in the use of DER risk scores. **Actual Performance:** (02/04/23) We conducted interviews with six industry stakeholders including utilities and DER aggregators. Q11: M5.2.2: Verify scoring methodology using BP3 dataset. **Actual Performance:** (02/01/24) The team has finalized the scoring methodology for both portfolios from M5.2.3. The team evaluated final versions of water heater scores and refined methods for HVAC scores for the first portfolio. For the second portfolio, the team finalized the bilateral scores. While the methods in M5.2.3 may improve, we do not expect any changes in the scoring methods. Q11: M5.2.3: Conduct counterfactual analysis for proposed DER score related methods using BP3 dataset. **Actual Performance:** (05/01/24) The project team completed simulation runs and analysis for the water heater fleet. Counterfactual analysis shows the value of the flexibility option product relative to real time energy arbitrage. A separate analysis compares the revenue of fleets with low and high DER scores. Q12: M5.2.4: Submit final report on DER scoring methodology, dynamic methods for real-time assessment of delivery risk and risk-score adjusted decisions by DER portfolio managers. **Actual Performance:** (07/05/24) The team completed all sets of analyses and has written the methods and results in the final project report.

Tasks	Milestones and Deliverables
Task 6: Phase 3: Wholesale Flexibility auction 6.1 Finalization of formulation and report on counterfactual analysis 6.2 Assess the value of novel insurance product using data by kWh Analytics.	Q10: M6.1.1: Summarize feedback received from at least five US Independent System Operators **Actual Performance:** (02/03/23) We presented our research to 13 representatives from 6 North American ISOs at EPRI's ISO/RTO Price Formation Working Group on January 27, 2023. We received feedback from many stakeholders and are engaging in follow-up discussions. Q11: M6.1.2: Model participation in the flexibility auction of agents who hedge delivery risk for market participants. **Actual Performance:** (11/01/23) The team has completed the software implementation of the flexibility auction model and has completed preliminary simulations. The team may make additional software updates based on analysis from Milestone 6.1.3. Q12: M6.1.3: Deliver final report on the value of the flexibility auction and novel insurance products. **Actual Performance:** (07/05/24) The team reran and completed market simulations under 4 cases with two system models representing the years 2019 and 2030. The team has written the methods and results for 2019 in the final project report. Q9: M6.2.1: Summarize feedback received from at least two entities who could potentially hedge delivery risk for market participants / grid resources. **Actual Performance:** (02/04/23) We completed three interviews with industry stakeholders as presented in the Q4 2022 quarterly meeting. Q11: M6.2.2: Apply the estimation methodologies of Task 4.3 on kWh Analytics dataset. **Actual Performance:** (05/01/23) The team analyzed the benefits of risk aggregation using kWh Analytics' Solar Revenue Put insurance product. This analysis compares the benefits of risk aggregation seen in a commercially available insurance product with the benefits from flexibility options.

Tasks	Milestones and Deliverables
Task 7: Technology to Market 7.1 T2M BP1 7.3 T2M BP2	Q1: M7.1: Deliver initial T2M plan. **Actual Performance:** (07/31/21) We have submitted the initial T2M plan, which includes a SWOT analysis for the DER scores and the flexibility auction. Moreover, we list the commercialization pathways for the DER scores and the decision-making process for a market modification at the CAISO. Over the course of the first year of the project, we had 30+ meetings with industry advisors and stakeholders. Finally, we have prepared initial pilot plans and upon discussions of the initial pilot plan with our industry advisor, our team has a clear understanding on next steps related to submission of a pilot plan proposal and the contents of it. Q6: M7.2: Organize T2M (virtual or physical) meeting or workshop with at least two US ISOs. **Actual Performance:** (10/01/21) In September 2021, EPRI hosted a virtual workshop with staff from all six US ISOs/RTOs and we had detailed followed up meetings with staff from two ISOs/RTOs (SPP, CAISO). In summary, we received feedback from all 7 US ISOs/RTOs. Q7: M7.3: Deliver revised T2M plan and draft pilot plan. **Actual Performance:** (08/17/22) T2M plan was shared via email with the ARPA-E team on 08/17/2022. Q10: M7.4: Organize T2M (virtual or physical) meetings or workshops 2,3, and 4. **Actual Performance:** (02/03/23) We have organized workshops, working group meetings, and interviews for milestones 6.2.1, 6.1.1, and 5.2.1. Q11: M7.5: Final IP Plan, Commercialization Plan, and Data Management Plan **Actual Performance:** (08/01/23) The team has reviewed the existing plans and no updates were necessary. Q12: M7.6: Deliver end of project T2M plan **Actual Performance:** (02/01/24) The project team has completed the final tech-to-market plan, which includes tech-to-market activities for DER scores and flexibility options. The plan includes a SWOT analysis, commercialization plans, past stakeholder meetings, and ongoing activities for both technologies.

Project Activities

The project team proposed the concept of a flexibility option (FO) product and conducted analysis to understand the value and impact of FOs in wholesale electricity markets. FOs are contracts issuing rights to their purchaser to buy or sell real-time energy imbalances with respect to a trigger quantity (determined in a forward U.S.-style market) at a determined strike price. The team developed a mathematical formulation and analysis to show the properties of FOs. The effects of FO on markets and participants were analyzed using a variety of methods and data sources, including comparisons with other risk hedging products, Shapley value analysis, calibrated analysis using historical data from the California Independent System Operator (CAISO), and scenario analysis using a production cost model with an Electric Reliability Council of Texas (ERCOT)-like system. Results show that FOs reduce overall system costs compared to an uncertainty-agnostic DA model, reduce revenue volatility for both buyers and sellers, promote day-ahead-to-real-time energy price convergence, keep the system operator revenue-adequate, and have similar cost-effectiveness as imbalance reserves (another risk-hedging market product).

In addition, the project team proposed the concept of DER flexibility scores and developed a DER aggregator bidding tool. A DER flexibility score uses many device parameters and usage patterns to measure the flexible capacity of an individual DER and explains the value of the DER in a way that is easy for aggregators and their customers to understand. The aggregator bidding tool, FLARE, uses a stochastic virtual battery model within an optimization framework to define the uncertainty-aware flexible capacity of a DER fleet and to determine optimal bidding and dispatch strategies of DER aggregators. The team evaluated multiple scoring methods by simulating aggregator bidding strategies and DER performance for various aggregations of DERs with different scores and under different environmental conditions. Results show FLARE can account for the operational constraints and intertemporal dependencies of a DER fleet and accurately estimate its delivery risk, leading to increased aggregator revenue and higher flexibility realization rates. Results also show that DER fleets with varying flexibility scores can lead to significant differences in the fleet's flexible capacity, delivery risk, and aggregator market revenue.

Project Outputs

A. *Journal Articles*

Helyette Geman and Yuanye Ma. 2023. "Distributed energy resources flexibility as volumetric options on electricity." *Frontiers of Mathematical Finance* 2(4): 478–496. doi: 10.3934/fmf.2023018

E. Spyrou, Q. Zhang, B.F. Hobbs, R. Hytowitz, S. Tyagi, M. Cai, M. Blonsky. "Flexibility Options: A Proposed Product for Managing Imbalance Risk." *IEEE Transactions on Power Systems*. Submitted June 2024. TPWRS-01096-2024

B. Papers

None

C. Status Reports

None

D. Media Reports

None

E. Invention Disclosures

None

F. Patent Applications

None

G. Licensed Technologies

None

H. Networks/Collaborations Fostered

EPRI ISO/RTO Price Formation Working Group. https://www.epri.com/research/products/3002013724

EPRI FESTIV Power System and Market Simulation User's Group. https://restservice.epri.com/publicdownload/000000003002029727/0/Product

I. Websites Featuring Project Work Results

FLARE: The Flexible Load Aggregator and Risk Estimator. https://www.nrel.gov/grid/flare.html

Spyrou, Elina. "Managing imbalance risk in DA electricity markets." 2024 ESIG Forecasting & Markets Workshop. June 2024. https://www.esig.energy/download/session-5a-managing-imbalance-risk-in-da-electricity-markets-elina-spyrou/?wpdmdl=11683&refresh=666c647d9ef061718379645

M. Cai and M. Blonsky. "Delivery-Risk-Aware Flexibility Scheduling and Dispatch for Aggregated Flexible Loads." INFORMS 2023. October 2023. https://www.nrel.gov/docs/fy24osti/89735.pdf

Blonsky, Michael. "Managing Uncertainty and Flexibility in Day-ahead Electricity Markets." 2023 ESIG Meteorology & Market Design for Grid Services Workshop. June 2023. https://www.nrel.gov/docs/fy23osti/86693.pdf

Flexibility Auctions: A Framework for Managing Imbalance Risk. 2021 MIT Fall EESG Seminar Series. November 2021. https://youtu.be/eBZ2uui_A3Y?si=XlRDvpxkjNYHBVh3

E. Spyrou, R. B. Hytowitz, B. F. Hobbs, M. Al-Ashery, M. Cai, E. Ela, and Y. Zhang. "Flexibility Auctions: A Framework for Managing Imbalance Risk". FERC Technical Conference on Increasing Real-Time and Day-Ahead Market Efficiency Through Improved Software. June 2021. https://www.ferc.gov/media/w3-spyrou

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

FLARE: The Flexible Load Aggregator and Risk Estimator. https://www.nrel.gov/grid/flare.html

Stochastic Virtual Battery Model. Open source codebase: https://github.com/NREL/stochastic-virtual-battery-model

FESTIV (Flexible Energy Scheduling Tool for Integrating Variable generation). https://www.osti.gov/biblio/1504740

K. Awards, Prizes, and Recognition

None

Follow-On Funding

No additional funding has been committed or received from other sources.

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