Analysis of Hybrid Smart Grid Communication Network Designs for Distributed Energy Resources Coordination

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***Abstract*—The rapid growth of distributed energy resources (DERs) has prompted increasing interest in the monitoring and control of DERs through hybrid smart grid communications. This paper develops a new method to investigate the impact of DER penetrations and applications on hybrid communications network designs. A suite of hybrid communications simulation models are developed using Network Simulator 3 (ns-3). The smart grid communications topologies with different DER penetrations are built on the utility-scale distribution grid. The simulation results show that (i) with increasing photovoltaic penetrations, nine hybrid communications designs achieve the expected latency albeit with higher packet loss rate; and (ii) both BPLC-Ethernet and BPLC-WiMAX designs can accommodate the DER applications with a high data rate up to 100 Mbps.**

***Index Terms*—hybrid communication architecture, smart grid communication, high penetration of distributed PV, distributed energy resources (DER), DER communication.**

I. INTRODUCTION

The rapid growth of distributed energy resources (DERs) has prompted increasing interest and multiple development efforts in the area of monitoring and control of millions of DERs at the levels of the distribution system operator (DSO) and transmission system operator (TSO) [1]–[3].DERs refer to distributed renewable generation, e.g. rooftop solar photovoltaic (PV) panels, small wind turbines, residential battery energy storage systems, and controllable loads. It is becoming necessary to enhance the coordination of ever-increasing DERs so that the voltage and frequency stability in power distribution systems can be maintained within acceptable levels [4]. Thus, it is important to assess the performance and vulnerability of hybrid communications networks when they serve as a critical infrastructure for wider visibility of DERs [5].

Hybrid communications architectures using both wireless and dedicated wired media at different network segments have been proposed and studied as a promising solution to smart grid communications infrastructures because of the balanced tradeoff between investments and benefits and meeting the critical requirements of smart grid applications. Specific hybrid communications architectures, such as power line communication (PLC), WiFi, and Ethernet, were developed and evaluated in pilot studies and real deployments [6]–[8]; however, the study provided limited perspectives on the generic hybrid communications design for the particular smart grid topologies. Hybrid communications designs for DER coordination were proposed in [9], and the authors evaluated the performance using the single technology simulation networks. To overcome the limitations of field and single technology simulation evaluation methods, we propose the generic hybrid communications simulation-based evaluation method considering the diversity and interoperability of hybrid technologies.

This paper presents a comprehensive performance evaluation of a suite of hybrid communications designs with different DER penetrations and applications. The main contribution of this paper is threefold. 1) a suite of hybrid communications simulation models are developed; 2) the communications topologies with different DER penetrations are built on the utility-scale distribution system; 3)an assessment of the maximum allowable DER penetration and application data rate of each hybrid design in terms of latency and packet loss rate (PLR) is given.Note that this paper focuses on the representative DER of rooftop solar PV panels because they are pervasive in the distribution system. The proposed method can be extended to other DERs.

II. HYBRID SMART GRID COMMUNICATIONS SYSTEMS

To remotely monitor and control the emerging DERs in the modern distribution grid, a suite of hybrid communications systems have been proposed and evaluated using the ns-3-based hybrid communications simulation models in [10]. The

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hybrid smart grid communications systems overview, design criteria, and ns-3-based hybrid simulation models are briefly summarized in what follows.

A. Hybrid Communications Networks

The envisioned hybrid smart grid communications system for DER coordination typically consists of three subnetworks 1) home area networks (HAN), where the solar PV panel and inverters are located; 2) neighborhood area networks (NAN), by which the DER monitoring information and control signals can be relayed at smart meters and data concentrators to the DSOs and further to TSOs; 3) and wide-area networks (WANs), through which both DSOs and TSOs can eventually have enough visibility into DERs [11], [12]. The HAN considers low-power wireless personal area networks (LoWPAN) and PLC technologies, whereas PLC also has narrowband PLC (NPLC) and broadband PLC (BPLC) alternatives because of using different frequency ranges. The NAN can choose three alternative communications technologies: WiFi ad-hoc, WiMAX, and Ethernet cables, whereas the WAN is assumed to employ high-speed optical cable. The NAN could have the tree topology for the Ethernet cables and WiMAX and the mesh topology for the WiFi. Thus, the hybrid communications network design can be narrowed to design the hybrid network of multiple HANs and NANs along with nine alternative hybrid designs, as shown in Table I.

TABLE I
HYBRID COMMUNICATIONS ARCHITECTURES.

Hybrid Type	Home Area Network	Neighborhood Area Network
Hybrid 1	LoWPAN	Ethernet cable
Hybrid 2	LoWPAN	WiFi
Hybrid 3	LoWPAN	WiMAX
Hybrid 4	BPLC	Ethernet cable
Hybrid 5	BPLC	WiFi
Hybrid 6	BPLC	WiMAX
Hybrid 7	NPLC	Ethernet cable
Hybrid 8	NPLC	WiFi
Hybrid 9	NPLC	WiMAX

B. Design Criteria

For DER coordination in the distribution system, three commonly used network performance metrics are employed to evaluate the reliability of designed hybrid communications architectures: (i) latency: the expected one-way latency is in the range of 300 ms–2 s; (ii) throughput: the requirement is 9.6–56 kbps; (iii) PLR: its benchmark value is set to 0.01–1% [12], [13].

C. Hybrid Communications Simulation Models

Within the development of a suite of ns-3-based hybrid communications simulation models, the notable challenges are to integrate 1) two different communications technologies and 2) two address mechanisms: IPv6 of the HAN and IPv4 of the NAN into one simulated network. To address Challenge 1, please refer to the ns-3 simulation model of the hybrid architectures in [10], wherein the smart meter node is configured with two sets of software net devices for both the MAC and physical layers to accommodate two communications technologies simultaneously. To meet Challenge 2), the NetRouter application module installed in the smart meter node is designed to decapsulate and encapsulate the IPv6 and IPv4 packets and to realize the successful integration of these two networks.

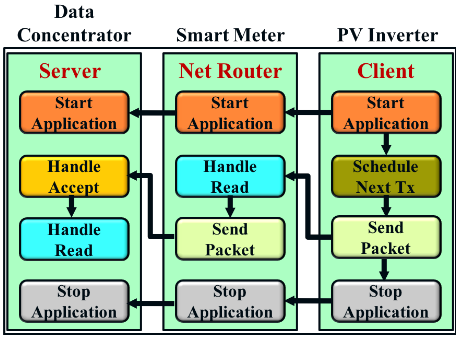


Fig. 1. Block diagram of application simulation mechanism

In addition, two customized application modules are developed in the PV and data concentrator nodes for two separate purposes. To accommodate the distributed PV coordination application, a customized Client module at the PV node is developed to mimic the real PV data packet by setting the packet size and data rate. A Server module attached at the data concentrator node is responsible for the autonomous online tracing and data post-processing, statistically collecting the network performance metrics. Therefore, the detailed structure of the application layer in the designed hybrid communications networks is shown in Figure 1. Three specific applications complete the PV information and control signals exchange between PV inverters and data concentrator via the smart meters. The PV inverter sends the packets with a time stamp after the client application starts. Upon receiving the packet, the net router application is informed via the HandleAccept method and reads the packet using the HandleRead method, then it sends the packet to the corresponding server application, which confirms the receipt via the HandleAccept method and triggers the HandleRead function to receive data and calculate the Quality-of-Service (QoS) information, such as single-trip delay, throughput, and PLR.

The purpose of this paper is to investigate how different PV penetration levels in a distribution system impact the hybrid communications system design by answering two primary questions: 1) with increasing distributed PV penetration, what performance can be expected from each potential hybrid design? 2) can these hybrid designs be expected to handle additional DER applications in the near future? The scalability feature and customized application modules of the hybrid communications simulations enable the conduction of this study.

III. POWER SYSTEM MODEL WITH DIFFERENT PV PENETRATIONS

The taxonomy feeder titled R2-25.00-1 containing 1,080 nodes, referred to as Reference Test Case A (RTC-A), has been selected for the hybrid communications architecture testing.

The location and availability of the existing communications infrastructure is modeled using data from the specific municipal utility district, which has rolled out smart meters across their utility network and uses the dedicated networks for data communications infrastructure. Typical smart meter installation rates and placement of data concentrators that have been built for current smart meter communications requirements are scaled to the R2-25.00-1 feeder. Therefore, modified communications infrastructure of the RTC-A consists of 275 smart meters, 10 data concentrators, one edge router, and a variable number of solar PV inverters depending on the PV penetration rate.

To evaluate the impact of different PV penetration levels on the hybrid communications system design, we further generated six sub-RTC-As: with 10%, 20%, 40%, 60%, 80%, and 100% penetration. To generate these sub-RTC-As, two steps are carried out: 1) In the Integrated Grid Modeling System (IGMS) developed at the National Renewable Energy Laboratory, the distributed PV inverters were automatically added to the feeders using *glmgen* [14] by specifying the percentage of PV penetration (as a fraction of annual energy consumption of a feeder, which is obtained as a product of the annual energy intensities of buildings $[W/ft^2]$ and their floor area $[ft^2]$). Then, the corresponding GridLAB-D model (glm) files of the RTC-A with different PV penetration levels can be obtained. 2) In RTC-A, there are 73 commercial smart meters attached to the corresponding large-size commercial building loads, each of which could contain several office loads, and 202 residential triplex smart meters attached to the corresponding triplex nodes. Following the deployment of inverters in the GridLAB-D *.glm file, we manually constructed PV nodes for the selected commercial smart meters and chose the location of the triplex node as the PV node location for the selected triplex meters on the RTC-A Google map. Thus, the communications node topologies of the RTC-A with different PV penetrations are shown in Fig. 2, and Table II demonstrates the detailed configuration information.

TABLE II
TYPE AND NUMBER OF COMMUNICATIONS NODES IN RTC-A

Node Type	Quantity
Edge Router	1
Data Concentrators	10
Smart Meters	275
10% of PV Inverters	51
20% of PV Inverters	72
40% of PV Inverters	117
60% of PV Inverters	160
80% of PV Inverters	179
100% of PV Inverters	259

IV. RESULTS AND DISCUSSION

In this section, the simulation results of nine hybrid networks integrated with six PV penetration scenarios of RTC-A are presented and discussed. There are two main focuses: 1) validation of the hybrid network performance in terms of latency and PLR with increasing PV penetration; 2) study of the capacity limitations of the hybrid designs. For the first focus, all nine ns-3 hybrid network simulations on top of six PV penetration scenarios ranging from 10% to 100% are conducted with the UDP packet size of 2,048 bytes and the data rate of 56 kbps for the distributed PV application. Referring to [6], we consider a maximum packet size of 2,048 bytes to study the worst-case performance limits of the network design. Note that the application data rate of 56 kbps requires the minimum bandwidth of 56 kbps of the network. For the second focus, the 100% penetration rate is only considered to achieve the capacity limitation with the variable data rate from 10 kbps to 1 Gbps and the constant packet size of 2048 Bytes. In every simulation event, 10,000 packets were sent at each PV node with different data rates. The results were averaged among all paths and 100 runs.

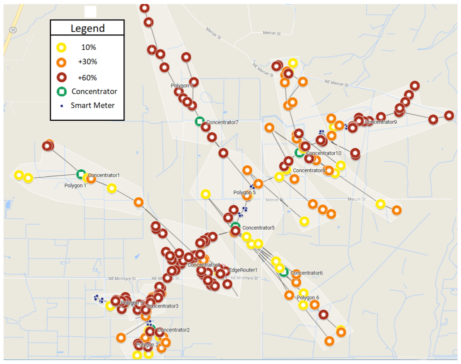
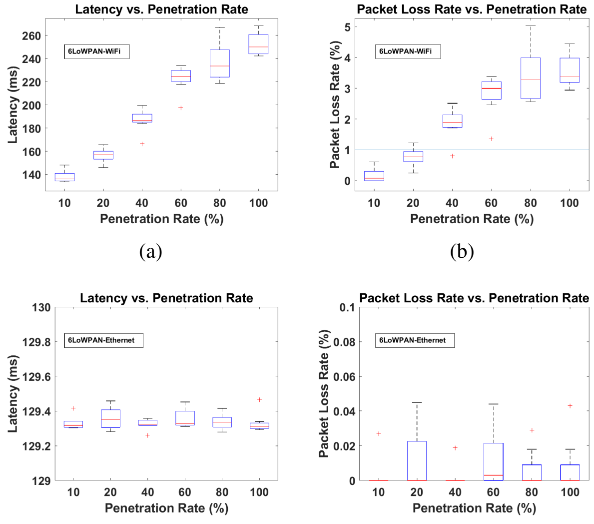


Fig. 2. Communication node infrastructures with different PV penetrations.



(a) (b)

(c) (d)

Fig. 3. Impact of PV penetration rate for LoWPAN-WiFi and LoWPAN-Ethernet

A. Impact of PV Penetration Rates

In this subsection, the impact of PV penetration rate on the hybrid network performance metrics of latency, PLR, and throughput are examined in detail. Although the PV data packets are transmitted through a HAN and a NAN subnetwork, the performance of the HAN is unchanged, and the PV data traffic dramatically increases in the NAN with the increasing PV penetration. Therefore, the performance characteristic of the hybrid designs with different penetration rates critically depends on the communications technology of the NAN. Note that throughout all nine hybrid designs, the throughput of each design is always around the data rate of 56 kbps, which satisfies the critical throughput requirement of 9.6 kbps, because the application data rate is the benchmark value of the throughput for the proposed hybrid network [10]. The subsequent network performance analysis focuses on the metrics of latency and PLR.

For the hybrid designs of LoWPAN-WiFi and LoWPAN-Ethernet, the latency and PLR results are shown in Fig. 3. For each blue box plot, the central mark indicates the median of the latency/PLR, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The red cross indicates the lowest and highest outliers. It is observed that both latency and PLR increase in a linear fashion with increasing PV penetration. This is mainly because the ad hoc WiFi supports only an 11-Mbps connection speed, less than the 100-Mbps bandwidth of Ethernet cable and 70-Mbps bandwidth of WiMAX. At a 56-kbps data rate and a packet size of 2,048 bytes, the resulting PV traffic is 2.8, 3.94, 6.4, 8.8, 9.8, 14 Mbps, corresponding to six PV penetration rates, respectively. Even the heaviest traffic of 14 Mbps is still much less than the bandwidth of Ethernet and WiMAX; thus, both latency and PLR almost keep constant with the increasing penetration rate, as shown in Fig. 3(c) and (d). Although the traffic increases linearly to close the ad hoc WiFi bandwidth and even exceeds it, the latency and PLR degrade correspondingly, as shown in Fig. 3(a) and (b). Additionally, the seven remaining hybrid designs have similar performance characteristics when compared to the LoWPAN-Ethernet design.

TABLE III
RESULTS OF IMPACT OF PV PENETRATION RATE

HAN	NAN	Max Penetration Based on Latency	Max Penetration Based on PLR
LoWPAN	Ethernet	100%	100%
	WiFi	100%	40%
	WiMAX	100%	100%
BPLC	Ethernet	100%	60%
	WiFi	100%	10%
	WiMAX	40%	20%
NPLC	Ethernet	100%	10%
	WiFi	100%	10%
	WiMAX	100%	20%

Table III shows the maxmium allowable penetration rates of hybrid designs in terms of latency and PLR, otherwise, the corresponding metric can not satisfy the requirement. From Table III, there are two interesting observations. 1) In terms of latency, the BPLC-WiMAX design can satisfy the latency requirement of 300 ms only when the penetration rate is less than 40%, and all of the other designs can achieve the required latency performance even when the penetration rate is up to 100%. 2) Regarding PLR, the NPLC-based designs have the worst performance.

These results indicate whether the hybrid communications systems design will support the smart grid communications requirements for high PV penetration in the near future. In addition, finding the penetration level at which the QoS starts degrading will serve as a guide to how many physical PV systems are capable of being monitored. This information dictates the limits of observability of distributed PV because of the communications system, though this can be overcome through the use of state estimation techniques that estimate unmeasured values based on historical data and spatial correlation characteristics.

B. Capacity Limitation of Hybrid Designs

Another interesting investigation of this paper is to identify the capacity limitation of each hybrid design according to the data rate. Assuming all packets are 2,048 bytes in size, the generation rate of 3 packets per second results in a network data rate of 48 kbps; however, it is envisioned that the packet generation and response rate of real-time DER applications might increase in the future, so the higher sampling rate is necessary and data rates from 10 kbps to 1 Gbps have been considered and simulated.

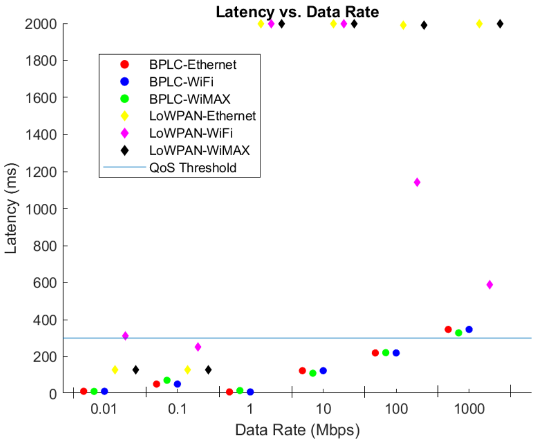


Fig. 4. Latency vs Data Rate at 100% Penetration

The simulation results are shown in Fig. 4 and 5. There are several interesting observations: 1) It is noticeable that the performance limitation of each hybrid network at higher data rates is mainly determined by the HAN link, because the HAN link has less bandwidth and the results are grouped by the HAN link type. 2) The NPLC-based designs show consistently poor performance because of the high PLRs and latencies shown in all penetration scenarios, and hence its usage in smart grid communications networks does not appear to be promising. 3) The LoWPAN-WiFi configuration shows very poor performance with both higher penetration and data rates. This implies that even though this hybrid design would be the most economic to implement, its performance is the least scalable among all candidate hybrid designs. 4) The performance metrics are achieved for the widest range of PV penetration using Hybrid 1, Hybrid 3, and Hybrid 4, except the 60% penetration scenario. All designs except Hybrid 2

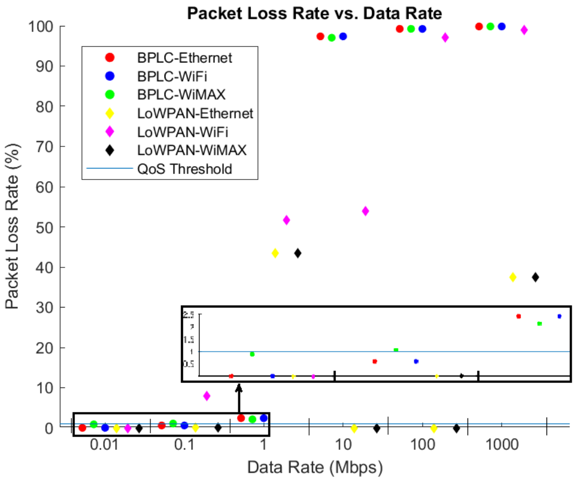


Fig. 5. Packet Loss Rate vs Data Rate at 100% Penetration

can maintain satisfied performance up to 1 Mbps. 5) The LoWPAN-based designs outperform the BPLC-based designs in the practice; however, the BPLC-based designs are preferred for the scenarios with much higher data rates.

TABLE IV
CAPACITY LIMITATION RESULTS OF HYBRID DESIGNS

HAN	NAN	Max Tested Data Rate Based on Latency	Max Tested Data Rate Based on PLR
LoWPAN	Ethernet	100 kbps	100 kbps
	WiFi	100 kbps	10 kbps
	WiMAX	100 kbps	100 kbps
BPLC	Ethernet	100 Mbps	100 Mbps
	WiFi	100 Mbps	10 Mbps
	WiMAX	100 Mbps	100 Mbps

The simulation results in Table IV indicate whether the hybrid design can support future smart grid communications requirements at the 100% penetration from the following points. None of the LoWPAN-based designs support data rates higher than 100 kbps. This implies that if the DER application requires a data rate more than 100 kbps, the HAN technology must be of a higher bandwidth, such as BPLC. The reason is that the throughput is limited by the bandwidth of the technology used, and the theoretical bandwidth is 250 kbps for LoWPAN and 500 Mbps for IEEE 1901 BPLC standard. Similarly, the results indicate that WiFi/LoWPAN is the least scalable NAN/HAN link solution. Among wireless solutions, WiMAX is the more scalable option. The BPLC-based designs show the greatest sensitivity to the higher packet size, but it is still the better option in terms of scalability. Additionally, the fully wireless solution of LoWPAN-WiFi, though the cheapest to implement, will support only up to 40% penetration at a 56-kbps data rate or 10-kbps data rate with 100% penetration.

V. CONCLUSION

This paper presents a new approach for studying the impact of distributed PV penetration on hybrid communications network design. Key findings from the simulations include: 1) because of the higher bandwidth of the NAN, the performance of the Ethernet and WiMAX-based designs are constant with increasing PV penetration. The LoWPAN-WiFi design shows a linear increase of latency and PLR because the PV traffic linearly scales in usage of the ad-hoc WiFi bandwidth. 2) With high data rates, the HAN link technologies determine the network performance because of their limited bandwidth. The BPLC-WiMAX and BPLC-Ethernet always can satisfy the three performance requirements and accommodate a wide range of DER applications and high DER penetrations. Future research includes the implementation of distributed state estimation algorithms that reduce the communications requirements in these hybrid designs and their impact on overall system performance.

REFERENCES

[1] "Wind and solar data projections from the u.s energy information administration: Past performance and planned enhancements," July 2017. [Online]. Available: https://www.eia.gov/outlooks/aeo/supplement/renewable/

[2] "The global annual market for the department of distributed solar pv plus energy storage is expected to exceed $49 billion by 2026," May 2017. [Online]. Available: https://www.navigantresearch.com/newsroom/the-global-annual-market-for-the-deployment-of-distributed-solar-pv-plus-energy-storage-is-expected-to-exceed-49-billion-by-2026

[3] M. G. Molina, "Distributed energy storage systems for applications in future smart grids," in *2012 Sixth IEEE/PES Transmission and Distribution: Latin America Conference and Exposition (T D-LA)*, Sept 2012, pp. 1–7.

[4] "Order no. 35369 addressing further technical issues pertaining to Hawaiian electric company, inc., Hawaii electric light company, inc. and Maui electric company, limited's tariffs filed pursuant to decision and order no. 34924," pp. 1–28, 2018.

[5] S. Howell, Y. Rezgui, J.-L. Hippolyte, B. Jayan, and H. Li, "Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources," *Renewable and Sustainable Energy Reviews*, vol. 77, pp. 193 – 214, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032117304392

[6] D.Giustina and S. Rinaldi, "Hybrid communication network for the smart grid: Validation of a field test experience," *IEEE Transcation on Power Delivery*, vol. 10, no. 1, pp. 251–261, March 2015.

[7] M. Zajc, M. Kolenc, and N. Suljanovic, "Virtual power plant communication system architecture," *Smart Power Distribution Systems*, pp. 231–250, 2018.

[8] Z.W.Sun, "Communication system architecture for hierarchical virtual power plant control," *Applied Mechanics and Materials*, vol. 631-632, pp. 878–881, 2014.

[9] M. A. Ahmed, Y. C. Kang, and Y.-C. Kim, "Communication network architectures for smart-house with renewable energy resources," *Energies*, vol. 8, no. 8, pp. 8716–8735, 2015. [Online]. Available: http://www.mdpi.com/1996-1073/8/8/8716

[10] J. Zhang, A. Hasandka, J. Wei, S. M. S. Alam, T. Elgindy, A. R. Florita, and B.-M. Hodge, "Hybrid communication architectures for distributed smart grid applications," *Energies*, vol. 11, no. 4, 2018. [Online]. Available: http://www.mdpi.com/1996-1073/11/4/871

[11] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Communication network requirements for major smart grid applications in han, nan and wan," *Computer Networks*, vol. 67, pp. 74–88, July 2014.

[12] U.S. Department of Energy, "Communications requirements of smart grid technologies," pp. 1–69, 2010.

[13] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "A survey on smart grid potential applications and communication requirements," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 28–42, Feb 2013.

[14] B. Palmintier, E. Hale, T. M. Hansen, W. Jones, D. Biagioni, H. Sorensen, H. Wu, and B. M. Hodge, "IGMS: An integrated ISO-to-appliance scale grid modeling system," *IEEE Transactions on Smart Grid*, vol. 8, no. 3, pp. 1525–1534, May 2017.