Cyber-Physical Systems for Resource Allocation in the Emerging Smart Electric Distribution Grid

Siddharth Suryanarayanan, Timothy Hansen, Anthony A. Maciejewski,
Edwin K. P. Chong, and Howard Jay Siegel

Department of ECE, Colorado State University, Fort Collins, CO
Email: {sid; timothy.hansen; aam; edwin.chong; hj}@colostate.edu

***Abstract*— The emerging *Smart Grid* is expected to transform the electric distribution grid, a hitherto overlooked domain in grid modernization, via an unprecedented increase in penetrations of renewable energy sources, distributed energy storage devices, electric vehicles (EVs), programmable loads, customer-driven controllers, and new operating philosophies such as dynamically priced electricity. Consequently, the levels of uncertainty in the availability and deployment of a multitude of the highly distributed assets that possess both temporal (such as renewables) and spatio-temporal (such as EVs) stochasticity, and the concomitant decision-making in control of the rest of the available assets become a tipping point. In that regard, this position paper proposes a transformational paradigm in multi-level, multi-scale energy management systems (EMS) extending from the individual end-user to the interface with the bulk transmission grid for realizing the *Smart Grid*. This will be aided by cyber-physical approaches to new structures, systems, methods, and tools related to electricity markets, power systems, advanced optimization theory, heuristics, high performance computing (HPC), and visualization.**

I. The Position on Cyber-Physical Systems for Emerging Smart Distribution Grid

Electricity supply must match the demand at any instant is the governing dictum of power systems operations. The growth in peak electricity usage in the US has outpaced the growth in transmission capacity by almost 25% each year in the last three decades [1]. Additionally, residential electricity sales in the US are projected to grow 24% in the next three decades with matching growth rates in generation capacities [2]. Given these trends, peak energy demands are expected to exceed the available transmission capability. Additional spending for increasing transmission capability in the US seems unlikely [1]. This may force the participation of expensive and *dirty* generators to supply the peak loads, more so than ever. As an alternative, curtailing loads during peak periods could drastically reduce the cost and need for expensive electricity. Under the *Smart Grid Initiative*, end-users empowered with timely information and control options may choose to curtail loads. This is supported by studies such as [3], where it was posited that "a 5% reduction in peak demand during the California energy crisis of 2000–2001 would have reduced the highest wholesale prices by 50%." However, uncoordinated load curtailments in the end-user realm may be counter-productive and could potentially collapse the stability of the grid [4].

The fundamental challenge is the development of transformational structures, systems, methods, and tools to reduce peak demands in the electric grid by **intelligently coordinating** the scheduling of **highly distributed** end-user assets away from the peak time, thus alleviating the peak demand, and offering a **benefit** to all parties. Based on the successful and continuing research of the authors in this area ([5]–[12]), we present a CPS for a new electricity retail market structure that involves an **aggregator**-based approach, where the aggregator is a proposed for-profit entity as shown in Figs. 1 and 2. The aggregator will possess a set of participating customers, indicated by $\{1...y\}$ in Fig. 2, each with a number of schedulable assets, as shown in Fig. 1. Using the information about all schedulable assets, the aggregator is able to enact a noticeable change on the overall system by scheduling the loads of many customers, where a single customer might not be able to, thus providing the end-user the chance to participate in the spot market, as shown in Fig. 3. The motivation of the customer for signing up with the aggregator, and agreeing to have their assets possibly be rescheduled, are twofold: (a) they would be paying less for electricity as dictated by the *transformational* **customer incentive pricing** provided by the aggregator with the information on spot prices in the bulk market and the dynamic pricing scheme from the local utility, as shown in Fig. 4; and, (b) if the inconvenience of rescheduling the load is not worth the reduced price, the end-users could refrain from participating with the aggregator and maintain the *status quo* with the distribution company. The latter is indicated by the set of customers $\{(y+1)...Y\}$ in Fig. 2.

Customer incentive pricing is a proposed pricing structure that the aggregator would offer the customer to allow the rescheduling of their loads where, instead of paying the distribution company the real-time price of electricity, the customer pays the aggregator the customer incentive price for the electricity. The end-user paying the customer incentive price for electricity to the aggregator at the time the asset has been rescheduled to (**S**, as shown in Fig. 2) is one part of the revenue of the aggregator. The other two components to the aggregator profit are: (a) the aggregator selling a negative load to the spot market where the assets have been rescheduled from (**N**, as shown in Fig. 2), and (b) the cost deduction arising from the aggregator buying spot market electricity where the assets have been rescheduled to (**B**, as shown in Fig. 2) [7]. It is noteworthy to mention that the results shown in Figures 3 and 4 correspond to cases with approximately $5,500$ end-users, each with its own sets and profiles of schedulable and fixed loads.

The broad areas of constituent research under this topic include:

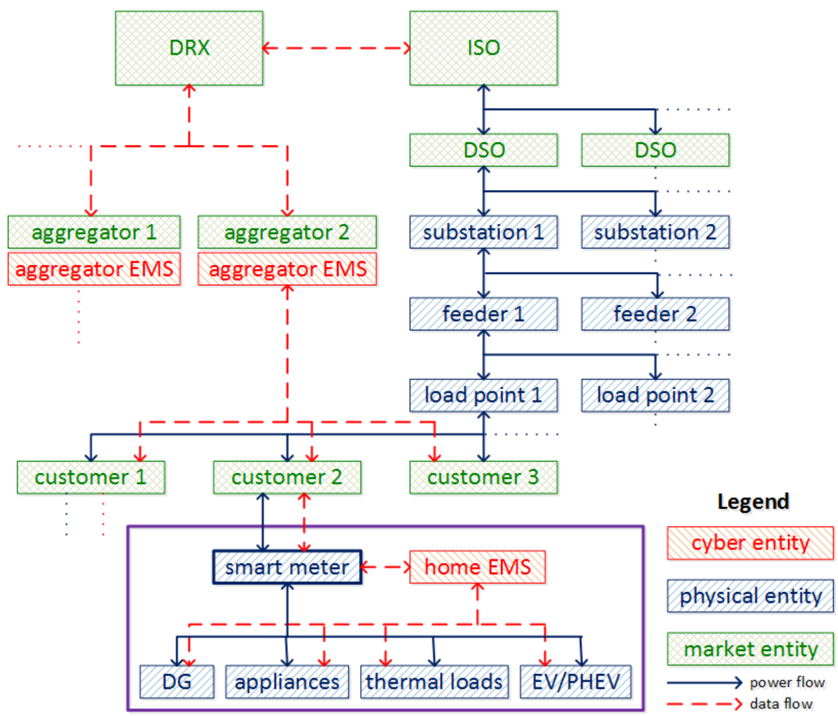

Fig. 1. CPS architecture. The red-dashed lines indicate a data flow between entities, constituting the flow of information in the cyber portion of the system. The solid blue lines indicate the physical flow of electricity. The combined CPS coordinates the operation of the customer households through the home energy management system and the distribution of the necessary electricity.

1) Development of a market structure capable of accommodating the interactions of highly distributed end-user assets and aggregators with the bulk electricity market [5], [7]
2) Reconciliation of temporal and spatio-temporal stochasticity among certain assets [8]
3) Development of methodologies for understanding customer-behavior [9]
4) Development of test beds with the capability of co-simulating power systems and artificial intelligence methods [10]
5) Leveraging the capabilities of HPC for implementing and demonstrating the coordinated action on computer models that are representative of practical system sizes [11]
6) Development of robustness metrics for quantifying the effectiveness of the above methods [6]
7) Development of visualization aids for interpreting and optimizing wide-area actions [12].

II. Counter Positions and Arguments

Some counter positions to the above point and arguments are:

1) Will the *emerging* distribution grid accommodate highly distributed assets with varying stochasticity? While this is a primary enabler for the research avenue proposed here, all indicators point to extensive and deep penetration of distributed assets, including renewable energy and electric vehicles, at various levels in the grid [2].

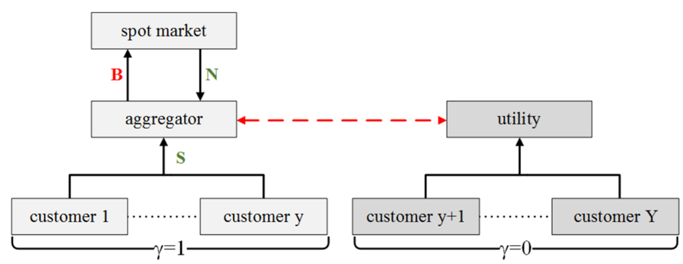

Fig. 2. Market interaction between the aggregator, customer, spot market, and utility company defined using a binary variable γ. When $\gamma = 1$, the customer (in this case, customers $1, ..., y$) has agreed to participate with the aggregator. However, when $\gamma = 0$, the customer (in this case, customers $y+1, ..., Y$) participate with the distribution utility company.

2) Will "aggregators" evolve in realistic markets? Aggregators are currently being viewed as the missing link between the deregulated bulk (wholesale) electricity market and the retail market, with plans to integrate their participation in the future [13].
3) Will this new research direction address the workforce issues of the US electric utilities industry? The electric utility industry is undergoing a fundamental transformation via the *Smart Grid Initiative* while facing a projected retirement and attrition of almost half of its workforce in the coming decade [14]. Research and education programs aimed at new technologies, structures, and operations aided by CPS in the *Smart Grid* hold the potential for rejuvenating and updating the power curricula in universities and preparing a well-educated workforce.

III. Conclusions

We proposed the development of robust cyber-physical systems, methods, and tools for the coordinated deployment of highly distributed assets in the emerging *smart* distribution grid as a key avenue of future research and education.

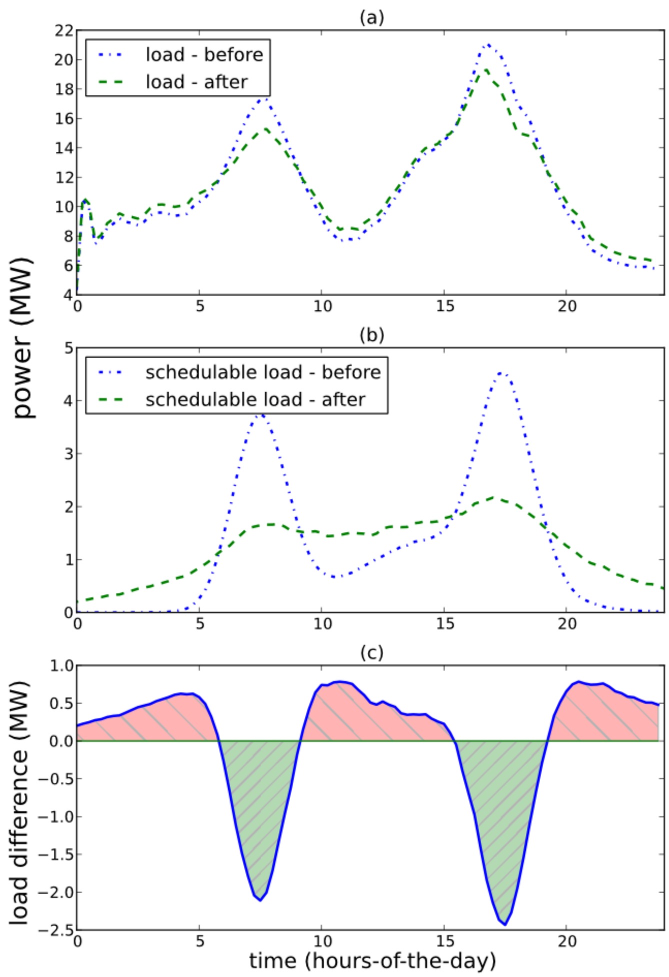

Fig. 3. Load curves before and after the CPS action. Graph (a) shows the overall system load (both the base load and the schedulable assets) of 5,555 customer homes. In graph (b), the base load is removed from consideration and only the portion of the load that is schedulable is shown. The total load difference between the load before and after the CPS action is given in graph (c). The green area with / hashing shows the peak load of the system being reduced by the CPS action. The red area with \ hashing shows to where the peak loads have been moved.

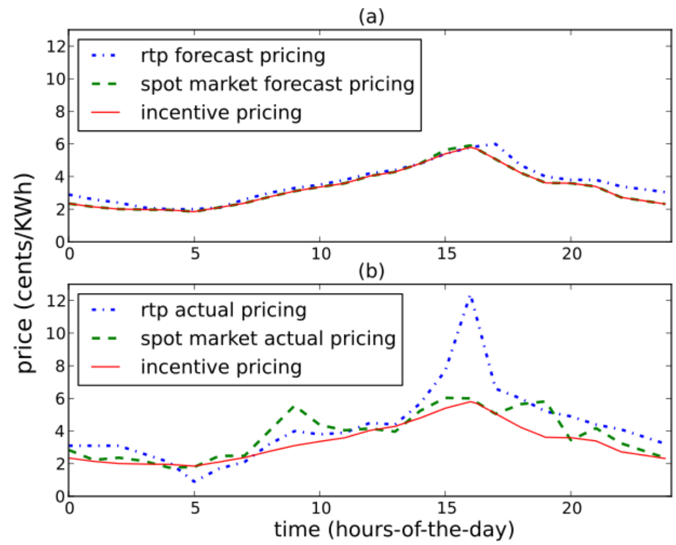

Fig. 4. Customer incentive pricing compared to the real-time price (rtp) and the spot market price. Graph (a) gives the forecast prices while graph (b) gives the actual price for the given 24-hour period.

References

[1] United States Department of Energy, "The Smart Grid: An introduction," 2009.

[2] United States Energy Information Administration, "Annual energy outlook 2013," 2013.

[3] J. Osborne and D. Warrier, "A primer on demand response. The power grid: Evolving from a dumb network to a smart grid," *Thomas Weisel Partners Equity Research*, 2007.

[4] M. Roozbehani, M. A. Daleh, and S. K. Mitter, "Volatility of power grids under real-time pricing," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 1926–1940, 2012.

[5] T. Hansen, R. Roche, S. Suryanarayanan, H. J. Siegel, D. Zimmerle, P. M. Young, and A. A. Maciejewski, "A proposed framework for heuristic approaches to resource allocation in the emerging Smart Grid," in *IEEE PES Int'l Conference on Power Systems Technology*, 6 pp., 2012.

[6] V. Shestak, J. Smith, A. A. Maciejewski, and H. J. Siegel, "Stochastic robustness metric and its use for static resource allocations," *Journal of Parallel and Distributed Computing*, vol. 68, no. 8, pp. 1157–1173, 2008.

[7] T. M. Hansen, R. Roche, S. Suryanarayanan, A. A. Maciejewski, and H. J. Siegel, "Heuristic optimization for an aggregator-based resource allocation in the Smart Grid," *under preparation*, 8 pp., 2013.

[8] E. K. Chong, C. M. Kreucher, and A. O. Hero III, "Partially observable markov decision process approximations for adaptive sensing," *Discrete Event Dynamic Systems*, vol. 19, no. 3, pp. 377–422, 2009.

[9] A. Zipperer, P. Aloise-Young, S. Suryanarayanan, R. Roche, L. Earle, D. Christensen, P. Bauleo, and D. Zimmerle, "Electric energy management in the smart home: Perspectives on enabling technologies and consumer behavior," *Proceedings of the IEEE*, vol. 101, no. 11, pp. 2397–2408, 2013.

[10] R. Roche, S. Natarajan, A. Bhattacharyya, and S. Suryanarayanan, "A framework for co-simulation of AI tools with power systems analysis software," in *23rd Int'l Workshop on Database and Expert Systems Applications (DEXA)*, 2012, pp. 350–354.

[11] R. Friese, B. Khemka, A. A. Maciejewski, H. J. Siegel, G. A. Koenig, S. Powers, M. Hilton, J. Rambharos, G. Okonski, and S. W. Poole, "An analysis framework for investigating the trade-offs between system performance and energy consumption in a heterogeneous computing environment," in *2013 IEEE 27th International Parallel and Distributed Processing Symposium Workshops PhD Forum (IPDPSW)*, 2013, pp. 19–30.

[12] T. M. Hansen, A. A. Maciejewski, S. Suryanarayanan, and H. J. Siegel, "A visualization aid for demand reponse studies," in *under preparation, IEEE Power and Energy Society General Meeting*, 5 pp., 2014.

[13] R. Burke, "Closing the gap between wholesale and retail," *Transactive Energy Workshop*, 2012.

[14] J. G. Kassakian, W. W. Hogan, R. Schmalensee, and H. D. Jacoby, "The future of electric grid: An interdisciplinary MIT study," 280 pp., 2011.