Pricing Bilateral Electricity Trade between Smart Grids and Hybrid Green Datacenters

Zhi Zhou, Fangming Liu*
Services Computing Technology & System Lab
School of Computer Science and Technology
Huazhong University of Science and Technology
{zhiz, fmliu}@hust.edu.cn

Zongpeng Li
Department of Computer Science
University of Calgary
zongpeng@ucalgary.ca

ABSTRACT

Datacenter demand response is envisioned as a promising approach for mitigating operational instability faced by smart grids. It enables significant potentials in peak load shedding and facilitates the incorporation of distributed generation and intermittent energy sources. This work considers two key aspects towards realtime electricity pricing for eliciting demand response: (i) Two-way electricity flow between smart grids and large datacenters with hybrid green generation capabilities. (ii) The geo-distributed nature of large cloud systems, and hence the potential competition among smart grids that serve different datacenters of the cloud. We propose a pricing scheme tailored for geo-distributed green datacenters, from a multi-leader single-follower game point of view. At the cloud side, in quest for performance, scalability and robustness, the energy cost is minimized in a distributed manner, based on the technique of alternating direction of multipliers (ADMM). At the smart grid side, a practical equilibrium of the pricing game is desired. To this end, we employ mathematical programming with equilibrium constraints (MPEC), equilibrium problem with equilibrium constraints (EPEC) and exact linearization, to transform the multi-leader single-follower pricing game into a mixed integer linear program (MILP) that can be readily solved. The effectiveness of the proposed solutions is evaluated based on trace-driven simulations.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Design studies; Modeling techniques; C.2.4 [**Computer-Communication Networks**]: Distributed Systems

Keywords

Geo-distributed Cloud; Hybrid Green Datacenters; Smart Grid; Demand Response; Multi-leader Single-follower Game

*Corresponding Author

SIGMETRICS'15, June 15-19, 2015, Portland, OR, USA.
ACM 978-1-4503-3486-0/15/06.
http://dx.doi.org/10.1145/2745844.2745884.

1. INTRODUCTION

The recent years have witnessed new technology advances in the ICT sector, two of which are of practical significance and of particular interest to this work. The first is the Internet-scale cloud services deployed over geographically distributed datacenters, serving enterprises and end users, indispensable for a wide variety of applications. The second is the evolution of the traditional power grids to smart grids, enabling sustainable, cost-effective, and environmental-friendly electric power generation and consumption.

Further developments of both cloud computing and smart grids are facing their respective challenges. In smart grids, the integration of a large number of generation units (*e.g.*, wind turbines and solar arrays) incurs operation stability concerns and hence economic issues, due to the intermittent nature of such distributed generation. For example, the enormous wind generation in Germany in May 2014 resulted in continuous negative electricity prices for five hours [5]. Furthermore, the soaring of peak demand exacerbates the vulnerability and price fluctuation of a power grid. These operational issues can be addressed by demand response from large loads, among whom datacenters are natural candidates. For a datacenter, the power drawn from the smart grid is often of very large volumes yet exhibiting an elastic nature. An individual datacenter can make up 50% of the load of a distribution grid nowadays [3] (*e.g.*, Facebook's datacenter in Crook County, Oregon). Despite its sheer volume, datacenter power consumption is a natural target in demand response since it is driven by user requests that can be split to geo-distributed datacenters, and be served by multiple energy sources. Thus, the power drawn by a datacenter from the smart grid can be flexibly adjusted by changing the workload routed to the former, or modulating the output of on-site generation.

Table 1: Renewable Generation at Large Datacenters.

Company	Location	Type	Capacity
Microsoft	Chicago, IL	Wind	175MW
Facebook	Altoona, IA	Wind	138MW
Google	Mayes, OK	Wind	48MW
Apple	Maiden, NC	Solar	40MW
Google	Council Bluffs, IA	Wind	114MW
Microsoft	San Antonio, TX	Wind	110MW

In response to escalating pressure from economic and environmental concerns, large-scale cloud providers such as Google and Microsoft start to install hybrid renewable energy systems that include off-site wind, solar farms and onsite fuel cell generators [4]. For economies of scale, the installed capacity of wind and solar generation is often very large, as illustrated in Table 1. The farms are constructed mostly at locations with desirable climate. However, storing the excess wind or solar power in energy storage device (ESD) is still technically challenging, and large capacity lead-acid ESD is not environment friendly. Fortunately, by participating in the existing *net metering* [2] program, the excess renewable power can be sold back to the smart grid, eliminating the need of expensive large capacity ESDs. Such an option is already adopted in reality, including the cloud providers in Table 1. Such backward flow of renewable energy is particularly desirable as a response to energy deficit within the smart grid, easing the latter's burden at peak-hour. Furthermore, thanks to rapid developments in fuel cell technology in the recent past, fuel cell generation is emerging as a reliable complement to intermittent renewable energy such as wind or solar, with predictable and controllable output levels. Compared to traditional onsite stand-by generation (*e.g.*, diesel generators), fuel cell generation running on direct biogas is carbon neutral, and hence much more environment-friendly [4].

A hybrid datacenter not only draws energy from the smart grid, but also sells excess renewable energy back to the latter. A datacenter can provide great potential to demand response, by setting the appropriate amount of energy drawn from or sold back to the smart grid. Unfortunately, despite the fact that datacenter demand response can be obtained by adjusting the electricity and/or net metering price in a real-time manner, eliciting a desired amount of demand response from the hybrid green datacenter is of great challenge to a smart grid. In particular, when a cloud runs on top of geo-distributed datacenters and couples multiple smart grids, a smart grid needs not only to anticipate the corresponding cloud's response to the price decisions, but also to consider the impact of other smart grids' price decisions on the cloud's response. In such competition scenarios, an efficient pricing strategy is needed by each smart grid to optimize its objective.

We study the pricing of the bilateral electricity trade between a cloud that runs on geo-distributed hybrid green datacenters and the smart grids that serve it, aiming to determine the electricity and net metering prices for each datacenter. In such price computation, each smart grid needs to anticipate how the cloud would response to a given price, by minimizing the latter's energy cost via *geographically load balancing*, *i.e.*, at each front-end server, determining the amount of workload distributed to each datacenter, and *green capacity planning*, *i.e.*, determining the amount of fuel cell generation, net metering and power drawn from the corresponding smart grid. Note that the price strategy of one smart grid can influence the demand response at another smart grid. Consequently, the pricing process becomes a non-cooperative game. If we further consider the cloud's response to the prices, the entire process can then be captured by a two-stage *multi-leader single-follower game* [1], in which each smart grid acts as a leader and sets the prices, while the cloud acts as the follower and responses to the prices by minimizing its cost.

2. CONTRIBUTIONS

At the cloud side, in quest for performance, scalability and robustness, the energy cost of the cloud is expected to be minimized in a distributed manner. We show that the green capacity planning subproblems at each datacenter can be decoupled from the master geographical load balancing problem. We first solve the green capacity planning subproblems at each datacenter analytically, and obtain the master geographical load balancing problem explicitly. Then, such global master problem is solved in a fully distributed manner, based on the technique of alternating direction method of multipliers (ADMM) [5]. ADMM is a simple yet powerful tool for large-scale convex optimization that has enjoyed successful applications in image processing, machine learning and applied statistics. The proposed distributed geographical load balancing algorithm follows a decomposition-coordination approach. Each facility (front-end servers and datacenters) first solves a small-scale subproblem, and then these local solutions are coordinated to find the global optimum of the energy cost minimization problem.

At the smart grid side, it is desirable to discover and analyze a practical equilibrium of the multi-leader single-follower game, at which point no player can improve his/her objective by changing his/her strategy unilaterally. However, detecting an equilibrium of a multi-leader single-follower game is particularly challenging, since each leader's strategy space is non-convex, ruling out direct applications of results on classic Nash games [1]. To address this challenge, we first replace the lower-level energy cost minimization for the cloud with its first-order optimality conditions that are represented as a primal-dual formulation. The resulting problem for each smart grid is a mathematical program with equilibrium constraints (MPEC) [1]. The joint consideration of all MPECs, one per smart grid, constitutes an equilibrium problem with equilibrium constraint (EPEC) [1]. The equilibrium associated with the EPEC is analyzed by solving the Karush-Kuhn-Tucker conditions of all MPECs, which can be linearized without approximation loss by mixed-integer linear programming (MILP) techniques. The resulting mixed-integer linear system allows determining a meaningful equilibrium that meets certain pre-established criteria through an auxiliary MILP problem.

3. ACKNOWLEDGMENTS

The Corresponding Author is Fangming Liu. The research was supported in part by a grant from The National Natural Science Foundation of China (NSFC) under grant No.61370232, by a grant from National Basic Research Program (973 program) under grant No.2014CB347800. Zongpeng Li's work was supported by Wedge Networks Inc.

4. REFERENCES

[1] S. A. Gabriel, A. J. Conejo, J. D. Fuller, B. F. Hobbs, and C. Ruiz. Complementarity modeling in energy markets. *International Series in Operations Research and Management Science*, 180:1–629, 2012.

[2] F. Kong, X. Liu, and L. Rao. GreenPlanning: Optimal Energy Source Selection and Capacity Planning for Green Datacenters. In *Proc. of ACM SIGMETRICS*, 2014.

[3] Z. Liu, I. Liu, S. Low, and A. Wierman. Pricing Data Center Demand Response. In *Proc. of ACM SIGMETRICS*, 2014.

[4] Z. Zhou, F. Liu, B. Li, B. Li, H. Jin, R. Zou, and Z. Liu. Fuel Cell Generation in Geo-Distributed Cloud Services: A Quantitative Study. In *Proc. of IEEE ICDCS*, 2014.

[5] Z. Zhou, F. Liu, Z. Li, and H. Jin. When Smart Grid Meets Geo-distributed Cloud: An Auction Approach to Datacenter Demand Response. In *Proc. of IEEE INFOCOM*, 2015.