Modeling and Optimization of the Smart Grid Ecosystem

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Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

I. Koutsopoulos, T. P. Papaioannou, and V. Hatzi. *Modeling and Optimization of the Smart Grid Ecosystem*. Foundations and Trends® in Networking, vol. 10, no. 2-3, pp. 115–316, 2015.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-159-7

Foundations and Trends® in Networking
Volume 10, Issue 2-3, 2015

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Foundations and Trends® in Networking, 2015, Volume 10, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in Networking
Vol. 10, No. 2-3 (2015) 115–316

DOI: 10.1561/1300000042

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Contents

Abstract

The smart energy grid has evolved into a complex ecosystem, with new entering actors such as aggregators, and traditional ones like consumers, operators and generators having fundamentally different, active roles in the system. In addition, advances in key technologies such as renewables, energy storage, communication and control have paved the way to new research directions and problems. In this work we attempt to give some structure to the complex ecosystem above, and we present key research problems that shape the area. The emphasis is on the control and optimization methodology toward approaching these problems. The first thread we consider is demand-response where the central theme is to optimize the demand load of consumers. The basic problem is the scheduling of demand load of consumers with the aim to minimize a cost function from the point of view of the utility operator or the consumer. Next, we review fundamental problems in energy storage management. The basic energy storage management problem amounts to deciding when and how much to charge and discharge the battery in order to achieve a certain optimization objective, either in terms of a generation cost or a mismatch between energy demand and supply, which again may capture the goals of the consumer or the utility. We also discuss the market interactions of various entities in the smart grid ecosystem and the impact of their strategic decisions on the market structure. Finally, we study key aspects of consumer behavior such as response to gamification models, and uncertainty due to consumer decisions that influence the system, and we discuss the role of data in building data-driven models for predicting consumer behavior. For each problem instance above, we provide an exposition that places emphasis on the related model and on key aspects of the analysis.

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DOI: 10.1561/1300000042.

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Introduction

The aim of the smart electric energy grid is to improve efficiency, flexibility and stability of the electric energy generation and distribution system, with the ultimate goals to bring added value of energy-related services to the end-consumer and to facilitate energy generation and prudent consumption toward energy efficiency.

Energy management and optimization have been linked more to the traditional electrical and power engineering fields, and to a lesser extent to traditional control engineering. It is only in the last few years that novel viewpoints have been considered for energy management, such as modern optimization methods, networking or network economics. This shift in the way we view the energy management system is mainly attributed to new components in the energy management system, such as modern sensors, smart meters, and novel technologies such as flexible electric energy storage facilities, bidirectional communication links between consumers and utility operators, and computational power capable to carry out advanced algorithms. Last but not least, the penetration of renewables down to the consumer level has played decisive role in the shift above.

In addition, new actors have entered the energy landscape, while other traditional ones have fundamentally changed their role. Consumer appliances have evolved from passive system elements to entities that can adjust, curtail or shift in time their energy loads. Consumers can now influence their power consumption profile, and they can generate and store power. Further, energy aggregator entities have entered the ecosystem as proxies between utility companies and consumers.

In this work, we attempt to give some structure to the complex ecosystem above, and we survey key research problems that have shaped the area. The emphasis is on the presentation of the control and optimization methodology towards approaching each of these problems. This methodology spans convex and linear optimization theory, game theory, and stochastic optimization. The goal of this work is to serve as a reference for researchers that would like to quickly dwell into fundamental principles and research problems underpinning the smart grid ecosystem, and into the main mathematical tools used to model and analyze such systems. We have categorized our approaches in four main areas:

- demand-response;
- electric energy storage management;
- market-based mechanisms;
- consumer engagement,

with the understanding that the problems addressed and the methods employed in each of these areas may overlap. Each of the chapters is followed by a brief literature survey.

The first aspect we consider in chapter 2 is demand-side management (DSM), and its central theme is to optimize the demand load of consumers. The basic problem is the scheduling of demand load of consumers. This problem is viewed first from the perspective of the utility operator which may directly control the load with the goal to minimize a cost function of the demand that stands for operational cost of the system. Different types of control are applicable depending on the type of load, such as splitting the amount of demand across time or time-shifting the demand load. Further, offline or online versions of the problem are defined, depending on whether the demand load is a priori known or it arises according to a dynamic process.

Next, the demand scheduling problem is studied from the point of view of a consumer that has the freedom to adjust her demand load in order to optimize her energy cost. The consumer actions are driven by an energy pricing scheme or other incentives which may be fixed or optimized by the entity that uses it. The selfish optimization of each consumer gives rise to game models in the context above.

In chapter 3, we review fundamental problems in energy storage management and dimensioning. The basic energy storage management problem amounts to deciding when and how much to charge or to discharge the battery in order to achieve a certain optimization objective. First, we look at energy storage management from the point of view of a supplier with the aim to minimize the long-term average cost of generated power. Demand requests and energy from renewables are both assumed to be generated according to some dynamic processes, and we present solutions for the online version of the problem.

Next, we discuss the problem of optimal matching of demand load and renewable energy generation, again from the supplier point of view. The optimal online storage facility management policy is characterized, which minimizes the long-term average power mismatch. Further, we discuss online dynamic storage control policies with the aid of Lyapunov optimization. The policy specifies the charging and discharging rates of the storage device, and the power that needs to be bought from the grid. The aim is to minimize the long-term average cost which includes the cost paid by the consumer, and the costs of charge and discharge. Finally, the joint impact of energy storage placement, dimensioning and control problem is studied. The chapter includes a primer on power flow analysis that is needed in the last problem.

The aim of chapter 4 is to discuss market implications and interactions of various entities in the smart grid ecosystem. The energy dispatch problem faced by an operator in the day-ahead wholesale energy market is discussed first. The determination of the strategy of a generator in terms of amount of generated energy and various other management decisions is studied next, in the presence of uncertainty about the energy trading price. Interactions and the market structure are studied for formed markets among competing generator companies in terms of the quantity of energy to generate and the price to set, and among many generator and intermediate entities that each aims at profit maximization. Finally, we study the interaction and associated optimization problems faced by the utility company, the aggregators and the customers in a hierarchical market setting.

Finally, in chapter 5, we study key models of consumer behavior and decision-making. First, we present a mathematical model of a simple gamification mechanism through which a demand-response entity aims to motivate consumers to adopt prudent energy consumption by setting up a contest of top-K, most prudent consumers and by providing them incentives in the context of a serious game. Next, we study the impact of uncertainty of consumer behavior on incentive design. A utility operator wishes to curtail some amount of demand load during peak hours in order to reduce energy generation cost. However, there exists uncertainty in whether the consumer will actually perform the curtailment. This uncertainty gives rise to a novel incentive mechanism, that of rewards in case of compliance, and fine in case of non-compliance with the curtailment agreement. Different game-theoretic market mechanisms are studied that involve the utility operator and the consumers.

Finally, we present a data-driven approach to profile the consumer and to bring in the foreground behavior-based models for predicting consumer behavior. The ultimate goal is to target incentives appropriately based on the different derived criteria that consumers employ to decide whether to perform a suggested load curtailment or shift. We use machine-learning tools to build such a model for the consumer. The model is based on logistic regression, and it may be seen as the prelude for more general behavioral-science inspired models for consumer decision-making, for which we provide an overview as well.

We conclude with chapter 6, where we outline various future directions and areas that warrant further investigation.

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