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Alireza Ghadertootoonchi · Armaghan Solaimanian · Mehdi Davoudi · Moein Moeini Aghtaie

Energy System Modeling and Optimization

A Practical Guide Using Pyomo

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Preface

Nowadays, in the field of energy system studies, it is a well-known stereotype to start by emphasizing that the reason behind the importance of the research is climate change, and this brief book is no exception. Usually, the main solution to tackle the problem of climate change is the integration of renewable energy sources like wind and solar. Nonetheless, another aspect of energy system studies that must not be underestimated is paying attention to people's well-being and satisfying their energy demand reliably. At the same time, they should be encouraged to reduce their energy consumption appropriately. Considering all these factors together for energy system optimization purposes is a complex task and is the subject of the current book.

The book is designed for any reader who is interested in learning more about how to enhance the sustainability and performance of energy systems. No background in energy engineering or energy system studies is needed since the modeling starts from scratch. Furthermore, no background in the Pyomo package is needed, as all the essential functions of Pyomo are first discussed and introduced and then used in the energy system optimization case studies. After reading this book, the reader will be able to model an energy system optimization problem from scratch, acknowledge the complexities of such a problem, describe the potential impacts of different constraints on the performance of the energy system, and demonstrate the advantages and limitations of energy system optimization studies.

The book explores different aspects of energy system optimization, such as the operational cost of power plants, which is directly linked to their fuel consumption, the operational and technical constraints of thermal power plants, the effect of renewable energy and energy storage integration on the energy network, the role of transmission lines, the effect of demand response programs, and the importance of reliability measures when optimizing and scheduling energy systems. To achieve this purpose, the book describes the mathematical foundation of modeling the system in an easy-to-follow but not oversimplified manner. To make the book more accessible to every reader, all the codes are implemented in Python using Pyomo, which are freely available. In addition, to solve the optimization problems, open-source solvers such as GLPK, CBC, and HiGHS are used, which are available online at no cost. Moreover, the codes used for modeling and optimizing the case studies in the book, along with input parameter templates, are available on the authors' GitHub. The reader can download the code, manipulate the parameters, and run multiple cases to see the impact of changes in modeling inputs on the results.

There are a total of five chapters in the book. Chapter 1 is the introduction and provides important information on the energy system supply side and its environmental impacts, as well as other concepts involved in the energy system such as renewables, transmission lines, reliability, and energy self-sufficiency. Chapter 2 is about how to effectively use Pyomo. This chapter has a practical approach to teach the reader how to work with the package and uses a variety of famous optimization problems for this purpose. Chapter 3 covers the mathematical equations that help formulate the optimization problem. The Python code for the energy system optimization problem is presented and discussed in Chap. 4. Finally, Chap. 5 presents the results of different case studies solved using the mentioned Python code.

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Chapter 1
Introduction

Abstract Two main parts of an energy system are the supply side and the demand side which are connected by the transmission and distribution lines. Historically, the supply side is equipped with thermal power plants consuming fossil fuel to generate electricity. However, the environmental impact of these power plants is considerable which is one of the main reasons behind the integration of renewable energies in the power system. Considering the demand side, energy consumption is rapidly increasing due to various factors such as population growth, economic development, and climate change. It is important to know the energy system's historical trends as well as its potential future direction. Therefore, this chapter aims to provide necessary background information on the current situation and future predictions of the energy system.

1.1 Introduction

Total final energy consumption of the world has increased steadily during past decades and reached from 194 EJ in 1973 to 418 EJ in 2019, a 115.5% growth over 47 years [1]. According to the International Energy Agency (IEA), the most rapid increase in the share of different energy sources in the overall energy consumption belongs to electricity which shows an approximately 10% growth from 9.5 to 19.7% as depicted in Fig. 1.1. This growth reflects the important role of electricity in final energy consumption.

Electricity consumption has increased due to various reasons, such as the addition of new loads [2], but the main ones are the population growth and the electrification of different devices of end users [3]. Furthermore, due to the important role of electricity in achieving net-zero emissions, which is one of the pivotal sustainable development targets, its share in final energy consumption will continue growing in the future. Based on the 2050 net-zero emission scenario, the share of electricity in the final energy demand should increase by 4% annually [4]. In addition, the electricity supply system is transitioning to a more distributed system from the conventional vertical structure in which several large-capacity and centralized power plants exist [5]. The

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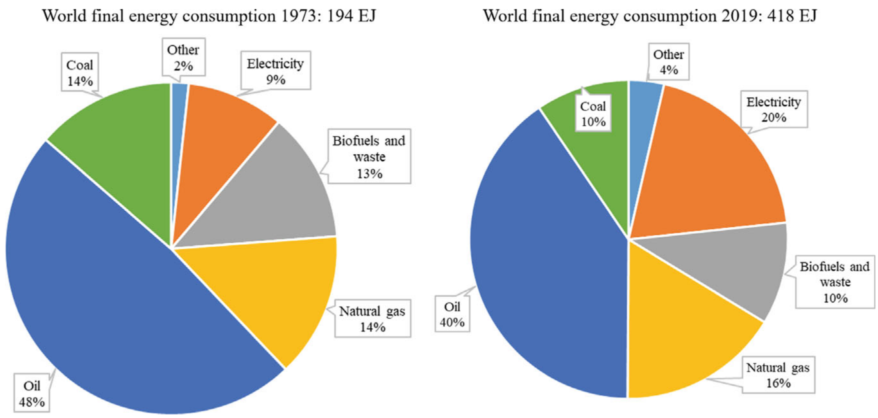

Fig. 1.1 Share of different energy sources in global energy consumption [1]

main motivations to transform the electricity generation and transmission system to a more distributed one are (i) deregulation of the system and introduction of the electricity markets which increases the efficiency of the electricity system and reduces the energy subsidies [6–8], (ii) growing trend of renewable energies integration to increase the sustainability of the system [9, 10], (iii) resiliency improvement of the electricity supply system [11, 12].

The deregulation of the electricity system can lead to cost reduction and more efficient resource allocation [13–15]. In addition, a deregulated and competitive electricity market can assist the energy transition goals such as effective implementation of carbon pricing and renewable energy integration [16, 17]. Renewable energy sources play a crucial role in the future electricity supply system and their share in the energy system is growing as shown in Fig. 1.2 [18]. Based on the IEA, total renewable electricity generation in 2022 experienced a 600 TWh growth, compared to 2021, and reached 8500 TWh with the majority coming from wind and solar technologies [19]. Therefore, when developing a large-scale model for the energy system, it is important not to neglect the impact of renewable energy integration.

The third reason behind the transition of the electricity system to a more distributed version is increasing the system's resiliency. Electricity systems can face several challenges such as natural disasters [20] and extreme weather events such as heat waves [21]. The central or traditional electricity system is more vulnerable to these conditions and can fail to provide electricity reliably [22]. However, decentralized systems that can operate independently from the central plants are emerging alternatives to address this issue [23]. Interested readers can find the resiliency indicators and their definitions in [21].

Considering the above, it can be seen that the structure of the power system is changing, and at the same time, electricity consumption is growing. Such a condition raises the need for increasing the accuracy and complexity of power system modeling. This can be done through the integration of new constraints into the simulation and