1

Introduction

> *To undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.*
>
> Article 4 of the Paris Agreement Apr. 2016

As mankind cannot rely only on a single energy source but on a mixture of multiple energy sources, hybridization is the eternal theme of human energy utilization, and the restructuring of the energy system is related to global security and stability, which requires systematic research. This chapter introduces the background of constructing hybrid energy systems (HESs), provides a detailed definition and classification of HESs, describes the motivation for hybridization of energy systems, and gives a logical relationship diagram of the whole book chapters.

1.1 Background

This section introduces the global mission of achieving carbon neutrality, the global passion of promoting energy transition, and the global status of developing HESs.

1.1.1 Global Mission of Achieving Carbon Neutrality

In the past few decades, global population has continued to grow, social economy has developed rapidly, living standards have improved significantly, electricity supply and demand have increased dramatically, and a large amount of fossil energy has been continuously exploited and utilized (Chen et al. 2016a). According to the *BP Statistical Review of World Energy 2021*, global power generation reached 2.68 billion kilowatt hour in 2020, of which coal, natural gas, and oil power generation accounted for 35.12%, 23.37%, and 2.82%, respectively. However, if these fossil fuels are still mined at 2020 levels, the world's remaining reserves of coal, natural gas, and oil will only last 139, 48.8, and 50 years (BP Global 2021). Not only that, the excessive

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burning of fossil fuels has resulted in massive emissions of sulfur dioxide, carbon dioxide, nitrogen oxides, and other gases, causing and exacerbating environmental problems such as global acid rain, greenhouse effect, and photochemical pollution (Liu et al. 2017). Statistics released by the International Energy Agency (IEA) in 2021 show that in 2019, the world's carbon emissions from fuel combustion reached 34.234 billion tonnes, of which 14.068 billion tonnes were directly attributable to heat and power production (International Energy Agency 2021a). Therefore, climate change caused by carbon dioxide and other greenhouse gas emissions has become the biggest non-traditional security risk in the twenty-first century, and reducing greenhouse gas emissions from energy use has become a common global issue.

In recent decades, the international community has made a series of efforts to address the climate crisis. In 1992, more than 150 countries and the European Economic Community signed the United Nations Framework Convention on Climate Change (UNFCC) in Rio de Janeiro, Brazil, and agreed to control the concentration of greenhouse gases in the atmosphere at a stable level. In 1997, the third Conference of the Parties to the Convention (COP3) was held in Kyoto, Japan, and formulated the first document in human history, the Kyoto Protocol, to limit greenhouse gas emissions in the form of regulations. The protocol sets greenhouse gas emission reduction targets for developed countries and countries with economies in transition but does not impose greenhouse gas emission reduction obligations for developing countries (The Ministry of Foreign Affairs of the People's Republic of China 2008). In 2009, at the 15th Meeting of the Parties to the Convention, relevant authorities from 193 countries and regions signed the Copenhagen Accord as a follow-up plan after the expiration of the Kyoto Protocol. The Copenhagen Accord, although not legally binding, lays the foundation for the first truly global agreement to limit and reduce greenhouse gas emissions in the future, the Paris Agreement (United Nations 2009). In 2015, the Paris Agreement, the first global emission reduction agreement covering nearly 200 countries and regions in human history, was finally reached, becoming the second legally binding agreement after the Kyoto Protocol. The Paris Agreement made a unified arrangement for the global response to climate change after 2020, and put forward the goal of controlling the global temperature rise within the range of 2 °C and working toward 1.5 °C.

According to the 2018 report of the United Nations Intergovernmental Panel on Climate Change (IPCC), to achieve the goal of no more than 2 °C, the world needs to reach carbon neutrality around 2070. To achieve the 1.5 °C target, carbon neutrality needs to be brought forward to around 2050. Therefore, since 2018, many parties have made carbon-neutral commitments. According to data from the World Resources Institute (WRI), at least 83 countries around the world have made carbon-neutrality commitments through legislation, promulgation of policies, and submission of statements of intent to the United Nations Framework Convention on Climate Change (Climate Watch 2022). China is the world's largest energy producer, the world's largest energy consumer, and the world's largest carbon emitter (International Energy Agency 2021a). At the federation conference in September 2020, China also made a solemn commitment to achieve carbon peaking by 2030 and carbon neutrality by 2060. According to data from the WRI, the common transition period in developed countries is 40–60 years from carbon peaking to carbon neutrality. For example, the United Kingdom and France achieved carbon peaks in 1991 and committed to carbon neutrality by 2050, with a transition period of 59 years. The U.S. reached its carbon peak in 2007 and pledged to achieve carbon neutrality by 2050, with a 43-year transition period. Japan achieved carbon peak in 2012, pledge to achieve carbon neutrality by 2050, with a transition period of 38 years.

The global mission of achieving carbon neutrality is pressuring energy transition from fossil fuel-dominated energy systems toward renewable energy-dominated energy systems; details are described in the following part.

1.1.2 Global Passion for Promoting Energy Transition

Due to the rapid increase in consumption of fossil energy and the increasingly severe impact of climate change, renewable energy has ushered in an unprecedented development opportunity; the third round of the energy revolution characterized by large-scale utilization of renewable energy is booming around the world. According to the IEA, the main sources of global carbon dioxide are the electricity and heat sector (power generation, 44%), the transportation sector (land, shipping, air transport, 26%), the industrial sector (metal smelting and chemical manufacturing, 20%), and the construction sector (building construction and home life, 9%) (International Energy Agency 2021b). Since electricity and heat production is the industry with the highest carbon emission in the world, if power supply cannot be very clean, the emission reduction target will be difficult to achieve (Energy Foundation 2021). Converting the dependence of electricity production on traditional fossil energy to clean energy and ensuring a diversified, stable, efficient, and clean power supply are becoming increasingly crucial to achieving the net-zero emission goal and promoting the transformation of the power structure.

Table 1.1 shows the power generation structure of several countries in 2020. Overall, the proportion of fossil fuel power generation in developing countries like China and India is very high, 60.75% and 70.56% of which comes from less clean coal, far exceeding the world's average coal power generation ratio of 33.79%. Although in terms of proportion, the proportion of fossil energy power generation in Japan is also close to 70%, more than 30% is from gas power with a higher degree of cleanliness. The same situation applies to the United States, although the proportion of fossil energy power generation in the United States also exceeds 60%, but more than 40% is from gas power. From the perspective of renewable energy power, European Union (EU) has a large number of wind and hydropower stations, and the proportion of renewable energy power generation (38.16%) is the highest around the world.

Based on the existing power supply structure, many organizations have forecast global power supply structure in 2050, as shown in Table 1.2. Among them, the World Energy Scenarios (2013) publication *World Energy Scenario: 2050 Energy Future* was released before the Paris Agreement was signed in 2013, the International Renewable Energy Agency publication *Global Energy Transition: 2050 Roadmap* was released after the agreement was signed in 2018, and the International Energy Agency's (2020) publication *Net Zero Emissions to 2050: A Roadmap*

Table 1.1 The power generation structure of different countries in 2020.

Country	Non-renewable power Coal (%)	Natural gas (%)	Oil (%)	Nuclear (%)	Hydro (%)	Renewable power Wind (%)	Solar (%)	Others (%)	Total (%)
World	33.79	22.8	4.36	10.12	16.85	6.15	3.27	2.71	28.98
EU 27	13.16	19.94	3.97	24.77	12.6	14.34	5.24	5.98	38.16
Japan	29.09	31.28	8.77	4.57	9.02	1.13	8.97	7.17	26.29
USA	19.11	40.23	0.71	19.5	7.06	8.31	3.27	1.8	20.44
India	70.56	3.88	0.02	3.32	12.19	4.5	4.38	1.05	22.22
China	60.75	3.32	2.1	4.8	17.78	6.12	3.42	1.7	29.02

Table 1.2 Proportion of global power generation by various power generation methods in 2050 under different scenarios.

Scenarios	Non-renewable power Coal (%)	Natural gas (%)	Nuclear (%)	Hydro (%)	Renewable power Biomass (%)	Wind (%)	Solar (%)	Geothermal (%)
WEC-Symphony	17.7	19.9	14.5	16.1	5.7	8.4	16.2	1.4
IREA-REmap	1	10	4	12	4	36	26	3
IEA-Netzero	0.9	1.3	7.7	11.9	4.6	34.8	34.9	1.2

for the Global Energy Sector comes at a time when parties to the agreement have made carbon-neutral commitments in 2021. The three documents are staggered in time and can be used to compare changes due to international policy. As can be seen from Table 1.2, in the World Energy Council's Energy Sustainability Forecast Scenario, the power generation ratio of non-renewable energy power is 52% (coal power 17.7%, gas power 19.9%, nuclear power 14.5%), the proportion of renewable energy power generation is 48%, of which photovoltaic (PV) and hydropower have the highest proportions, both exceeding 16.2%. The International Renewable Energy Agency's Renewable Energy Pathway Scenario (IREA-REmap) is based on the premise that the global temperature rise is kept below 2 °C. The proportion of wind power and PV power generation will rise to 36% and 26%, respectively. The IEA's net-zero emissions scenario (IEA-Netzero) is based on the premise of a temperature control of 1.5 °C. Under this premise, net-zero emissions need to be achieved in 2050, and the proportion of renewable energy in the power structure exceeds 87.4%. As can be seen from the data, renewable energy will become the main force of power supply in 2050.

Table 1.3 shows the proportion of power generation by different power generation methods in the world in 2020 and 2050. It can be seen that from 2020 to 2050, the global power structure will require major adjustments. The most obvious change is that the proportion of coal-fired power generation will be significantly reduced,

Table 1.3 Proportion of different types of power generation in the world in 2020 and 2050.

		World	
Category	**Generation**	**2020 (%)**	**2050 (%)**
Non-renewable	Coal	33.79	0.9–17.7
	Natural gas	22.8	1.3–19.9
	Nuclear	10.12	4.0–14.5
Renewable	Hydro	16.85	11.9–16.1
	Wind	6.15	8.4–36.0
	Solar	3.27	16.2–34.9

from 33.79% to 0.9–17.7% globally. The proportion of gas-electric power generation in the world will decrease from 22.8% to 1.3–17.7%. On the whole, the proportion of hydropower generation will be slightly reduced. This is because the development of hydropower is relatively mature and will be close to saturation. The increased power demand in the future will be mainly provided by new energy sources such as solar and wind power. It can be seen from the table that the proportion of wind power and PV power generation in the world will increase to 35–36%. In general, in order to achieve the goal of net zero emissions as much as possible, the electricity supply will show a trend of high cleanliness by 2050. The proportion of coal power supply would have dropped sharply, and clean energy such as solar, wind power, and hydropower will take over 60–90% of the power supply tasks in the world.

It can be seen that converting the dependence of electricity production on traditional fossil energy to clean energy has become an irreversible trend. As an effective solution to mitigate this issue, establishing HESs becomes the most feasible option and has drawn wide attention around the world, as shown in the following part.

1.1.3 Global Status of Developing Hybrid Energy Systems

Here we use the Web of Science (WOS) database to search HES-related researches to find out the global development status.

The search codes in WOS are “hybrid energy system*” (Topic) or “hybrid renewable energy system” (Topic) or “multi-energy system*,” and the article type includes “Article” or “Review Article” or “Proceeding Paper” or “Early Access,” and totally 2585 papers written in English were extracted from Science Citation Index Expanded (SCI-Expanded) and Social Sciences Citation Index (SSCI) databases. The authors conducted the search on 30 June 2023.

Ranking the retrieved literature by their publication year, the results can be seen in Figure 1.1. It can be seen that the first literature appeared in 1984, and since then a small amount of literature has focused on HESs every year, but until 2008, the number of papers per year was still less than 10; since 2008, the number of papers

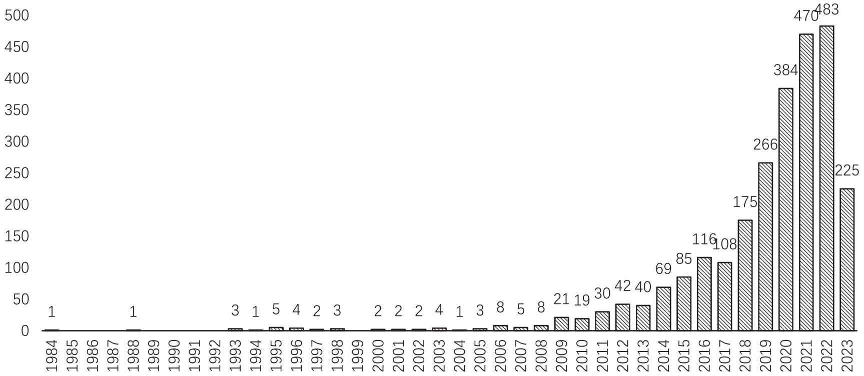

Figure 1.1 Research papers on hybrid energy systems (in order of year).

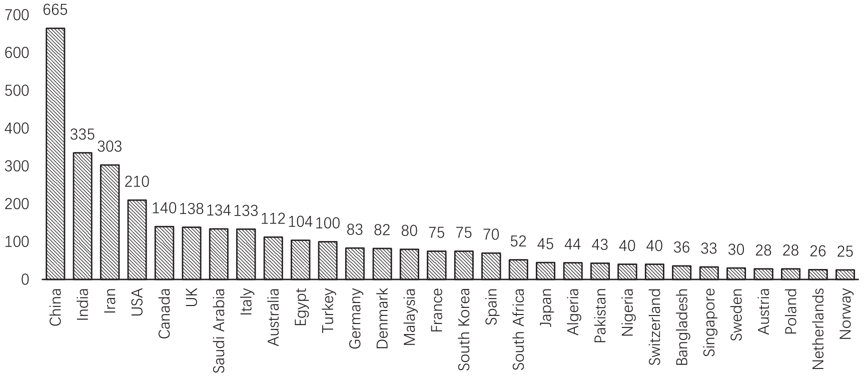

Figure 1.2 Research papers on hybrid energy systems (in order of country).

has increased, but still less than 100 papers per year; since 2016, the number of papers has increased rapidly, and in 2022 the number of papers in just one year reached 483.

Ranking the retrieved literature by their publication country, the results can be seen in Figure 1.2. As can be seen from the figure, developing countries are the main force in HESs research, with China, India, and Iran authors accounting for the top three places among all countries, and China leading the way with 665 papers accounting for 26% of the total literature. Developed countries USA, Canada, and UK also published 130–210 relevant papers, respectively, ranking 4th to 6th.

We exported the retrieved literature and imported it into the literature analysis software Citespace to visualize research hotspots. In Citespace, we set the Time Slicing from 1993 to 2023 and one year per slice, Set the Nodetype as Reference, and chose the Selection Criteria as *g*-index ($g = 25$); the pruning method is pathfinder, the sliced networks and the merged network are pruned at the same time to simplify the keyword network and highlight the structures of these researches. Then the knowledge map of references' clusters is obtained, as shown in Figure 1.3. It can be seen that current research mainly focuses on four categories.

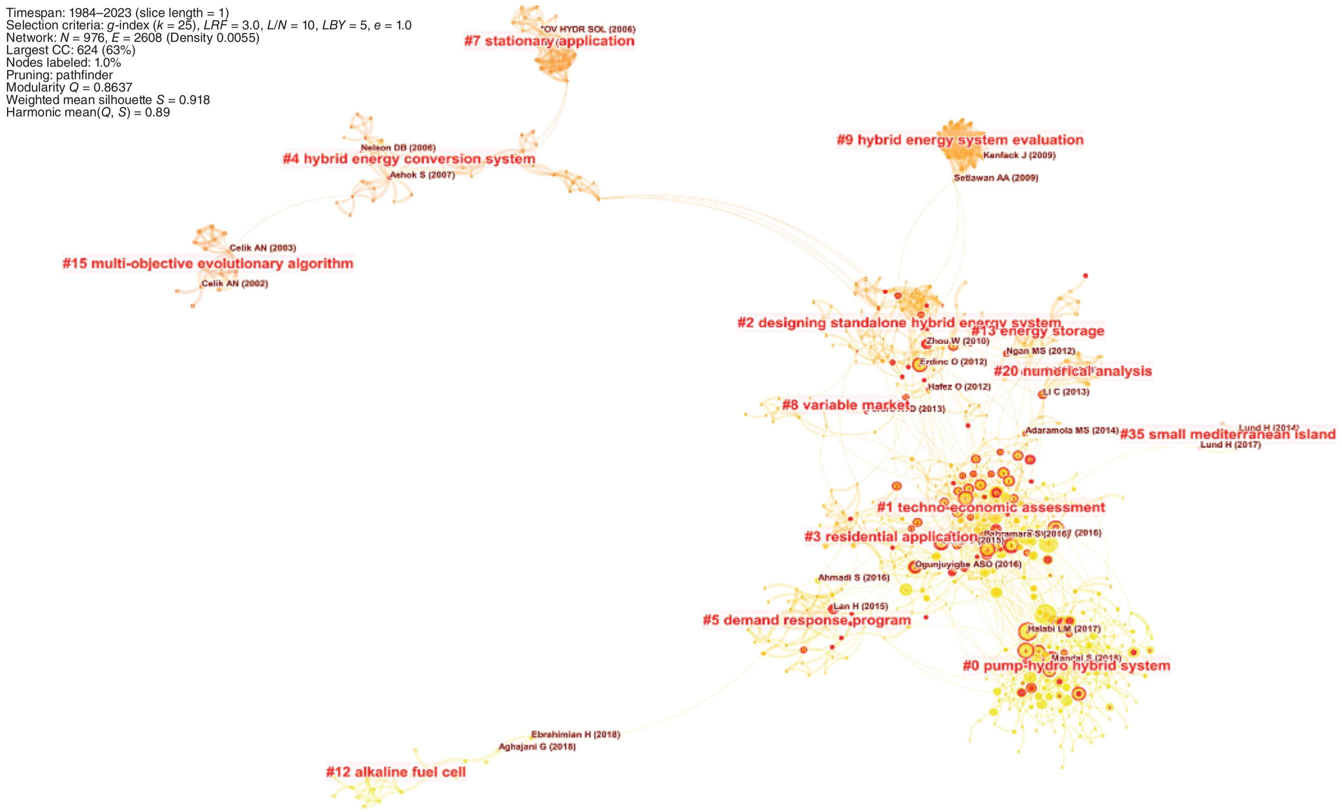

Figure 1.3 Cluster of references.

The first category focuses on Research Objects, including #0 pumped-hydro hybrid system, #4 hybrid energy conversion system, and #12 alkaline fuel cell, where pumped-hydro hybrid system refers to hybrid hydro–wind and/or PV system that is equipped with pumped hydro storage systems to smooth the output, and alkaline fuel cell refers to the HES that used alkaline fuel cell for energy storage.

The second category focuses on Research Method, including #1 techno-economic assessment, #15 multi-objective evolutionary algorithm, and #20 numerical analysis, which are usually applied for the optimization of HES configuration and scheduling; these researchers usually propose mathematical optimization models and apply these models to case studies to conduct numerical analysis.

The third category is Research Content, including #2 designing standalone hybrid energy system, #5 demand response program, #8 variable market, and #9 hybrid energy system evaluation. Cluster #2 refers to the selection and sizing of generation sources to deploy a HES, and Cluster #5 refers to managing the customers' demand so as to balance power demand and supply.

The fourth category is HES Applications, including #3 residential application, #7 stationary application, and #35 small Mediterranean island; most of the above-mentioned applications are focused on distributed power plant level, like industrial parks, and community and remote area power supply.

Although there are many studies focusing on specific hybrid systems, few studies have defined and categorized hybrid system's at a macro level. To the best of the authors' knowledge, only Arent et al. (2021) and U.S. Department of Energy (2021) have defined HESs at a macro level, but the former is a perspective paper and the latter focuses on research opportunities. To fill this gap, this book clearly distinguished it into three kinds and explored four groups of comprehensive approaches to build sustainable hybrids through mathematical modeling and case studies.

1.2 Hybrid Energy Systems

This section presents the definition, classification, and motivation for establishing HESs.

1.2.1 Definition

The term "hybrid" is employed in many disciplines to refer to a system that comprises multiple distinct constituent parts that are combined and integrated to take advantage of each one's unique characteristics and the synergies between them (U.S. Department of Energy 2021). In this book, we define hybrid energy system (HES) as:

> *Multiple energy generation technologies, generation fuels, and storage technologies that are integrated-through co-location, co-operation, and co-combustion-to achieve cost savings, efficiency, and environmental performances etc. when producing energy products (electricity, heat, liquid fuels etc.) and non-energy products (freshwater, chemicals, materials etc.).*

The generation technologies that can be integrated to form a hybrid system are very wide, including fossil fuel generation technology (coal, natural gas, diesel), renewable generation technology (wind, solar, hydro, biomass, geothermal), fuel cell generation, or nuclear. The hybridization pathways include co-location, co-combustion, and co-operation. And the system products include energy products (electricity, heat, hydrogen, and liquid fuel) and non-energy products (freshwater, chemicals, and materials)

The universe of possibilities for HESs that result from this definition is summarized in Figure 1.4. Multiple forms of HES have been established and used across the energy sector today, and they can be classified as Multi-input Single-output Hybrid Energy Systems, Single-input Multi-output Hybrid Energy Systems, and Multi-input Multi-output Hybrid Energy Systems (Arent et al. 2021). Here we refer to those integrating at least two generation resources or generation fuels or storage technologies as inputs to generate electricity as multi-input single-output HESs. An example is coal-biomass co-combustion thermal power plants, which integrates two generation fuels in the generation process for enhanced environmental performance. Another example is co-operation of wind, solar, and thermal power plants within an energy base, which optimizes power outputs to increase power supply quality and reliability. Those using a single-generation source to produce two or more energy or non-energy products are single-input multi-output HESs, the cogeneration, combined heat and power plant (CHP) that uses one fuel to produce electricity and heat as a vivid example. Those integrating multiple generation technologies and producing multi-products are called multi-input multi-output HESs, the distributed wind–solar-storage system that generates both electricity and hydrogen is an example.

1.2.2 Classification

This book focuses on multi-input single-output HES (as shown in the gray square in Figure 1.4) that generates electricity (Dykes et al. 2020). Fuels, generation technologies, and storage technologies that may potentially be integrated in the HESs include coal, biomass (agroforestry waste, solid waste, sewage, etc.); wind turbines, photovoltaics, concentrated solar power, hydro, geothermal, natural gas, nuclear; chemical storage; mechanical storage; and thermal storage. Based on the hybridization pathway, the multi-input single-output HES can be further categorized as co-located HES, co-combusted HES, and co-operated HES. Details are as follows.

Co-located HES refers to the distribution-level hybrid system that sites multiple generation technologies at the consumer side (as shown in Figure 1.5), for example, the hybrid wind–solar–natural gas system deployed in industrial parks, hybrid wind–solar-storage diesel system deployed in remote areas, and hybrid solar-storage system deployed on buildings. The design, configuration, and operation of the constituent technologies are fully integrated, and the system is operated under a single control scheme so that the entire system can operate more efficiently and be treated as a single resource.

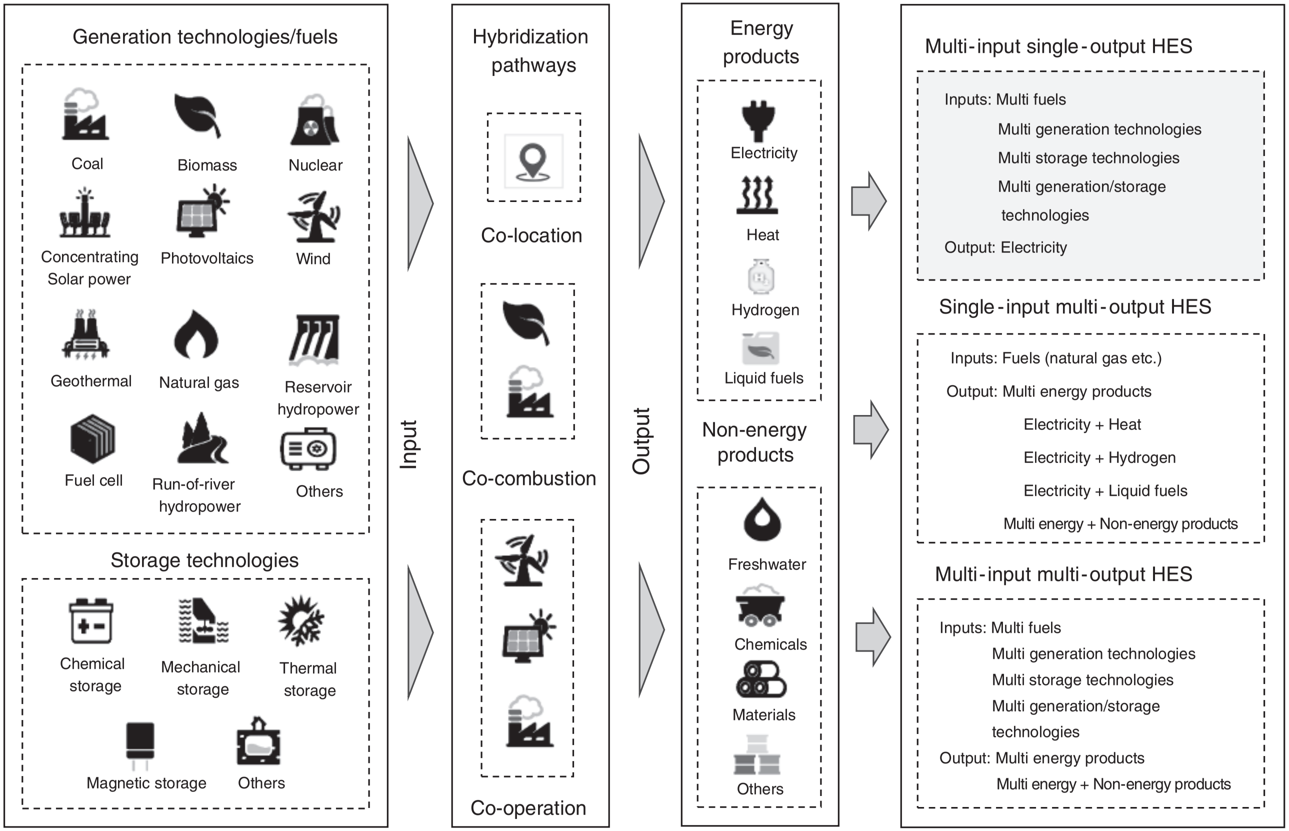

Figure 1.4 Definition of hybrid energy systems (this book focus on multi-input single-output hybrid energy systems, shown in gray).

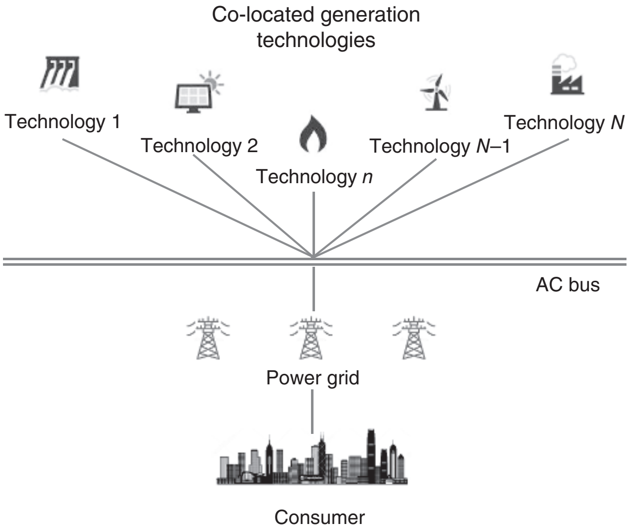

Figure 1.5 Co-located hybrid energy system.

Co-combusted HES involves two or more generation fuels that are burned together within a thermal power plant (as shown in Figure 1.6). For example, a coal-sewage co-combustion power plant, a coal-solid waste co-combustion power plant, or an agroforestry waste-municipal solid waste co-combustion power plant. Co-combustion of different fuels provides opportunities for carbon emission reductions caused by coal combustion and is treated as an important transformation path of traditional coal-fired power plants.

Co-operated HESs involve multiple generation technologies that are linked locationally, for example, they are located within an energy base and share the

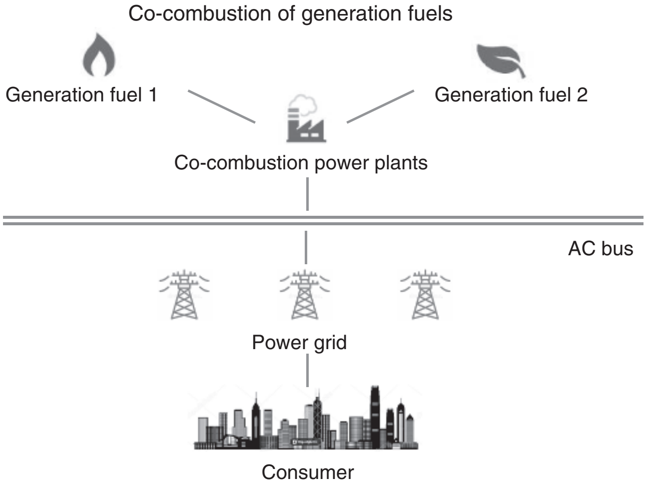

Figure 1.6 Co-combusted hybrid energy system.

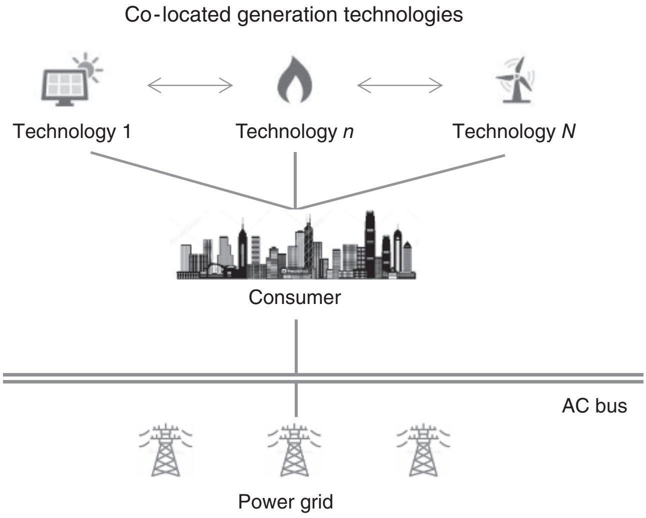

Figure 1.7 Co-operated hybrid energy system.

same interconnection for power sending (as shown in Figure 1.7). They are usually deployed far from the consumer and operated at the concentrated multi-power plant level by unit commitment. The power generation technologies (wind, solar, coal, hydro) are usually owned by different enterprises, and the operation of these power plants in co-operated HES is independent.

1.2.3 Advantages

The hybridization of multi-generator power sources possesses several advantages and offers opportunities for building energy systems with greater resilience, reliability, affordability, security, and sustainability, and is a major motivation for engineers and researchers worldwide to investigate them.

Improved power system resilience. Resilience refers to the abilities of energy system to withstand high impact-low probability events, rapidly recover from these disruptive events, and prevent the impacts of similar future events (Panteli and Mancarella 2015). On the one hand, a HES's multiple generation and storage subsystems can maintain power during an event, and provide additional recovery services after an event has happened. On the other hand, hybrid power generation plants can also provide self-black starts as well as power system black starts, operate in islanded mode, and participate in power system restoration schemes. There is no doubt that HESs offer new possibilities for improving the resilience of power systems.

Increased power supply reliability. Reliability is power system's capacity to offer power and electrical energy to customers continuously according to acceptable quality standards and the required quantity (ZMSkvcable 2021). The production of renewable energy is fraught with risk due to the fluctuating properties of wind and solar resources and how much they depend on their environment. A HES combines variable renewable energy sources with reliable fossil fuel engines and energy storage facilities, offering an excellent way to reduce variation (Tian and Seifi 2014).

Enhanced power system flexibility. Flexibility denotes energy system's capacity to adjust promptly to changes in electricity supply and demand (Babatunde et al. 2020). A HES can be created to offer great flexibility and a wide range of grid services to an increasingly high-renewables grid by integrating renewable energy, storage, controls, and/or flexible loads (ESIG 2022). For example, hydropower has the advantage of being flexible to start and stop, and can be used as a backup station for PV power generation. When PV power output is affected by weather conditions and day/night turnover, hydropower mitigates the intermittency of PV by quickly adjusting output. Compared with just using PV power supply, it obviously improves the flexible adjustment ability of the power supply side.

Improved energy security. An important element of energy security is a reliable and assured energy supply, so it is crucial that HESs make a positive contribution to securing an adequate and stable electricity supply. In fact, HESs are instrumental in the development of new energy sources, and more power plants offer the possibility of securing an adequate electricity supply; moreover, because renewable energy sources such as wind and photovoltaics are highly volatile, HESs use more stable conventional electricity to smooth out these fluctuations, thus seemingly allowing the system to output more stable, higher quality electricity. At the same time, diversification is an important component of energy security. HESs are developed in a variety of modes and play an important role in ensuring the security of electricity supply from diversification.

Increased energy economics. Linking various technologies could improve the use of facilities and delay the need for additional infrastructure investment by enabling the sharing of electrical and physical infrastructure. Meanwhile, the high fuel costs of thermal units can be replaced by energy arbitrage through hybridization with renewable energy systems. In addition, the hybridization of conventional baseload thermal with other energy sources enables resource operational optimization to prevent off-design operations that raise emissions and unit operating costs.

Improved environmental sustainability. Replacing coal, oil, and natural gas with electricity at the end consumption side is considered a more sustainable way to consume energy, and customer-side HESs provide a new way to do so. On the other hand, the large-scale development of new energy sources such as wind power and PV will squeeze the power generation capacity of coal power, force the flexibility of traditional coal power to be modified, and reduce the carbon emission of the power generation process. Therefore, HESs play an important role in environmental sustainability.

1.3 Chapter Organization

This book focuses on four key challenges of HESs. Namely, the deployment optimization of co-located HES, the emission quota allocation of co-combusted HES, the scheduling coordination of co-operated HES, and the optimal implementation

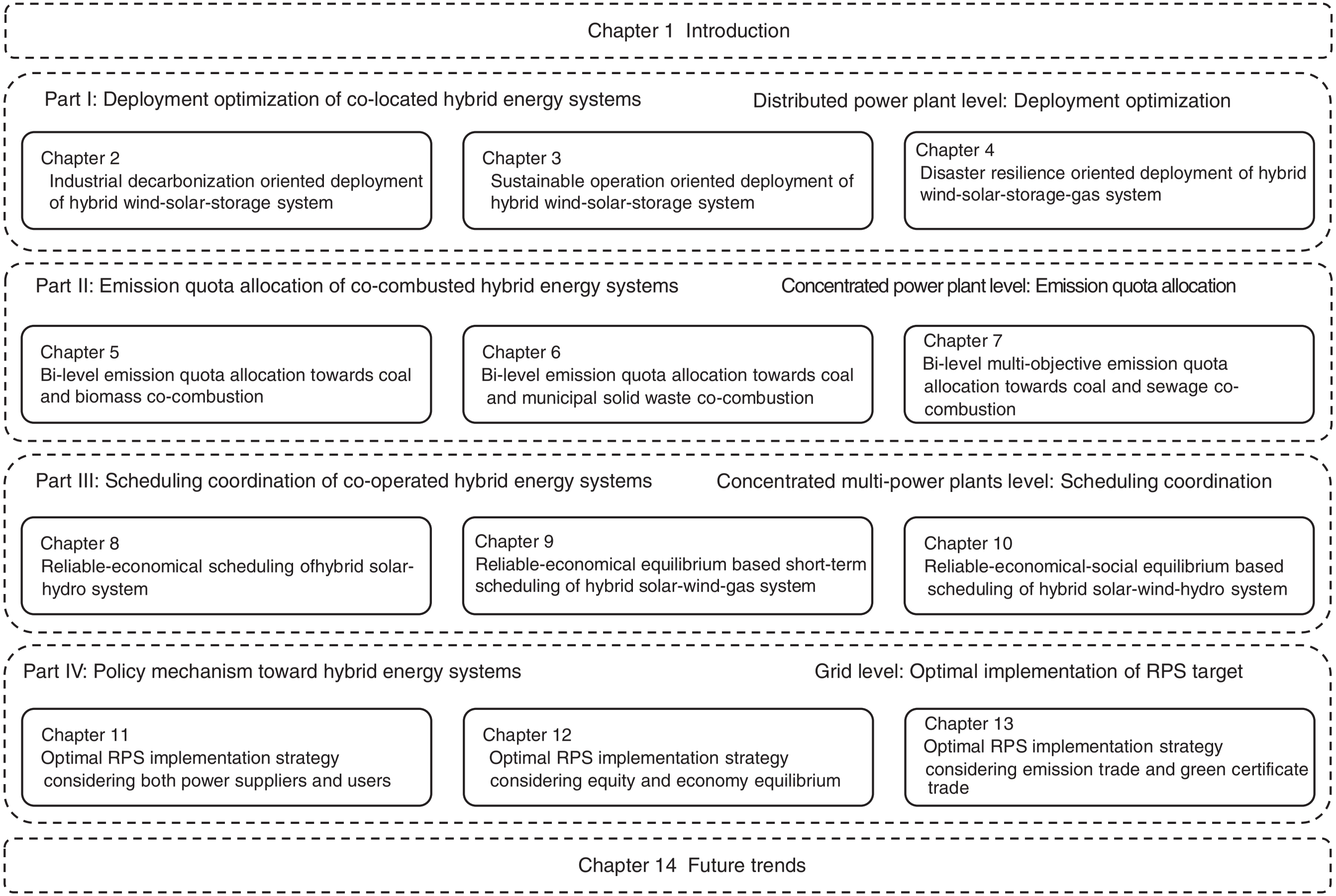

Figure 1.8 Structure of book chapters.

of renewable portfolio standard (RPS) policy toward HESs. Structure and detail contents of book chapters can be seen in Figure 1.8.

The deployment optimization of co-located HESs is discussed in Chapters 2–4. Distributed power plant level co-located HES can be deployed in residential communities, office buildings, commercial areas, campuses, data centers, hospitals, and airports, but the performance must first be guaranteed through configuration optimization (Zhang and Wei 2022). During the system deployment process, various generation technologies and storage technologies are integrated, the type and capacity of each source will be determined, and the operation strategy will be proposed to improve the system's affordability, energy effectiveness, and environmental friendliness (Hakimi et al. 2022). Chapters 2–4 focus on industrial decarbonization-oriented HES deployment optimization, sustainable operation-oriented HES deployment optimization, and disaster resilience-oriented HES deployment optimization separately.

The emission quota allocation of co-combusted HESs is discussed in Chapters 5–7. Reasonable and effective apportion of carbon emission responsibility is an important foundation for controlling total carbon emissions (Wang et al. 2019a). According to the "top-down" approach of allocating carbon emission quotas, the quotas are first distributed to each province in accordance with the amount of energy used in each region, and then they are distributed to industries in accordance with the amount of energy consumed or the nature of the production process (Zhang and Fan 2022). This book focuses on the more micro-level emission quota allocation – allocation among different power plants in the generation industry. In Chapters 5–7, the multi-objective emission quota allocation toward coal-biomass HES, bi-level emission quota allocation toward coal-biomass HES, and bi-level multi-objective emission quota allocation toward coal-biomass HES will be discussed in detail.

The scheduling coordination of co-operated HES is discussed in Chapters 8–10. Power generation scheduling analyzes the operation of the power system network and the economic dispatch of each power plant to optimize the overall energy delivery under given constraints, such as power supply reliability, economy, and environmental friendliness (Gartner Glossary 2022). This was originally a topic widely studied traditionally by researchers and engineers, but the large-scale access of uncertain new energy sources makes the traditional scheduling scheme no longer applicable, and how to achieve coordinated scheduling by taking into account various attributes from a system perspective becomes a new difficulty (Wang et al. 2019b). In Chapters 8–10, the reliable-economical scheduling of hybrid solar–hydro system, reliable-economical scheduling of hybrid solar–wind–gas system, and reliable-economical-social equilibrium based scheduling of hybrid solar–wind–hydro system will be studied.

The optimal implementation of RPS target to build HESs is discussed in Chapters 11–13. The RPS has been adopted worldwide to encourage the use of renewables (Yu et al. 2023; Rouhani et al. 2016). It is a policy instrument that mandates a minimum market share for clean energy technologies in order to stimulate the development of those technologies (Shayegh and Sanchez 2021). Setting reasonable standards for each region and enforcing them rigorously can serve the purpose of stimulating investment and use of renewable electricity, thus creating a virtuous cycle. Therefore, in Chapters 11–13, the optimal RPS implementation strategy considering both power supplier and users, equity and economy equilibrium, and emission trade and green certificate trade will be studied.

The deployment optimization of co-located HES, the emission quota allocation of co-combusted HESs, the scheduling coordination of co-operated HES, and the optimal implementation of RPS target provide carbon-neutral approaches for energy systems, and are organized from the distributed power plant level, the concentrated power plant level, the concentrated multi-power plant level, and the grid level. Each of the above-mentioned chapters will be developed along the lines of background introduction – key problem statement – mathematical modeling and model solving – case study. The main methods used to build mathematical model are multi-objective planning and bi-level planning, which have been widely applied to characterize objective conflicts and achieve equilibrium among decision makers.

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