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Concentrated Solar Power Systems

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This work is as much yours as it is mine.

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About the Authors

Dr. Bellamkonda Pragathi is a prominent researcher and educator with a deep expertise in renewable energy systems, machine learning, and Internet of Things (IoT)-based applications. She has contributed extensively to the field through her research on energy management systems, hybrid renewable energy systems, and IoT-driven smart grids. Dr. Pragathi's academic work is widely recognized, and she has co-authored numerous research papers and book chapters on the integration of advanced technologies in energy systems, with a focus on enhancing efficiency, stability, and sustainability.

Dr. Pragathi is also actively involved in mentoring young researchers and has been associated with various international conferences and workshops, contributing to the dissemination of knowledge in the field of renewable energy and emerging technologies. Her collaborative work on CSP systems, alongside Prof. Kothari, represents her commitment to finding innovative solutions for global energy challenges and advancing the frontiers of clean energy technologies.

Together, Prof. D. P. Kothari and Dr. B. Pragathi bring a wealth of knowledge and experience to the study of Concentrated Solar Power systems, offering readers a comprehensive understanding of the principles, challenges, and future directions of this vital renewable energy technology.

D. P. Kothari is a highly respected figure in the field of electrical power systems and renewable energy. With a distinguished career spanning several decades, he has made significant contributions as a researcher, academic, and author. Professor Kothari has held several prestigious positions, including Director General of VITS, Indore, and Director of IIT Delhi, among others. His extensive research in the areas of power systems,

energy management, and renewable energy integration has earned him numerous accolades and recognition both nationally and internationally.

Professor Kothari has authored over 50 books and more than 850 research papers in national and international journals, covering a wide array of topics in electrical engineering and renewable energy. His work has inspired generations of engineers and researchers, and his commitment to advancing sustainable energy solutions is reflected in his numerous contributions to the field of renewable energy. Through this work on *Concentrated Solar Power Systems*, he continues to demonstrate his passion for driving innovations in clean energy technologies and addressing the challenges of global energy demand.

Preface

Concentrated Solar Power (CSP) systems represent a pivotal advancement in renewable energy technology, offering a promising pathway for harnessing the sun's vast potential to generate electricity. As the global community increasingly turns toward sustainable energy sources to mitigate the adverse effects of climate change, CSP systems have emerged as a crucial component in the portfolio of clean energy solutions. Unlike photovoltaic (PV) systems that directly convert sunlight into electricity, CSP systems utilize mirrors or lenses to concentrate sunlight onto a small area to generate heat, which is then used to produce electricity. This unique approach to solar energy generation not only provides opportunities for large-scale power production but also integrates thermal energy storage, enabling CSP plants to supply electricity even when the sun is not shining.

The importance of CSP systems lies in their ability to complement other renewable energy sources such as wind and PV by providing dispatchable power. By storing thermal energy, CSP plants can generate electricity during peak demand periods, contributing to grid stability and reliability. This ability to provide on-demand energy addresses one of the main challenges associated with renewable energy—the intermittency of power supply. Furthermore, CSP systems can be integrated with other power generation technologies, such as natural gas or biomass, to create hybrid systems, further enhancing their flexibility and reliability.

This preface introduces readers to the fundamental concepts, importance, and emerging trends in CSP systems. The transition to renewable energy is driven by the need to reduce greenhouse gas emissions, promote energy independence, and create sustainable economic growth. CSP technologies offer a versatile and scalable solution to meet these objectives, particularly in regions with high solar insolation, such as deserts and arid climates. Moreover, advances in CSP technology are continually improving efficiency and reducing costs, making it a more viable option for large-scale energy production.

In this work, we explore the intricate workings of CSP systems, their various configurations, and their applications in today's energy landscape. From parabolic troughs to solar power towers, this text delves into the engineering principles, economic considerations, and environmental impacts of CSP technology. It also addresses the challenges faced by CSP systems, such as the need for significant land area and water resources, while highlighting ongoing research aimed at overcoming these barriers.

As CSP systems continue to evolve, they are positioned to play a vital role in the global transition to a sustainable energy future. This book aims to provide a comprehensive understanding of CSP technology, from its foundational principles to its potential to revolutionize the energy sector. We hope this exploration will inspire further innovation and development in the field, fostering a future where renewable energy is both abundant and accessible to all.

December, 2024

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First and foremost, we extend our heartfelt thanks to our families for their unwavering support and understanding. Their patience and encouragement have been the foundation upon which we have been able to devote our time and energy to this project.

We also express our sincere appreciation to our mentors, colleagues, and peers. Their insightful feedback, expert knowledge, and continuous encouragement were instrumental in refining the scope and direction of our work. Your contributions have been invaluable, and this work is a reflection of the intellectual and collaborative spirit we share.

A special thanks to the academic institutions and research organizations that provided the resources and tools necessary for the successful completion of this project. Access to their extensive libraries, databases, and technical expertise has been essential in shaping the depth and accuracy of our research.

We also acknowledge the pioneering researchers and innovators in the field of renewable energy, whose groundbreaking work on CSP systems inspired our exploration of this fascinating and crucial technology. Their commitment to sustainable energy solutions continues to motivate us in our own contributions to the field.

Lastly, we extend our gratitude to the editorial team, the publishers, and everyone involved in bringing this manuscript to fruition. Your attention to detail and professionalism ensured that the quality of our work met the highest standards.

To all those who offered their support, guidance, and encouragement, both directly and indirectly, we thank you. This work is the result of collective efforts, and we are proud to have had the opportunity to collaborate and contribute to the ever-evolving field of renewable energy.

1

Conventional Energy Sources

An important factor to consider when deciding whether a country is considered developed is the amount of energy consumed per person. Maximum energy output is defined by a country's needs, and these needs can only be satisfied if everyone has access to sufficient amounts of energy for things like electricity, transportation, and agriculture. The majority of the world's resources, including coal, oil, and natural gas, are now produced via conventional methods to satisfy global demand. India presently imports about 75% of its crude oil, but this ratio is expected to climb significantly shortly due to the country's expanding economy and rapid expansion. Although only 6% of the world's primary energy is consumed there, India is home to 18% of the world's population. The majority of the world's electricity is generated by burning coal, oil, and natural gas. To create energy, these fossil fuels are burned, which increases the amount of carbon dioxide in the atmosphere and releases several hazardous compounds. The rise in global temperatures is a result of the potent greenhouse gas (GHG) carbon dioxide. The second drawback of using fossil fuels as a source of energy is that their proven reserves have a short shelf life—less than a century, in certain cases. Finding a different electricity production source is required as a result. Power production planning is significantly influenced by two important factors. The principal energy source, which might be any of the three fossil fuels, is an essential component. It is well recognized that all three of these fuels contribute to global warming and environmental harm. The second group of topics relates to the economics of electrical power. Significant losses are experienced during power production, transmission, and distribution. A challenging task that could cut expenses as well as losses in reducing losses or discovering an alternative strategy, like a smart grid or microgrid. The general public and those who create and administer regulations both want access to electricity while avoiding contributing to global warming [1].

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1.1 Energy Resources and Their Potential

1.1.1 Oil

Depending on how much oil is used, the world has been split into three categories. Some nations are oil rich, while others are highly industrialized with productive farmland. The majority of the Middle Eastern or Arabian countries are the first group's representatives. The Organization for Economic Cooperation and Development (OECD) is the representative of the other group. There is a third group, which lacks oil and is not as developed as the OECD group. The question of whether oil-producing nations will continue to supply the world with oil until the supply runs out, decide to hoard the oil for their use, or limit sales to nations who support their policies has long been a concern. The Arab nations' lack of food resources led to the current system, in which oil is supplied to industrialized nations. They received food in exchange for the oil, though it wasn't a formal barter deal. The Arab nations gradually became more powerful economically, established new ventures, and began to voice their opinions on global affairs. There is now a kind of unspoken divide between the Arabs and the developed nations. The current terrorism situation and American operations in the Middle East are further highlighting the contrasts, and when the oil taps run dry, the distinctions will become clearer. In the beginning, Arabs were content to receive food in exchange for oil, which helped keep the scales balanced. As can be seen, the exchange rate between food and oil was one bushel of food for every barrel of crude oil between 1950 and 1973, even though the scales had tipped in favor of oil suppliers. Two bushels per barrel in 1974, 5 bushels per barrel between 1975 and 1998, 6 bushels in 1999, and currently 10 bushels or more per barrel of crude oil, which grew by currency rates. Oil is undoubtedly necessary for agriculture and the transportation of food, but the Arab nations have located food sources outside of the OECD [2].

1.1.2 Natural Gas

Over the past 15 years, technology for producing power from natural gas has advanced. By 2020, it's anticipated that natural gas utilization in the creation of power would rise by 87%. According to the most accurate projections, natural gas will support 30% of energy generation in industrialized countries while providing 17% of electricity in emerging nations. Many nations intend to use natural gas since it has been technically developed for use in combined-cycle gas turbines, which are used to generate power. Additionally, while producing the same amount of energy as coal and oil, gas emits less carbon dioxide. It is a cleaner fuel and is utilized in public transportation, such as in Delhi, specifically

to preserve the environment. With roughly 33% of global consumption occurring in the former Soviet Union, gas usage for power is already high in those nations. Up to 63% of electricity in the former Soviet Union's nations is anticipated to be produced from gas by 2025. In 2001, the East European nations generated 9% of their electricity from gas; to reach their goal of 50% electricity generation, they plan to import more gas from Russia. Gas consumption for electricity generation in Western Europe increased to 413 billion cubic meters in 2000 and is anticipated to reach 670 billion cubic meters by 2025, having a declining share. Due to the region's use of nuclear energy, the gas portion of power generation is expected to rise from 17% in 2001 to 38% in 2025. Since the 1973 oil crisis, when Western European countries first experienced fluctuating natural gas use. The European Union began limiting the use of gas for generating electricity in 1975. It was 5% in 1981 and stayed there throughout the 1980s. The region began importing gas from Russia, North Africa, and recently discovered sources in the North Sea in the early 1990s; as a result, the share of gas in the electricity market rose, and this pattern is still present today.

Africa and Asia do not yet consume a lot of gas. Nearly one-fourth of the gas consumed by Asian nations is consumed in Japan, which imports all of its gas as liquefied natural gas (LNG). India will end up being a major gas user, and 12.6% of its power is produced using gas.

The majority of the gas used in the United States is imported from Canada, but some gas is also obtained by pipelines from the Alaskan North Sea. From 18% in 2001 to 24% in 2025, gas is anticipated to have a larger part of the electricity market. All of the recently built power plants in the United States, totaling 141,000 MW, are gas based. Overseas imports are probably going to keep rising. In 2002, the United States brought in 4.8 million metric tons of gas or 4% of global consumption. At roughly 46 million metric tons in 2010, the import had more than doubled since 2002. As a result, in addition to importing oil, the United States imports enormous amounts of gas. By 2025, Canada wants to grow its gas-powered electricity generation from 3% to 11%.

The price of natural gas is rising. Prices have more than doubled since 1993. Gas was priced at $2.55 per million British thermal unit (BTU) in 2000, but by 2003 it had risen to $6.31. Russia, Iran, and Qatar, three nations with respective gas reserves of 31%, 15%, and 9%, stand to gain from international gas trading [3].

1.1.3 Coal

The earliest source of energy for producing electricity is coal. It is disliked in developed countries because it creates more carbon dioxide than oil and gas, along with numerous other air pollutants. In addition to carbon dioxide, it also releases sulfur dioxide, nitrous oxide, mercury, and particulate matter. Electricity production

uses 64% of all coal production. In 2001, the production was 94.5 Exa Joule (EJ) equivalent. By 2025, it is anticipated that production will rise to 138 EJ. However, all projections indicate that coal will have a decreasing role in the production of power. Although its share of power will drop to 31% by 2025, it was responsible for 34% of electricity in 2001 and 40% of electricity in 2005. By 2025, coal-fired energy will only account for 12% of all electricity produced in Europe, down from 20% now. In 2001, the United States used 40% of the world's coal, compared to 27% combined use by China and India. Coal was used to generate 72% of the electricity in China and India. By 2025, China will produce 73% more power from coal than it does today. However, India's use of coal for energy production will decrease to 63%. By 2025, it is expected that the proportion of coal in US electricity will mostly remain unchanged at 50%.

Coal made up 27% of the electricity in Eastern Europe and the former Soviet Union in 2001. The availability of Russian gas, however, will cause this percentage to decline by 6% by 2025. Eastern Europe is becoming the most polluted region in the world due to the burning of coal. In general, Europe is phasing out the use of coal for electricity. The majority of those coal mines received government funding. Only three nations—the United Kingdom, Germany, and Spain—continue to manufacture hard coal as a result of the European Union's strategy of lowering or eliminating such subsidies. Table 1.1 lists the coal deposits found worldwide.

Every day, a typical 600 MW coal-fired power station will consume 8,193 tons of coal, which may need to be transported over a distance of up to 1,000 km from coal mines. Such a massive amount of coal will need to be transported by regular daily train movements, and there are numerous such factories located all over the world. Although the transportation itself will consume a lot of fuel and produce a lot of carbon dioxide and other pollutants, this calls for a rail system that is effective and has good haulage capacity. 17,900 tons of nitrous oxide, 8,200

Table 1.1 Coal deposits in the world.

Region	Deposit (Gt)	Percent
Asia Pacific	292.5	23.7
North America	257.8	26.2
Former Soviet Union	230	22.4
Europe	125.4	12.7
Africa	55.4	5.6
South & Central America	21.8	2.2
Middle East	1.7	0.2
World	**984.6**	**100**

tons of sulfur dioxide, 4,207,200 tons of carbon dioxide, and 70 kg of mercury are normally produced when coal is burned. Additionally, radioactive substances and fly ash are released by the plants. The factory's modern appearance makes it appear as though it and its surroundings are clean, yet the gases and ash that escape the chimney have an impact on places that are 50–100 km away from the plant. An individual living within 1 km of a coal-fired power station receives a radiation dose that is 1–5% above the typical natural background level, according to studies carried out in the United States between 1975 and 1985. In contrast, residing close to a nuclear power station often results in an increase of 0.3–1% above background levels. Coal-fired power stations' radiation is not controlled in any way. The health impact of mercury is significantly more serious and has not yet been addressed. Mercury is a hazardous, enduring, bioaccumulative contaminant that has an impact on human neurological growth. The effects of airborne mercury are greatest in developing children and infants. It will be challenging to extract mercury from flue gas at a concentration of 1 ppb (part per billion) because the technology for capturing mercury from flue gas has not yet been developed [4].

1.1.4 Hydropower

150 years ago, the Industrial Revolution was powered by the free kinetic energy of flowing water. Water that was flowing and water that was falling from a great height both encountered bladed wheels. The machinery was originally powered by the motion of the water turbines, and then the electrical generators. Because the water turbines could be produced in such huge sizes and the technology for erecting dams was established, which supplied a source of water year-round, hydropower was later totally dedicated to electricity generation. Dams are presently present in several nations, including the United States, China, Brazil, Venezuela, Sudan, Pakistan, and India. Tata built a hydroelectricity plant in India's Western Ghats around the beginning of the twentieth century. When the Bhakra-Nangal hydro project was finished after independence, a huge step was made. After that, several dams were constructed. India has the capacity to produce roughly 84,000 MW of electricity from hydropower. Sources used up until this point total 15,000 MW. Increased hydropower development has mostly as a result of opposition from the general populace. The population is displaced and many species' habitats are destroyed as a result of the dams, which result in a sizable body of water. In addition, silt deposits cause the depth of the water reservoir behind the dam to keep declining. Dredging operations are challenging and expensive to remove the silt. The preference is for small hydro plants over huge ones. Few kilowatt of power are produced by the small plants, which can be enough for a limited area. The best locations for small hydro plants are rivers that flow through steep terrain, such as those in the Indian Himalayan regions.

2,726 TWh were consumed globally in 2000. Despite being the top consumers of hydroelectricity—together using 43% of it—Canada, Brazil, the United States, and China produced roughly 99% of it, and Brazil used it for 87% of its needs. 65% of the hydroelectricity produced worldwide is consumed by industrialized nations. The usage of hydroelectricity is expected to reach 4,000 TWh/year by 2020, with developing countries contributing 800 TWh/year and developed nations providing 600 TWh/year. By 2020, the gap in per capita consumption will widen while the disparity in hydroelectricity generation between industrialized and developing countries will close. Recent years have seen extensive hydroelectricity generation facility construction in Central Asia, South America-Caribbean, Sub-Saharan Africa, and South Asia. It is concerning to note that despite the installation of 5,738 TWh/year hydro capacity in 1997, the amount of power produced from this source was only 2,600 TWh/year, representing a capacity loss of 55% [5].

1.1.5 Nuclear Energy

Contrary to popular assumption, nuclear energy offers a cleaner kind of energy. It does not cause the greenhouse effect and does not release airborne particles. Nuclear fuel requires significantly less of it to create the same quantity of energy than any fossil fuel, and its delivery generates much less air pollution. A nuclear power plant costs less than a power plant using renewable energy sources (RES), but it is still more expensive than any other type of thermal power plant. The issue with nuclear power, however, is that it is not widely accepted because of the widespread belief that these plants are a source of lethal nuclear radiation and that the risk will continue to exist due to nuclear waste from spent fuel.

Although it was the United States that encouraged nations like Japan and France to rely on nuclear electricity, the public perception has generally been influenced by the United States' policy of abandoning the nuclear pathway for electricity in light of widespread public sentiment against nuclear power. Then, in the collective unconscious, there is a mental association between nuclear energy and the atomic bomb, which decimated the two cities of Japan and tragically brought an end to World War II. The concept that terrorists could obtain nuclear weapons and use them against any group of people has mainly been propagated to the American public. As a result, they are opposed to using nuclear energy altogether.

The Japanese were keen not to fall behind in this technology as the world was on the verge of a post-World War II economic and industrial rebirth. The research and technology organization in Japan was granted a $1.88 billion budget to begin with. In 1970, the first industrial power plant started operating. Currently, Japan's 41 commercial reactors provide 33,000 MW of electrical power

or roughly 27% of the nation's power needs. The United Kingdom sold Japan its initial gas-cooled, graphite-moderated nuclear reactor. The Japanese were the first to import pressurized water reactor (PWR) and boiling water reactor (BWR) designs when Westinghouse and General Electric of the United States offered them. Then, under license, General Electric and Westinghouse began producing them. Although it was first done for show, Japan now sees nuclear energy as essential because it imports 80% of its energy in the form of Chinese coal and Middle Eastern oil. In terms of global electricity consumption per person, Japan ranks fourth.

The French government may have felt the need to create its Atomic Energy Commission (CEA) as soon as the war ended in 1945 due to a lack of energy supplies. Unfortunately, they focused more on developing bombs than nuclear electricity, returning to it only after the test nuclear device explosion in 1960. At that time, three gas-graphite commercial nuclear reactors and one PWR were also being built. The public, bureaucrats, and politicians all put up a lot of resistance against Electricité de France (EDF) and CEA. After French President Giscard d'Estaing proclaimed that nuclear electricity was the government's policy in 1977, the way toward nuclear energy became apparent. In the late 1970s, several plants were established. In France, nuclear energy produces 75% of the nation's electricity. France has 54 reactors that generate 63,000 MW of power or 4,931 kWh of electricity per person. With 2,265 kWh/person in the United States and 1,450 kWh/person in Japan, this is a highly favorable comparison. France has created reprocessing facilities for old nuclear fuel that are used by numerous European nations as well as Japan. Finland, Norway, and Germany have made the decision to reduce their nuclear electricity production. Germany is of the opinion that it can rely on renewable energy. A German politician said that if Germany couldn't create all the energy it required, it would import it from France. Under the direction of Prime Minister Jawaharlal Nehru and Homi Bhabha, India's CEA was created in 1948, marking the country's entry into this field. The commission, which is currently known as the Bhabha Atomic Research Centre (BARC), has conducted research and development in the field of nuclear science and engineering. In 1969, Tarapur's nuclear power station, built by General Electric, began to run. In 14 plants, it currently generates 2,700 MW of electrical power. By 2020, this is anticipated to rise to 20,000 MW. The issue is that India only has very limited access to the primary uranium-containing mineral, despite the possibility of using thorium, which is more frequently available. Success will be based on how well thorium is used as a nuclear fuel. Meanwhile, India must rely on alternative fuel sources, and agreement with the United States has turned into a political problem. Nevertheless, it is preferable for the government to support

a nuclear program for producing electricity. Universities and laboratories should encourage research. India's preference for nuclear power has the dual benefits of generating revenue and preventing the combustion of fossil fuels, which is the main contributor to the greenhouse effect and climate change. We could maintain our environment cleaner by not producing carbon dioxide, sulfur dioxide, nitrous oxide, and particulate matter.

India now generates 1,650 MW of power from its 17 reactors, which have a combined capacity of 4,120 MW. Due to an unstable and insufficient fuel supply, these reactors are not being operated to their maximum potential. India continues to rely on coal for electricity, which is quite harmful in terms of GHG, air pollutants, and particle matter. 55% of Indian electricity comes from coal, and if RES choices like solar, biomass, wind, and hydro and nuclear electricity do not become available, that percentage will rise in the future. Even if sufficient fuel supplies are guaranteed, meticulous calculations by the BARC limit nuclear electricity to 10,000 MW, despite highly optimistic forecasts that position the contribution from the nuclear source at 40,000 MW by 2020. Even without assistance from any other nation, the administration intends to add electricity-generating facilities with greater capacity. Continuing examples include the work of two units each of 220 and 1,000 MW located at Rawatbhata, Kaiga, and Koondankulam, respectively. Although the economy of scale may encourage larger size units, it will be best to keep the unit size small, approximately 220 MW will be better to prevent severe power shortages in case of failure. India's business community has begun making plans to switch to nuclear power. Negotiations between Reliance Power and top nuclear power companies abroad have already begun. The business is looking to join forces in strategic alliances. After the nuclear electricity business is opened to private investment, Tata Power, another energy behemoth in the private sector, aims to either go alone or in a joint venture. Tata Power intends to make a Rs. 12,000 crore initial investment. A major producer of power equipment in the nation, Bharat Heavy Electricals (BHEL), intends to spend Rs. 1 lakh crores over the next five years to enhance its nuclear power infrastructure. The manufacturing behemoth Larsen and Toubro (L&T) also intends to manufacture nuclear equipment. A total of 40 businesses, including Videocon and the Sajjan Jindal Group, are in negotiations to work together on a 2 lakh crore rupee investment. Delegations from Nuclear Supplier Group (NSG) nations have begun to visit India to investigate the market for nuclear electricity. The NSG waiver has raised stock prices for many companies and generally cheered up the stock market. All of these ambitions, however, are subject to the successful conclusion of an Indo-American nuclear agreement. Figure 1.1 depicts India's power generation across the nation, while Figure 1.2 provides a visual representation of the country's installed capacity [6].