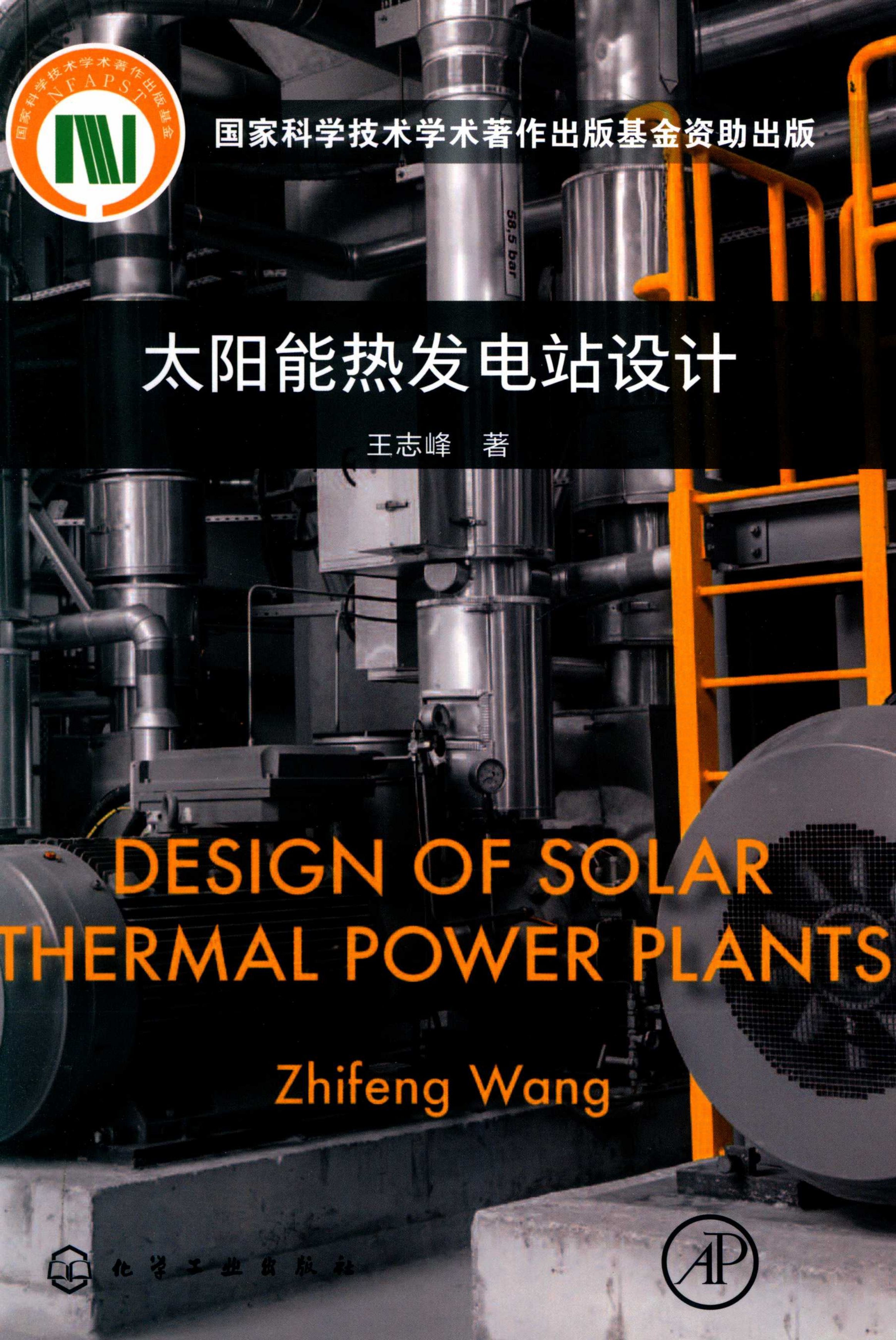
国家科学技术学术著作出版基金资助出版

太阳能热发电站设计

王志峰 著

DESIGN OF SOLAR THERMAL POWER PLANTS

Zhifeng Wang



化学工业出版社

国家科学技术学术著作出版基金资助出版

太阳能热发电站设计

王志峰 著

DESIGN OF SOLAR THERMAL POWER PLANTS

Zhifeng Wang

化学工业出版社
·北京·

ELSEVIER
ACADEMIC PRESS
An imprint of Elsevier
elsevier.com/books-and-journals

本书是《太阳能热发电站设计》的英文版。本书介绍了太阳能热发电站的基本设计方法，主要面向从事太阳能热发电工程的技术人员。

太阳能热发电站分为聚光、吸热、储热和动力四大模块，本书着重介绍了前三部分的设计方法和工艺布置中需要注意的重点。本书对太阳能热发电站中与常规火电厂相同的部分，如汽轮机、辅助锅炉及相关部分基本没有叙述。本书对太阳能聚光和吸热部分有较深的理论描述，并结合实际工程给出了算例，对太阳能热发电站的选址也做了较为详细的阐述。内容具有较强的理论和实用价值。

本书可供从事太阳能热发电工程的研究人员和技术人员使用，也可供能源相关专业的高校教师和研究生参考。

图书在版编目（CIP）数据

太阳能热发电站设计＝DESIGN OF SOLAR THERMAL POWER PLANTS：英文版／王志峰著．—北京：化学工业出版社，2019.8

ISBN 978-7-122-34405-2

Ⅰ.①太… Ⅱ.①王… Ⅲ.①太阳能发电-电站-设计-英文 Ⅳ.①TM615

中国版本图书馆CIP数据核字（2019）第082667号

责任编辑：戴燕红　　　　　　　　　　　　　　　帧设计：韩　飞
责任校对：王　静

出版发行：化学工业出版社（北京市东城区青年湖南街13号　邮政编码100011）
印　　装：三河市延风印装有限公司
710mm×1000mm　1/16　印张30¾　字数595千字　2019年9月北京第1版第1次印刷

购书咨询：010-64518888　　售后服务：010-64518899
网　　址：http：//www.cip.com.cn
凡购买本书，如有缺损质量问题，本社销售中心负责调换。

定　　价：298.00元　

DESIGN OF SOLAR THERMAL POWER PLANTS

太阳能热发电站设计

This book is applicable to the construction design of new solar thermal power plants and existing facility expansions that use water and steam working medium. Steam pressure parameters include secondary MP (medium pressure), MP, and secondary HP (high pressure), the nominal evaporation capacity corresponding to the output power of the receiver is 8—800 t/h, *and the capacity of the condensing steam turbine is 1—100* MW.

Heat transfer medium for solar collector fields in the book can be water/steam, synthetic oil, molten salt, air/ceramic, etc. Concentration modes include parabolic trough, power tower, and Fresnel reflectors for concentrated solar thermal power plants.

Preface

SOLAR THERMAL POWER PLANT DESIGN

Since the beginning of China's research on solar thermal power (also known as concentrating solar power, CSP) generation in 1996, CSP generation technologies have gone through the entire development process from inception to realization. Ever since "the 11th Five-Year Plan," CSP generation technologies have enjoyed rapid development throughout the country, with the appearance of a large variety of experimental solar thermal collection and storage systems and experimental power plants. Breakthroughs have also been made in the manufacturing techniques of core components and materials; professional CSP generation equipment manufacturers have also appeared. The first China state standard for CSP technology was released in September 2011. Along with a further deepening of technologies during "the 12th Five-Year Plan" as well as commercial development, this reference book for CSP plant design has become a requisite work for understanding solar power plant commercialization. Currently, there is no other reference book in the world that systematically describes the design methods of CSP plants.

The book mainly focuses on CSP technologies, and those mainly consist of power tower and parabolic trough collector technologies and thermal storage. The book not only describes the design of CSP systems, but also explains the design methods and operation modes of key facilities in detail, such as the heliostat, heliostat field, parabolic trough concentrator, parabolic trough receiver tube, and whole-plant distributed control system, or DCS. It also discusses the fundamental basis of designing CSP plants and system as well as the key design points that should be considered.

CSP generation design mainly includes resource evaluation, site selection, design of the optical efficiency of the concentration field, thermal control of the receiver and electrical design, thermal storage capacity, thermal storage charging and discharging design, heat exchanger and evaporation design, whole-plant electrics, whole-plant thermal control instruments, power plant construction, and whole-plant security design. By focusing on the contents just mentioned, the book offers calculation and design methods separately in different chapters and provides examples by integrating with practices of the author, so as to facilitate the understanding of readers.

Solar irradiation serves as the basis for solar power utilization. The evaluation of solar resources used by CSP generation is the most fundamental process for solar power plant design and site selection. Although it has been stated in numerous articles, the author further discusses solar resource evaluation by integrating his own research, especially stressing its relationship with the site selection of thermal power plants.

Solar concentrators, solar receivers, and thermal storage are three major core components for CSP systems. The section of the book that discusses these topics mainly explains equipment application, evaluation methods for equipment performance, and the thinking and methods for equipment design.

In equipment performance evaluation, great difficulties have been encountered in the facula error analysis of the heliostat. The book offers mathematical approaches and test methods corresponding to facula error analyses of various types of heliostats, which basically have been derived from the research achievements of the author and his graduate students.

Heat loss of receivers is the subject at the core of receiver design, with a variety of analysis methods. The book offers a relatively simple calculation method and corresponding examples.

The book was preliminarily defined as a reference book similar to a design manual by specifically referring to China's state standard of "Code for Design of Small-size Thermal Power Plant" (GB 50049), which may be recognized by readers from its general arrangement. However, as writing progressed, the author discovered that books about and references for CSP generation technologies had rarely been seen in China, while many methods were still under development and evolution. Thus, it was determined that the major concepts and methods should be explained more explicitly to benefit readers. By introducing these descriptions and analyses, the book is easier to be understand and greater reference value as well. These gains were made by sacrificing its original style as a "design manual."

The book was mainly composed by Wang Zhifeng with coauthors Guo Minghuan (2.4, 3.2.1, 3.2.2, 3.2.3, 4.2.2, 4.2.3), Li Xin (5.5), Yu Qiang (2.6), Gong Bo (4.7), and others.

The book was summarized and made by the author, his colleagues and students, and the coauthors based on multiple years of research and engineering practice in CSP technology. It is written by following the principles of sharing his own "fruits planted by himself" with readers and thus striving for fewer examples extracted from the achievements of others. The writing work started at the beginning of 2010 with a hope that the book could be finished within a year and be capable of catching up to "Chinese National 11th Five-Year Plan" 863 Program project acceptance at the end of 2011. However, additional progress in research work, especially steam production by the Beijing Badaling power tower solar power plant in July 2011, its power generation in August 2012, and its gradual commissioning, the author's knowledge of CSP generation technologies deepened. The author discovered that content that was as useful as possible would not be sufficient without the author's original theories and experiments. Particularly, CSP generation technologies still remain at the development stage, and many basic concepts and terms have been expressed in diversified ways in the articles and writings of different world-renowned scholars, such as the most important concept in power plant design, namely the "design point." As for similar major content, the author expresses his own opinions in the book by conducting in-depth theoretical and experimental research. Therefore, after 5 years, this book can finally be dedicated to its readers. Henceforth, along with the deepening of research work, the book may be modified regularly so that upgraded "achievements"—for example, improvements in the design and operation mode of the thermal storage unit—can be dedicated to readers and the industry as well.

Special thanks should be given by the author to Mr. Xu Jianzhong, Academician of the Chinese Academy of Sciences, and Mr. Huang Ming, Chairman of Himin Solar Energy Group Co., Ltd., who have made every endeavor possible, for more than a decade, to support the author in conducting research on solar thermal power generation and its practices; meanwhile, the author is also grateful for care and support from his family. During research on solar thermal power generation and its practices, the author has been deeply grateful for tremendous support from the national "863 Program" (2006AA050100), (2006AA050100), "973 Program" (2010CB227100), "the National Natural Science Fund of China," "Beijing Municipal Science and Technology Project," "Knowledge Innovative Project of CAS," "International Cooperation Program of the Ministry of Science and Technology," and the "6th and 7th" Framework Programmes for Research of the European Union.

This edition is Co-published with Elsevier Inc. In accord with Elsevier's edition, this book follows the typeset of Elsevier, including but not limited to upright italic letters, as a courtesy.

The book assimilates the development experiences and essence of CSP technologies both at home and abroad and provides them to readers. Yet due to the author's limited knowledge, as well as insufficient practices in CSP plant R&D and construction, many imperfections may exist. It would be greatly appreciated if readers could provide the author with critiques and corrections of these imperfections for use in future editions.

Zhifeng Wang
March, 2019

Contents

CHAPTER

1

Introduction

Since the beginning of the 21st century, energy and environmental problems have become increasingly more noticeable. Due to limited nonrenewable fossil energy resources and the severe influences of excessive use of these resources on the environment, excessive greenhouse gas emissions, global warming, and severe deterioration of regional climates and ecological environments appeared and have greatly endangered the living space of humans. The prominent advantages and development potential of concentrating solar power (CSP)—also known as solar thermal power (STP) or concentrated solar power—generation technology have aroused widespread concern. The main challenge it faces right now is to reduce its power generation costs so that it can compete with fossil fuels. In the next two decades, it is estimated that stable and economic CSP generation technology will gradually mature and become strongly competitive commercially. CSP generation technology features stable and constant power output, low costs, and outstanding technical and economic advantages; the development strategy of this technology is of great significance.

The basic process of CSP generation involves concentrators, receivers, thermal storage, thermal power conversion, etc. Thermodynamics, heat transfer, optics, mechanics, materials science, information science, and many other disciplines and interdisciplinary studies serve as the theoretical foundation of CSP generation technologies. Only by mastering these key technologies can we greatly improve the efficiency of the system and further reduce power generation costs so that we may further push forward its large-scale commercialization and development, and realize the effective utilization of solar energy.

For power plant design and operational targets, the following two questions are key points to be solved in terms of CSP research and engineering; they are also the main contents of this book:

1. Optical efficiency and cost of the concentrator. High-density concentration of solar irradiation acts as the basic process of CSP generation. Concentrator costs in solar tower and parabolic trough

Design of Solar Thermal Power Plants
https://doi.org/10.1016/B978-0-12-815613-1.00001-8

systems account for 45%–70% of the primary investment; the annual mean efficiency of a concentration field is normally 58%–72%, so research on the concentration process greatly influences the efficiency and cost of the system.

Energy losses in the concentration process mainly include cosine, reflection, air transmission, and receiver interception losses caused by concentrator errors. In addition, the limits of working environmental conditions and concentrator shelf life, while still ensuring concentrator precision, mean that concentrator cost reductions now face great restrictions. Considering both of these factors, it is necessary to carry out in-depth research on the collection of optical energy and high-precision concentration using aspects of optics, mechanics, and materials science and overcome the influences of concentrator mirror shape aberration and tracking errors on energy flow transmission efficiency as well as the problem of low CSP system conversion efficiency caused by spatial and temporal distribution of the energy flux failing to satisfy the requirement of receiver; an integrated design method of solar beam concentration and thermal absorption based on the highly efficient energy flow transmission must be established.

2. CSP system conversion efficiency and reliability of devices. When the efficiency of an CSP system is increased by 1%, the levelized cost of electricity from CSP generation will decrease by 8%, and the corresponding total capital investment will be reduced by 5%–6%. System efficiency has significant impacts on CSP system costs. Future technical developments shall be mainly based on stable operation of the system, improvements in system efficiency, and development of major technical equipment techniques, system integration techniques, equipment performance evaluation methods and their respective testing platforms, technical standards, and regulations in the large-scale CSP generation system. Conventional thermal power conversion efficiency was improved along with increases in the parameters of the working medium, and the basic approach to improving the efficiency of the cycle was to increase the temperature and pressure of the working fluid. During CSP generation, however, the efficiency of solar receiver system conversion decreases with increases in the temperature of the heat transfer medium, which is also accompanied by intensive unsteadiness in time, nonuniformness in space, and transient strong energy flow impact. Therefore, improvements in thermal power conversion efficiency shall not be accomplished by completely relying on the regular thermal cycle, and the laws of fluid flow and heat transfer processes are also distinguished from regular ones. To greatly improve the efficiency,

TABLE 1.1 Comparison of Solar Thermal Power Generation and Solar Photovoltaic Power Generation

Items to Be Compared	Solar Thermal Power	Photovoltaic Power Generation
Power Generation Mechanism	Sunlight energy- thermal energy-power, with working process	Photoelectric effect of materials, sunlight energy-power, without working process
Definition of Efficiency	Annual mean efficiency, Generation energy/annual solar irradiation, kWh/kWh	Peak value efficiency, generation power/input power, kW/kW
Capacity	No scale limits; dish system is suitable for distributed power generation; tower-type and parabolic trough systems are suitable for large-scale projects	No scale limits; can be either separately applied, or applied in large-scale project
Solar Spectrum	300–3000 nm	300–600 nm
Power Quality	Small load fluctuation, high quality	Large fluctuation without power storage impacts on power grid, poor quality
Cost	High	Lower

it is not possible to simply apply conventional materials systems. These technical considerations pose challenges to the conventional techniques being applied right now. The development of large-scale, highly efficient CSP cycle technologies requires new and further research on highly efficient concentrator fields, unsteady high-temperature heat transfer and thermal storage mechanisms, materials design, reliability of the CSP-generation system and its recurring effects on the overall system, etc.

3. Differences between CSP generation and solar photovoltaic power generation. The two solar energy power generation modes are compared in Table 1.1.

1.1 GENERAL PRINCIPLES OF SOLAR THERMAL POWER PLANT DESIGN

Design of the CSP plant shall follow the general principles of (1) tallying to national conditions, advances in technology, economic feasibility, and operating in a safe and reliable manner; (2) striving for economic and social benefits, saving energy, engineering investment, and raw materials, and shortening the construction period; and (3) being in line with existing Chinese state standards and regulations for saving land, water conservancy, and environmental protection, as well as exercising requirements for labor safety and industrial hygiene.

1.1.1 Constitution of the Solar Thermal Power Plant

An CSP plant consists of three major units: solar energy collection, thermal energy storage, and a thermal power generation unit. The first two mainly include the irradiation concentrator, the receiver, thermal storage, and the evaporator, whereas the last mainly includes the turbine, the power generator, control of the power cycle, the electricity system, water treatment, and the supply system.

Capacity of an CSP plant shall be determined according to the capacity of the generator unit, which is irrelevant to solar irradiation resources, environmental and meteorological conditions and concentrator power. Power plants of equivalent capacity may correspond to concentration fields (mirror fields) of different sizes.

An CSP plant can be constructed economically by using combined heating and electricity based on solar direct normal irradiation (DNI) resources, the current status of the local power load, and thermal load.

CSP can be complemented by coal, petroleum, or natural gas in a mixed-fuel power plant constructed according to circumstances in areas with an abundant solar resource and coal or petroleum resources.

According to the needs of thermal and power load development in corporate planning, construction of a self-contained heating-type CSP plant with an appropriate scale is suggested.

1.1.2 Selection of Pressure Parameters for Power Generation Units

It is suggested that the water steam pressure parameters of generator units be selected according to unified short-term and long-term construction plans while being in-line with the following rules:

1. For a generator unit with a stand-alone capacity of 1.5 MW and below, a medium-pressure (MP) or lower MP steam turbine is suggested. For one with a stand-alone capacity of 3 MW, a MP steam turbine is suggested. For one with a stand-alone capacity of 6 MW or above, an MP or secondary high-pressure (HP) steam turbine is suggested.
2. For a condensing-type generator unit with a stand-alone capacity of 3 MW, lower MP parameters are suggested; for one with a stand-alone capacity of 6 MW or above, MP or lower HP parameters are suggested.

3. For solar collectors within the same power plant, the same type of collector with the same output parameters should be used; generator units within the same power plant should also use the same parameters. For a parabolic-trough-and-tower mixed-CSP plant, the parabolic trough system should be used as the preheater with the tower used for the superheated part.
4. When designing the concentration field, the influences of sun beam shading and blocking between the reflectors on concentration efficiency shall be considered; attention should also be paid to the land use rate and future expansion needs of the concentration field and thermal storage system. Normally the land coverage of a parabolic trough concentration field is about 2.5 times that of the total aperture area of the concentrators, whereas the land coverage of a solar tower concentration field is 4–6 times that of the total aperture area of the heliostats and also related to the height of tower. In some countries, land quotas are quite complex.

1.1.3 Heat Transfer Fluid of the Receiver

Water/steam, synthetic oil, air, or molten salt can be selected as the heat transfer fluid. The working medium of a steam turbine is water/steam. For a CSP plant that uses steam as the corresponding working medium, water pretreatment equipment must use desalinated water; otherwise, permanent damage may be caused to the reverse osmosis water system.

1.1.4 Schedule Capacity of the Power Plant and Number of Installed Units

New power plants can be designed and constructed all at once or in sections according to incremental load speed based on scheduled capacity. Due to the comparatively large investment, the concentration field corresponding to a power plant can be designed all at once but constructed in sections. The major loop for synthetic oil, the design and construction of the parabolic trough collector field, and the height of the receiver tower in the tower power plant shall be configured to match the intended ultimate capacity of the power plant. A large-scale collector field can be divided into different thermal collection modules, the thermal fluid output of which will flow into the thermal storage unit. In the thermal collection system that directly produces steam, the steam will be discharged to the main pipe of the power plant.

The number of condensing power turbines shall not exceed four in one plant. For a power tower plant with an installed capacity of less than 100 MW, no more than one receiver corresponding to the concentration field shall be installed [1]. For a large-capacity tower power plant, the multitower system shall be considered when designing the concentration field. A single-tower system is recommended for a tower power plant that uses molten salt as endothermic fluid because of great difficulties in the high-temperature molten-salt transmission process, poor reliability, and high pipeline cost.

The turbine and boiler configuration, model selection of main auxiliary facilities, major production process system, and main powerhouse layout in the power plant shall be determined through technical and economic analyses. While satisfying the safe, economical, and reliable operation of the power plant, the system and/or layout can be simplified in an appropriate manner.

1.1.5 Control of Power Plant Influences on the Environment

In designing the power plant, it is necessary to indicate the disposal plan for the concentrator as well as the thermal storage and heat transfer materials, especially thermal storage medium to be used in large amounts. The working medium of water/steam for heat transfer and thermal storage is very environmental friendship.

If landscaping is damaged during concentration field construction, a land restoration program shall be provided.

Wastewater, sewage, light pollution, noise, and all kinds of other pollutants shall be prevented, controlled, and discharged by implementing and executing national laws, regulations, and standards for environmental protection, and the relevant rules for labor and industrial hygiene must be tallied. These items can only be discharged by satisfying the respective standards.

Engineering facilities for pollutant prevention and control as well as labor and industrial hygiene facilities must be designed, constructed, and placed into operation with the core work on a simultaneous basis.

1.1.6 Power Plant Seismic Resistance and Windproof Design

The solar collection system consists of concentrators and receivers. Concentrators use optical equipment with high precision requirements. Any deformation of the foundation or supporting structure of the concentrator will greatly influence the precision of the concentrator and have major impacts on the overall working conditions of the power plant and could even result in scrapping of the concentration field. The seismic design of the concentrator shall be based on the hundred-year earthquake. The design of the receiver tower must be conducted by executing the current China state standard. Seismic resistance shall also be considered during design of the power plant's concentrator.

Wind-resistant design for the concentrator and receiver tower of a CSP power plant shall be conducted according to the hundred-year wind scale of the plant's applicable locality.