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西北勘测设计研究院有限公司
NORTHWEST ENGINEERING CORPORATION LIMITED

环境因素对光伏工程发电量影响研究

Study on the Influence of Environmental Factors on the Power Generation of Photovoltaic Engineering

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2018年11月20日

摘要/Abstract

由于太阳能光伏发电效率与其本身的温度有直接关系，而太阳能光伏板温度又会受到自然环境、光伏组件安装阵列以及运行工况的影响。本项目使用试验研究、数学建模、数值计算模型相结合的方法研究太阳电池组件温度分别与日照强度、环境空气温度、风速、风向等因素的关系；得到了有价值的成果。

Since the efficiency of solar photovoltaic power generation is directly related to its own temperature, the temperature of the photovoltaic panel will be affected by the natural environment, the array of photovoltaic modules installed and the operating conditions. This project uses the combination of experimental research, mathematical modeling and numerical calculation model to study the relationship between solar cell module temperature and sunshine intensity, ambient air temperature, wind speed and wind direction, and obtains valuable results.

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西勘院简介Introduction to Northwest Engineering

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01 Company Profile

Established in 1950, Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST) is an important member enterprise of a Fortune Global 500 conglomerate——POWERCHINA Corporation (POWERCHINA Limited) .

After decades of business endeavoring, POWERCHINA NORTHWEST has developed into an international (technology-based) engineering corporation, with the integrated capability of Engineering Design, EPC Contracting, and Investment & Operation. With distinctive features in our leading technologies of comprehensive utilization of hybrid energy (water, solar, wind and geothermal energies) , water eco-environment management, solar thermal power generation, waste disposal & utilization, urban utility tunnels, and regional socio-economic planning, POWERCHINA NORTHWEST boasts the full-range ability offering integrated engineering solutions for the clients.

- **Clean Energy Development**

POWERCHINA NORTHWEST has accomplished hydropower planning for more than 30 rivers, and performed the survey, investigation, and engineering design services for more than 140 large-or-medium-scale hydropower projects in China and abroad. More than 100 hydropower projects worldwide we participated in have been commissioned or under construction, with an aggregate capacity of 34 GW.

The gross capacity of renewable energy projects designed by our company ranks No. 1 in China (including 20 GW wind power projects, accounting for 14.7%, No. 1 in China; 4.5 GW solar PV power projects, accounting for 20%, No. 1 in China) .We are capable of offering the planning, investigation, engineering design, consultancy and construction supervision services for complex pumped storage power plants.

30	140	100	34 GW
hydropower planning for more than 30 rivers	design services for 140 large-or-medium-hydropower projects	hydropower projects commissioned or under construction	aggregate capacity

02 光伏实验平台介绍

Introduction to photovoltaic experiment platform

1、研究方法和技术路线Research methods and technical routes

本项目采用理论研究和工程实践相结合的方法，以我院已经完成的数十项光伏发电工程前期设计工作为依托，以已经并网发电的电站为基础，采取调研、收集运行资料、统计分析、实验分析、理论分析、仿真分析（数值模拟）、计算研究等方法，完成拟研究的内容。

The project adopts a combination of theoretical research and engineering practice. Based on the pre-design work of dozens of photovoltaic power generation projects that have been completed by our institute, based on the power plants already connected to the grid, research, collection of operational data, statistical analysis , experimental analysis, theoretical analysis, simulation analysis (numerical simulation), computational research and other methods to complete the content of the proposed study.

2、技术路线Technical routes

（1）气象条件件影响因素辨识。

（2）研究组件化学热过程特点及对系统性能的影响。

（3）光伏阵列的布置对系统性能的影响。

（4）进行太阳能光伏系统实际运行测试，进一步验证研究结果。

(1)Identification of influencing factors of meteorological conditions.

(2) Study the characteristics of the chemical thermal process of components and their impact on system performance.

(3)The influence of the arrangement of the photovoltaic array on the system performance.

(4)Carry out the actual operation test of the solar photovoltaic system to further verify the research results.

实验工程概况Experimental project overview

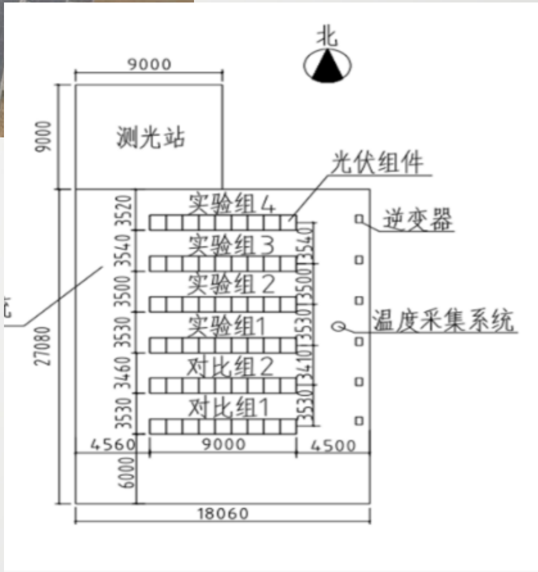
3、实验概况Experimental overview

本项目组在西安市中电投太阳能电力公司内搭建了环境因素对光伏发电工程发电量影响研究试验场，在该试验场中可以获取研究所需的环境气象、光伏组件温度及发电量等数据，这些试验数据将用以研究环境因素对光伏发电系统热性能及电性能的影响，同时对建立的可用于工程实践的数学模型进行验证。

The project team set up a research and test site for the impact of environmental factors on the generation of photovoltaic power generation in Xidian Zhongdian Solar Power Company.

西安市中电投太阳能电力公司试验场

Xi'an Zhongdian Solar Energy Power company test site



试验场占地约489平方米，设置6个同类型的太阳能电池方阵，分为4个实验组，2个对比组。每个方阵有9块电池组件，组件间长边与长边紧挨布置，电池组件的背板上装有热电偶进行温度测量，每个方阵均安装逆变器，实验场地的北边设有测光站，测量太阳辐射、环境温度、风速、风向等气象数据。

The test site covers an area of about 489 square meters, and six solar cell arrays of the same type are set up, which are divided into four experimental groups and two comparison groups.

实验工程概况Experimental project overview

4、实验项目experimental project：

（1）实测不同辐射强度、温度、风速、风向条件下太阳电池组件温度的变化；

The change of temperature of the solar cell module under different radiation intensity, temperature, wind speed and wind direction is measured;

（2）实测不同辐射强度、电池片温度下每组太阳电池组件的瞬时最大输出功率（以组串式逆变器单路MPPT跟踪的直流输入功率减去灰尘遮挡损耗、组件不匹配损耗、线路损耗、二极管损耗等）；

Measure the instantaneous maximum output power of each group of solar modules under different radiation intensity and cell temperature (DC input power of single-chip MPPT tracking by string inverter minus dust blocking loss, component mismatch loss, line loss, diode Loss, etc.)

（3）对于成阵列布置的太阳电池组件，在同等行间距条件下，实测不同倾角布置时，逆变器单路MPPT跟踪的直流输入功率变化；

For the solar cell modules arranged in an array, the DC input power of the single channel MPPT tracking of the inverter changes when the different inclination angles are measured under the same line spacing condition;

（4）对于成阵列布置的太阳电池组件，在同等行间距条件下，实测不同方位角布置时，逆变器单路MPPT跟踪的直流输入功率变化；

For the solar cell modules arranged in an array, the DC input power of the single channel MPPT tracking of the inverter changes when the different inclination angles are measured under the same line spacing condition;

（5）实测灰尘遮挡对太阳电池组件发电量的影响

The effect of measured dust shielding on the power generation of solar modules

实验工程概况Experimental project overview

5、热电偶测温Thermocouple temperature measurement：

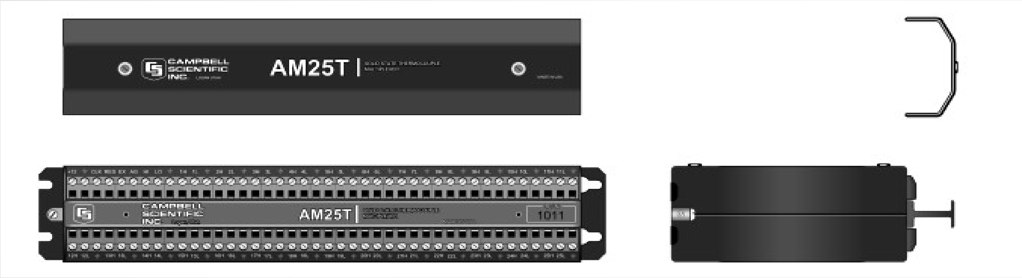
采用选择T型（TC-TFF-30），即为铜-康铜热电偶进行温度数据采集工作，热电偶安装位置为太阳能电池板的背板。

Temperature data acquisition is performed by selecting T-type (TC-TFF-30), and the thermocouple is installed at the back panel of the solar panel.

6、温度采集系统Temperature acquisition system：

本试验所用温度采集系统为美国Campbell公司出品的AM25T通道固态扩展板（如下图1）和CR1000数据采集器（如下图2）。AM25T可以连接多达25个热电偶，

The temperature acquisition system used in this test is the AM25T channel solid state expansion board (Figure 1) and the CR1000 data collector (Figure 2) from Campbell Corporation of the United States. The AM25T can connect up to 25 thermocouples.



1.AM25T通道固态扩展板AM25T channel solid state expansion board

2.CR1000数据采集器CR1000 data collector

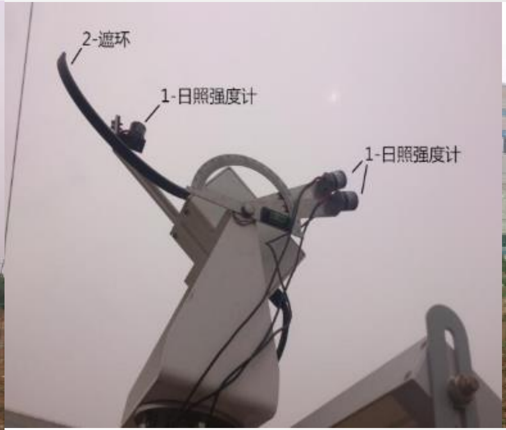
实验工程概况Experimental project overview

温度采集系统 Temperature acquisition system

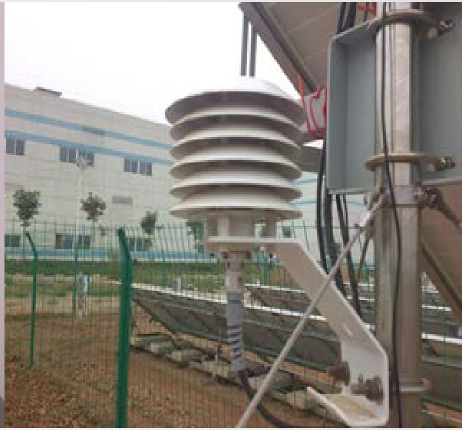
每根热电偶首尾两端都用标签进行编号

旋转式太阳能测量系统 Rotary solar measurement system

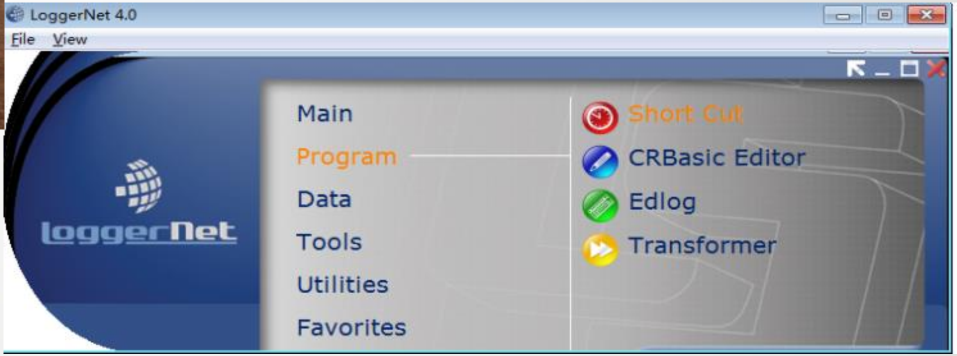
RSR1OOO旋转式太阳能测量系统，精确测量总辐射，散射，直接辐射



遮环以及日照传感强度计Occlusion ring and sunshine sensor intensity meter



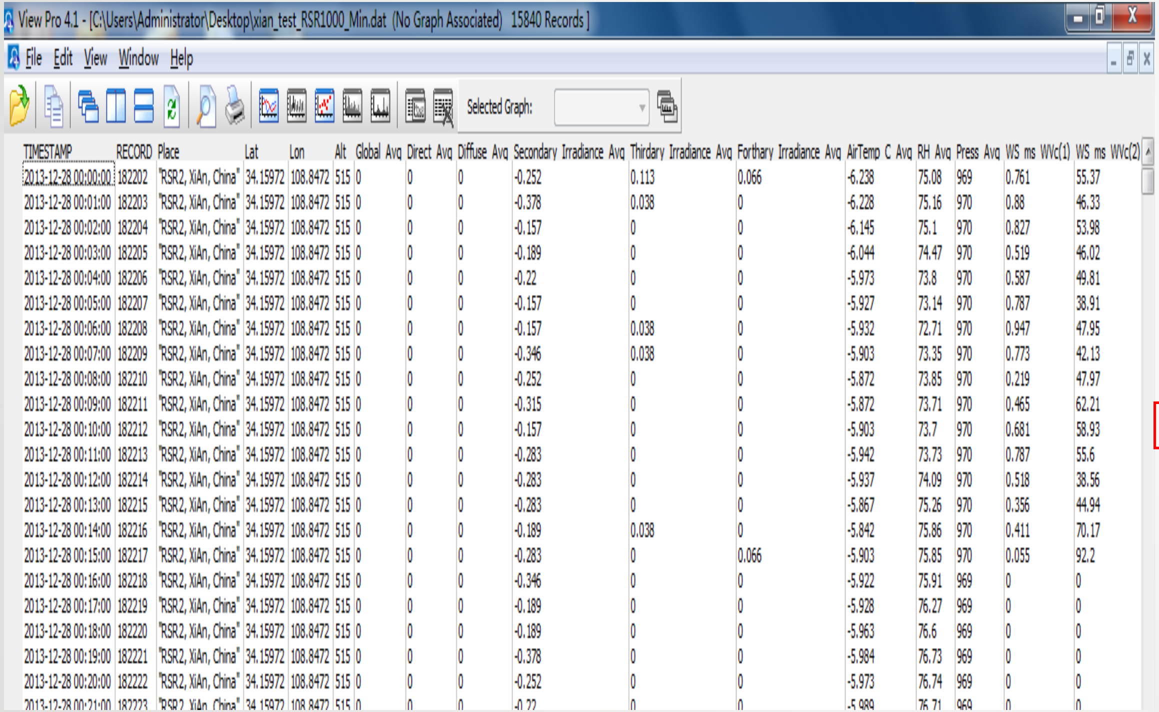
湿度传感器 Humidity Sensor



采集数据软件：Logger Net操作界面

实验工程概况Experimental project overview

View pro数据图
View pro data map



TIMESTAMP	RECORD	Place	Lat	Lon	Alt	Global Avg	Direct Avg	Diffuse Avg	Secondary Irradiance Avg	Thirdary Irradiance Avg	Forthary Irradiance Avg	AirTemp C Avg	RH Avg	Press Avg	WS ms WVc(1)	WS ms WVc(2)
2013-12-28 00:00:00	182202	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.252	0.113	0.066	-6.238	75.08	969	0.761	55.37
2013-12-28 00:01:00	182203	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.378	0.038	0	-6.228	75.16	970	0.88	46.33
2013-12-28 00:02:00	182204	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.157	0	0	-6.145	75.1	970	0.827	53.98
2013-12-28 00:03:00	182205	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.189	0	0	-6.044	74.47	970	0.519	46.02
2013-12-28 00:04:00	182206	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.22	0	0	-5.973	73.8	970	0.587	49.81
2013-12-28 00:05:00	182207	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.157	0	0	-5.927	73.14	970	0.787	38.91
2013-12-28 00:06:00	182208	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.157	0.038	0	-5.932	72.71	970	0.947	47.95
2013-12-28 00:07:00	182209	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.346	0.038	0	-5.903	73.35	970	0.773	42.13
2013-12-28 00:08:00	182210	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.252	0	0	-5.872	73.85	970	0.219	47.97
2013-12-28 00:09:00	182211	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.315	0	0	-5.872	73.71	970	0.465	62.21
2013-12-28 00:10:00	182212	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.157	0	0	-5.903	73.7	970	0.681	58.93
2013-12-28 00:11:00	182213	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.283	0	0	-5.942	73.73	970	0.787	55.6
2013-12-28 00:12:00	182214	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.283	0	0	-5.937	74.09	970	0.518	38.56
2013-12-28 00:13:00	182215	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.283	0	0	-5.867	75.26	970	0.356	44.94
2013-12-28 00:14:00	182216	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.189	0.038	0	-5.842	75.86	970	0.411	70.17
2013-12-28 00:15:00	182217	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.283	0	0.066	-5.903	75.85	970	0.055	92.2
2013-12-28 00:16:00	182218	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.346	0	0	-5.922	75.91	969	0	0
2013-12-28 00:17:00	182219	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.189	0	0	-5.928	76.27	969	0	0
2013-12-28 00:18:00	182220	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.189	0	0	-5.963	76.6	969	0	0
2013-12-28 00:19:00	182221	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.378	0	0	-5.984	76.73	969	0	0
2013-12-28 00:20:00	182222	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.252	0	0	-5.973	76.74	969	0	0
2013-12-28 00:21:00	182223	"RSR2, XiAn, China"	34.15972	108.8472	515	0	0	0	-0.22	0	0	-5.989	76.71	969	0	0

RSR1000系统1分钟数据表（系统采样时间间隔3S）
RSR1000 system 1 minute data sheet(Time interval 3S)

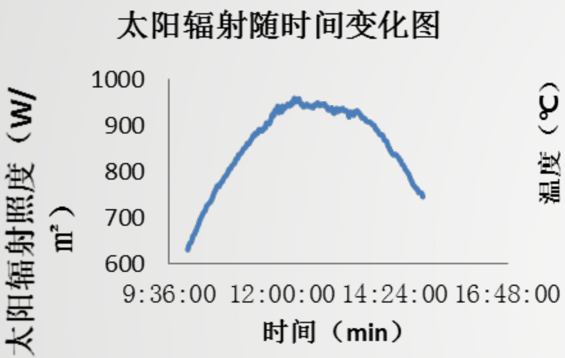
变量名	含义
TIMESTAMP	时间标签
RECORD	记录数
Place	测量数据的所在地
Lat	纬度
Lon	经度
Global_Avg	水平总辐射分钟平均辐照度
Direct_Avg	直接辐射分钟平均辐照度
Diffuse_Avg	散射辐射分钟平均辐照度
Secondary_Irradiance_Avg	倾角为35°时分钟平均辐照度
Thirdary_Irradiance_Avg	倾角为30°时分钟平均辐照度
Forthary_Irradiance_Avg	倾角为25°时分钟平均辐照度
AirTemp_C_Avg	环境温度分钟平均值
RH_Avg	湿度分钟平均值
Press_Avg	气压分钟平均值
WS_ms_WVc(1)	分钟矢量合成风速
WS_ms_WVc(2)	分钟矢量合成风向
WS_ms_Max	分钟风速最大值
ZenDeg_Avg	天顶角分钟平均值
Rain_mm_Tot	分钟雨量总计

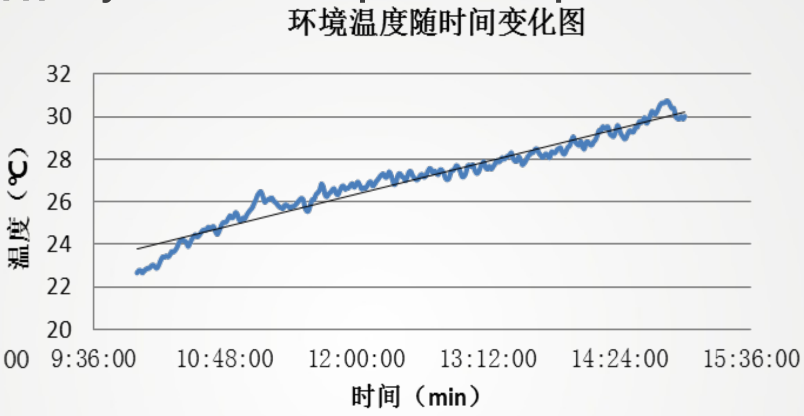
04 环境因素对组件影响实验研究

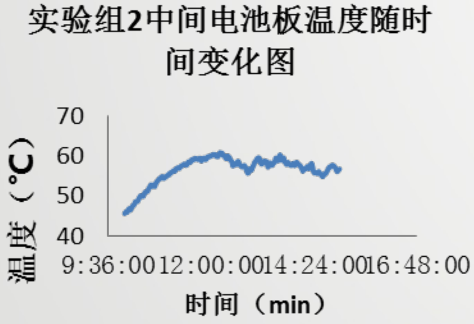
Experimental study on the influence of environmental factors on components

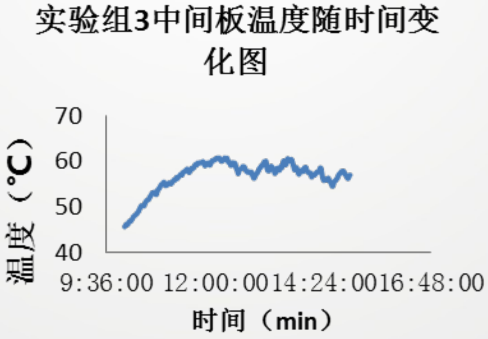
环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

太阳电池组件温度响应的滞后性Hysteresis of temperature response of solar modules







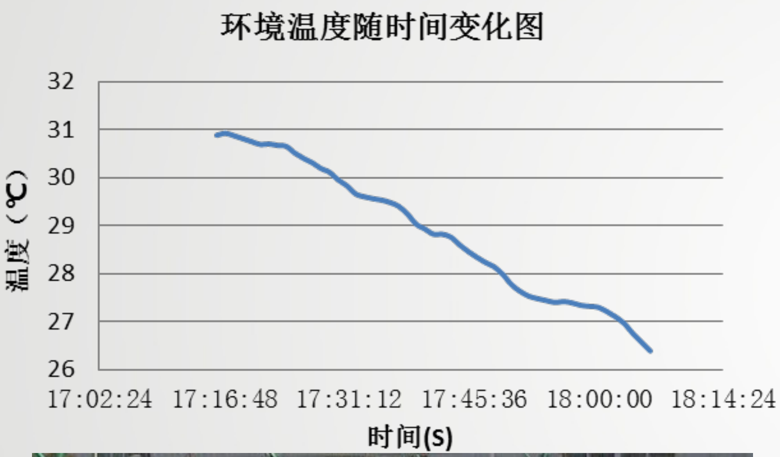


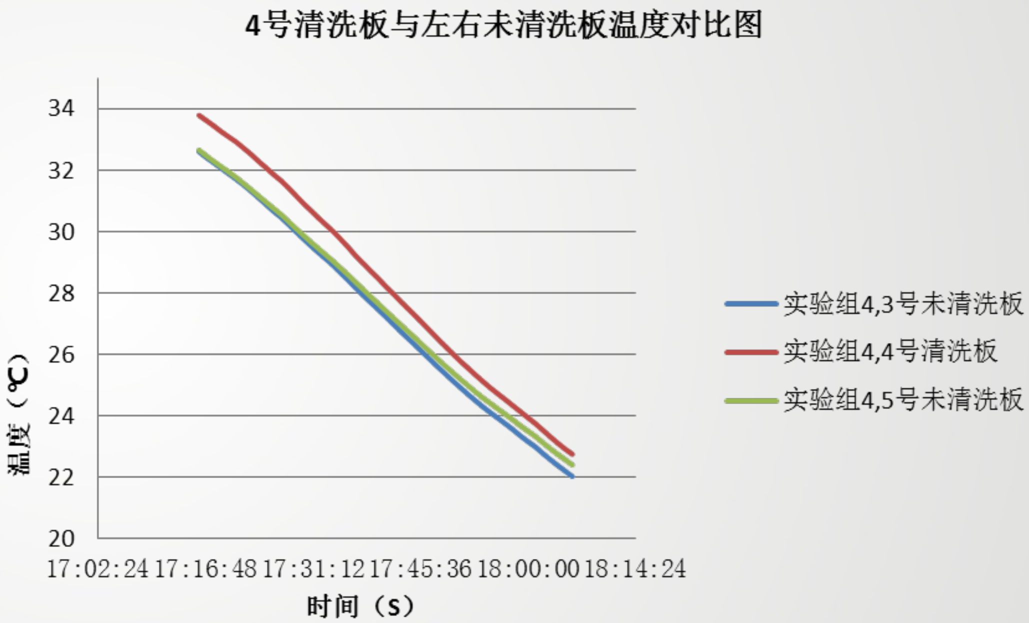
试验记录的数据为每一时刻所对应的太阳辐射照度以及太阳能电池板背板的温度。对于成阵列布置的通过以上分析表明，在保持风速，风向，环境因素相对稳定的条件下，电池板温度的最大值，与太阳辐射照度最大值同步。在太阳辐射的照射下，电池模块温度响应可以认为是同步的，没有滞后。

Under the condition of maintaining wind speed, wind direction and relatively stable environmental factors, the maximum temperature of the panel is synchronized with the maximum solar irradiance. Under the illumination of solar radiation, the battery module temperature response can be considered synchronous without hysteresis.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

灰尘遮挡对组件温度影响Dust shielding affects component temperature



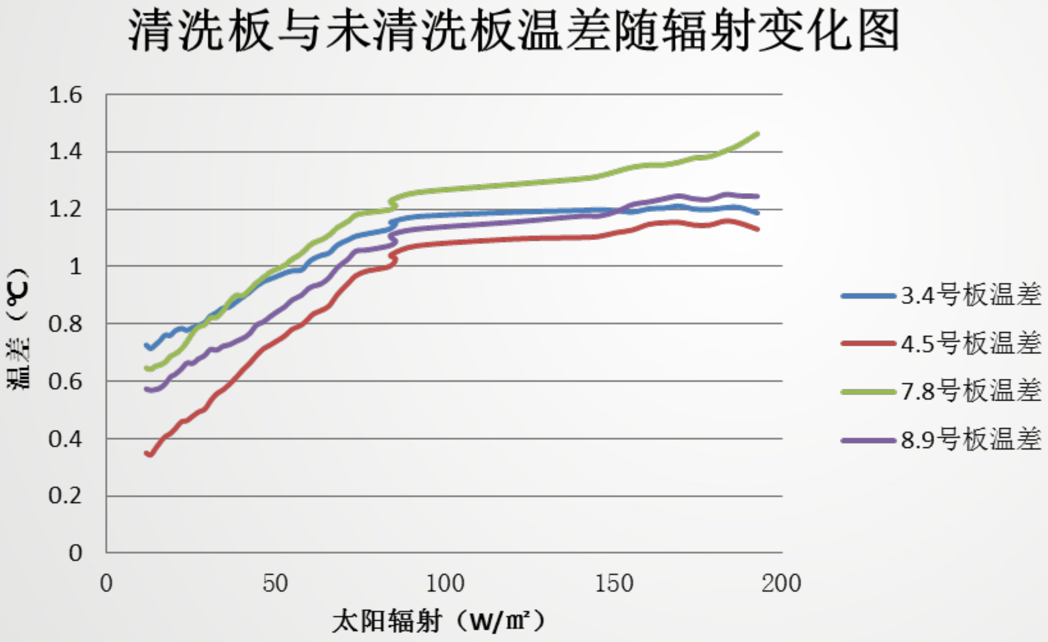


选取无风的情况下，最大程度降低环境风速对太阳能电池板温度的影响。

When no wind is selected, the effect of ambient wind speed on solar panel temperature is minimized.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

灰尘遮挡对组件温度影响Dust shielding affects component temperature

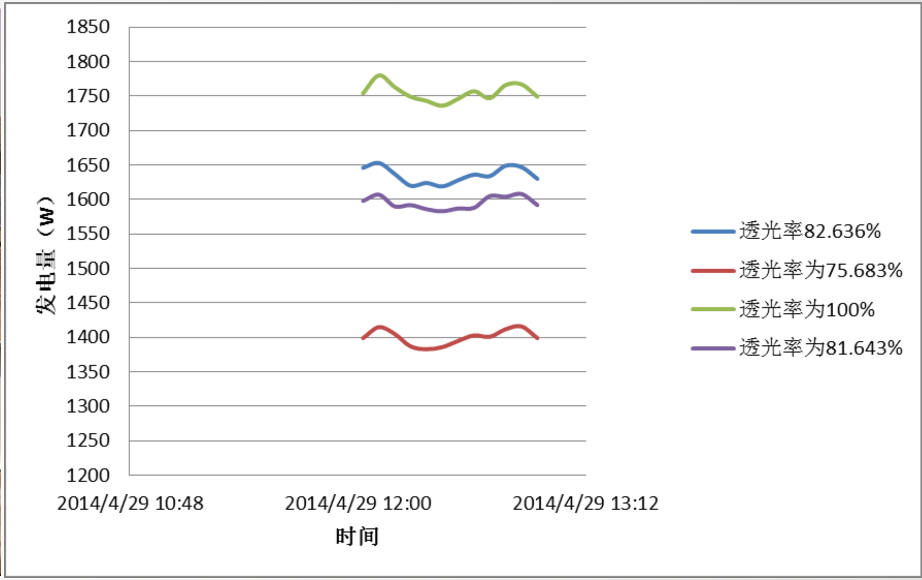


没有灰尘覆盖的电池板的温度明显高于有灰尘覆盖的，在风很小的情况下，太阳辐射强度在192.8W/㎡时，温差最大可以达到1.46C°，最小也在1.13C°，平均值的最大温差为1.257C°。

The temperature of the panel without dust is obviously higher than that covered by dust. When the wind is small, the solar radiation intensity is 192.8W/m^2, the temperature difference can reach 1.46 °C, and the minimum is 1.13 °C. The maximum temperature difference is 1.257 °C.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

灰尘遮挡对发电量的影响The effect of dust occlusion on power generation



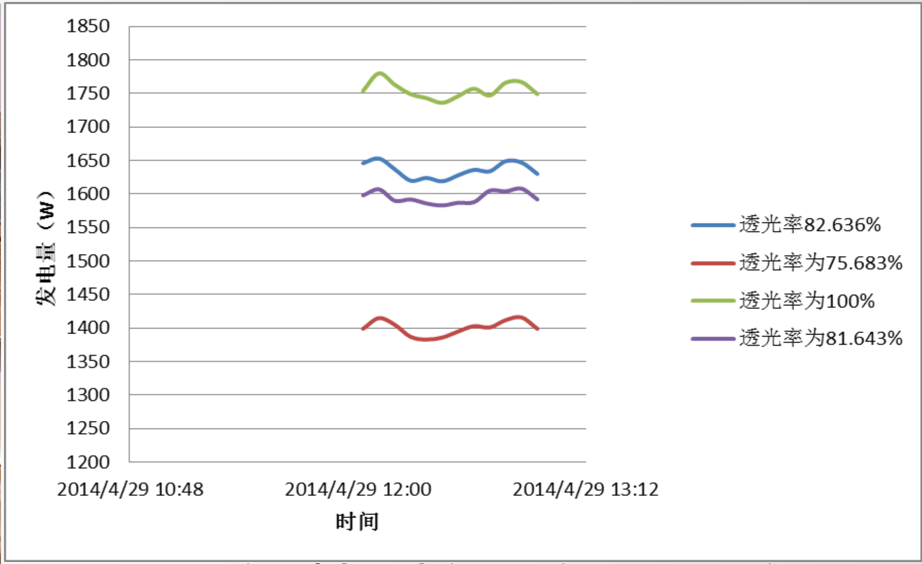
不同透光率下光伏组发电量对比图

灰尘取自试验场周边的尘土，通过纤维布的筛分，使其粒径尽量接近自然降落的灰尘粒径，灰尘重量分别为1.26g，1.89g，3.15g，组件同一倾角布置，分别铺上灰尘，一块表面清洁，在两块板的背面分别水平放置1个日照辐射探头。

结论：自然积灰8天，玻璃盖板的透光率就会减小到80%，发电相对率只有0.8794，即发电量相对减少了12%之多。所以建议清扫灰尘的周期定为一周为宜。

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

灰尘遮挡对发电量的影响The effect of dust occlusion on power generation



Comparison of photovoltaic generation power generation under different transmittances

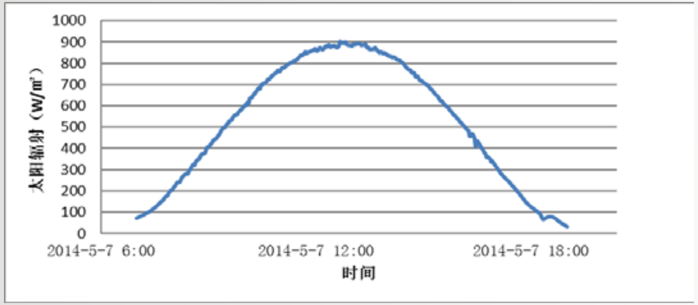
The dust is taken from the dust around the test field. The particle size is as close as possible to the particle size of the natural falling dust. The dust weight is 1.26g, 1.89g, 3.15g, and the components are arranged at the same inclination. Dust, one surface is clean, and one solar radiation probe is placed horizontally on the back of the two boards.

Conclusion: Natural light accumulation for 8 days, the light transmittance of the glass cover will be reduced to 80%, the relative rate of power generation is only 0.8794, that is, the power generation is reduced by as much as 12%. Therefore, it is recommended to set the period for cleaning dust to be one week.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

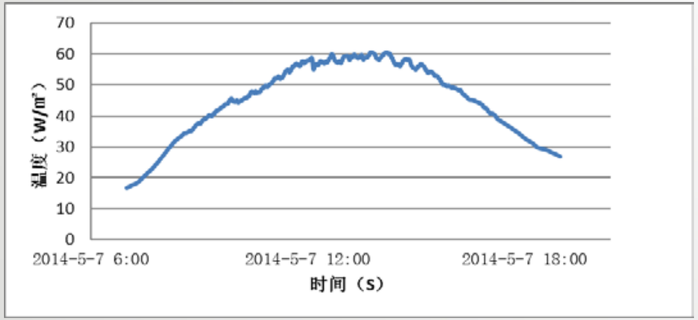
太阳辐射、环境温度、风速对组件的温度及发电量的影响——

太阳辐射对组件温度及发电量的影响规律

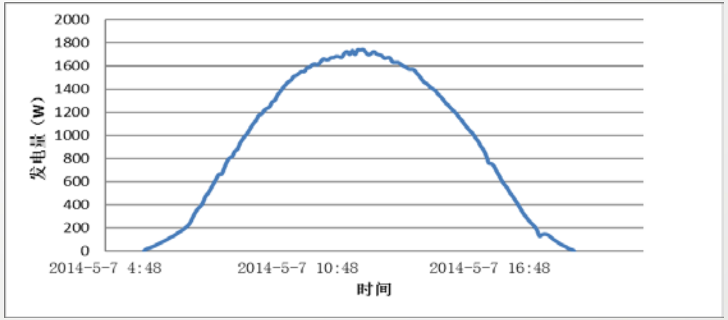


太阳辐射随时间变化图

环境温度随时间变化图



太阳能电池组件温度随时间变化图

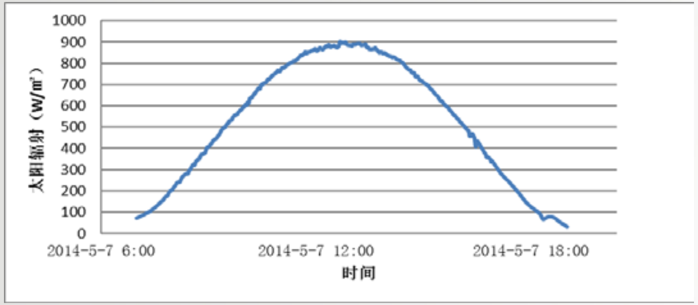


电池组件发电量随时间变化图

结论：从图中看到，两个曲线的变化规律都与太阳辐射变化规律一致，都为抛物线形。由此可见，电池组件温度和发电量变化与太阳辐射成正比关系，当太阳辐射升高时，电池组件温度和发电量也升高；当太阳辐射处于峰值时，电池组件的温度和发电量也处于峰值，且出现峰值的时刻也相同；当太阳辐射降低时，电池组件温度和发电量也随着降低。

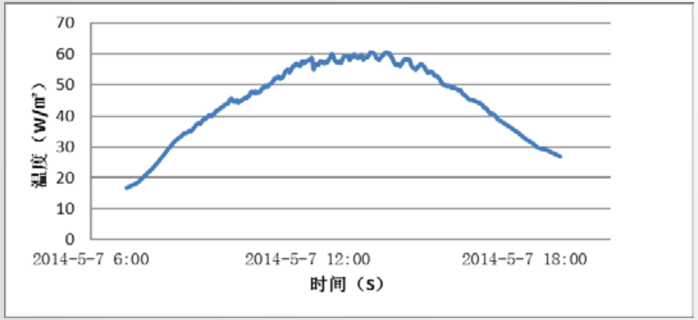
环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

Effects of solar radiation, ambient temperature, and wind speed on component temperature and power generation—— The effect of solar radiation on component temperature and power generation

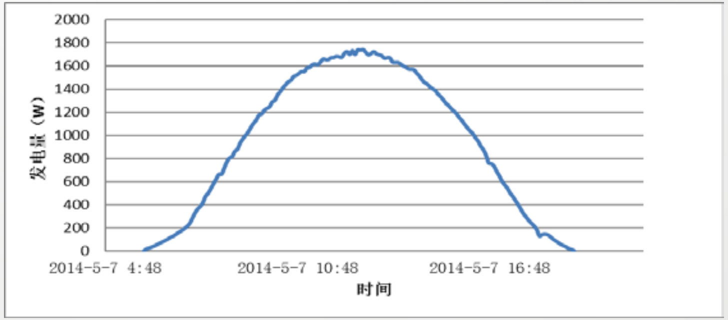


Solar radiation over time

Ambient temperature versus time graph



Solar cell module temperature change with time



Battery module power generation with time

Conclusion: It can be seen from the figure that the changes of the two curves are consistent with the law of solar radiation and are parabolic. It can be seen that the change of battery module temperature and power generation is proportional to solar radiation. When the solar radiation increases, the temperature and power generation of the battery component also increase. When the solar radiation is at the peak, the temperature and power generation of the battery component are also The time is at the peak and the peak occurs. When the solar radiation is lowered, the battery module temperature and power generation are also reduced.

太阳辐射、环境温度、风速对组件的温度及发电量的影响

Effects of solar radiation, ambient temperature, and wind speed on component temperature and power generation

实验组4， 1~9号组件温度及发电量平均值

时间	4月28日平均温度	4月29日平均温度
2014.4.28 13:30	51.739	53.3291
2014.4.28 13:31	51.6694	53.6972
2014.4.28 13:32	51.7944	53.9672
2014.4.28 13:33	52.1181	53.9713
2014.4.28 13:34	52.4148	53.7513
2014.4.28 13:35	52.2347	53.6041
实验组4平均温度	52.00	53.6
发电量平均值	1749	1554

时间	5月7日平均温度	5月20日平均温度
2014/5/7 14:30	55.3503	53.8684
2014/5/7 14:31	55.6279	53.4527
2014/5/7 14:32	55.7812	53.0625
2014/5/7 14:33	55.4452	53.1045
2014/5/7 14:34	55.083	53.5252
2014/5/7 14:35	55.7756	53.8824
2014/5/7 14:36	56.0143	53.9326
2014/5/7 14:37	56.0191	53.6308
2014/5/7 14:38	56.5764	53.797
2014/5/7 14:39	57.0595	53.9801
实验组4, 平均温度	55.87	53.62
发电量平均值	1498	1551

用控制变量法，即选取两个时间段，使这两段时间的太阳辐射相同，风速相同，但环境温度有明显差异，来比较环境温度不同对电池组件温度和发电量的影响。

结论：环境温度可以提高组件的温度，风速会降低组件温度，迎风面的组件低于背风面，组件温度高会降低组件发电量。

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

太阳辐射、环境温度、风速对组件的温度及发电量的影响

Effects of solar radiation, ambient temperature, and wind speed on component temperature and power generation

Group 4 , Average temperature and power generation of components 1～9

时间	4月28日平均温度	4月29日平均温度
2014.4.28 13:30	51.739	53.3291
2014.4.28 13:31	51.6694	53.6972
2014.4.28 13:32	51.7944	53.9672
2014.4.28 13:33	52.1181	53.9713
2014.4.28 13:34	52.4148	53.7513
2014.4.28 13:35	52.2347	53.6041
实验组4平均温度	52.00	53.6
发电量平均值	1749	1554

时间	5月7日平均温度	5月20日平均温度
2014/5/7 14:30	55.3503	53.8684
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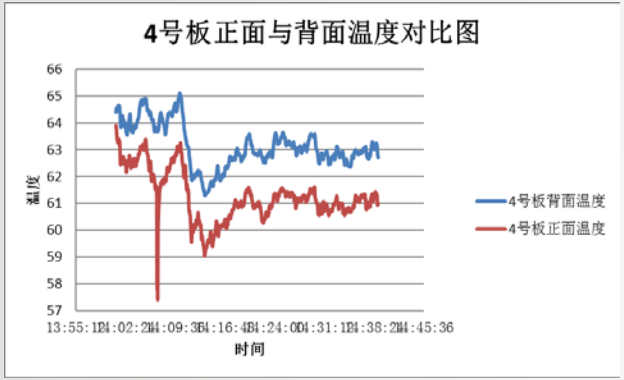
2014/5/7 14:36	56.0143	53.9326
2014/5/7 14:37	56.0191	53.6308
2014/5/7 14:38	56.5764	53.797
2014/5/7 14:39	57.0595	53.9801
实验组4, 平均温度	55.87	53.62
发电量平均值	1498	1551

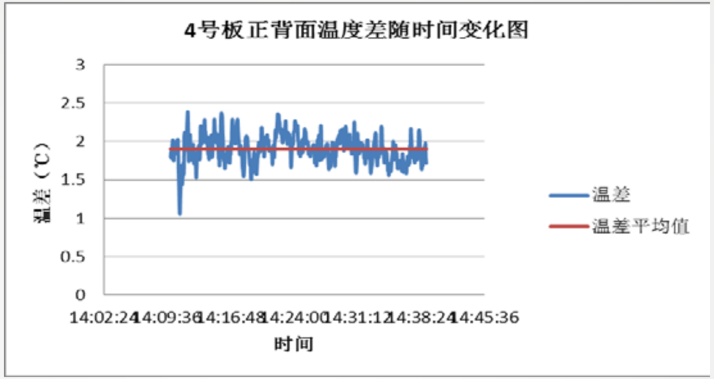
Using the control variable method, two time periods are selected so that the solar radiation in these two periods is the same, the wind speed is the same, but the ambient temperature is significantly different to compare the effects of different ambient temperatures on the temperature and power generation of the battery components.

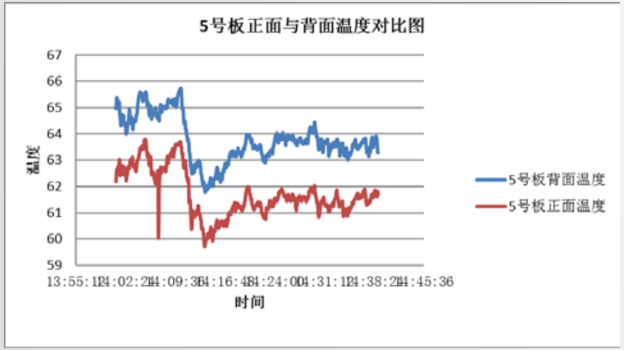
Conclusion: Ambient temperature can increase the temperature of the component. The wind speed will lower the temperature of the component. The components on the windward side are lower than the leeward side. The high temperature of the component will reduce the power generation of the component.

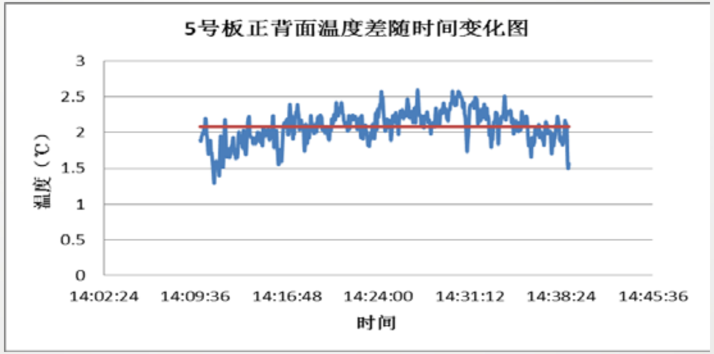
环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

组件正、背面温度关系Component front and back temperature relationship









选取实验组1的4号组件和5号组件作为研究对象。在4号组件和5号组件的中间位置同时分别测量正、背面温度，保证正面板的测量位置与背面板的相对应。

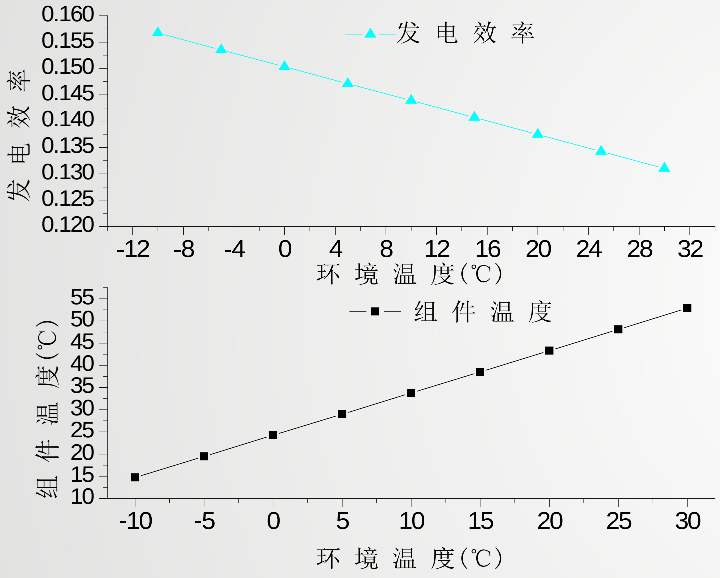
The No. 4 component and the No. 5 component of the experimental group 1 were selected as research objects.

结论：电池组件的背面温度要高于正面温度，且背面温度和正面温度的波动规律都是相同的，即背面和正面温度的差值是在一条水平线上下小幅波动的。

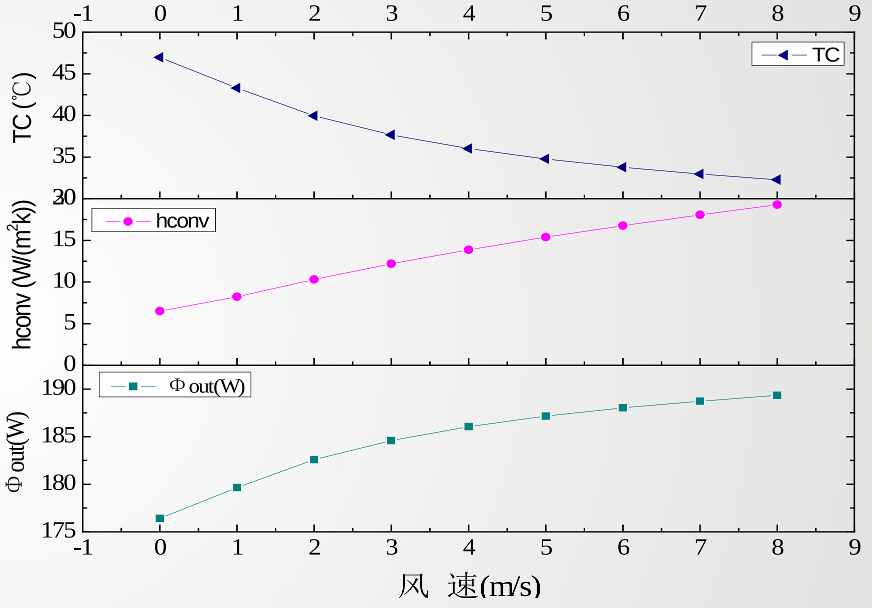
Conclusion: The temperature of the back side of the battery pack is higher than the front temperature, and the fluctuations of the back temperature and the front temperature are the same, that is, the difference between the back and front temperatures fluctuates slightly under a horizontal line.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

控制条件下单因素影响研究Study on single factor influence under control conditions



环境温度单因素与组件温度和发电效率的关系图



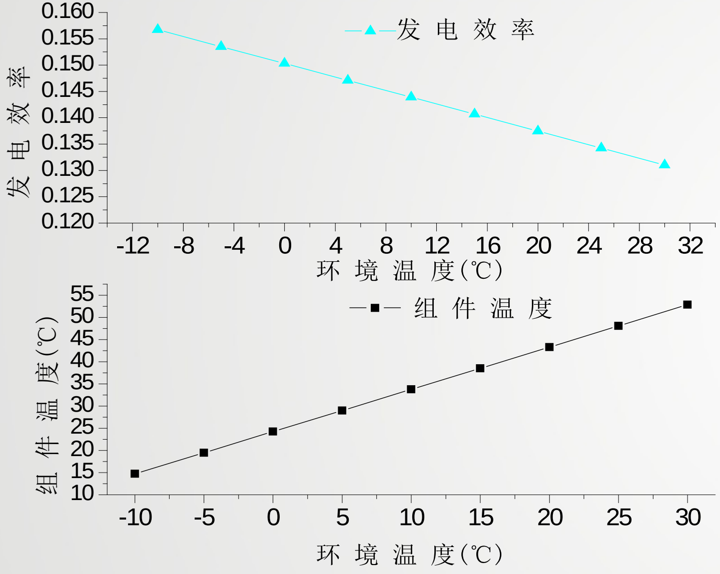
风速单因素与T_C、对流换热系数和单位输出功率的关系图

光伏电池组件的工作温度随着环境温度线性上升，与之形成对比的是发电效率随着环境温度线性下降。环境温度的升高主要对于光伏电池组件的性能产生着负影响。

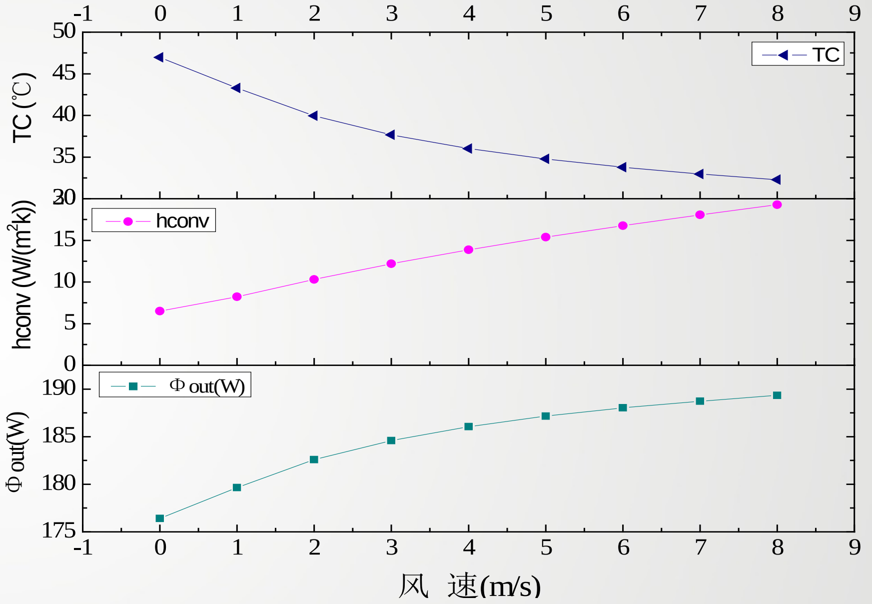
光伏电池组件温度随着风速的增加不断减小，因此在太阳辐射照度恒定的条件下，发电效率增加，使得电输出功率增加。因此风速的增加对于光伏电池组件的性能产生的是正影响，特别是在低温环境下。

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

控制条件下单因素影响研究Study on single factor influence under control conditions



Relationship between single factor of ambient temperature and component temperature and power generation efficiency



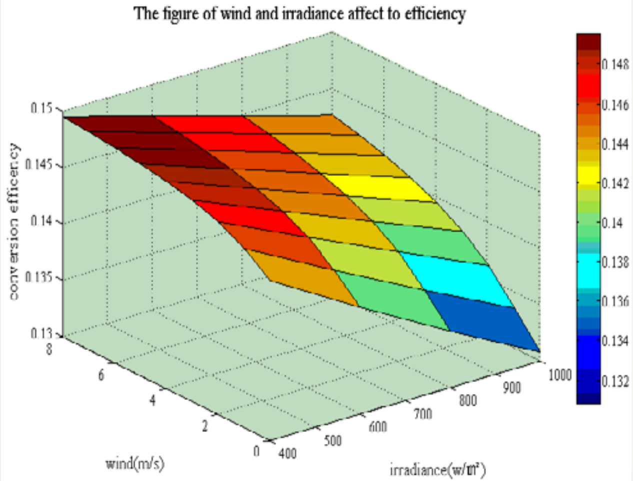
Relationship between single factor of wind speed and TC, convective heat transfer coefficient and unit output power

The operating temperature of a photovoltaic cell module rises linearly with the ambient temperature, in contrast to the linear decrease in power generation efficiency with ambient temperature. The increase in ambient temperature has a major negative impact on the performance of photovoltaic modules.

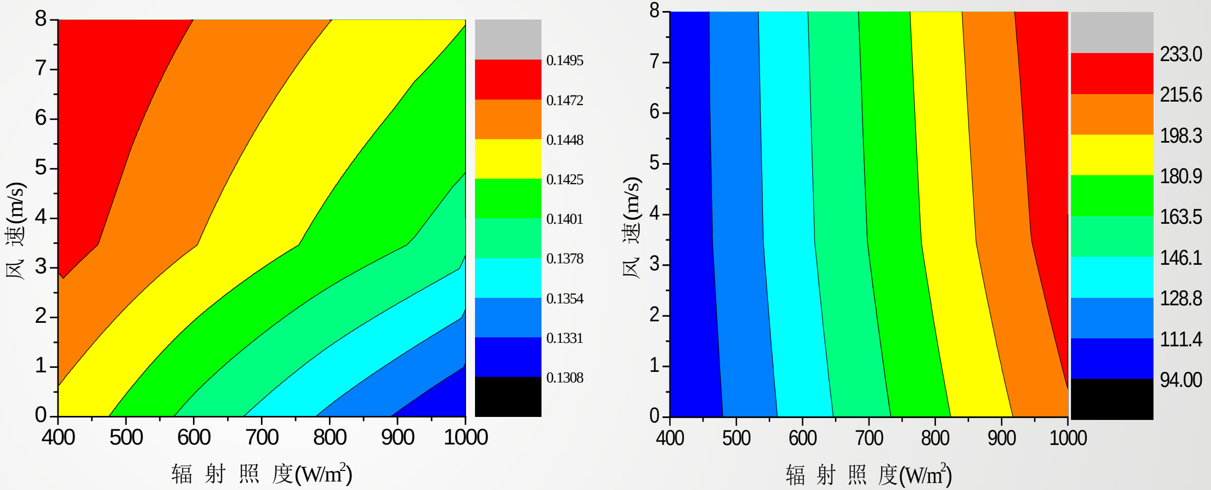
The temperature of the photovoltaic cell module decreases as the wind speed increases, so that under the condition that the solar irradiance is constant, the power generation efficiency increases, so that the electric output power increases. Therefore, the increase in wind speed has a positive impact on the performance of photovoltaic modules, especially in low temperature environments.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

辐射照度与风速共同作用的影响研究Study on the influence of radiance and wind speed



太阳辐射照度与风速共同影响下发电效率三维mesh图



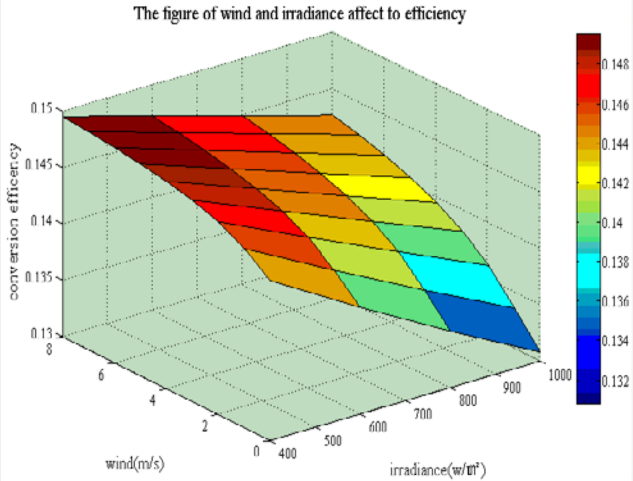
太阳辐射照度与风速共同影响下发电效率和电输出功率变化等值图

上图表明，发电效率在高辐射照度低风速条件下最低，而在低辐射照度高风速条件下最高，与单因素影响条件下的规律是相符合的。

上图表明，在低风速阶段，随着太阳辐射照度的增强，光伏电池组件的发电效率的衰减很快，而在高风速条件下发电效率的衰减很慢。在电输出功率变化上同样也发现了这个现象，在4m/s的风速下，电输出功率的等值线出现了明显的拐角。

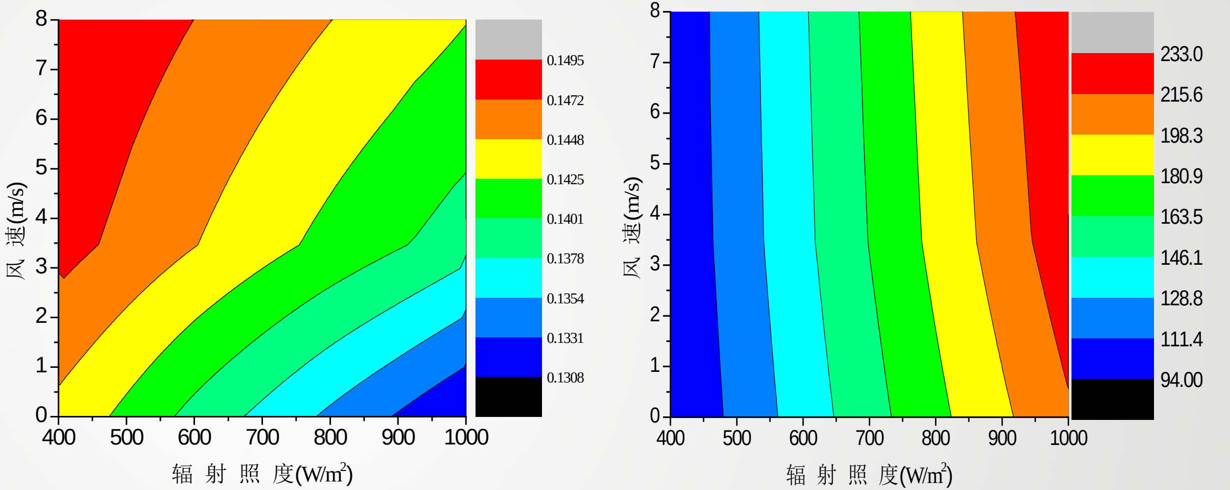
环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

辐射照度与风速共同作用的影响研究Study on the influence of radiance and wind speed



3D mesh map of power generation efficiency under the influence of solar irradiance and wind speed

The power generation efficiency is the lowest under the condition of high irradiance and low wind speed, and the highest under the condition of low irradiance and high wind speed, which is consistent with the law under the single factor influence condition.



Equivalent diagram of power generation efficiency and electric output power under the influence of solar irradiance and wind speed

In the low wind speed phase, as the solar irradiance increases, the power generation efficiency of the photovoltaic cell module decays rapidly, while the power generation efficiency decays slowly under high wind speed conditions. This phenomenon was also found in the change in electrical output power. At a wind speed of 4 m/s, the contour of the electrical output power showed a sharp corner.

环境因素对空载电池组件温度影响的数值模拟——稳态工况风速、风向对单列组件影响的数值分析

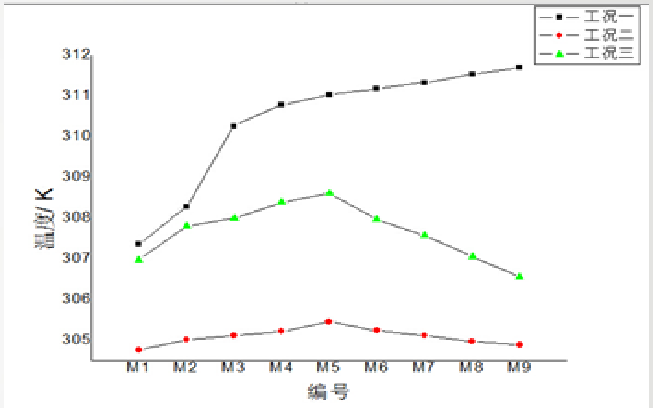
工况设置条件对比表

工况编号	工况一	工况二	工况三	工况四
风向	西北风	正南风	正北风	西北风
方向向量（X,Y,Z）	（0.996118,0,0.088025）	（0,0，-1）	（0,0，1）	（0.996118,0,0.088025）
风速（m/s）	1.17	1.17	1.17	0.3

工况一与工况四光伏组件温度值

编号	S41	S42	S43	S44	S45	S46	S47	S48	S49
工况一平均温度（K）	307.35	308.27	310.26	310.77	311.03	311.17	311.32	311.52	311.69
工况四平均温度（K）	309.24	311.38	311.77	311.75	311.75	311.65	311.48	311.55	311.45

由上表可以看出，在风向相同的情况下，受风速影响，工况一的光伏组件的散热好于工况四的光伏组件。



相同风速工况条件下组件温度值对比图

上图表明，在风速相同的情况下，不同风向对光伏组件温度分布有着直接影响。

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

Numerical Simulation of the Influence of Environmental Factors on the Temperature of No-load Battery Packs——Numerical Analysis of Influence of Wind Speed and Wind Direction on Single-column Components in Steady Operating Conditions

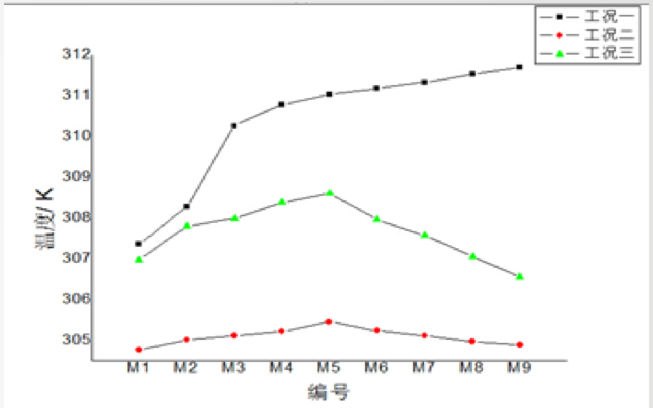
Working condition setting condition comparison table

工况编号	工况一	工况二	工况三	工况四
风向	西北风	正南风	正北风	西北风
方向向量（X,Y,Z）	（0.996118,0,0.088025）	（0,0，-1）	（0,0，1）	（0.996118,0,0.088025）
风速（m/s）	1.17	1.17	1.17	0.3

Working condition 1 and working condition 4 photovoltaic module temperature value

编号	S41	S42	S43	S44	S45	S46	S47	S48	S49
工况一平均温度（K）	307.35	308.27	310.26	310.77	311.03	311.17	311.32	311.52	311.69
工况四平均温度（K）	309.24	311.38	311.77	311.75	311.75	311.65	311.48	311.55	311.45

In the case of the same wind direction, due to the wind speed, the heat dissipation of the PV module of the working condition is better than that of the PV module of the working condition.

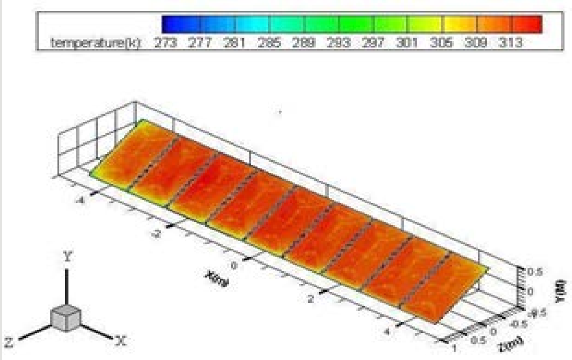


Comparison of component temperature values under the same wind speed conditions

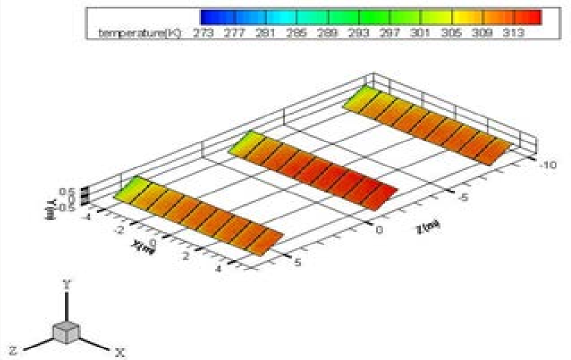
At the same wind speed, different wind directions have a direct impact on the temperature distribution of the PV modules.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

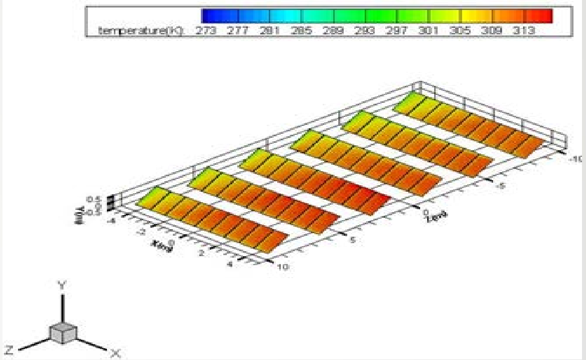
环境因素对空载电池组件温度影响的数值模拟——稳态工况风速、风向对多列组件影响的数值分析



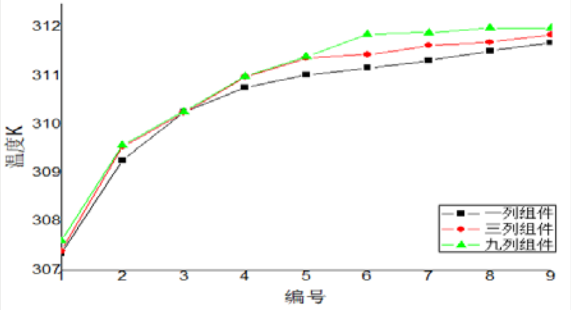
单列光伏组件温度分布图



三列光伏组件温度分布图



六列光伏组件温度分布图

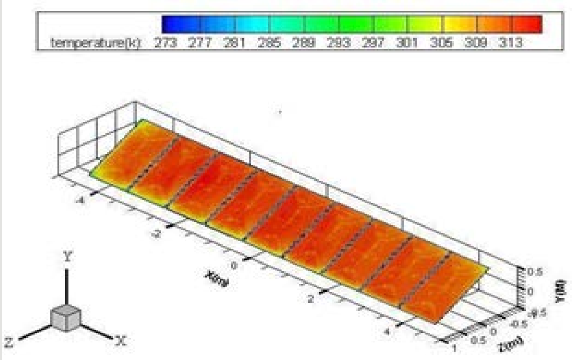


三种工况温度值对比图光伏组件温度值对比图

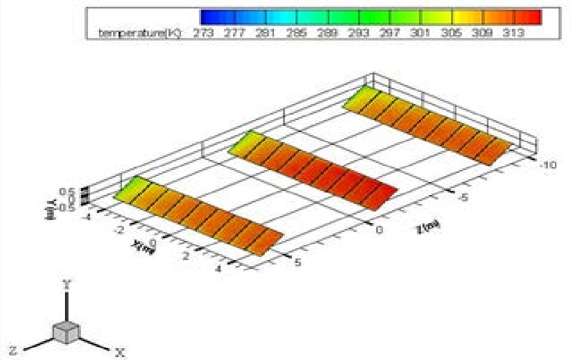
结论：通过对比不同列数的光伏阵列温度分布，对东西布置、南北布置光伏组件温度数据进行分析研究，得到在东西方向布置的光伏组件因为与空气换热，当受到风速及风向的影响下，下风向的对流换热性会被减弱的结论；而在南北方向布置的光伏组件，由于列与列之间的换热影响，处于中间位置的光伏组件温度高于两侧的光伏组件温度。因此，建议布置光伏组件阵列时，尽可能的减小东西方向的布置长度；同时，在布置占地面积允许的情况下，尽可能的加大光伏阵列列与列之间的间距，以减少并网发电时，由于各个光伏组件性能工况的不同所造成的互联效应的影响。

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

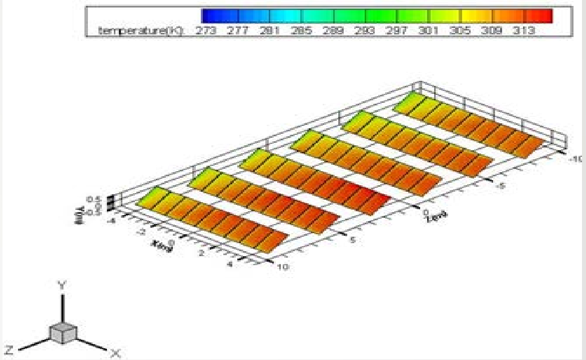
Numerical Simulation of the Influence of Environmental Factors on the Temperature of No-load Battery Packs——Numerical Analysis of Influence of Wind Speed and Wind Direction on Multiple-column Components in Steady Operating Conditions



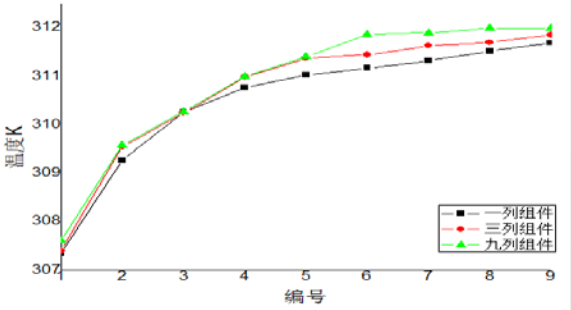
Single row



Three columns



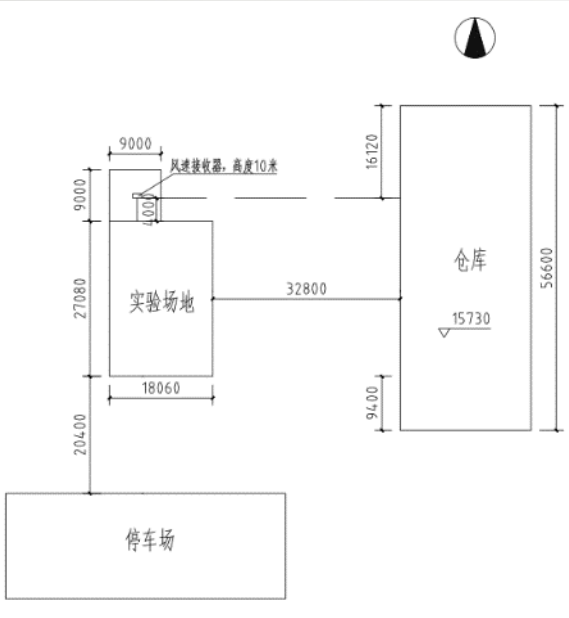
Six columns



Comparison of temperature values of three working conditions

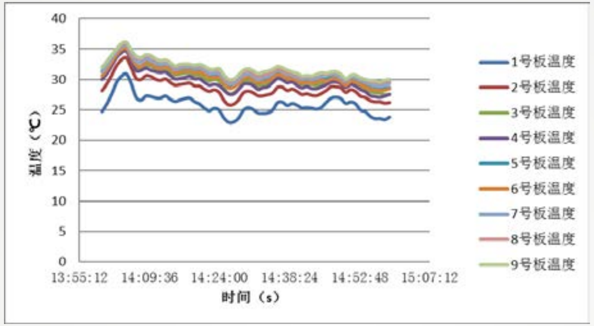
Conclusion: By comparing the temperature distribution of PV arrays with different columns, the temperature data of PV modules in east-west layout and north-south layout are analyzed. It is obtained that the PV modules arranged in the east-west direction are affected by wind speed and wind direction due to heat exchange with air. The convective heat transfer of the downwind direction will be weakened; while the PV modules arranged in the north-south direction, due to the heat transfer between the columns and columns, the temperature of the photovoltaic module in the middle position is higher than the temperature of the photovoltaic modules on both sides. Therefore, it is recommended to reduce the arrangement length of the east-west direction as much as possible when arranging the photovoltaic module array; at the same time, as far as the layout area is allowed, increase the spacing between the columns and columns of the photovoltaic array as much as possible to reduce When the network is generating electricity, the interconnection effect is caused by the difference in performance conditions of various photovoltaic modules.

光伏组件换热与光伏阵列布置之间关系的试验研究——光伏阵列对光伏组件换热的试验研究

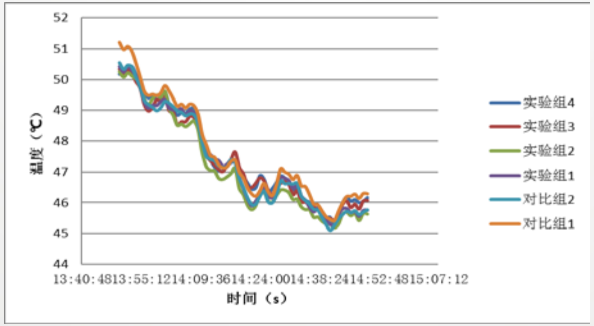


实验场地与周边建筑相对位置图

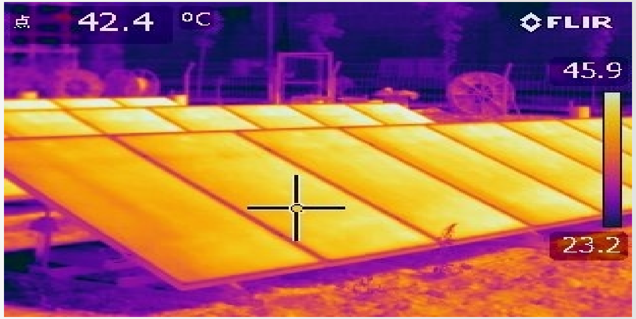
上述分析所采用的数据为太阳能电池组件为非运行且安装倾角均为30°的工况。



图西风情况下1～9号板温度对比图



北风情况下光伏组中心板中心点温度对比图



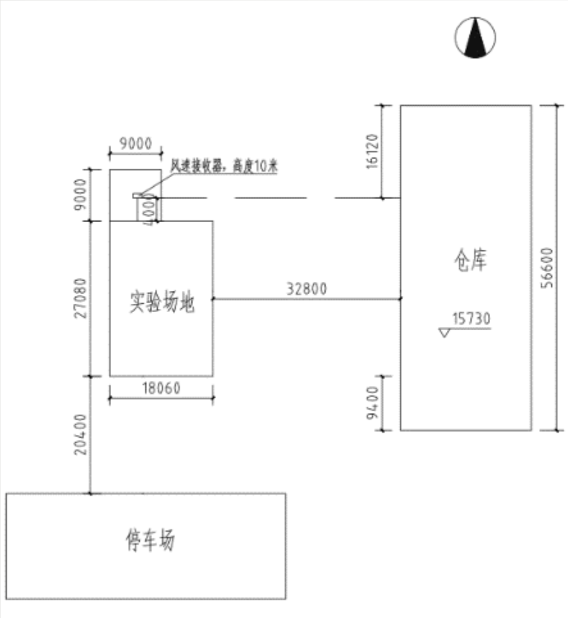
红外热像仪拍摄的整场热像图

从上图可以看出，对在不同的时刻，总是西边的板温度低，处于东边板的温度高，即1号板温度最低，9号板温度最高，电池板温度由西向东逐渐升高。这种温差的变化是由西向东逐渐变小的。

对南北横向排开的阵列，北风对各组温度的影响没有规律性。由于在试验数据中没有南风的较稳定的工况，因此南风的影响就不讨论了。

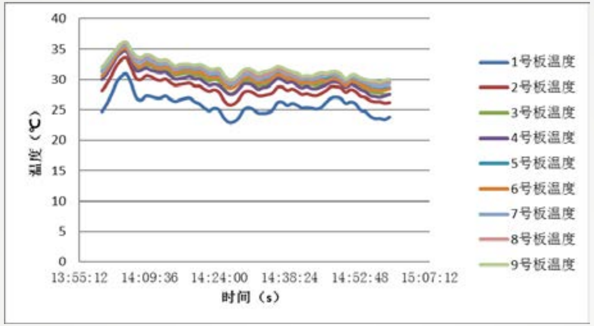
环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

Experimental study on the relationship between heat transfer of photovoltaic modules and photovoltaic array layout——Experimental study on heat transfer of photovoltaic modules by photovoltaic arrays

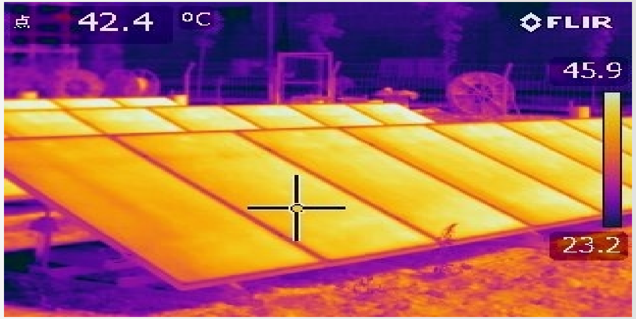


Relative position map of experimental site and surrounding buildings

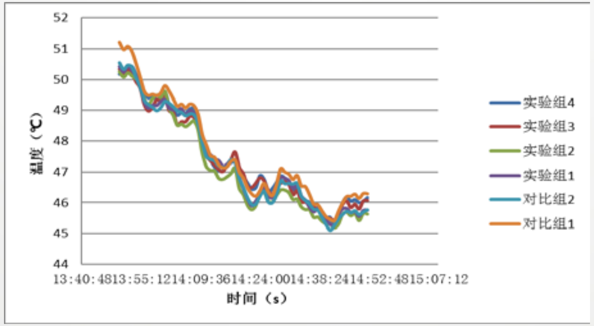
上述分析所采用的数据为太阳能电池组件为非运行且安装倾角均为30° 的工况。



West wind ,No.1～9 Plate temperature comparison chart



The whole thermal image taken by the infrared camera



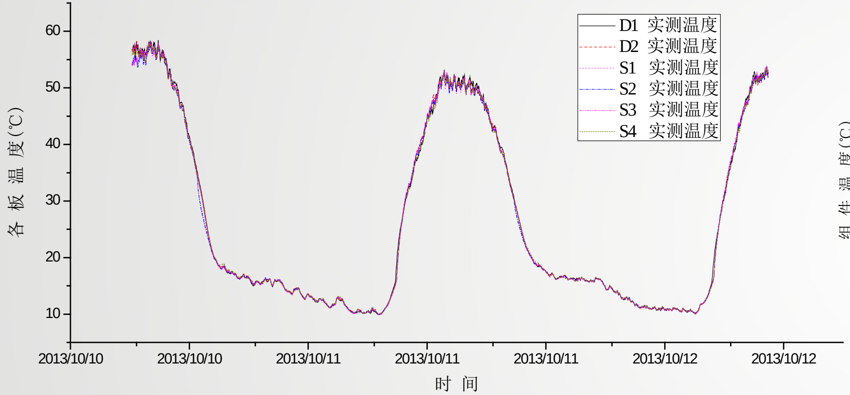
Temperature comparison diagram of center point of photovoltaic center plate under north wind

At different times, the temperature of the plate in the west is always low, and the temperature in the east plate is high, that is, the temperature of the No. 1 plate is the lowest, the temperature of the No. 9 plate is the highest, and the temperature of the panel gradually increases from west to east. This change in temperature difference is gradually decreasing from west to east.

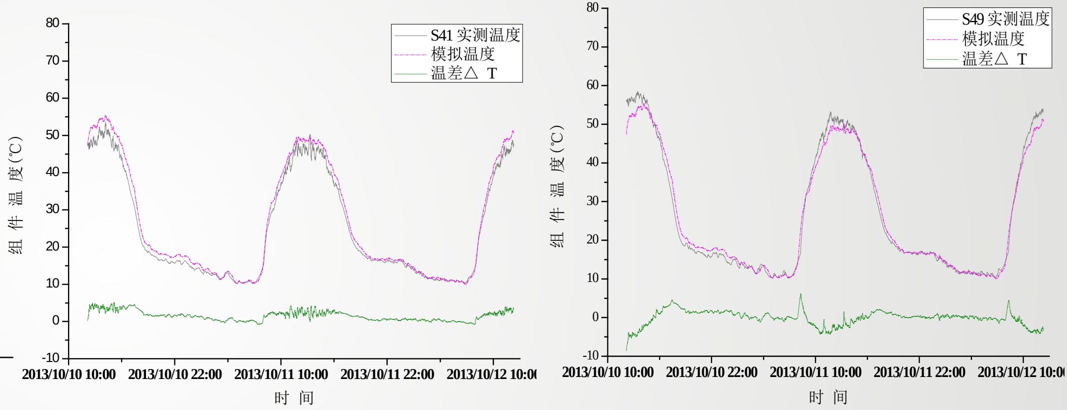
For the array of horizontally arranged north and south, the influence of north wind on the temperature of each group is not regular. Since there is no relatively stable working condition of the southerly wind in the test data, the influence of the southerly wind will not be discussed.

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

光伏组件换热与光伏阵列布置之间关系的试验研究——光伏阵列对光伏组件换热的理论与试验对比



2013年10月10日-12日南北布置的各板上实测温度数据对比图



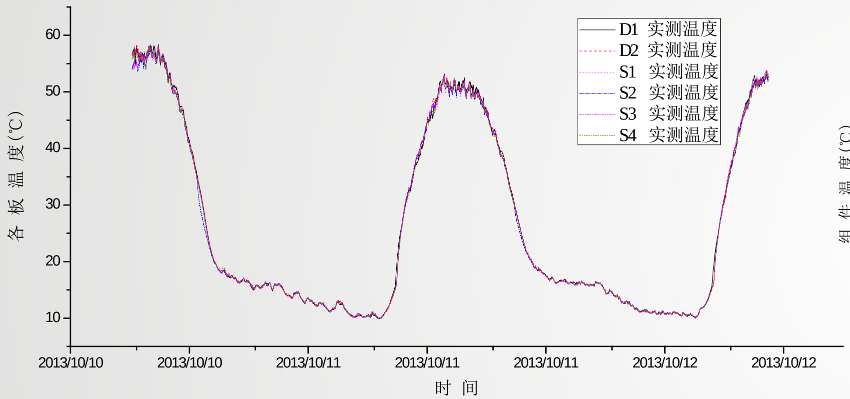
2013年10月10日-12日模拟数据与西边S41和东边S49组件实测数据对比图

从上图可以看出，各光伏电池板的温度数据完全吻合，细微的差别都在精度范围以内，因此可以肯定本次项目的南北布置几乎不会对各光伏电池板之间的热性能产生影响。

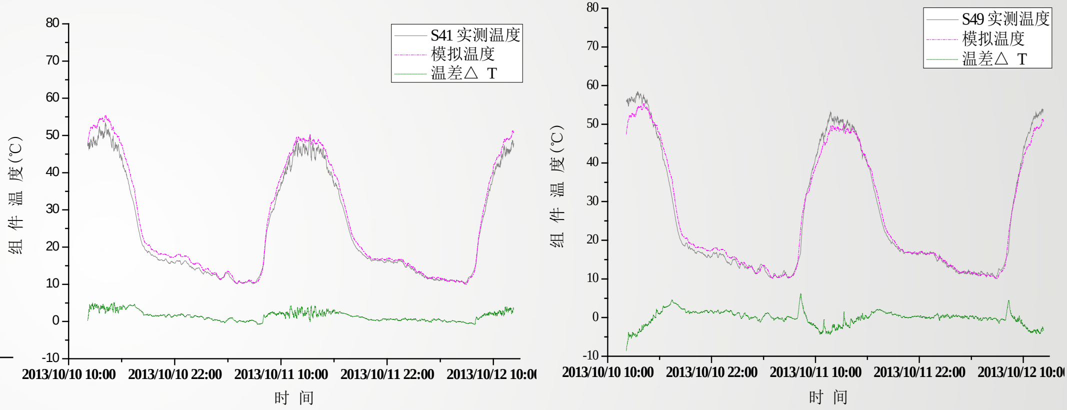
从上图可以看出，板上东西布置的光伏电池组件因为会与空气换热，当受到风速及风向的影响，在光伏电池组件的工作温度上升阶段处于下风向的光伏电池组件的对流换热性会被能减弱

环境因素对组件影响的试验研究Experimental study on the influence of environmental factors on components

Experimental study on the relationship between heat transfer of photovoltaic modules and photovoltaic array layout——
Theoretical and experimental comparison of photovoltaic arrays for heat transfer of photovoltaic modules



Comparison chart of measured temperature data on each board arranged in the north and south on Oct.10-12, 2013



Comparison of simulated data between West S41 and East S49 components, Oct.10-12, 2013

The temperature data of each photovoltaic panel is completely consistent, and the subtle differences are within the accuracy range. Therefore, it can be confirmed that the north-south arrangement of this project will hardly affect the thermal performance between the photovoltaic panels.

The photovoltaic cell components arranged on the board are heat exchanged with the air. When subjected to the wind speed and wind direction, the convective heat transfer of the photovoltaic cell module in the downwind direction during the rising temperature of the photovoltaic cell module can be weakened.

主要结论Main conclusion

1、试验研究Experimental Research

（1）太阳能组件的热响应基本没有滞后性。

The thermal response of the solar module is essentially free of hysteresis.

（2）有、无灰尘覆盖组件之间的温差随辐射强度的降低而缓慢降低；另外，当风速小的时候，温差大，风速较大时，温差小。

The temperature difference between the components with or without dust covers slowly decreases with the decrease of the radiation intensity; in addition, when the wind speed is small, the temperature difference is large, and when the wind speed is large, the temperature difference is small.

（3）灰尘的覆盖，对光伏组件发电量有很大的影响，灰尘密度越大，发电量下降越多。建议清理周期定为一周为宜（要视当地空气质量）。

The coverage of dust has a great influence on the power generation of photovoltaic modules. The higher the dust density, the more the power generation decreases. It is recommended that the cleaning cycle be set to one week (depending on local air quality).

（4）南北向光伏组件是处于同一气流组织下的，即可以不考虑南风、北风对光伏组件的影响。

The north-south PV modules are under the same airflow organization, that is, the influence of the southerly wind and the north wind on the photovoltaic modules can be ignored.

（5）当组件温度远大于环境温度时，组件正面的气流波动大于背面，使得太阳能电池组件的正面温度低于背面温度。

When the component temperature is much greater than the ambient temperature, the airflow on the front side of the component fluctuates more than the backside, so that the front surface temperature of the solar cell module is lower than the back surface temperature.

（6）组件的温度变化规律与太阳辐射的变化规律相同；在太阳辐射一定的情况下，环境温度和组件温度成正比关系（负载工况）；在太阳辐射和环境温度一定的情况下，风速能够降低组件温度；电池组件的温度制约着组件的发电量。

The temperature variation of the component is the same as that of solar radiation; in the case of certain solar radiation, the ambient temperature is proportional to the component temperature (loading condition); when the solar radiation and the ambient temperature are constant, the wind speed can reduce the component. Temperature; the temperature of the battery pack limits the amount of power generated by the component.

主要结论Main conclusion

2、理论研究Theoretical research

通过建立了可用于工程实践的综合考虑各类环境因素影响的电池组件温度与发电量关联的解析模型，其分析结果同上述实验结果相吻合。

Through the establishment of an analytical model that can be used in engineering practice to comprehensively consider the influence of various environmental factors on the temperature of the battery component and the amount of power generation, the analysis results are consistent with the above experimental results.

3、数值研究Numerical study

（1）在风速一定时，不同风向对光伏组件温度分布影响效果明显，当光伏组件正面，即玻璃面为迎风侧时，组件自身散热较好；当风向一定时，风速越大越有利于光伏组件与空气之间的对流换热，散热效果也越明显。

When the wind speed is constant, the influence of different wind directions on the temperature distribution of the PV module is obvious. When the PV module is on the front side, that is, the glass surface is on the windward side, the component itself has better heat dissipation; when the wind direction is constant, the wind speed is more favorable for the PV module and the air. The convection heat transfer between the two, the more obvious the heat dissipation effect.

（2）通过建立不同阵列数的光伏组件数值模拟模型，其结果表明列与列之间的光伏组件存在相互影响，因此，建议在南北侧在占地面积允许的可能下，尽可能增加光伏组件列与列之间的距离，提高光伏阵列整体散热性。

By establishing a numerical simulation model of PV modules with different array numbers, the results show that the PV modules between the columns and columns have mutual influence. Therefore, it is recommended to increase the PV module columns and columns as much as possible under the permission of the north and south sides. The distance between them improves the overall heat dissipation of the photovoltaic array.

04 精细化设计与系统效率提升

Refined design and system efficiency

什么是精细化设计

精细化
streamline

精refinement

技术先进、功能完善、安全美观，与业主要求和法律法规要求符合性较好，经济指标达到先进水平。
Advanced technology, perfect function, safe and beautiful.

细meticulousness

关注细部设计，表达充分完善，绘图规范、细致、完成度高、统一性好，专业间矛盾少，设计深度满足要求。
Pay attention to detail design and fully express

利用计算和分析工具帮助我们从设计上做出更多的方案比选，从而达到一个更好的设计效果。

Using calculation and analysis tools to help us make more choices in design, so as to achieve a better design effect.

为什么要精细化设计

01 节约集约化用地Saving intensive land

为了提高收益率，光伏电站精细化设计成为必然趋势。国土资源部《光伏发电站工程项目用地控制指标》（国土资规〔2015〕11号）、《国家能源局、工业和信息化部、国家认监委关于提高主要光伏产品技术指标并加强监管工作的通知》（国能发新能〔2017〕32号）等文件都反映了土地的节约集约利用。

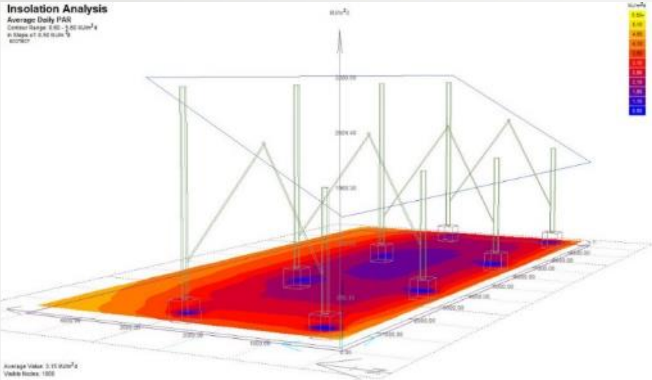
02 提升电站投资收益Increase the investment income of power stations

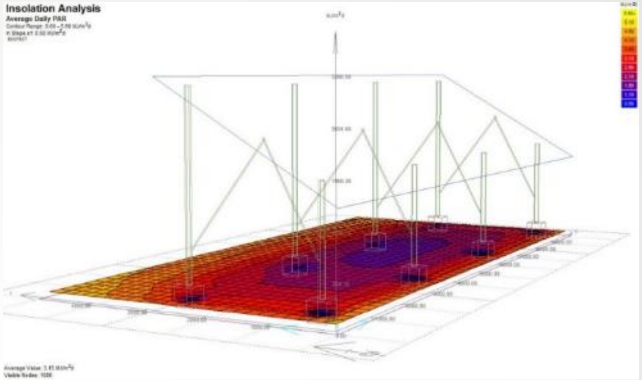
在领跑基地效应的带动下，我国光伏行业技术水平快速提高，产业链日渐成熟，上网电价不断降低，光伏投资的微利时代正在一步步到来，若要提高电站的经济性，就必须不断创新，通过精细化设计达到降本增效的目的。

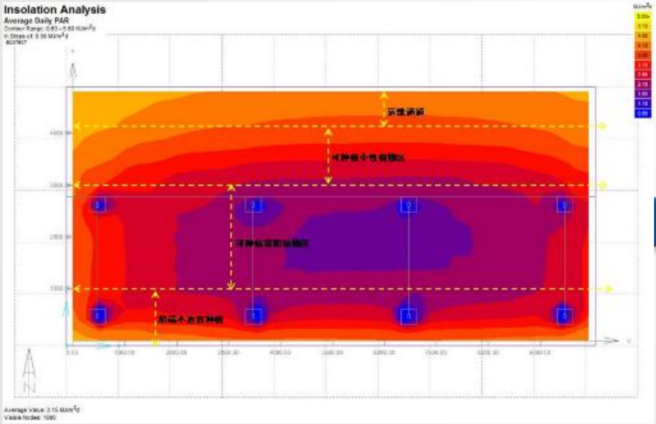
03 定制化与友好型设计Customized and friendly design

光伏发电与农业、养殖业、生态治理等各种产业融合发展模式也在不断创新，进入了多元化、规模化发展的新阶段。在未来的设计中要更加注重考虑到拆除对环境的影响以及完善的环境管理方式，可有效的避免电站的建设给环境带来负担。

为什么要精细化设计

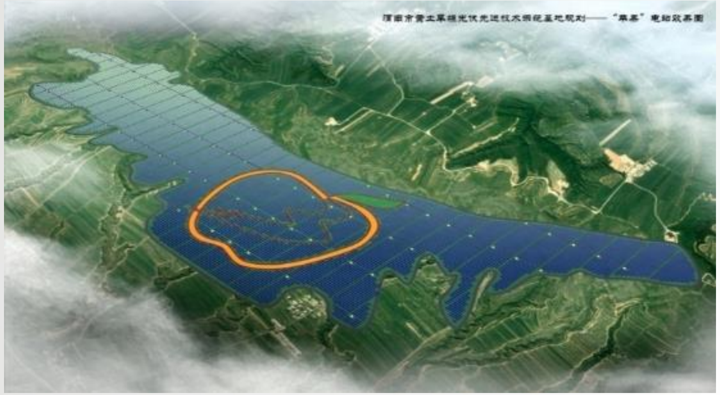






光伏组串下光环境仿真Photovoltaic simulation of photovoltaic string

为什么要精细化设计



光伏入画、艺术光伏Art photovoltaic

精细化设计做什么

01 资源评估 Resource assessment

02 方案优化 Program optimization

03 节约投资 saving investment

资源高效利用Resource efficient use

继续加强测光站的建设

建立完整年太阳能资源和环境因素的精细化评估体系

提高系统效率Improve system efficiency

保证稳定的高额回报

挖掘更多地区的开发价值

实现平价上网，扩大装机规模

优化方案Optimization

设计阶段的方案优化对整个工程造价的优化占比可达85%

以设计为龙头的EPC优化效果更加明显

衡量电站吸性能的标准：PR（Performance Ratio）

IEC 61724（1）给出的定义： $PR_T = \frac{E_T}{P_e \cdot h_T} = \frac{1}{P_e} \cdot \frac{E_T}{h_T}$

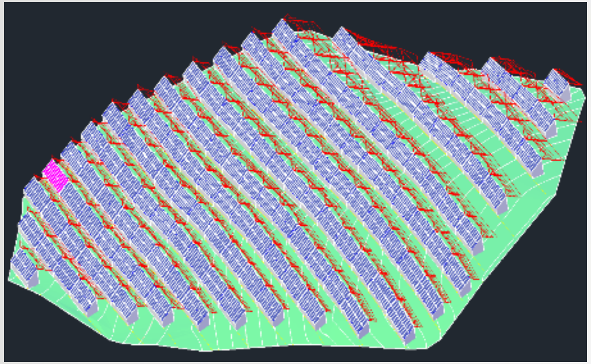
PR_T：在T时间内电站的平均系统效率

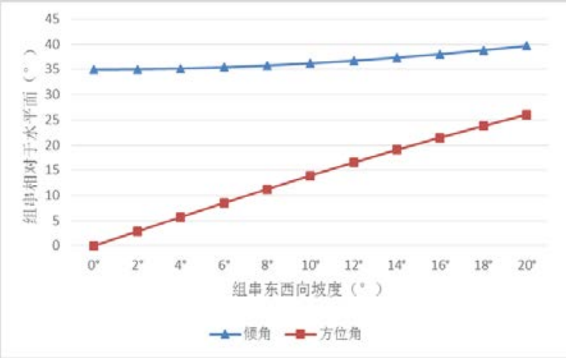
E_T：在T时间内电站输入电网的电量

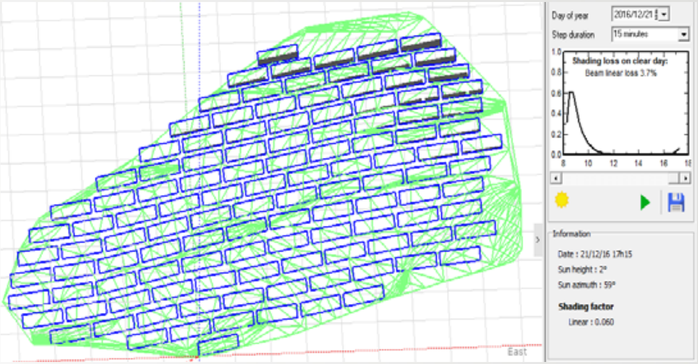
P_e：电站组件装机的标称容量

h_T：在T时间内阵列面上的峰值日照时数

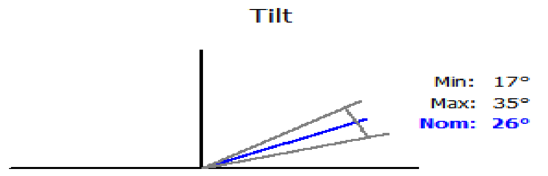
由于由于太阳辐射和环境因素是时刻变化的，这样光伏电站在一天内的不同时段，和一年内的不同季节所体现的系统效率会有很大的差异，但是从外部环境因素的周期性来看，光伏电站1年内的系统效率更能反映真实的性能，因此通常以年平均值来衡量电站的系统效率。

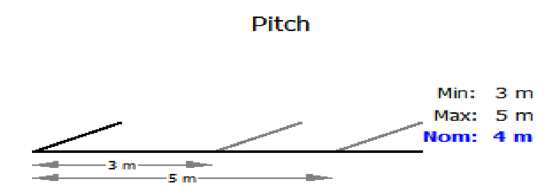


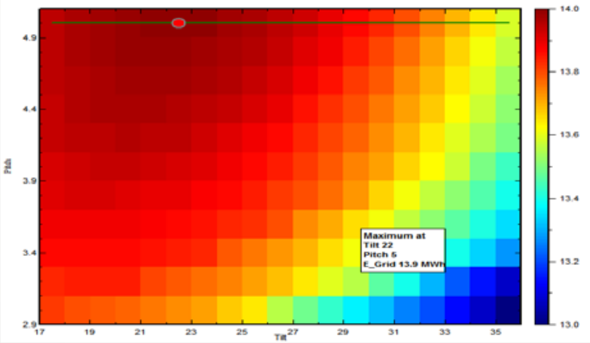




变间距和辐射量分析优化Variable pitch and radiation analysis optimization







间距和倾角同时优化

Simultaneous optimization of pitch and inclination

$$PR_T = \frac{1}{P_e} \cdot \frac{E_T}{h_T}$$

PR_T增大

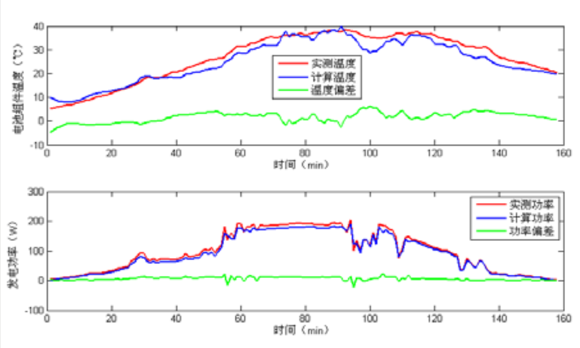
$$PR_T = \frac{1}{P_e} \cdot \frac{E_T}{h_T}$$

PR_T增大

温度损失

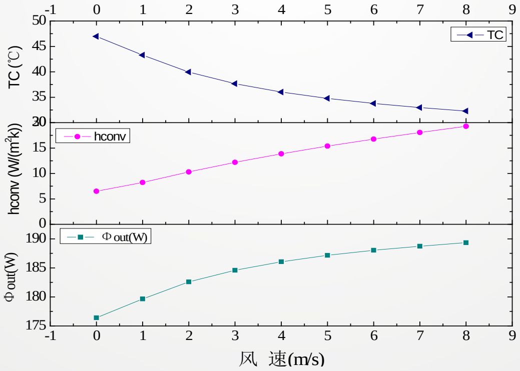
温度升高不改变光伏阵列面上峰值日照时数，它直接影响着电站的发电量，而且温度是对发电量影响最大的因素之一。合理优化由于电站总平面布置所造成的组件热性能影响。目的就是增强电站对流换热性能，降低组件温度，提高电站发电量和系统效率。

The increase in temperature does not change the peak sunshine hours on the PV array. It directly affects the power generation of the power station, and temperature is one of the factors that have the greatest impact on power generation. Reasonably optimize the thermal performance of the components due to the general layout of the power station. The purpose is to enhance the convective heat transfer performance of the power station, reduce the temperature of the components, and increase the power generation capacity and system efficiency of the power station.



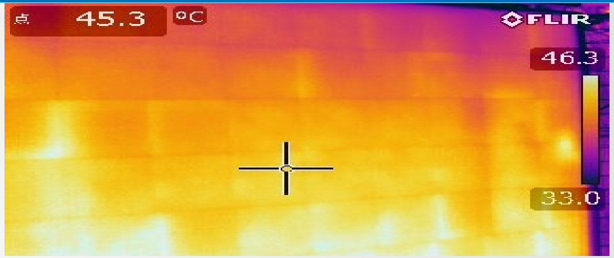
组件温度与发电量计算模型

Component temperature and power generation calculation model

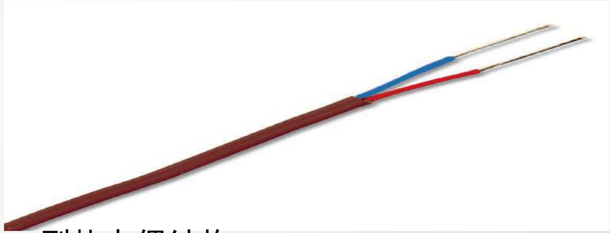


风速与环境温度、对流换热、输出功率关系

Wind speed and ambient temperature, convective heat transfer, output power relationship



组件热成像图Component thermography



T型热电偶结构T-type thermocouple structure

组件背板测温Component back panel temperature measurement

05 结语

Conclusion

结语

通过领跑计划和平价示范基地的实施，太阳能在经历规模化发展、技术创新、电力系统以及其它支撑技术的进步后，将从补充能源过渡为替代能源，并逐步成为低碳、可持续、价格低的能源体系的主力之一。

“风光电创造清洁能源，设计引领绿色未来”，中国电建集团西北勘测设计研究院有限公司将借助自身的技术实力和开拓进取的精神，不断发挥设计的龙头和引领作用，致力于为我国乃至世界风能、太阳能等可再生能源开发利用做出新的贡献！

Through the implementation of the lead-running plan and the demonstration base, solar energy will transform from supplementary energy to alternative energy after experiencing large-scale development, technological innovation, power system and other supporting technologies, and gradually become low-carbon, sustainable and low-priced. One of the main forces of the energy system.

“Wind and Light creates clean energy and design leads the green future” . China Electric Power Construction Group Northwest Survey and Design Institute Co., Ltd. will continue to give play to the leading and leading role of design with its own technical strength and pioneering spirit, and is committed to China and even New contributions to the development and utilization of renewable energy such as wind energy and solar energy in the world!

诚信为先 创新为魂 共赢为本
Integrity Innovation All-Win

中国电建
POWERCHINA

西北勘测设计研究院有限公司
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感谢您的聆听

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