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聚光光伏

——原理、系统与应用

Concentrator Photovoltaics

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内容提要

低成本的太阳能发电技术一直是国内外的研究热点，聚光光伏通过采用低成本的聚光跟踪装置替代昂贵的太阳电池，具有大幅度降低光伏发电成本的潜力。本书全面介绍了国际聚光光伏的发展历程、现状与前景，论述了聚光光伏系统与关键单元技术的基础理论，并系统介绍了国际知名科研机构与企业在商业化发展中所做的工作。“中国的聚光光伏发展”一章补充论述了国内聚光光伏技术和产业的发展情况。

本书可供从事光伏尤其从事聚光光伏发电的科研、开发及应用方面的工程技术人员参考，也可供大专院校教学使用。

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译　序　1

规模化的聚光光伏发电技术可成为提供经济太阳能电力的重要途径。它利用了太阳能热发电的聚光技术和平板光伏的电池技术。由于集成了这两种太阳能工业中最好的技术，聚光光伏才有机会进一步推动太阳能发电技术的发展。

Concentrator Photovoltaics 一书涵盖了聚光光伏发展过程中的部分工作。多种聚光形式都在发展之中，如中央聚光太阳塔、碟式聚光、菲涅尔透镜聚光和线性聚光。聚光光伏系统可安装在任何拥有高直散比的地方。而且，聚光器使得高效昂贵的太阳电池的使用变得经济。在澳大利亚国立大学我们在置于建筑屋顶的线性微聚光器的焦斑处放置高效硅太阳电池，用来提供太阳热和电力，这些内容我已写入本书的第3章“聚光硅太阳电池”。

我们可以看到，聚光光伏在快速发展，许多研究者和企业都在加入这个领域。中国、澳大利亚、西班牙、美国和其他国家都在建设规模可观的示范系统。新的产品和制造企业在不断涌现。中国有着太阳能资源丰富的广袤的西部地区，对于开发利用聚光光伏有着得天独厚的条件。这个潜力反映在不断发展壮大的聚光光伏研究和商业开发中。所以，当该书的译者朱丽博士提出为这本 *Concentrator Photovoltaics* 出中文译本的时候，我给予了大力的支持。新的一章“中国的聚光光伏发展”的编写无疑将增加这本书的指导意义。我想这份工作会对中国的聚光光伏的发展起到不可忽视的推动作用。本书将使得中国读者知晓聚光光伏的发展历史、现状和趋势。它同时会提供给中国读者更多的有关聚光光伏系统和单元组成的知识。中国在聚光光伏领域的巨大进步将激励他们更加努力地投入聚光光伏的工作当中。

我于2006年认识本书译者朱丽，那时我们开始了第一个国际合作项目——亚太清洁发展和气候伙伴计划合作项目，一起对新型高效聚光光伏系统进行研究。继而我们又成功合作了中澳特别合作资金项目。她对聚光光伏的热情让我相信这本中文译著将会成为中国科研工作者和企业人员手中一本很好的参考书。我希望她的努力会给中国聚光光伏的发展做出贡献。

Andrew Blakers

Foreword 1

Concentrator photovoltaics (CPV) could be an important avenue for solar electricity to become economical in mass production. It shares the technology of solar concentration with the solar thermal industry, and the technology of photovoltaic (PV) solar conversion with the conventional non-concentrator PV industry. Drawing from and combining the best from both industries creates an opportunity to further diversify the sources of solar electricity.

The book *Concentrator Photovoltaics* covers some of the work being contributed to the development of CPV. Many different forms are under development including central receiver-heliostat fields, parabolic dishes, Fresnel lens concentrators and linear concentrators. Location of CPV systems can be anywhere that has a high proportion of direct beam sunlight. In particular, concentrators allow the economical use of highly efficient (albeit expensive) solar cells. At the Australian National University our focus is on the use of highly efficient silicon solar cells at the focus of linear micro concentrators for the production of both solar heat and solar electricity on the building roofs. Hence, in Chapter 3 I wrote about "Silicon Concentrator Solar Cells".

CPV is developing very fast, and we see many researchers and entrepreneurs joining this field. Substantial demonstration systems are being established in China, Australia, Spain, the USA and elsewhere, and products and companies are emerging. China, with its vast sunny arid regions in the west, has excellent prospects for CPV. This potential is reflected in the rise of Chinese research and commercial engagement in CPV. However, Chinese language guidebooks and references are very limited. So, when Dr. Li Zhu, the translator of this book, asked me to support her in providing the Chinese language version of *Concentrator Photovoltaics*, I gave my full support since this would be a great contribution to the development of CPV in China. The addition of one more chapter addressing the development of CPV in China is significant. The Chinese version of *Concentrator Photovoltaics* will inform Chinese readers of the history, state-of-the-art, and development trends in CPV. It will also give more knowledge of CPV system and components to Chinese readers. The great progress made in their own country is summarized in the new chapter "CPV in China" will encourage and attract Chinese researchers to devote time and energy to CPV work.

I have known Li since our first collaboration in an Asia-Pacific Partnership on Clean Development and Climate project in 2006. We have further collaborated through the China-Australia Special Fund project. Her enthusiasm for CPV makes me believe that this translated version will be a good guidebook for Chinese researchers and entrepreneurs, and worth the considerable translation effort. I hope that Li's efforts in providing the translated version of *Concentrator Photovoltaics* can make contributions to the development of CPV in China.

A Blakers

Andrew Blakers

Foreword

译 序 2

自第一个现代光伏聚光系统在桑迪亚国家实验室被制作出来，聚光光伏技术已历经了30多年的发展。经历了几次因石油市场而引起的波动后，由于政策上的支持和技术上的突破，如高效率的Ⅲ-Ⅴ族多结电池的出现，现在聚光光伏已经做好了起飞和快速成长的准备。因为聚光光伏是解决平板光伏面临的硅原料短缺问题的有效途径，欧盟积极支持该项技术的发展。阳光充足的西班牙自1976年就已经展开了聚光光伏技术方面的工作，成果深受关注，目前在该领域取得了突出的地位。我们在西班牙马德里理工大学的国际太阳能中心（IES-UPM）很早就已经致力于聚光光伏系统的开发。一些工作被整理在本书的第13章“欧几里德（EUCLIDES）聚光光伏系统”，这是由欧盟资助的世界上第一个也是最大的聚光光伏示范工程。现在我们正继续采用更高效的太阳电池和更好的聚光技术开展聚光光伏系统方面的工作。

自2009年，中国已经取得了平板光伏领域国际领先者的位置，它的平板光伏的制造量和安装量都处于世界第一。可是很长一段时间内，中国在聚光光伏领域是沉寂的。幸运的是，近期由于政府的支持和研究者的热忱，聚光光伏在中国迎来了其快速发展的特殊时刻。很多积极的因素已在合力促进产业化和商业化活动的起步。中国国内市场的聚光太阳电池的效率已达到38%以上。已有好几家公司进入市场，并且其他公司也宣布即将进入。兆瓦级高倍聚光光伏示范电站已经建造。世界知名的聚光光伏公司，比如EMCORE，AMONIX，SOITEC和ISOFOTON已经进入中国市场，并在当地组建了一些新公司来生产太阳电池和聚光光伏系统。所有这些都展示了聚光光伏产品在中国的繁荣发展。

作为聚光光伏的先驱和倡导者，看到中国的这些积极变化令我非常高兴，因为这些变化会对聚光光伏在世界上的地位产生巨大贡献。然而聚光光伏方面的中文参考书的缺乏会降低对这方面感兴趣的人们的热情。因此，将*Concentrator Photovoltaics*这本书翻译成中文是一件明智的事情。朱丽博士是一个对自己感兴趣的事物很专注的人，因此我相信她所做的努力会使得本书成为一本优秀的中国聚光光伏从业者的指导书。

马德里，2012年1月1日

加布里埃尔·萨拉（Gabriel Sala）

Concentrator photovoltaics have been developed for over 30 years since the first modern PV concentrator was made at Sandia National Laboratories. After several times fluctuation caused by oil market, now the concentrator photovoltaic seems ready to take off and grow rapidly because of policy support and technology breakthroughs like very high efficiency III-V multi-junction cells. European Commission has been very active in supporting the development of CPV since it is an effective way solving the problem of silicon feedstock shortage being faced by flat PV panels. Because of its sunny climate, Spain has worked on photovoltaic concentration technology since 1976 and the country has attained an outstanding and well regarded position for this work. Our center IES-UPM has been devoted to the development of concentrator since a very early time. Some of the relevant work was given in Chapter 13 "The EUCLIDES Concentrator", the first and biggest CPV demonstration project in the world and funded by EU. Now we are continue working on CPV systems with higher efficiency solar cells and better concentrating technologies.

China has achieved its dominant role on flat PV panels since 2009. It already took the first place of manufacture and installation of flat PV. However, for a long time, China has been quiet in CPV. Fortunately, thanks to the government support and researchers' enthusiasm, CPV in China now meets its special moment for fast development. Positive factors have come together to promote the launching of industrial and commercial activity. Concentrator solar cell efficiency has reached over 38% in Chinese domestic market. Several companies are already entering the market and others have announced their forthcoming presence. MW scale HCPV demonstration stations have been constructed. World famous CPV companies such as EMCORE, AMONIX, SOITEC and ISOFOTON have entered Chinese market, and formed some local new companies producing solar cells and concentrator systems. All these show the prosperous development of concentrator product in China.

As a pioneer and advocator of CPV, I am very happy to see these positive changes in China, since this will make great contribution to the world status of CPV. But the shortage of Chinese reference books on CPV may decrease the enthusiasm of interested people, and then hinder the development of concentrator technologies. So, it's a wise thing to translate the book Concentrator Photovoltaics into Chinese. Dr. Li Zhu is a very dedicated person to the things she is interested in, so I believe that the efforts she made will make the Chinese version a good guide book to Chinese CPV people.

Madrid, January 1st, 2012

Gabriel Sala

Preface 前言

在国际聚光光伏发展如此迅速的背景下，*Concentrator Photovoltaics* 这本书全面介绍了国际聚光光伏的发展历程、现状与前景，对聚光光伏系统与关键单元技术的基础理论给予了深入浅出的阐述，并系统介绍了国际知名科研机构与企业在聚光光伏商业化发展中所做的工作，对于该领域的科研和产业化工作者都是本很好的参考书。

本书译者在澳大利亚国立大学做访问学者从事聚光光伏合作研究时，阅读了施普林格出版社出版的这本书，感觉有必要将书中内容共享给更多从事聚光光伏研究和产业化的人员。了解到国内从事聚光光伏工作的人员并非都具有很好的英语基础，便产生了将此书译成中文并出版的念头。幸运的是，译者在澳大利亚国立大学的合作伙伴、可持续能源系统研究中心的主任安德鲁·布莱克斯教授为本书第 3 章"聚光硅太阳电池"的作者，便与他沟通此想法。布莱克斯教授对此积极支持，并给施普林格出版社发送了希望能够将此书翻译成中文版本的支持函。

在进行具体翻译工作时，考虑到英文版本的资料综述结束于 2006 年，而近几年聚光光伏发展尤其迅速，同时原著中对于中国的聚光光伏发展没有提及，便在原有章节基础上，加入第 16 章"中国的聚光光伏发展"。

中国自 2008 年已成为世界光伏产量最大的国家，2009 年世界前 15 名光伏企业中国就占了 9 家。2009 年，世界光伏产量的 75% 来自亚洲，而中国以 4.4 GW 的产量高居榜首。中国以低制造成本的优势在光伏组件生产上处在了世界领先地位，但是由于光伏发电成本较高，主要应用还是集中在政府资助力度较大的欧洲市场。中国的平板光伏还存在原材料的短缺和技术的对外依赖问题。相较而言，具有低成本优势的聚光光伏可能会在中国光伏领域中具备发展前景。首先，聚光光伏在国内外的发展时间差别不大，短期内的快速发展与技术进步会降低其对国外知识的依赖程度；其次，聚光光伏由于大大减少了太阳电池的使用，对原材料的依赖程度也会降低；最后，我国广袤的戈壁沙漠地区会方便大规模的聚光光伏电站建设。

中国的科研工作者自 20 世纪 70 年代就开始了聚光光伏发电方面的研究，经过近 30 年的辛苦工作，取得了可喜的进展与成果。尤其是近几年，政府的支持、技术进步的需要和绿色环保的紧迫要求短期内促进了聚光光伏发电技术及系统的大力发展。让人兴奋的是几个聚光光伏发电的示范电站也相继建立，为聚光光伏的规模化发展奠定了技术与工程基础。

"中国的聚光光伏发展"一章首先对 2006 年至今的国际聚光光伏最新发展做了全面综述，算是对英文版本内容的补充更新；其次从聚光太阳电池、聚光器、接收器、跟踪系统和散热系统各个方面对国内研究机构和公司的技术水平、最新研究成果和

产品进行了分析,其中不少的篇幅是用来介绍新型液浸冷却技术方面的工作进展及成果;最后聚光光伏的示范及产业化发展是本章中不可缺少的内容,体现了我国聚光光伏领域的发展程度,这一部分还就可能的技术突破给出了分析。本章结束语指出中国的聚光光伏发展将具有广阔的前景。

本书得以完稿出版需要感谢许多人的支持与辛劳工作。首先,原著第3章“聚光硅太阳电池”的作者安德鲁·布莱克斯教授给施普林格出版社发送了希望能够将此书翻译成中文版本的支持函,使得本书在中国出版成为可能。其次,由于本书内容专业,又涉及众多学科领域,翻译难度较大,许多科研工作者都投入到了本书的翻译和校核工作中,他们是朱明泽、熊伟丞、李亚品、李文波、尹兆江、张玉香、张志英、段然、刘菲、车辑、范春宇、罗君子、张鎏、杨达、徐磊、张晓慧、周浩、袁忠强、张妍、孙勇、赵正简、张辉、向海军、张博阳、陈为强,在此,谨向他们表示感谢。另外,为了方便读者查找和理解,参考文献均保留原文。最后,希望本书能为中国的聚光光伏的发展起到一定的推动作用。

译者:朱丽

2012.1.1

Preface

英文版前言

虽然早在1839年亚历山大·埃德蒙·贝克勒尔在他给法国科学院递交的研究成果中就表明入射至由薄膜分割的电解液中的光会产生电流,由此标志着光生伏打效应被发现,但是,直到1877年威廉姆·亚当斯教授和他的学生理查德·戴给伦敦皇家学会提交的实验结果才明确给出“仅有光的作用可以在硒中产生电流”的结论。他们的实验已在汇聚光线下展开。

1973年石油危机以后,光伏技术被认为是从太阳中获取永不枯竭的能量的最好方法,聚光光伏也作为选择方案之一开始被研究。当时出现了一些重要的技术进步,但是随后的石油危机的影响从整体上减少了人们对光伏技术的兴趣,对于聚光光伏的影响更大。自那时开始,推动光伏技术开发的动力就是人类可持续发展的愿望。可持续发展一直是强有力的推动力,使得1996至2004年间光伏工业成为增长最快的工业类型之一,每年的增长率为33.4%,远远高于半导体工业6.2%的增长速率,也使得光伏这一新型技术拥有了可以承受的更合适的发展节奏。

然而,当时的情况对于推动聚光方案的应用却不适合。基于居住功能的建筑的光伏应用需要考虑建筑的美观,其他边远地区或小型的光伏应用也不适合采用聚光光伏。

尽管光伏技术具有巨大的发展潜力,但是对于它们是否能够实现大规模的开发利用太阳资源仍让人质疑。光伏发电的成本下降过于缓慢,研究者们需要寻找可以使成本快速降低的突破点。夏普公司,这个每年提供全世界25%硅电池的最大硅太阳电池生产商,指出这个突破已经到来,这就是拥有39%超高效率的新型太阳电池的出现,而且太阳电池的效率还在提高。以开发其他超高效率电池概念的公开资助计划也开始蓬勃发展。

在这些情况下,许多已建立的或新成立的公司,都宣称它们准备将自己的相关产品投入市场。一个价值1 620万欧元的大型示范项目正在由西班牙公共管理机构(卡斯蒂利亚拉曼恰区域)资助建设,该项目主要用于安装聚光光伏电站。

在这个充满挑战的时刻,本书的编辑们基于1979年在聚光光伏领域的贡献——同时但独立地出版了两部聚光光伏方面的开拓性的书籍(分别用英语和俄语编著),又重新针对这一主题开始著书立说。但这次他们将这本书作为一个平台,让为目前聚光光伏技术发展中做出贡献的人,以及从事聚光光伏技术工业化和商业化挑战性工作的人们都有机会参与进来成为作者。

为了这个目的,本书按照下述结构组织编写。

本书主要由三部分组成,即引言、聚光光伏基础和商业化聚光光伏系统和组成。

引言部分阐述了聚光光伏发展的历史进程，同时指出了目前该领域的现状，并对聚光光伏技术的发展前景进行了合理的预测。引言中还合理解释了"为什么是聚光光伏?"这个问题。除了介绍可行的新的发现和发明，作者对于基于目前技术进行太阳电池和组件的规模化生产中面临的材料可获取性和工业化制造潜力给出了详细的分析。

在第二部分，"聚光硅太阳电池"是本书中唯一涉及硅太阳电池的章节。该章主要讨论了如何获得高效晶硅电池和它们在点聚光与线性聚光系统中的应用。该章还探讨了硅太阳电池与Ⅲ-Ⅴ族类型太阳电池一起形成多结电池栈的可行性，并对比分析了硅太阳电池与Ⅲ-Ⅴ多结太阳电池。

在"聚光多结太阳电池"一章中，作者指出了通过使用叠层异质结构可大幅提高聚光Ⅲ-Ⅴ太阳电池的效率。作者综述了该类型多结电池的发展，并介绍了它们的制造与表征方法。本章还讨论了新的太阳电池概念。

"Ⅲ-Ⅴ族多结太阳电池用于超高倍聚光光伏系统面临的挑战"一章针对性地论述了实际应用中在非常高倍数的阳光汇聚条件下，Ⅲ-Ⅴ多结太阳电池会遇到的问题，以及对这些问题的规避方法。本章介绍了如何开发至少可在1 000×聚光比下工作的Ⅲ-Ⅴ多结太阳电池，并对该类型光伏电站安装的成本进行了分析。

在"光学聚光器"一章中，作者主要介绍了不同类型阳光汇聚光学器件的设计和性能评价，用于获得高光强的聚光系统。同时，还指出了相关技术产品商业化过程中存在的问题。

"太阳电池的冷却"一章主要对太阳电池副产热量的散热方法进行了综述，内容包括各类冷却技术的性能、附加成本和系统可靠性等。

"地面聚光光伏系统"中介绍了聚光组件的设计、室内表征和太阳跟踪器的相关内容。本章还给出了聚光光伏组件室内外测试的数据。

"太阳热光伏发电技术"一章给出了太阳热光伏系统的研究与进展，对有关系统中太阳聚光器、发射器和热光伏电池等组件方面的内容给出了详细介绍。太阳热光伏系统的效率潜力在本章中也有论述。

本书最后一部分商业化聚光光伏系统和组成的各章节详细介绍与论述了聚光光伏系统和太阳跟踪装置的研发成果，这些成果分别来自美国(Spectrolab 公司，Amonix 公司)、西班牙(Inspira SL 公司，太阳能研究所)、德国(Concentrix 太阳能有限公司)和日本(丰田工业大学，大同特殊钢公司，夏普公司)的企业和研究院所。

Antonio Luque

Viacheslav Andreev

Preface 英文版前言

Although the discovery of the photovoltaic effect is attributed to Alexandre Edmond Becquerel, who in 1839 presented to the Academy of Sciences of Paris a study on the effects of the light on the electric currents going through an electrolyte with a separating membrane, Prof. William G. Adams and his student, Richard E. Day, presented to the Royal Society of London in 1877 the experiments that led them to unequivocally conclude 'a current could be started in the selenium by the action of the light alone'. These experiments had already been carried out under concentrated light.

After the oil crisis of 1973, when photovoltaics was considered as the best chance to get inexhaustible energy from the sun, the option of using concentrators was examined. Important technological developments took place then, but the subsequent assimilation of the oil-crisis effects reduced the interesting photovoltaics in general and, more acutely, in concentrated photovoltaics. The driving force of photovoltaic development has been, since then, the wish of sustainability. This has been a powerful driving force that has led the photovoltaic industry to be one of the fastest-growing industries —33.4% per year as compared with the 6.2% of the semiconductor industry between 1996 and 2004 —and a much more appropriate one for the rhythm of the development that this new technology can withstand.

This scenario has been inappropriate, however, to promote concentrator solutions. It has been based on home applications, often attributed to the aesthetics of the building, or other small and isolated applications where concentrated photovoltaics is not practical.

Despite the tremendous potential of the present photovoltaic solutions, however, it is doubtful if they can reach the coveted exploitation of the sun's resources in a massive form. Prices in photovoltaics are decreasing too slowly. That is why researchers are looking for a breakthrough that will permit prices to decrease faster. According to Sharp, the biggest silicon solar cells producer that manufactures 25% of all the cells in the world, this breakthrough has already arrived. It is the novel super-high-efficiency solar cells which have reached an efficiency of 39% and are attempting to go further. Publicly funded programs to develop other super-high-efficiency concepts are starting to flourish.

Under these circumstances a number of companies, both established and start-ups, are declaring that they are ready to put their products on the market. A large-scale (16.2 million Euros) demonstration program is being funded by one Spanish public administration (Region of Castilla La Mancha) in order to install photovoltaic concentrator plants.

At this challenging moment the editors, who in 1979 presented simultaneously, but independently, two pioneering books on photovoltaic concentration (in English and Russian), are revisiting the subject but are giving the floor to various authors who have contributed to the development of our present knowledge concentrated photovoltaics, and to those who are getting involved in the challenging endeavour of industrializing and commercializing it.

For this purpose, the book is therefore organized as follows:

The book consists of three sections: 'introduction', 'Concentrator Foundation' and 'Commercial Concentrator Systems and Components'. The section 'introduction' presents a historical survey o PV concentrator developments together with the recent situation in this field and the reasonable future of the PV concentrator technology. An unambiguous answer to the question 'Why CPV?' is also given. Despite feasible new discoveries and inventions, the authors give a detailed analysis of the material availability and manufacturing potential for extending the present technologies for mass production of solar cells and arrays.

In the second section, the chapter 'Silicon Concentrator Solar Cells' is the only chapter in the book which deals with Si solar cells. Requirements for obtaining high-efficiency cells and their use in point-focus and linear-concentration systems are discussed. The feasibility of applying such cells in a multijunction cell stack together with Ⅲ-Ⅴ solar cells is also considered. A comparative analysis of Si and Ⅲ-Ⅴ multijunction cells is presented.

In the chapter 'Multijunction Concentrator Solar Cells' the authors show that the efficiency of a concentrator Ⅲ-Ⅴ solar cell can be drastically increased by the use of tandem heterostructures. They present an overview of development of such multijunction cells and describe their manufacture and characterization. New solar cell concepts are discussed as well.

The chapter 'Very-High-Concentration Challenges of Ⅲ-Ⅴ Multijunction Solar Cells' focuses on the problems which Ⅲ-Ⅴ multijunction solar cells encounter when operating at very high sunlight concentrations under real conditions, and how those problems can be circumvented. An approach to develop Ⅲ-Ⅴ multijunction cells capable of operating at least at 1000 × concentration and a cost analysis of PV installations are presented.

In the chapter 'Concentrator Optics' consideration is given to design and performance of different types of optical sunlight concentrators aimed to obtain high-flux PV systems. Problems of commercialization are considered as well.

The chapter 'Solar Cell Cooling' deals with the ways of heat removal from a cell which has resulted from excess solar energy, and which is not converted into electricity, including their performance, cost and reliability.

In the chapter 'Terrestrial PV Concentrator Systems' concentrator module design, indoor characterization of the modules and sun trackers are described. Data on indoor and outdoor measurements of concentrator modules are presented as well.

Chapter 'Solar Thermophotovoltaics' concerns solar thermophotovoltaic system research and development. Detailed consideration is given to solar concentrators, emitters and TPV cells for such systems. Efficiency potentialities of solar TPV systems are discussed.

The chapters of the section 'Commercial Concentrator Systems and Components present detailed description and discussion of R&D of concentrator photovoltaic systems and sun tracking carried out in the firms and research institutions in the United States (Spectrolab Inc., Amonix Inc.), Spain (Inspira SL, Instituto de Energia Solar), Germany (Concentrix Solar, GmbH) and Japan (Toyota Technological Institute, Daido Steel Corp., Sharp Corp.).

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