太阳能光伏产业

——光伏发电技术及应用系列教材

光伏专业英语

郭连贵 主 编




FU ZHUANYE

化学工业出版社

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·北京·

本书的课文和阅读材料全部选自近年来英国、美国、澳大利亚等国太阳能光伏专业教材和专业刊物，共8个单元，50篇课文。涵盖了太阳辐射、半导体材料、晶体硅太阳电池、薄膜太阳电池、太阳电池组件、光伏发电系统概述、光伏发电系统应用及其他可再生能源等内容。所选文章题材多样，内容新颖，学科前沿知识丰富，融知识性和趣味性于一体。

本书可作为应用型高等院校的半导体物理与器件、材料科学与工程、光伏材料加工与应用等专业的教材，也可作为高职高专太阳能光伏技术与应用相关专业的教材和光伏企业的培训教材，同时可供从事太阳能光伏相关行业研究和开发的工程技术人员参考使用。

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前　言

太阳能光伏发电是通过半导体器件将太阳辐射能转化为电能的一种发电方式，开发利用太阳能对于解决能源危机、改善生态环境和改善人民生活条件具有巨大的经济、政治和社会效益。英语作为一种重要的全球化的交流工具，发挥着重要的作用。学好光伏专业英语，是学生、学者和工程技术人员获取国外光伏科研信息、掌握国外光伏学科发展动态、参加国际光伏学术交流的基本前提。为此我们编写本书，希望能对从事太阳能光伏发电的本科生、专科生和工程技术人员的专业英语水平的提高有所帮助。

本书每一章均由若干篇课文和一篇课外阅读材料组成，且所选阅读材料提供了与该章课文对应的背景知识或者是课文的续篇，从而进一步拓展了课文的内容。本书分为8章，包括阅读材料在内共50篇课文，其中前7章的内容分别对应于太阳能光伏发电从上游到下游的整个产业链，内容涵盖了太阳辐射、半导体材料、晶体硅太阳电池、薄膜太阳电池、太阳电池组件、光伏发电系统概述及光伏发电系统应用。此外，本书最后一章简单介绍了除太阳能光伏发电外的其他可再生能源（如太阳热能、风能等）。

本书是以提高学生专业英语阅读能力、拓展和深化学生对太阳能光伏发电技术的认知、为学生应用能力的培养而编写的基础专业英语课，具有以下特色。

1. 内容阐述针对性强：本书只讲述与太阳能光伏发电技术相关的各类专业知识，力求使论述的概念清楚、准确、简练。

2. 内容全面新颖：本书所选的文章全部来自近年出版的原版英文教材、科技报告、专业期刊和著作，内容按照太阳能光伏发电从上游到下游的整个产业链顺序全面编排，学科前沿知识丰富，特别突出高效太阳电池的研究进展及光伏产业在环保、交通、建筑等方面的应用。

3. 词汇丰富、量大：本书所选的文章几乎涵盖了光伏电池和光伏产业的专业词汇，在形式上注重图文并茂，疑难句有注释，既可作为光伏专业的英语教科书，也可以用于自学。

本书由郭连贵主编，并负责全书的编写和统稿；周青、张洪涛编写了部分内容；曾玉、胡志鹏、陈芝、郭芳芳收集整理了部分资料；同时本书在编写过程中参阅和利用了国内外相关文献资料，充实和丰富了本书的内容；江西省省级特色专业材料科学与工程建设项目和化学工业出版社对本书的出版也给予了大力支持，在此一并表示感谢。太阳能光伏发电技术涉及面广、发展迅速，由于本书作者水平有限，书中难免有不足和疏漏之处，恳请各位专家、同仁和广大读者批评指正。

编者

2012 年 5 月

Contents

Chapter 1 Introduction to Photovoltaics

1.1 What is Photovoltaics?

Photovoltaics (abbreviated PV) is the most direct way to convert **solar radiation** into electricity and is based on the **photovoltaic effect**, which was first observed by **Becquerel** in 1839①. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically all **photovoltaic devices** incorporate a **PN junction** in a **semiconductor** across which the **photovoltage** is developed (see Chap. 2). These devices are also known as **solar cells. Light absorption** occurs in a semiconductor material. The semiconductor material has to be able to absorb a large part of the **solar spectrum.** Dependent on the **absorption properties** of the material, the light is absorbed in a region more or less close to the surface. When **light quanta** are absorbed, **electron hole pairs** are generated, and if their **recombination** is prevented they can reach the junction where they are separated by an electric field. Even for a weakly absorbing semiconductor like silicon, most **carriers** are generated near the surface. This leads to the typical solar cell structure of Fig. 1. 1.

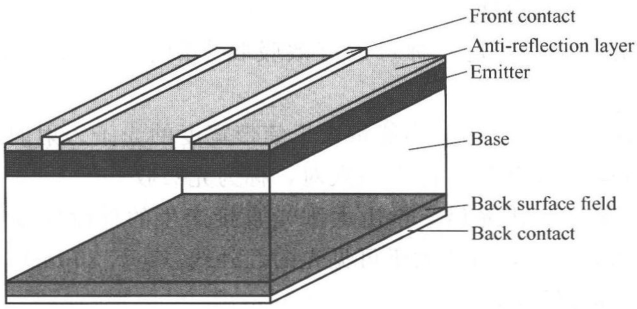

Fig. 1. 1 Typical solar cell structure

The pn junction that separates the **emitter** and **base layer** is very close to the surface in order to have a high collection probability for the **photogenerated charge carriers**②. The thin emitter layer above the junction has a relatively high resistance which requires a well designed **contact grid**, also shown in the figure.

For practical use solar cells are **packaged** into **modules** containing either a number of **crystalline Si cells** connected in series or a layer of **thin-film material** which is also internally series connected. The module serves two purposes: It protects the solar cells from the ambient and it delivers a higher voltage than a single cell, which develops only a voltage of less than 1 Volt. The **conversion efficiencies** of today's production cells are in the range of 16% to 18%, but module efficiencies are somewhat lower. The best laboratory efficiency of crystalline silicon achieved so far is 24.7%, which approaches the theoretical limit of this type of solar cell③.

New Words and Expressions

1. Photovoltaic *a.* 光生伏打的，光伏的，是一项将太阳光能转换成为电能的技术.
2. solar radiation 太阳辐射，指太阳向宇宙空间发射的电磁波和粒子流.
3. photovoltaic effect 光伏效应，指光照使不均匀半导体或半导体与金属结合的不同部位之间产生电位差的现象，它是由光子（光波）转化为电子、光能量转化为电能量的过程，是形成电压的过程，当有导线连通时就会形成电流的回路.
4. Henri Becquerel 贝克勒尔，法国物理学家，他在1839年发现光照能使半导体材料的不同部位之间产生电位差，这种现象后来被称为“光生伏打效应”，简称“光伏效应”.
5. photovoltaic device 光伏装置，光伏器件.
6. PN junction PN结，指采用不同的掺杂工艺，将P型半导体与N型半导体制作在同一块硅片上，在它们的交界面形成的空间电荷区称为PN结.
7. semiconductor *n.* 半导体，指常温下导电性能介于导体（conductor）与绝缘体（insulator）之间的材料，其导电性是由“导带”（conduction band）中含有的电子数量决定的，当电子从“价带”（valence band）获得能量而跳跃至“导带”时，电子就可以在带间任意移动而导电。一般半导体材料的能隙约为1～3eV，通过电子传导或空穴传导的方式传输电流.
8. photovoltage *n.* 光电压.
9. solar cell 太阳电池，是一种可以有效吸收太阳能并将其转化成电能的半导体器件.
10. light absorption 光吸收，当能量大于禁带宽度的光子入射时，太阳电池内的电子能量从价带迁到导带，从而产生电子-空穴对，称为光吸收.
11. solar spectrum 太阳光谱，指由太阳光直接产生的连续发射光谱，主要集中在可见光部分（0.4～0.76μm），波长大于可见光的红外线（>0.76μm）和小于可见光的紫外线（<0.4μm）的部分较少.
12. absorption property 吸收性能.
13. light quanta 光量子，是以能量的形式并以光的速度运动，并且进入电池板内激发电子和空穴对的物质.
14. electron hole pairs 电子-空穴对，半导体吸收一个光子，释放出一个电子和一个空穴.
15. recombination *n.* 复合，半导体中电子受光作用从价带激发到导带，创造了电子-空穴对，该固体表面可能会通过“复合中心”俘获少数载流子和多数载流子，造成电子-空穴对的部分消失，从而达到稳定状态，这一过程称为复合.
16. carriers *n.* 载流子，在半导体内运动的电荷载体，一般是自由电子或空穴.

17. emitter layer　发射层.

18. base layer　背底层，晶体太阳能电池板背部附加的电子层.

19. photogenerated charge carriers　光生电荷载流子.

20. contact grid　接触栅线，指太阳能电池板上的金属导线，电阻越小越好，这样能量损失少.

21. package　*vt.* 封装.

22. module　*n.* 组件，指具有封闭及内部联结的、能单独提供直流电输出的、最小不可分割的太阳电池组合装置.

23. crystalline Si cell　晶体硅电池，包括单晶硅电池和多晶硅电池.

24. thin-film material　薄膜材料.

25. conversion efficiency　转换效率，指受光照太阳电池的最大功率与入射到该太阳电池上的全部辐射功率的百分比.

Notes

① Photovoltaics (abbreviated PV) is the most direct way to convert solar radiation into electricity and is based on the photovoltaic effect, which was first observed by Henri Becquerel in 1839.

参考译文：光生伏打（简称 PV）是转换太阳辐射能为电能的最直接方式，并基于1839 年 Henri Becquerel 首先发现的光伏效应。

句中 which 是非限制性定语从句，用以说明光伏效应。

② The pn junction that separates the emitter and base layer is very close to the surface in order to have a high collection probability for the photogenerated charge carriers。

参考译文：将发射层和背底层分开的 PN 结非常接近表面，以便有很高的光生载流子收集概率。

③ The best laboratory efficiency of crystalline silicon achieved so far is 24.7%, which approaches the theoretical limit of this type of solar cell.

参考译文：迄今为止晶体硅太阳电池的最好实验室效率是 24.7%，接近于这类太阳电池的理论极限。

1.2 Short History of Photovoltaics

1. Technology

The photovoltaic effect remained a laboratory curiosity from 1839 until 1959, when the first silicon solar cell was developed at **Bell Laboratories** in 1954 by Chapin et al. It already had an efficiency of 6%, which was rapidly increased to 10%. The main application for many years was in **space vehicle power supplies**.

Terrestrial application of photovoltaics (PV) developed very slowly. Nevertheless, PV fascinated not only the researchers, but also the general public. Its strong points are:

—direct conversion of solar radiation into electricity,

—no mechanical moving parts, no noise,

—no high temperatures,

—no pollution,

—PV modules have a very long lifetime (25 years),

—the energy source, the sun, is free, **ubiquitous**, and **inexhaustible**,

—PV is a very flexible energy source, its power ranging from microwatts to megawatts.

Solar cell technology benefited greatly from the high standard of silicon technology developed originally for **transistors** and later for **integrated circuits**①. This applied also to the quality and availability of single crystal silicon of high perfection. In the first years, only **Czochralski** (Cz) grown single crystals were used for solar cells. This material still plays an important role. As the cost of silicon is a significant proportion of the cost of a solar cell, great efforts have been made to reduce these costs. One technology, which dates back to the 1970s, is **block casting** which avoids the costly pulling process. Silicon is melted and poured into a square SiO/SiN-coated graphite crucible. Controlled cooling produces a **polycrystalline silicon** block with a large crystal grain structure.

From solid state physics we know that silicon is not the ideal material for photovoltaic conversion. It is a material with relatively low absorption of solar radiation, and, therefore, a thick layer of silicon is required for efficient absorption. Theoretically, this can be explained by the semiconductor **band structure** of silicon in which the **valence band** maximum is offset from the **conduction band** minimum②. Since the basic process of light absorption is excitation of an electron from the valence to the conduction band, light absorption is impeded because it requires a change of momentum. The search for a more suitable material started almost with the beginning of solar cell technology. This search concentrated on the thin-film materials. They are characterized by a direct band structure, which gives them very strong light absorption.

Today, the goal is still elusive, although promising materials and technologies are beginning to emerge. The first material to appear was **amorphous Silicon** (a-Si). It is remarkable that even the second contender in this field is based on the element silicon, this time in its amorphous form. Amorphous silicon has properties fundamentally different from crystalline silicon. However, it took quite some time before the basic properties of the material were understood. The high expectancy in this material was curbed by the relatively low efficiency obtained so far and by the initial **light-induced degradation** for this kind of solar cell (so-called Staebler-Wronski effect). Today, a-Si has its fixed place in consumer applications, mainly for indoor use. After understanding and partly solving the problems of light-induced degradation, amorphous silicon begins to enter the power market. Stabilized cell efficiencies reach 13%. Module efficiencies are in the 6%-8% range. The visual appearance of thin-film modules makes them attractive for **facade applications**.

Beyond amorphous silicon there are many other potential solar cell materials fulfilling the requirement of high light absorption and are therefore suitable for thin-film solar cells. They belong to the class of **compound semiconductors** like GaAs or InP, which are Ⅲ-Ⅴ compounds according to their position in the periodic table. Other important groups are Ⅱ-Ⅵ and Ⅰ-Ⅲ-Ⅵ compounds, which, just like the elemental semiconductors, have four bonds per atom. It is clear that an almost infinite number of compounds could be considered. From the mostly empirical search only very few promising materials have resulted. Foremost are **Copper Indium Diselenide** (CIS) and **Cadmium Telluride** (CdTe). Already by the early 1960s cadmium sulfide/copper sulfide solar cells were under development. Problems with low efficiency and insufficient stability prevented further penetration of this material.

The new technology is based on the **ternary compound** semiconductors $CuInSe_2$, $CuGaSe_2$, $CuInS_2$ and their multinary alloy $Cu(In, Ga)(S, Se)_2$. The first results of single crystal work on $CuInSe_2$ (CIS) were extremely promising, but the complexity of the material looked complicated as a thin-film technology. Pioneering work, however, showed immediate success. It became evident that CIS process technology is very flexible with respect to process conditions. In later developments, the addition of Ga and S helped to increase the efficiency. The best laboratory efficiency has recently reached a remarkable 18.9%. CIS/CIGS modules are now available on the market in small quantities.

Thin-film solar cells based on CdTe have a very long tradition and are also just at the onset of commercial production. After a long and varied development phase, they arrived at cell efficiencies of 16% and large-area module efficiencies of over 10%.

In spite of the complicated manufacture and the high cost, crystalline silicon still dominates the market today and probably will continue to do so in the immediate future③. This is mostly due to the fact that there is an abundant supply of silicon as raw material, high efficiencies are feasible, the ecological impact is low, and silicon in its crystalline form has practically no **degradation**.

The various forms of crystalline silicon have together a share of 93%. Single crystal and cast poly material had about equal share for a long time. Recently, cast material has surpassed single crystals. Newer types of crystalline silicon like **Ribbon** and Si film are not yet very important. A newcomer is a-Si on crystalline silicon. Of the true thin-film materials which are summarized as "others" amorphous silicon is dominant. As mentioned before, its market is mainly in consumer products. These market shares are rather stable and change only in an evolutionary manner. The dominance of the element silicon in its crystalline and amorphous forms is an overwhelming 99%. Of all the other materials only CdTe has a market share of only 0.4%.

2. Applications

The need to provide power for space vehicles provided an excellent point of entry for solar cells starting in the late 1950s. Solar cells can work reliably and without maintenance for long periods. This provided an opportunity for further development. Efficiency was increased and resistance against radiation was studied and improved. At the same time, PV energy supply systems for those very demanding conditions were developed.

In 1958, the first 108 solar cells for the supply of the **Vanguard satellite** were put into orbit. They performed even better than predicted and powered the satellite much longer than expected. The demand for solar cells climbed rapidly in the following years, leading to a small industrial production. The consequence was not only an improvement of the electrical parameters of the cells, but also a drop in prices. This, in turn, lead to a modest use of solar cells in terrestrial applications, but space remained the main market for more than a decade.

The **breakthrough** for terrestrial photovoltaics can be traced directly to the **oilshock** of 1973/1974④. Experts in all industrialized nations started to look for **alternatives** to the scarce and expensive mineral oil. They discovered photovoltaics and recognized a possible candidate for a future nonfossil energy supply. Newly emerging development institutions in the United States, Europe, and Asia occupied themselves not only with the development of cells, but also with systems and system components. The problems to be solved were formidable: The cost of PV energy had to be reduced by a factor of 1000. This referred not only to the cells, but also to the entire system.

Since then, the price for **grid-connected systems** has been reduced by a factor 100. How was this accomplished? Obviously, an energy source as expensive as PV has no chance in an open market. Governments in some European countries, the U. S. , and Japan initiated large support programs, because they were convinced of the great potential of photovoltaics. The success of cost reduction resulted from an interaction of several more or less coordinated initiatives: Development of better solar cells and systems, demonstration programs for testing and optimization of systems, and, finally, market support programs for grid-connected generators.

As a result, production expanded with remarkable growth rates between 20 and 40% per year with corresponding cost reductions. The most important demonstration and market support programs are:

—The German 1000 Roof Measurement and analysis program.

—The 100000 **Roof Program** in Germany.

—The 1 Million Roof Program in the U. S.

—The Italian Roof top Program.

—Smaller programs were introduced in Austria and Switzerland.

Probably the most important tool for market development are the feed-in laws in several European countries and Japan. These laws provide a more or less adequate compensation for PV energy fed into the grid. Today, we have generators ranging from several milliwatts in consumer products to grid-connected systems in the kilowatt range up to central power plants of several megawatts.

New Words and Expressions

1. Bell Laboratory 贝尔实验室，总部位于美国新泽西州的默里·希尔，是晶体管、激光器、太阳能电池、发光二极管、数字交换机、通信卫星、电子数字计算机、蜂窝移动通信设备、长途电视传送、仿真语言、有声电影、立体声录音以及通信网等许多重大发明的诞生地；自 1925 年以来，贝尔实验室共获得两万五千多项专利，现在平均每个工作日获得三项多专利；贝尔实验室同时还培养了多名诺贝尔奖获得者.

2. space vehicle power supplies 空间飞行器（如卫星、火箭、空间站等）电源.

3. terrestrial application 地面应用.

4. ubiquitous *a.* 普遍存在的；无所不在的.

5. inexhaustible *a.* 用不完的；取之不尽、用之不竭的.

6. transistor *n.* 晶体管，是一种固体半导体器件，可以用于检波、整流、放大、开关、稳压、信号调制和许多其他功能.

7. integrated circuit 集成电路，是一种微型电子器件或部件，采用一定的工艺把一个电路中所需的晶体管、二极管、电阻、电容和电感等元件及布线互连一起，制作在一小块或几小块半导体晶片或介质基片上，然后封装在一个管壳内，成为具有所需电路功能的微型结构.

8. Czochralski *n.* 丘克拉斯基法，一种晶体提拉法，是一种直接熔化原料，然后利用种晶从熔体中提拉出单晶体的方法.

9. block casting 块模浇铸法，即将熔体直接浇铸进块体模具中成型的方法.

10. polycrystalline silicon 多晶硅，单质硅的一种形态，其高温熔融状态下，具有较大的化学活泼性，能与几乎任何材料作用，具有半导体性质，是极为重要的优良半导体材料；多晶硅又是生产单晶硅的直接原料，是当代人工智能、自动控制、信息处理、光电转换等半导体器件的电子信息基础材料.

11. band structure 能带结构.

12. valence band 价带，指半导体或绝缘体在 0K 时能被电子占满的最高能带。对半导体而言，此能带中的能级基本上是连续的，全充满的能带中的电子不能在固体中自由运动；但若该电子受到光照，它可吸收足够能量而跳入下一个允许的最高能区，从而使价带变成部分充填，此时价带中留下的电子可在固体中自由运动.

13. conduction band 导带，指半导体或是绝缘体材料中一个电子所具有能量的范围，这个能量的范围高于价带（valence band），而所有在传导带中的电子均可经由外在的电场加速而形成电流.

14. amorphous Silicon 非晶硅，单质硅的一种形态，不具有完整的金刚石型晶胞，纯度不高，熔点、密度和硬度等数值也明显低于晶态硅；化学性质比晶态硅活泼。非晶硅可由活泼金属（如钠、钾等）在加热下还原四卤化硅（SiF_4 或 $SiCl_4$）或在高温下用碳或镁等还原剂与二氧化硅作用制得.

15. light-induced degradation 光致衰减效应，指太阳能电池板的效率会随着光照时间增加而降低的现象.

16. facade application 幕墙应用.

17. compound semiconductors 化合物半导体.

18. Copper Indium Diselenide 铜铟硒化合物，该材料制作的太阳电池具有生产成本低、污染小、不衰退、弱光性能好等显著特点，光电转换效率居各种薄膜太阳电池之首，接近于晶体硅太阳电池，而成本只是它的三分之一，被称为下一代非常有前途的新型薄膜太阳电池.

19. cadmium Telluride 碲化镉，缩写 CdTe，位于Ⅱ-Ⅵ位的半导体，其禁带空隙值为 1.45eV，有很好的光吸收性，应用于超薄太阳能电池板.

20. ternary compound 三元化合物.

21. degradation *n.* 衰减，退化，降级.

22. ribbon silicon 带硅.

23. Vanguard satellite 先锋卫星.

24. breakthrough *n.* 突破；突破性进展.

25. oilshock *n.* 石油危机；石油冲击.

26. alternative *n.* 替代品；供替代的选择.

27. grid-connected system 并网发电系统，不经过蓄电池储能，通过并网逆变器直接将电能输入公共电网的发电系统.

28. roof program 屋顶计划.

Notes

① Solar cell technology benefited greatly from the high standard of silicon technology developed originally for transistors and later for integrated circuits.

参考译文：太阳电池技术从最初发展的晶体管及后来发展的集成电路高标准硅技术中受益匪浅。

② Theoretically, this can be explained by the semiconductor band structure of silicon in which the valence band maximum is offset from the conduction band minimum.

参考译文：从理论上讲，这可以从硅的半导体能带结构得到解释，即价带最大值与导带最小值之间的偏差。

③ In spite of the complicated manufacture and the high cost, crystalline silicon still dominates the market today and probably will continue to do so in the immediate future.

参考译文：晶体硅尽管制造复杂并且成本高昂，但在当今市场仍然起主导作用，而且在不久的将来可能会持续下去。

④ The breakthrough for terrestrial photovoltaics can be traced directly to the oilshock of 1973/74.

参考译文：地面光伏应用取得突破可以直接追溯到 1973～1974 年的石油危机。

1.3 The Future of Photovoltaics

1. Boundary Conditions for the Future Development of Photovoltaics

The cost development of conventional electricity is a very important boundary condition for the future use of photovoltaics. Generally, it can be assumed that the cost of grid electricity will slowly rise over the next decades. The slope of this rise depends on the following influences: degree of liberalization of electricity markets, margins for the security of supply, proportion of distributed generation, e. g., **cogeneration**, environmental restrictions, and last but not least, the fate of atomic energy. Practically all these influences, with the exception of liberalization, point toward higher cost of electricity. Another influence comes from the development of storage technologies. Presently, storage of electricity is not a technical, but an economic problem. Large-scale, grid-connected storage is only possible with pumped hydro installations, which are very limited in their potential. **Storage batteries** are widely used in stand-alone and mobile systems, but are much too expensive for storing grid electricity. If the full potential of photovoltaics is to be realized, better means of storage are necessary. The hydrogen economy would be a solution to the storage problem, as will be pointed out later.

The liberalization of the electricity market that is going on worldwide will influence the penetration of grid-connected PV. The following tendencies can be recognized:

—Liberalization will lead to more economics, i. e., lower electricity prices, but this may be limited to large-scale consumers. Therefore, the overall consequence could be neutral relative to the expansion of PV in distributed systems.

—Electricity prices will reflect the real cost of generation. Prices will fluctuate widely depending on the time of day and season. Since a large part of solar electricity is generated during the high price period, this will be beneficial for PV.

—The cost of reserve capacity will lead to a lower security of supply. The role of PV as a back-up source will be favorable for this market.

2. Cost and Market Development of Stand-Alone and Grid-Connected Systems

The future of PV depends mainly on the cost development for modules and entire systems①. For modules, which are the most expensive part of a system, has been well established for more than twenty years. It predicts a 20% price reduction for every doubling of cumulated production. Assumptions have to be made about market growth for such a prediction. If present support mechanisms are maintained, the current growth rate will continue into the future. An estimate for the market development is given by W. Hoffmann: 30% per year until 2010 and 25% thereafter.

Future development of markets: The grid-connected market will remain the most important sector, but the other sectors, remote industrial, developing countries and consumer products together reach almost the same size. These markets are, of course, interdependent. Only by price reductions due to expanding grid-connected markets can the other sectors grow accordingly.

3. PV in a Future Liberalized and Partly Decentralized Energy System

Future electricity grids will have a mixture of central and decentralized generation capacity. Central conventional and renewable plants will cooperate with small and medium distributed generation. Modern electronics will permit a high degree of control, leading to a rapid adjustment of the economic optimum. Very important in this concept is the possibility of local storage of electricity.

Present models of a distributed energy system envision PV at many rooftops or similar structures interacting with an electricity grid and other local generators and consumers. Demand can be adjusted to some degree by central control. Besides PV, other small generators may be connected to the grid like combined heat and power plants, some based on biofuels, fuel cells, and local storage in batteries or more likely by hydrogen. Central plants can be planned by weather forecasts predicting wind and sunshine. Different **renewable energies** acting together have much lower fluctuation than each one by itself. A considerable proportion of local generation and storage may reduce the cost of distribution grids and enhance the security of supply. Much work remains to be done in working out grid and control structures for such a scenario. Undoubtedly, PV will play a major role in such a new electricity scene. The Edison project supported by the German Ministry of Economics and Technology has the goal of developing and demonstrating modular intelligent systems for such distributed grids. It involves, in particular, the combination of electricity grid and communication systems. The structure of such a future electricity distribution network is shown in Fig. 1. 2.

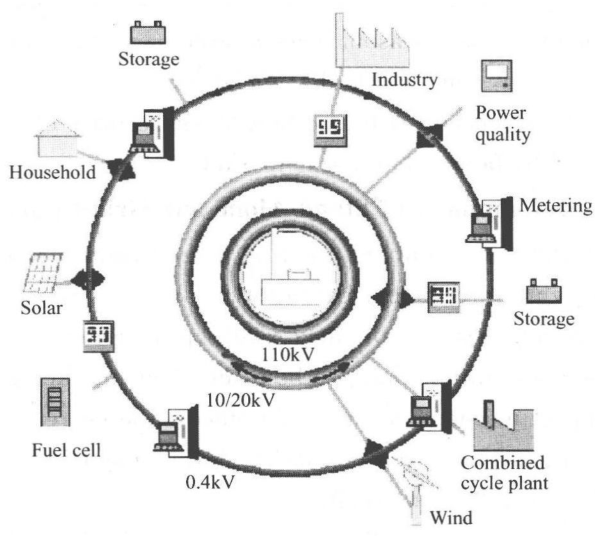

Fig. 1. 2 Structure of a future electricity distribution network

A fully autonomous system has already been demonstrated as the **Self-Sufficient Solar House.** In this project, most of the above mentioned techniques were already incorporated and tested. When they will become reality is mainly a question of cost. Fuel cells are under very intense development for mobile applications which are more demanding than stationary ones. If fuel cells become more available, local storage of hydrogen will make distributed systems more independent. From today's point of view, complete autonomy is not a very likely option. But the grid is already in place, so why not use its advantages. If a dwelling with local generation is grid-connected, it can deliver surpluses into the grid and local storage does not have to cover extreme situations. Energy stored locally can be fed into the grid at times of peak power and fetch a higher price. Such a dwelling would have a low heating demand that would be covered by a combined heat and power plant, which could, besides covering local demand, feed energy into the grid when demand is high.

A further scenario developed some time ago recognizes the fact that as energy efficiency in buildings improves the center of demand shifts to mobility. The engine of an automobile is, after all, a combined heat and power plant.

4. PV in a Centralized Energy System

PV could in a very long-term scenario also play a role in a centralized energy system. Large PV power plants in the multi-megawatt range can be envisioned to produce electricity in forever sunny desert areas or even in outer space. Such scenarios require very low but still possible cost for modules and systems. It is quite clear that these visions can only become reality in the distant future, maybe around the middle of this century.

Deserts are regions of abundant sunshine but of very little other use. It is tempting to imagine large-scale solar energy installations in such areas where they are much more efficient than in the areas where most energy is consumed. The big challenge is to transport the energy over large distances to the consumers. Two main techniques can be identified today: high tension power lines and conversion to hydrogen.

Transmission of electricity by power lines over long distances is technically possible today. High voltage dc transmission works with low losses and has been operational for many years. Such lines could be set up, for instance, between Northern Africa and Europe or from the Gobi desert to Japan. An even further reaching idea is to establish a worldwide electricity grid. Then the storage problem could be solved very elegantly, because the sun is always shining in one half of the world. And seasonal differences can also be overcome by energy exchange between the northern and southern hemispheres. Such grids could also be used for wind energy, since many areas with very good wind resources are located in remote parts of the world. The cost of transmission has recently been estimated for transport from north Africa to central Europe. A 5000km transmission line has 18% loss at 600 kV and 14% loss at 800 kV. The cost of the losses is estimated at 0.5 cts per kW • h and the cost of transmission at 0.5 to 1.0 cts per kW • h.

The second option for energy transport is hydrogen. Water is split into hydrogen and oxygen by electrolysis and hydrogen can then serve as the energy carrier②. Transport of hydrogen can be accomplished in three different ways:

—Hydrogen is liquefied near a harbor and then transported away by tankers.

—Hydrogen is pressurized and piped to the consumers by pipeline.

—The third pathway is the least explored and its realiability is uncertain: Hydrogen is chemically reacted to form a liquid energy carrier that can be transported, as outlined