Chapter 1: History of Solar Cell Development

Chapter · June 2014

DOI: 10.1007/978-3-319-07530-3_1

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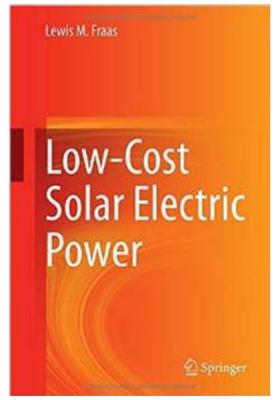
L. M. Fraas, *Low-Cost Solar Electric Power*,
DOI: 10.1007/978-3-319-07530-3_1,



It has now been 175 years since 1839 when Alexandre Edmond Becquerel observes the photovoltaic (PV) effect via an electrode in a conductive solution exposed to light [1]. It is instructive to look at the history of PV cells [2] since that time because there are lessons to be learned that can provide guidance for the future development of PV cells.

The Discovery Years

This 175 year history can be conveniently divided into 6 time periods beginning with the discovery years from 1839 to 1904. Table 1.1 gives the most significant events during this first period. In 1877, Adams and Day observed the PV effect in solidified selenium [3] and in 1904, Hallwachs made a semiconductor-junction solar cell with copper & copper oxide. However, this period was just a discovery period without any real understanding of the science behind the operation of these first PV devices.

Theoretical Foundation

A theoretical foundation for PV device operation and potential improvements was formulated in the second phase of the history of PV in the period from 1905 to 1950 as summarized in Table 1.2. Key events in this period were Einstein's photon theory [4], the adaptation of the Czochralski crystal growth method for single crystal silicon and germanium growth [5] and the development of band theory for high purity single crystal semiconductors [6, 7]. The PV cell theory developed emphasized the importance of high purity single crystal semiconductors for high efficiency solar cells. This theoretical foundation will be reviewed in Chapter 4 in this book. These developments laid the foundations for the 3rd phase of PV device development.

Table 1.1: 1800s–1904: Discovery Years

- **1839 - Alexandre Edmond Becquerel observes the photovoltaic effect via an electrode in a conductive solution exposed to light [1].**
- **1877 - W.G. Adams and R.E. Day observed the photovoltaic effect in solidified selenium, and published a paper on the selenium cell [3]. 'The action of light on selenium,' in "Proceedings of the Royal Society, A25, 113.**
- **1883 - Charles Fritts develops a solar cell using selenium on a thin layer of gold to form a device giving less than 1% efficiency.**
- **1904 - Wilhelm Hallwachs makes a semiconductor-junction solar cell (copper and copper oxide).**

Table 1.2: 1905 to 1950: Scientific Foundation

- **1905 - Albert Einstein publishes a paper explaining the photoelectric effect on a quantum basis [4]**.
- **1918 - Jan Czochralski, a Polish scientist, produces a method to grow single crystals of metal. Decades later, the method is adapted to produce single-crystal silicon.**
- **1928 – F. Bloch develops band theory based on single crystal periodic lattice [5].**
- **1931 – A. H. Wilson develops theory of high purity semiconductor [6].**
- **1948 - Gordon Teal and John Little adapt the Czochralski method of crystal growth to produce single-crystalline germanium and, later, silicon [7].**

The First Single Crystal Silicon Solar Cell

Table 1.3 summarizes the events between 1950 and 1959 leading to the practical silicon single-crystal PV device. The key events were the Bell Labs announcement of the Silicon solar cell [8] in 1954 with the Pearson, Chapin, and Fuller patent in 1957 for the 8% efficient Silicon solar cell [9]. The foundation was now laid for the development of a variety of markets for PV as will be discussed in more detail in Chapters 2 & 3 herein.

Enthusiastic Support for PV in USA and New PV Devices

The next three phases of PV development can best be divided according to the political climate of the time. The 4th phase of PV history from 1960 to 1980 was defined by enthusiastic support in the US for PV solar cells first for applications on space satellites and then for initial terrestrial applications. Table 1.4 shows the timeline for significant events in this period.

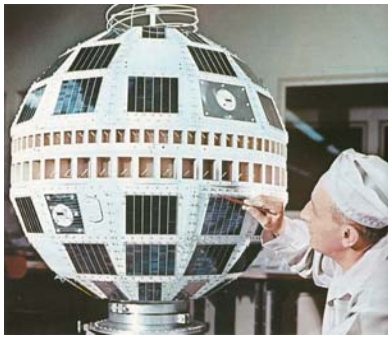
This period began with the success of the first Telstar communication satellite [10] launched in 1962 and powered by silicon solar cells as shown in figure 1.1a. Then in the 1970s, silicon cells were evolved for use in terrestrial installations. Figure 1.1b shows a typical terrestrial silicon solar cell today. The present author began working in the solar field in 1973. This was the year of the Arab oil embargo [11] and the first gas lines in the US.

Table 1.3: 1950-1959: First Practical Device Demonstration

- **1950s - Bell Labs produce solar cells for space activities.**
- **1953 - Gerald Pearson begins research into lithium-silicon photovoltaic cells.**
- **1954 - Bell Labs announces the invention of the first modern silicon solar cell [8]. These cells have about 6% efficiency. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun."**
- **1955 - Western Electric licences commercial solar cell technologies. Hoffman Electronics-Semiconductor Division creates a 2% efficient commercial solar cell for $25/cell or $1,785/Watt.**
- **1957 - AT&T assignors (Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller) receive patent US2780765, "*Solar Energy Converting Apparatus*."[9] They refer to it as the "solar battery." Hoffman Electronics creates an 8% efficient solar cell.**
- **1958 - T. Mandelkorn, U.S. Signal Corps Laboratories, creates n-on-p silicon solar cells, which are more resistant to radiation damage and are better suited for space. Hoffman Electronics creates 9% efficient solar cells. Vanguard I, the first solar powered satellite, was launched with a 0.1W, 100 cm^2 solar panel.**
- **1959 - Hoffman Electronics creates a 10% efficient commercial solar cell, and introduces the use of a grid contact, reducing the cell's resistance.**

Table 1.4: 1960-1980: US Enthusiastic Support & New PV Devices

- **1960 - Hoffman Electronics creates a 14% efficient solar cell.**
- **1961 - "Solar Energy in the Developing World" conference is held by the United Nations.**
- **1962 - The Telstar communications satellite is powered by solar cells [10].**
- **1967 - Soyuz 1 is the first *manned* spacecraft to be powered by solar cells**
- **1970 - First highly effective GaAs heterostructure solar cells are created by Zhores Alferov and his team in the USSR [12].**
- **1971 - Salyut 1 is powered by solar cells.**
- **1972 – Hovel and Woodall at IBM demonstrate AlGaAs/GaAs solar cell with 18% to 20% efficiency [13].**
- **1973 - Skylab is powered by solar cells.**
- **1975 – First JPL Flat Solar Array block buy to transition Silicon PV from Space to Terrestrial applications.**
- **1976 - David Carlson and Christopher Wronski of RCA Laboratories create first amorphous silicon PV cells, which have an efficiency of 1.1% [16].**
- **1977 - The Solar Energy Research Institute is established at Golden, Colorado.**
- **1977 - President Jimmy Carter installs solar panels on the White House and promotes incentives for solar energy systems.**
- **1977 - The world production of photovoltaic cells exceeded 500 kW**
- **1978 - First amorphous silicon solar-powered calculator[17]**
- **Late 1970s: the "Energy Crisis"[11]; groundswell of public interest in solar energy use: photovoltaic and active and passive solar, including in architecture and off-grid buildings and home sites.**
- **1978 – L. Fraas & R. Knechtli describe the InGaP/GaInAs/Ge triple junction concentrator cell predicting 40% efficiency at 300 suns concentration [14].**
- **1978 – US Public Utilities Regulation Act (PURPA) passed [18].**



(a) (b)

Fig. 1.1: (a) Telstar satellite [10] (b) typical silicon soar cell or photovoltaic (PV) cell [1].

USA Abandons Renewable Energy and Energy Independence

The political climate in the 5th period from 1980 to 2000 shifted from enthusiastic support for Energy Independence to a de-emphasis on Energy Independence and a commitment beginning with President Reagan to an emphasis on protecting the oil supply from the middle-east with the US military as necessary. This led to a slowing of solar PV development in the US with no major demonstration projects in the US between 1980 and 2000. President Reagan removed the solar panels from the white hose in 1986. Table 1.5 shows some of the major events during this period.

Table 1.5: 1980-2000: Slowed Development Phase

- **1981 – First Concentrating PV system using Fresnel Lenses goes into operation with 350 kW funded by US and Saudi Arabia SOLERAS project.**
- **1983 - Worldwide photovoltaic production exceeds 21.3 megawatts, and sales exceed $250 million.**
- **1985 - 20% efficient silicon cells are created by the Centre for Photovoltaic Engineering at the University of New South Wales.**
- **1986 - President Ronald Reagan removes solar panels from the White House.**
- **1990 – L. Fraas, J. Gee, k. Emery, et al describe the 35% efficient Two-Chip Stack GaAs/GaSb Concentrator Solar Cell [20].**
- **1991 - President George H. W. Bush directs the U.S. Department of Energy to establish the National Renewable Energy Laboratory (transferring the existing Solar Energy Research Institute).**
- **1992 – Kuryla, Fraas, & Bigger report 25% efficient CPV module using GaAs/GaSb stacked cell circuit [21].**
- **1993 - The National Renewable Energy Laboratory's Solar Energy Research Facility is established.**
- **1994 - NREL develops a GaInP/GaAs two-terminal concentrator cell (180 suns) which becomes the first monolithic two Junction solar cell to exceed 30% conversion efficiency [19].**
- **1998 – Demonstration of First ThermoPhotoVoltaic Heat & Electricity Co-generation MidnightSun™ Stove by JX Crystals Inc [23]**

The DOE Solar Energy Research Institute (SERI) was renamed the National Renewable Energy Lab (NREL) in 1991. SERI and NREL spent most of their R&D funds on non crystalline thin film solar cells with little tangible results. Most of the US government funded PV cell advances in this period even at NREL related to space cells. The InGaP/GaAs two junction monolithic cell was developed for space with the 30% CPV cell being a spin off for terrestrial applications [19].

Fraas et al with funding from NASA and the DOD demonstrated the GaAs/GaSb 35% efficient stacked cell for concentrator applications in 1990 [20]. Then Kuryla, Fraas, and Bigger with IR&D funding from Boeing reported a 25% efficient CPV module with a GaAs/GaSb stacked Cell circuit. This 25% efficiency was measured in outdoor sunlight at the STAR test facility in Arizona [21]. Figure 1.2 shows a photo of a similar CPV module fabricated for a Photovoltaic Advanced Space Power flight. This CPV PASP+ module was tested successfully in space in 1994 [22].

Figure 1.2: Photograph of PV Advanced Space Power (PASP+) module fabricated at Boeing using GaAs/GaSb stacked two-junction cells and flown in space by NASA in 1994 [22].

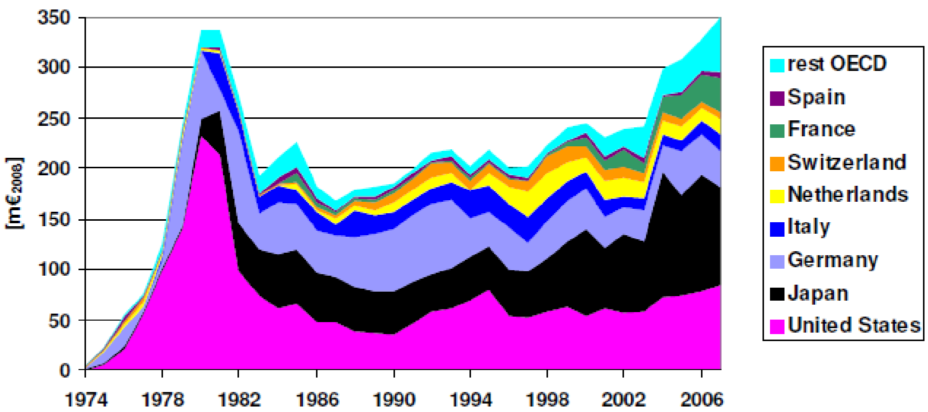


Figure 1.3: Annual public funding in PV by OECD countries from 1974 to 2008 [24]. US R&D funding fell steeply in 1980 and R&D support for PV passed over to Japan and Germany. Annual funding levels fell from over 300 million to 200 million Euros and did not reach 300 million again until 2003.

Also in 1998, Fraas et al at JX Crystals Inc with internal funding developed the first ThermoPhotoVoltaic product, the MidnightSun™ Stove [23]. GaSb infrared cells are used in TPV to generate electricity for combined heat and power applications. Here again, one encounters non-solar IR PV cells in an application that works day and night. TPV will be the subject of chapter 11 in this book.

During this period, PV development funding passed over to Japan and Germany as shown in figure 1.3 [24].

International Support and Volume Production at Low Cost

The 6th and final historical period from 2000 until the present is characterized by a shift to international participation in PV cell deployment with the US playing primarily an R&D role. Table 1.6 presents the key events in this period. Germany, China, and Japan are dominant in this period. This period begins with the German Renewable Energy Sources Act [25] which creates a Solar Feed-In-Tariff or FIT which creates a solar market in Europe. Suntech Power [26] is then formed in China in 2001 and this begins a period of commitment to solar manufacturing with government subsidies and low cost labor in China. Cumulative solar PV installed capacity world wide then grows from 1 GW in 2002 to 134 GW in the beginning of 2014 [27]. The silicon solar PV cell is now established as the dominant cell. This is phenomenal growth which continues today. See figure 1.4.

Table 1.6: 2000 – Present: International Support & New Opportunities

- **2000 – Germany's Renewable Energy Sources Act creates Feed-In-Tariff (FIT) for solar [25].**
- **2001 – Suntech Power founded in China [26]**
- **2002 – Amonix and Arizona Public Service install 175 kW High Concentration (HCPV) utility system at Prescott AZ [Chapter 7]**
- **2004 – K. Araki et al demonstrate 28% efficient CPV module [30]**
- **2004 - SunPower Corp first manufacturing facility (Fab 1) making 20% A-300 cells comes online in the Philippines and the company's first utility-scale power plant comes online in Bavaria [Chapter 5].**
- **2006 - Polysilicon use in photovoltaics exceeds all other polysilicon use for the first time.**
- **2006 – L. Fraas et al demonstrate 33% efficient Dual Focus HCPV Module [Chapter 7]**
- **2006 - New World Record Achieved in Solar Cell Technology - New Solar Cell Breaks the "40 Percent Efficient" Sunlight-to-Electricity Barrier [Chapter 8}**
- **2007 - Construction of Nellis Solar Power Plant, a 15 MW PPA installation using SunPower Corp modules.**
- **2010 - President Barack Obama orders installation of additional solar panels and a solar hot water heater at the White House[10]**
- **2011 - Fast-growing factories in China push manufacturing costs down to about $1.25 per watt for silicon photovoltaic modules. Installations double worldwide [27]**
- **2011 – Solyndra investment fiasco based on CIGS technology severely slows solar in US**
- **2013 – Amonix demonstrates a 35.9% efficient HCPV module [Chapter 7]].**
- **2013 – Fraas proposes mirrors in space in dawn dusk sun synchronous orbit deflecting sunlight down to terrestrial solar farms in early morning and evening hours [Chapter 12].**
- **2013 – Cumulated world wide solar PV installations passes 100 GW [27]**

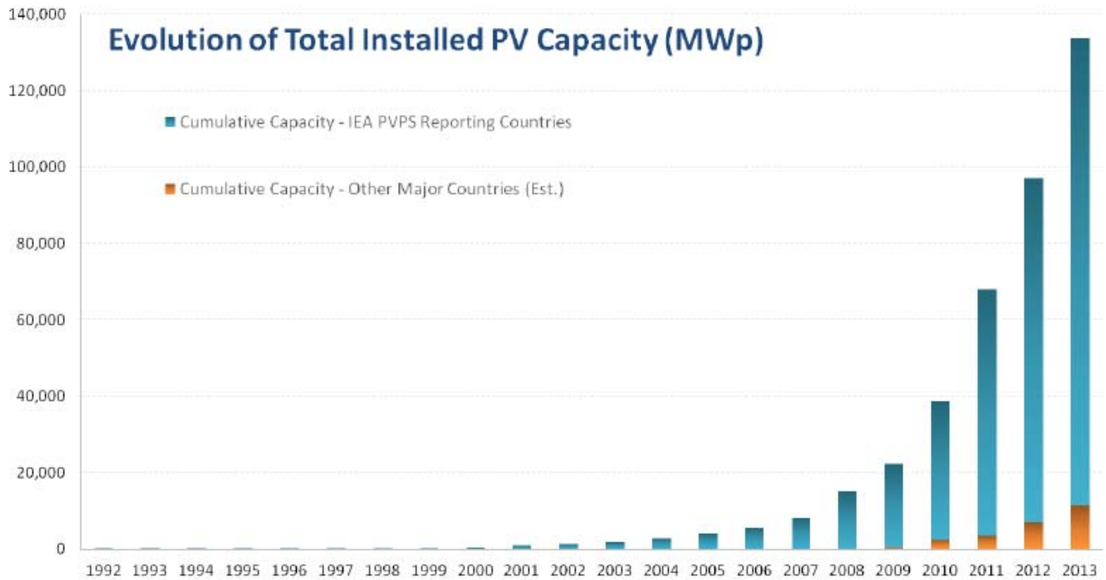


Figure 1.4: Evolution of Total PV Installed Capacity from 1992 to 2013 [27] - in MW

The PURPA in the US [18] and the German FIT [25] created good market conditions and this along with the technical innovations over the years and the Chinese government's investment in solar PV module manufacturing allowed for the solar PV module market expansion shown in figure 1.4 along with module and installed system continuous price reductions as shown in figures 1.5 and 1.6. Prices for both modules and systems have been consistently dropping year after year in both Germany and the US. However, note that the installed system pries are lower in Germany in 2013 at $2.35 per W (correcting Euro to $) than for similar systems in the US at $4 per W. This difference will be discussed in the next chapter.

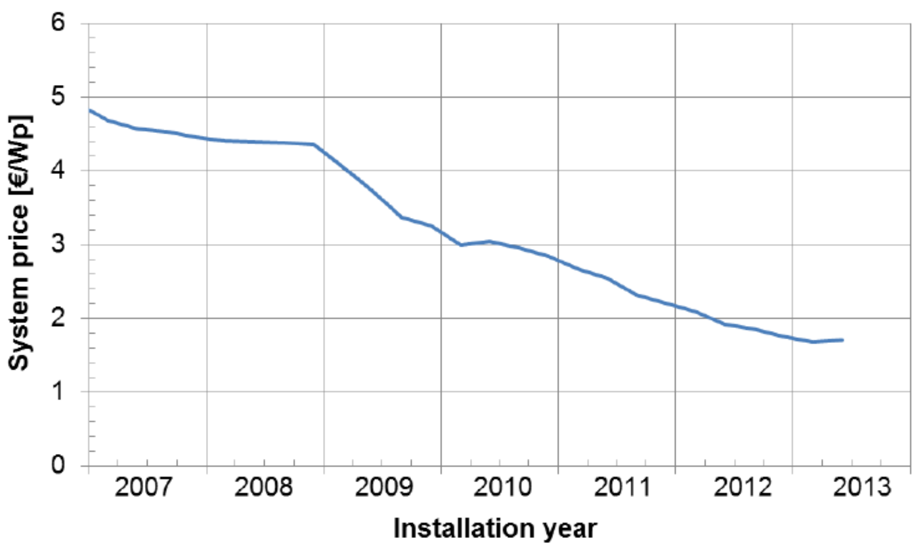


Figure 1.5: Average end customer price (net system price) in Germany [28] for installed rooftop plants with rated power of up to 10 kWp, data from [BSW].

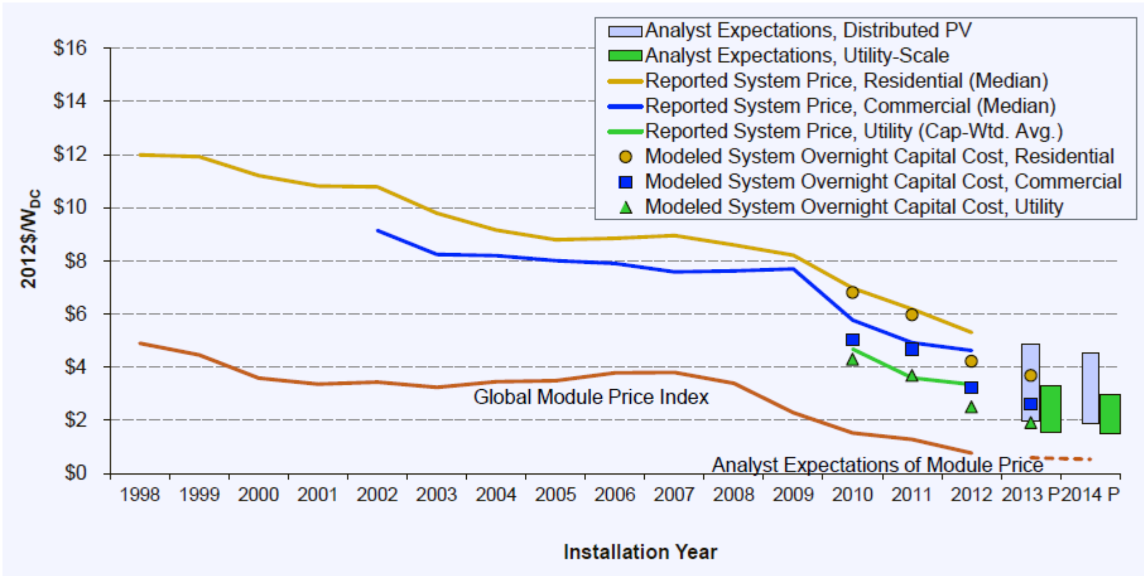


Figure 1.6: Reported, Bottom-Up, and Analyst-Projected Average U.S. PV System Prices over Time [29]

In any case, installed system prices are consistently dropping and there are opportunities for continued improvements as will be discussed in subsequent chapters herein.

However, there are some indications of new opportunities as well as some pitfalls indicated in Table 1.6. Concentrator PV (CPV) development is an opportunity because of the higher module efficiencies. In 2004, K. Araki from Japan demonstrated the 28% efficient module [30] shown in figure 1.7. Note the resemblance to the CPV module in Figure 1.2. CPV module efficiencies are continuing to rise with the most recent module efficiency at 35.9% as will be discussed more here in chapter 7. CPV obviously represents a future opportunity for development potentially leading to lower cost solar electric power.

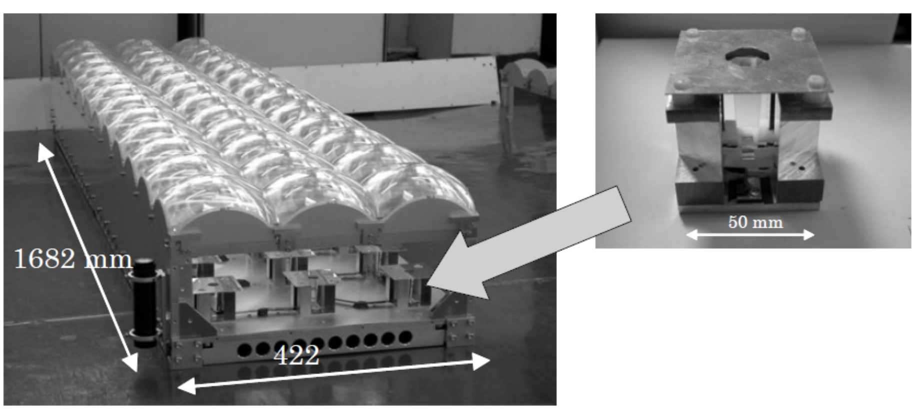


Figure 1.7: Domed Fresnel Lens Terrestrial 28% Efficient 200 W CPV Module [30]

Table 1.6 also highlights some pitfalls. For example, note the Solyndra disaster in 2011 associated with CIGS thin film technology. After 50 years of development, the efficiencies for non crystalline thin film modules are still well below 15%.   In this authors opinion, it is not wise to continue emphasizing the development of non crystalline thin film solar PV modules. Higher efficiency will be a key to lower cost along with extending the hours of operation beyond the traditional terrestrial sunlight hours. Ideas will be presented in chapter 12 related to solar power from space.

Figure 1.8 shows photographs of large solar PV systems in operation today.

Figure 1.8: Large solar PV fields in operation today [27]

This chapter has been a review of the history of PV cell development. There is a lot more to cover in the following chapters.

References:

1. E. Becquerel (1839). "Mémoire sur les effets électriques produits sous l'influence des rayons solaires". *Comptes Rendus* **9**: 561–567. Issue date: May 7, 1935.
2. http://en.wikipedia.org/wiki/Timeline_of_solar_cells
3. W.G. Adams and R.E. Day (1877) “The action of light on selenium” in Proceedings of the Royal Society, A25, 113.
4. Einstein, A, “On the Quantum Theory of Radiation” Phyikalische Zeitschrift 18 (1917).
5. David C. Brock (Spring 2006). "Useless No More: Gordon K. Teal, Germanium, and Single-Crystal Transistors". *Chemical Heritage Newsmagazine* (Chemical Heritage Foundation) **24** (1). Retrieved 2008-01-21.
6. Bloch, F, Z. Phys. (1928), 52, 555.
7. Wilson, A. H., Proc. Roy. Soc. A (1931), 133, 458; 134, 277.
8. D. M. Chapin, C. S. Fuller, and G. L. Pearson (May 1954). "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power". *Journal of Applied Physics* **25** (5): 676–677. doi:10.1063/1.1721711
9. Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller(AT&T) receive patent US2780765, "*Solar Energy Converting Apparatus*."(1957)
10. http://en.wikipedia.org/wiki/Telstar
11. http://en.wikipedia.org/wiki/1973_oil_crisis
12. Alferov, Zh. I., V. M. Andreev, M. B. Kagan, I. I. Protasov, and V. G. Trofim, 1970, ‘‘Solar-energy converters based on p-n AlxGa12xAs-GaAs heterojunctions,’’ Fiz. Tekh. Poluprovodn. 4, 2378 (Sov. Phys. Semicond. 4, 2047 (1971))
13. H. J. Hovel and J. M. Woodall, “High Efficiency AlGaAs-GaAs Solar Cells”, Appl. Phys. Lett. **21**, 379-381 (1972).
14. R. Loo, R. Knechtli, S. Kamath, et al, “Electron and Proton Degradation in AlGaAs-GaAs Solar Cells”, 13th IEEE Photovoltaic Specialist Conference, 562 (1978).
15. L. M. Fraas and R. C. Knechtli, “Design of High Efficiency Monolithic Stacked Multijunction Solar Cells”, 13th IEEE Photovoltaic Specialist Conference, 886 (1978).
16. D. E. Carlson and C. R. Wronski, “Amorphous silicon solar cell” Appl. Phys. Lett. **28**, 671 (1976)
17. http://www.vintagecalculators.com/html/calculator_time-line.html
18. http://en.wikipedia.org/wiki/Public_Utility_Regulatory_Policies_Act
19. Friedman D et al., Prog. Photovolt.: Res. Appl. 3, 47–50 (1995)

20. Lewis Fraas, James Avery, James Gee, Keith Emery, et. al., “Over 35% Efficient GaAs/GaSb Stacked Concentrator Cell Assemblies for Terrestrial Applications”, 21st IEEE PV Specialist Conference, p. 190 (1990).

21. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930018773.pdf

22. http://www.ionbeamoptics.com/pdf/SSU_9-17-07.pdf

23. Lewis Fraas, Russ Ballantyne, She Hui, Shi-Zhong Ye, Sean Gregory, Jason Keyes, James Avery, David Lamson, Bert Daniels, “Commercial GaSb cell and circuit development for the Midnight Sun® TPV stove” AIP Conference Proceedings 03/1999; 460(1):480-487. DOI:10.1063/1.57830

24. http://www.qcells.com/uploads/tx_abdownloads/files/17_RESEARCH_AND_DEVELOPMENT_Paper_02.pdf

25. http://en.wikipedia.org/wiki/German_Renewable_Energy_Act

26. http://en.wikipedia.org/wiki/Suntech_Power

27. PVPS_report_-_A_Snapshot_of_Global_PV_-_1992-2013_-_final_3.pdf; http://en.wikipedia.org/wiki/Agua_Caliente_Solar_Project

28. 2014_MAR_19_Recent_Facts_about_PV_in_Germany - Final.docx26.03.14

29. https://haiti-now.org/wp-content/uploads/2013/08/Photovoltaic-System-Pricing-Trends-2013.pdf.

30. K Araki et al, A 28 % Efficient, 400 X & 200 WP Concentrator ...,www.physics.usyd.edu.au/app/solar/.../pdf/19thEUPV_5BV_2_20.pdf