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Photovoltaic cell – the history of invention – review

Abstract: The discovery story of photovoltaic cells is entirely typical. Chance played a role in it, and before it went to the average user, it first served the army. In addition, as with the discovery of electricity, there are many scientists and more than 100 years of technological development behind how modern photovoltaic cells and solar panels work. The first photovoltaic panels were able to power, at most, a radio. Today their power allows for the production of energy for the entire household. Technology is continuously developing, and the hence achieved efficiency keeps growing. Modern silicon solar cells of large photovoltaic farms power thousands of buildings, and this installation can be seen more and more often. This article describes the development of the use of solar energy since ancient times and the comprehensive history of the invention of the photovoltaic cell, starting with the discovery of the photoelectric effect by Edmond Becquerel in 1839 to the achievement of nearly 50% efficiency under laboratory conditions. The advances in photovoltaic cell efficiency and the price of energy production per watt over the years are also shown. Examples of the first applications of photovoltaics are given, and profiles of figures who contributed to the development of solar technology are introduced. The considerable influence of Polish scientists on the development

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of the photovoltaic cell is also highlighted. Without them, this method of obtaining energy would perhaps not be at high levelh level today.

Keywords: photovoltaic cell, solar panel, solar energy history, photoelectric effect invention

Introduction

Since the prehistoric times of the first plants and animals on Earth, solar radiation has been warming and nurturing all life forms on our planet. The Sun is the primary source of all ways of obtaining energy on Earth (except geothermal). This statement also applies to fossil fuels, which are formed by the decomposition of buried dead organisms over a very long period (Berner 2003). These organisms developed their bodies millions of years ago through photosynthesis or by feeding on other photosynthesis-capable organisms. Photosynthesis is a biological process that enables plants, algae, and some bacteria to convert solar energy and carbon dioxide from their environment into carbohydrate molecules (Fischer et al. 2016). In fact, the electricity generated in a coal-fired power plant also comes from the Sun. Unfortunately, it takes many millions of years for dead plants and animals to turn into carbon, so no usable amount of carbon will be created in the time we have. If all the coal had been extracted and all the oil had been pumped out, there would simply be no more, making fossil fuels non-renewable.

On the other hand, renewable technologies can be called technologies that use solar energy directly to convert it into another type of energy, such as heat or electricity. Solar technology is not new. In its primitive form, solar energy has been used practically since man's appearance on Earth. The oldest records of solar energy use are related to the 7th century BC, a magnifying glass to focus a beam of sunlight to light a cooking fire (Perlin 2022). In the 3rd century BC, the Greeks and Romans reflected sunlight using unique mirrors to light lanterns used in religious ceremonies (Perlin 2022). Ancient rooms were situated facing the Sun to collect natural heat. Buildings with a facade facing south intercepted the Sun's rays and stored heat energy in Roman baths, and this simple technology is still used today. There is also a legend related to the Greek scientist Archimedes, who was said to have set fire to enemy ships of the Roman Empire before they could reach the shore, using the Sun's rays reflected from special shields made of bronze (Sigismondi and Oliva 2005). This would be a prototype solar laser. There is no certainty that this event ever took place. However, in the 1970s, for scientific purposes, the Greek army conducted a similar experiment setting fire to a wooden test ship 50 meters away, using only reflective bronze shields and solar energy. The experiment was successful, and thus it is likely that there is at least the proverbial grain of truth in the legend.

At present, the total installed solar photovoltaic power capacity in the European Union is about 160 GW (Jäger-Waldau 2020; SolarPower Europe 2022). About 60% of this capacity is from residential and commercial rooftop installations. The cumulative installed capacity in the

European Union and the United Kingdom accounts for about 21% of those worldwide (Masson et al. 2018). The number of solar photovoltaic power plants (some with storage) is growing yearly in more and more countries. In 2021, the primary solar market was Germany, with 5.3 GW of newly installed capacity, followed by Spain (3.8 GW), the Netherlands (3.3 GW), Poland (3.2 GW), and France (2.5 GW). In 2021, 25 of the 27 EU member states deployed more solar than the year before (https://www.solarpowereurope.org/ 2022).

1. Solar cell invention

The invention of the solar cell dates back to 1839, when French physicist Edmond Becquerel discovered the photovoltaic effect by experimenting with a cell made of metal electrodes through which a current flowed (Becquerel 1839). He noted that the amount of electricity produced increases when the cell is exposed to sunlight (Brusso 2019). Afterward, in 1873, Willoughby Smith discovered that selenium could be a photoconductor (Smith 1876). Three years later, William

Fig. 1. Modern photovoltaic panels on the roof of a residential building (Stock 2022a)

Rys. 1. Nowoczesne panele fotowoltaiczne na dachu budynku mieszkalnego

Grylls Adams and Richard Evans Day combined these two discoveries while noting that it was possible to produce electricity using sunlight (Dhingra 2021). In 1883, American inventor Charles Fritts created the first fully functioning solar cell based on selenium (Kuppusamy et al. 2022). In today's cells, the element most often used is silicon, but the invention based on selenium was the prototype of the current technology. Many other physicists also played their part in developing the invention of photovoltaic cells, but Becquerel and Fritts are considered the fathers of the technology. They came up with the idea that was developed over the years and led to today's shape of solar panels, which we can see on many household roofs in our neighborhood. Modern photovoltaic panels mounted on residential roofs are found below.

2. First applications

Albert Einstein was one of the earliest proponents of solar energy and its potential. In 1905, he published a paper on the photoelectric effect and how energy is transferred by light (Einstein

Fig. 2. Photovoltaic panel on modern spacecraft (Stock 2022b)

Rys. 2. Panel fotowoltaiczny na nowoczesnych statkach kosmicznych

1905). This statement resulted in considerable interest in the scientific world in using solar energy on a broader scale. However, it was in 1954 that three *Bell Labs* scientists – Daryl Chapin, Calvin Fuller, and Gerald Pearson created a more practical solar cell using silicon for its construction (Chapin et al. 1954). Advantages of this element include higher efficiency and much greater availability than selenium. In the 1950s, there was a significant development of space expansion and spacecraft technology, which began to be equipped with photovoltaic cells. The first such machines were the *Vanguard I* (1958), *Vanguard II*, *Explorer III*, and *Sputnik-3* satellites (Wolfe 2018). In 1964, the US government agency responsible for the national spaceflight program, NASA, launched the *Nimbus* satellite, which was powered solely by a 470-watt photovoltaic panel array (Arepalli and Moloney 2015). Shortly after, the technology gradually began to be used in homes, factories, and public buildings.

3. Photovoltaic panels as an alternative energy source

In the 1970s, the fuel crisis made the American public and other countries aware of the heavy dependence on imported deposits. This was a period of severe inflation, significant budget cuts,

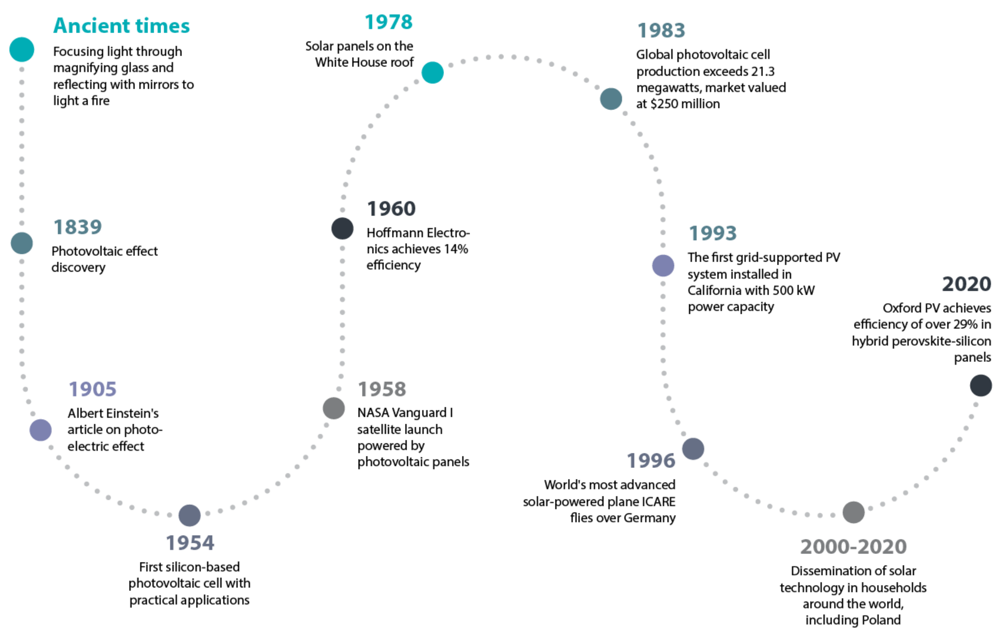

Fig. 3. Development progress of photovoltaic cell (Fraas 2014; Bosio et al. 2020)

Rys. 3. Postęp w rozwoju ogniwa fotowoltaicznego and the need to develop new, low-cost power generation technology. At that time, then-President Jimmy Carter decided to install photovoltaic panels on the roof of the White House in 1978 (Fraas 2014). This was to set an example for US citizens and to expand the use of clean solar energy while offering hope of ending the energy crisis. Despite the substantial public interest, solar technology was still expensive, and needed to be more return on investment.

Nevertheless, more advanced solar cells began to be built, cheaper yet more efficient. However, the most remarkable progress in the development of solar technology on a global scale can be seen only over the past 20 years. It should be emphasized that Polish scientists have also made a considerable contribution here. Various materials and cell designs were researched to achieve the highest possible efficiency, which was not very high until the end of the 20th century. Progress in the development of photovoltaic cell technology is shown in the figure above and described in the next chapter.

4. The efficiency of solar cells over the years

The first solar cells based on Becquerel's invention had an efficiency of 1%, costing about \$300 per watt to produce energy using them. At the time, producing electricity from coal cost about \$2–3 per watt. *Bell Labs'* silicon panels in 1954 operated with an initial efficiency of about 6% (Perlin 2004), but after applying many improvements and conducting numerous tests, a dizzying 11% was achieved. However, this was a considerable advance and it was possible to power some electrical devices for up to several hours for the first time in history. In 1959, *Hoffman Electronics* produced panels with an efficiency of 10%, and in 1960 they managed to raise it to 14% (Zaidi 2018). This improvement reduced the cost of generating 1 watt of electricity to a price of \$100, which was many times higher than the most common coal. In the 1970s, *Exxon* funded the research of Dr. Eliot Berman (Shahidehpour and Schwartz 2004), who developed cheaper cells and lowered the cost of production to about \$20 per watt. Starting in the 1980s, the cost of photovoltaic panels fell by an average of 10% each year. In 1983 global photovoltaic cell production exceeded 21.3 megawatts, and the whole market was valued at \$250 million (Rani et al. 2020). Due to US government efforts and scientific achievements in this field, in 1993, Pacific Gas and Electric in Kerman, California, installed the first grid-supported photovoltaic system having a power capacity of 500 kilowatts (Spinka 2010). Some point of interest is the first flight of an ICARE plane, powered by 3,000 solar cells, built at the University of Stuttgart in 1996, which flew over the whole of Germany (Ross 2008). The efficiency of solar cells was constantly growing in laboratory conditions, but the latest technology was only sometimes introduced to industry and households. Today, manufactured photovoltaic cells have 15–18% efficiencies, which still seems low, but the cost of producing 1 watt is below \$0.5.

Improvements in technology and cost reductions are due to the many scientists working on using solar energy to produce electricity, considered clean, "green energy". Polish scientists have

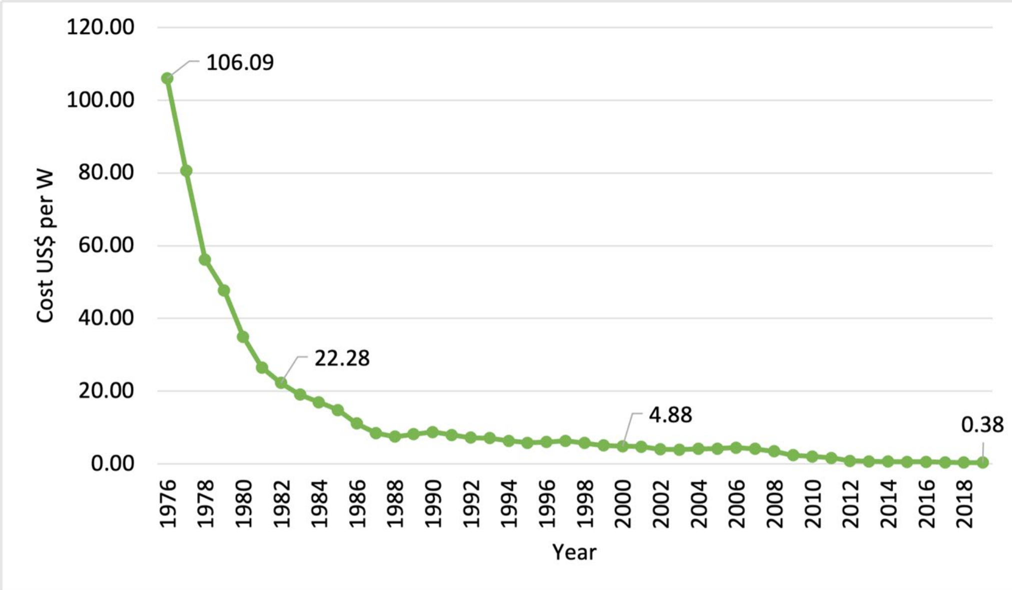

Fig. 4. Global average price of solar photovoltaic (PV) modules, measured in 2019 US$ per Watt (Lafond et al. 2017; Taylor et al. 2020)

Rys. 4. Średnia światowa cena modułów fotowoltaicznych (PV), mierzona w USD za wat w 2019 roku

also made their contribution here. Modern solar panels were only possible thanks to the contribution of Polish chemist and metallurgist Jan Czochralski. At the beginning of the 20th century, he invented the method of producing monocrystalline silicon, from which solar cells are still made today (Tomaszewski 2003). Without this scientific breakthrough, there would be no interest in photovoltaics today. At present, solar cells based on silicon are classified as first-generation solar cells. About 80% of solar cell production is based on monocrystalline, polycrystalline, amorphous, and hybrid silicon (Kalogirou 2009). After all, commercial use of the Sun's unlimited energy requires a suitable material to convert light. Silicon solar cells have stood the test of time. The next improvement for solar cells was the construction of their layers as a thin film (few microns) (second-generation solar cells). These solar cells include amorphous solar cells and two nonsilicon-based solar cells (cadmium telluride and copper indium gallium diselenide) (Petti et al. 2012). The cost of fabrication is much less than first-generation solar cells, however, the use of cadmium can be a serious environmental issue. The maximum efficiency recorded for these cells was 24.7%. Another curiosity and an inevitable breakthrough is the perovskite-based technology developed by Olga Malinkiewicz, a Polish physicist, co-founder, and co-owner of *Saule Technologies* (Malinkiewicz et al. 2013). On the other hand, Oxford PV succeeded in developing a hybrid perovskite-silicon cell with an efficiency of more than 29% in 2020. However, scientists believe that much higher values are possible. Recently, the focus of the research has been to enhance efficiency by using innovative nanomaterials such as silicon nanowires, nanotubes, nonsilicon materials, organic dies, and conducting polymers (third-generation solar cells) (Tahir et al. 2020). The maximum efficiency recorded for a third-generation solar cell is about 44%, but the studies have not yet been commercialized. Under laboratory conditions, a maximum value of 47.1% has so far been achieved (Geisz et al. 2020) (Fig. 5).

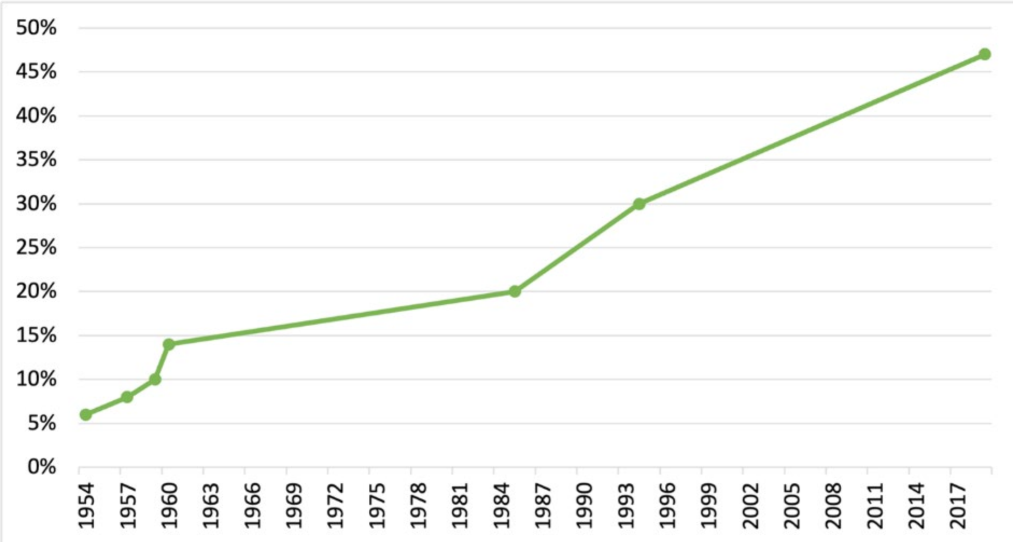

Fig. 5. Best achieved photovoltaic cell efficiency over the years (Goetzberger et al. 2003; Geisz et al. 2020)

Rys. 5. Najwyższa osiągnięta wydajność ogniw fotowoltaicznych na przestrzeni lat

Summary and conclusions

Solar technology dates back to ancient times, and it can be assumed that man has been trying to harness the heat, light, and energy provided by our closest and most precious star – the Sun – since the beginning of time. The total energy it sends out is much higher than humankind's current needs, but the technologies that can fully utilize it still need to be created. The typical real efficiency of the devices produced today is at most 20%, yet they are installed and used on a large scale both in industry and private homes. Solar energy is clean, emitting no harmful substances into the environment. The issue of the disposal of used photovoltaic panels, which, according to manufacturers, retain their efficiency for about 20–30 years, is still a matter of debate. However, research work is being carried out in this area as well. Photovoltaic panels are a constantly developing technology. In fact, their efficiency is improving from year to year, so the price of generating 1 watt of "green" electricity is continuously falling. An additional factor contributing to the increasing popularity of photovoltaics in recent times is high inflation and a substantial increase in the price of fuel and, thus, electricity. Solar technology is constantly being developed, and it is particularly gratifying that Polish scientists are also making a considerable contribution here.

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Panel fotowoltaiczny – historia wynalazku – artykuł przeglądowy

Streszczenie

Pod wieloma względami historia odkrycia instalacji fotowoltaicznych jest dość typowa. Odegrał w niej rolę przypadek, a zanim trafiła do zwykłego użytkownika, najpierw służyła armii. Ponadto, podobnie jak w przypadku odkrycia energii elektrycznej, za tym, w jaki sposób pracują współczesne ogniwa fotowoltaiczne oraz panele słoneczne, stoi wielu naukowców i więcej niż 100 lat rozwoju technologii. Pierwsze panele fotowoltaiczne były w stanie zasilić co najwyżej radio, dziś ich moc pozwala na produkcję energii dla całego gospodarstwa domowego. Technologia jest stale rozwijana, a co za tym idzie osiągana efektywność wzrasta. Współczesne krzemowe ogniwa słoneczne wielkich farm fotowoltaicznych zasilają kilkadziesiąt tysięcy budynków, a tego typu instalacji stale przybywa. W niniejszym artykule opisano rozwój wykorzystania energii słonecznej od czasów starożytnych oraz kompleksową historię wynalazku ogniwa fotowoltaicznego począwszy od odkrycia efektu fotoelektrycznego przez Edmonda Becquerela w 1839 roku na osiągnięciu niemal 50% sprawności w warunkach laboratoryjnych. Przedstawiono także postępy w zakresie efektywności ogniwa fotowoltaicznego oraz ceny produkcji energii w przeliczeniu na 1 wat na przestrzeni lat. Podano przykłady pierwszych zastosowań fotowoltaiki oraz przybliżono sylwetki postaci mających swój wkład w rozwój technologii solarnej. Podkreślono również niemały wpływ polskich naukowców na rozwój ogniwa fotowoltaicznego, bez których być może ten sposób pozyskiwania energii nie byłby dziś na tak wysokim poziomie.

Słowa kluczowe: ogniwo fotowoltaiczne, panel solarny, historia energii solarnej, efekt fotoelektryczny