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The new paradigm of photovoltaics: From powering satellites to powering humanity

Le nouveau paradigme de l'énergie solaire photovoltaïque : de l'alimentation électrique des satellites à celle de l'humanité

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ABSTRACT

The photovoltaic effect has been discovered by Edmond Becquerel in 1839. Then it took 115 years to make the first efficient solar cell, with a few watts produced, about 50 years to deploy 3 GW of production capacity worldwide, and only 13 years to reach 300 GW in 2016. 500 GW are expected in 2020, and the TW within the next decade. How did this occur? How does photovoltaics work? What is the physical limit of conversion efficiency? What road map for photovoltaics in the energy transition? This paper aims at providing a review and discussion of these aspects, from the historical background to the state of the art and the emerging devices and concepts.

RÉSUMÉ

L'effet photovoltaïque a été découvert par Edmond Becquerel en 1839. Il a fallu 115 ans pour fabriquer la première cellule efficace à hauteur de quelques watts, puis environ 50 ans pour atteindre 3 GW de capacité installée dans le monde, et seulement 13 ans pour atteindre 300 GW en 2016. 500 GW sont attendus en 2020, et plus d'un TW au cours de la prochaine décennie. Comment une telle accélération a-t-elle été possible ? Quels sont les mécanismes de la conversion photovoltaïque ? Son rendement maximum ? Quels scénarios sont établis pour le futur dans le contexte de la transition énergétique ? L'article examinera tous ces aspects, en partant du contexte historique jusqu'à l'état de l'art actuel, en incluant les cellules solaires émergentes et les nouveaux concepts.

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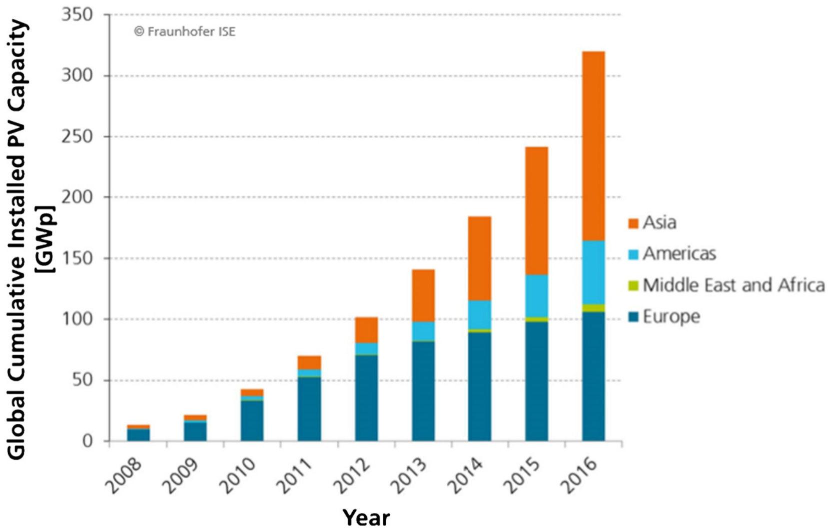

Fig. 1. Evolution of the global cumulated installed photovoltaic capacity, with regional subdivisions. From: Photovoltaic report 2017, ISE Fraunhofer [2].

1. Introduction

The photovoltaic effect has been discovered by Edmond Becquerel in 1839 during the study of electrical effects occurring between two electrodes dipped in electrolytes [1]. At that time, the scientific community was fully engaged in exploring the new field of electricity opened in 1800 after A. Volta's discoveries. E. Becquerel reported the production of a photocurrent when electrodes covered by copper or silver halides salts were illuminated by solar light. He discovered also the effect of wavelength on the production of the electrical current, which is now explained by the semiconducting character of these salts with the existence of band gaps. It took 115 years to make the first efficient solar cell, with a few watts produced, about 50 years to deploy 3 GW of production capacity worldwide and only 13 years to reach 300 GW in 2016 (see Fig. 1 [2]), 500 GW are expected in 2020 and the TW within the next decade. How did this occur? How photovoltaics work? What is the potential for further development of photovoltaics in the energy transition? This paper aims to bring an overview and a discussion of all these aspects from an historical perspective.

2. Historical survey

30 years later after Becquerel's discovery, during the course of establishing electrical communication networks around the world, the search for flaw detections led to both the discovery of photoductivity in selenium rods by W. Smith [3], and the premises of an operating solar cell by W. Adams and R. Days [4]. The first operating solar cell based on a copper/selenium film/gold junction was created by C. Fritts in 1883 [5] and adopted by W. von Siemens [6] and J. Maxwell [7]. These inventors already considered that photovoltaic solar energy could supply energy to the earth, and a first solar array was even installed on a roof top in New York in 1884 by C. Fritts. So was also the statement of A. Mouchot at about the same period for solar energy conversion with thermal machines [8]. However, the mechanism of photovoltaic action was not understood and these first cells were mostly considered with skepticism as "Fritts 'magic' plates, as perpetual motion machines" [9] since light was not perceived as a fuel. It came out in the following years that the photovoltaic effect had the same origin as the photoelectric effect: the quantum nature of light, chiefly introduced by A. Einstein in 1905 [10].

The poor performances of selenium cells and the development of coal- and petrol-based energy economy made this discovery restricted to limited use as exposure meters, but found regained applications in radio telecommunications rectifiers known as "cat-whiskers" during the First World War. The development of vacuum tubes electronics in the 1930s then replaced these solid-state rectifiers for radio telecommunications, but failed to be adapted for shorter wavelength applications needed for the development of radars in the period of World War II, creating a revival of interest for "old" cat whiskers solid-state rectifiers [11]. In the course of revisiting this area at Bell telephone's laboratories, Russel Ohl discovered the superior performances of silicon with reaching photopotentials up to 0.5 V, much more that selenium or copper oxide previous materials. He found that the photoeffect is maximum in specific zones of recrystallized silicon boules, leading to the discovery of the p–n junction, and incidentally of the doping phenomenon with Al (n type) and P (p type). The first application was silicon solar cells and modules based on his findings, that he patented in 1941 [12]. An intense research activity was then developed at Bell's laboratories to increase the efficiency of the solar cell, the best efficiency with Ohl's technology reaching 1% in 1952 [13] with limitations arising from the processing technologies (He bombardment). The introduction of Li diffusion wraparound led to 4.5% in 1953, then its substitution by boron diffusion led to a spectacular take off of the efficiency up to 6% in January 1954 and 11% in May 1955 (as reported in R. Bube's book [14]). The key milestone of efficiencies higher than 5% fixed by the Bell's management for industrial credibility was thus presented in the 6% efficiency famous