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Research Article

Advanced Research of Photovoltaic Technologies in Solar

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Abstract: This paper provides the components of a standalone photovoltaic system. The word standalone refers to the fact that the system works without any connection to an established power grid. We have presented the basic concepts of the generation and storage of photovoltaic solar energy. We have also provided a method for designing a functional solar system with limited access to information and resources. This paper discusses the use of solar energy for the direct production of electricity (photovoltaic solar energy). Solar energy can also be used to heat fluids (thermal solar energy) which can then be used as a heat source or to turn a turbine to generate electricity.

INTRODUCTION

Solar radiation represents the largest energy flow entering the terrestrial ecosystem. After reflection and absorption in the atmosphere, some 100,000TW hit the surface of Earth and undergo conversion to all forms of energy used by humans, with the exception of nuclear, geothermal, and tidal energy. This resource is enormous and corresponds to almost 6,000 fold the current global consumption of primary energy (13.7 TW)[1]. Thus, solar energy has the potential of becoming a major component of a sustainable energy portfolio with constrained greenhouse gas emissions. Solar radiation is a renewable energy resource that has been used by humanity in all ages. Passive solar technologies were already used by ancient civilizations for warming and/or cooling habitations and for water heating; in the Renaissance, concentration of solar radiation was extensively studied and in the 19th century the first solar-based mechanical engines were built[2]. The discovery of photovoltaic effect by Becquerel in 1839 and the creation of the first photovoltaic cell in the early 1950s opened entirely new perspectives on the use of solar energy for the production of electricity. Since then, the evolution of solar technologies continues at an unprecedented rate. Nowadays, there exist an extremely large variety of solar technologies, and photovoltaics have been gaining an increasing market share for the last 20 years. Nevertheless, global generation of solar electricity is still small compared to the potential of this resource[3]. The current cost of solar technologies and their intermittent nature make them hardly competitive on an energy market still dominated by cheap fossil fuels. From a scientific and technological viewpoint, the great challenge is finding new solutions for solar energy systems to become less capital intensive and more efficient. Many research efforts are addressing these problems. Low-cost and/or high-efficiency photovoltaic device concepts are being developed. Solar thermal technologies are reaching a mature stage of development and have the potential of becoming competitive for large energy supply. Intermittency is being addressed with extended research efforts in energy storage devices, such as batteries and other electric storage systems, thermal storage, and the direct production of solar fuels (typically hydrogen). All these are valuable routes for enhancing the competitiveness and performance of solar technologies. This analysis is a bottom-up approach; solar technologies are organized by energy conversion paths and the discussion focuses, when possible, on the fundamental processes and the related technical challenges. Also, the cited references are meant to indicate the state-of-the-art and not to be a comprehensive snapshot of the ongoing research. Where possible, reviews were referenced that will provide the reader with more.

Solar Radiation

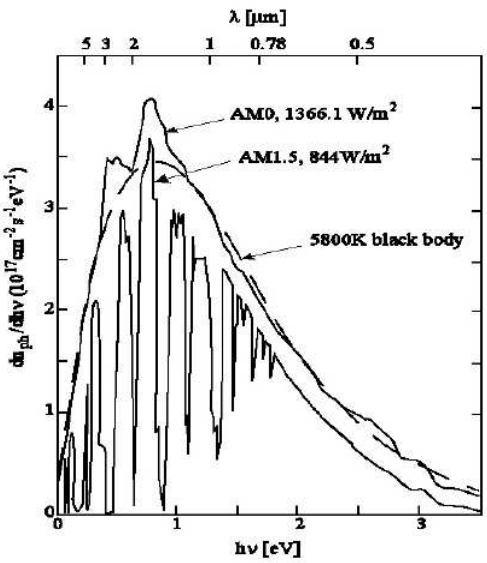

Fig. 1: Extraterrestrial (AM0) and ground level (AM1.5) spectra of the solar radiation [5].

Solar radiation is an electromagnetic wave emitted by the Sun's surface that originates in the bulk of the Sun where fusion reactions convert hydrogen atoms into helium. Every second 3.89.1026J of nuclear energy is released by the Sun's core[4]. This nuclear energy flux is rapidly converted into thermal energy and transported toward the surface of the star where it is released in the form of electromagnetic radiation. The power density emitted by the Sun is of the order of 64MW/m2 of which ~1370W/m2 reach the top of the Earth's atmosphere with no significant absorption in the space. The latter quantity is called the *solar constant*. The spectral range of the solar radiation is very large and encompasses nanometric wavelengths of gamma- and x-rays through metric wavelengths of radio waves. The energy flux is divided unevenly among the three large spectral categories. Ultraviolet (UV) radiation (λ<400nm) accounts for less than 9% of the total; visible light (VIS) (400nm<λ<700nm) for 39%; and infrared (IR) for about 52%. As shown in Fig. 1, the pattern of the solar spectrum resembles closely the radiation of a perfect black body at 5800K. In the figure, AM0 indicates the *Air Mass Zero* reference spectrum measured – and partially modeled – outside the terrestrial atmosphere[5]. Radiation reaching the Earth's surface is altered by a number of factors, namely the inclination of the Earth's axis and the atmosphere that causes both absorption and reflection (*albedo*) of part of the incoming radiation. The influence of all these elements on solar radiation is visible in the ground-level spectrum, labeled AM1.51 in **Fig. 1,** where the light absorption by the molecular elements of the atmosphere is particularly evident. Accounting for absorption by the atmosphere, reflection from cloud tops, oceans, and terrestrial surfaces, and rotation of the Earth (day/night cycles), the annual mean of the solar radiation reaching the surface is 170W/m^2 for the oceans and 180W/m^2 for the continents[4]. Of this, about 75% is direct light, the balance of which is scattered by air molecules, water vapor, aerosols, and clouds.

PHOTOVOLTAIC SYSTEM COMPONENTS

A basic photovoltaic system consists of four main components: the solar panel, the batteries, the regulator, and the load. The panels are responsible for collecting the energy of the sun and generating electricity. The battery stores the electrical energy for later use. The regulator ensures that panel and battery are working together in an optimal fashion. The load refers to any device that requires electrical power, and is the sum of the consumption of all electrical equipment connected to the system. It is important to remember that solar panels and batteries use direct current (DC). If the range of operational voltage of your equipment does not fit the voltagesupplied by your battery, it will also be necessary to include some type of converter. If the equipment that you want to power uses a different DC voltage than the one supplied by the battery, you will need to use a DC/DC converter. If some of your equipment requires AC power, you will need to use a DC/AC converter, also known as an inverter. Every electrical system should also incorporate various safety devices in the event that something goes wrong. These devices include proper wiring, circuit breakers, surge protectors, fuses, ground rods, lighting arrestors, etc.

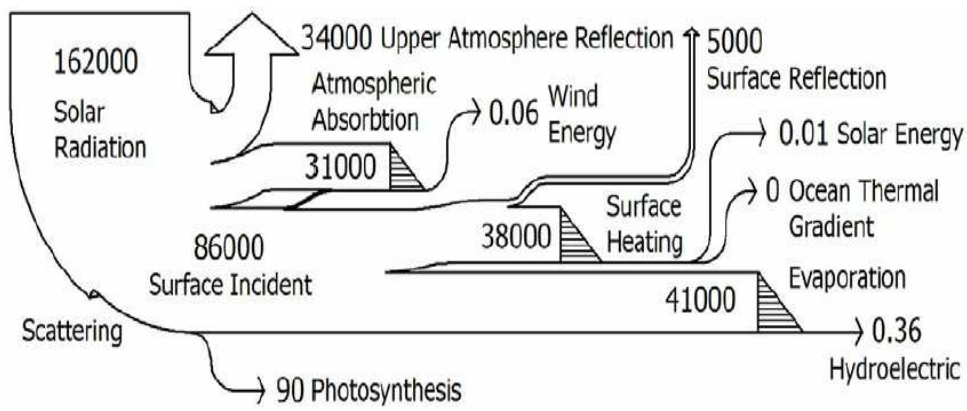

Fig. 2: Solar radiation exergy flow diagram (units in TW) [6].

The diagram in **Fig. 2** illustrates the flow of the work potential, or exergy, of the solar energy into the atmosphere and the terrestrial ecosystem. This quantity represents the upper limit to the work obtainable from solar radiation conversion, a limit that is imposed by the 2nd law of thermodynamics and is independent of any conceptual device. Of the 162PW of solar radiation reaching the Earth, 86PW hit its surface in the form of direct (75%) and diffused light (25%). The energy quality of diffused radiation is lower (75.2% of exergy content instead of 93.2% for direct light [7]), with consequences on the amount of work that can be extracted from it. 38PW hit the continents and a total exergy of 0.01TW is estimated to be destroyed during the collection and use of solar radiation for energy services. This estimation includes the use of photovoltaics and solar thermal plants for the production of electricity and hot water. Similar estimates are shown for wind energy (0.06TW), ocean thermal gradient (not yet exploited for energy production), and hydroelectric energy (0.36TW)[6].

Potential Application of Solar Energy: The global solar energy potential ranges from 2.5 to 80TW (see Appendix). The lowest estimate represents around 18% of the total current primary energy consumption (13.7TW)[1], an exceeds 10% of the estimated primary energy demand by 2030 (21.84TW)[1]. More optimistic assumptions give a potential for solar energy exceeding 5 fold the current global energy consumption. Despite the relatively low power density of the solar flux, solar energy has the potential of supplying a non-negligible fraction of our energy needs. In the case of the US for example, the total electricity demand (418GW in 2002) could be satisfied by covering a land surface of 180 km square with photovoltaics. This surface represents 0.35% of the total land area and roughly corresponds to the surface covered by roads in the country ($3.6.1010m^2$)[8]. All US electricity could hence be potentially produced by covering the paved roads with photovoltaic (PV) modules. Of course this cannot be applied to all countries, where the required land fraction can be more important (*e.g.* 24% for Belgium[9]), with subsequent large social and environmental impacts. The market share of solar energy is still low. Current electricity generation from PVs is only of the order of 2.6GW3 compared to 36.3GW for all renewable energies, hydroelectric power excluded[1,10]. Developed countries are steadily increasing their investments in solar power plants, and IEA projections for 2030 give an enhancement of solar electricity generation up to 13.6GW (80% of which will be from photovoltaic, and the rest (2.4GW) from solar thermal plants). However, this amount will not exceed 6% of the total electricity production from non-hydro renewable energies **(Fig. 3**). It is worth noting that passive solar technologies for water heating, not included in these statistics, represent a fairly large amount of power. IEA estimates a power production of 5.3GW in 2002 and an increase[1] up to 46GW by 2030.

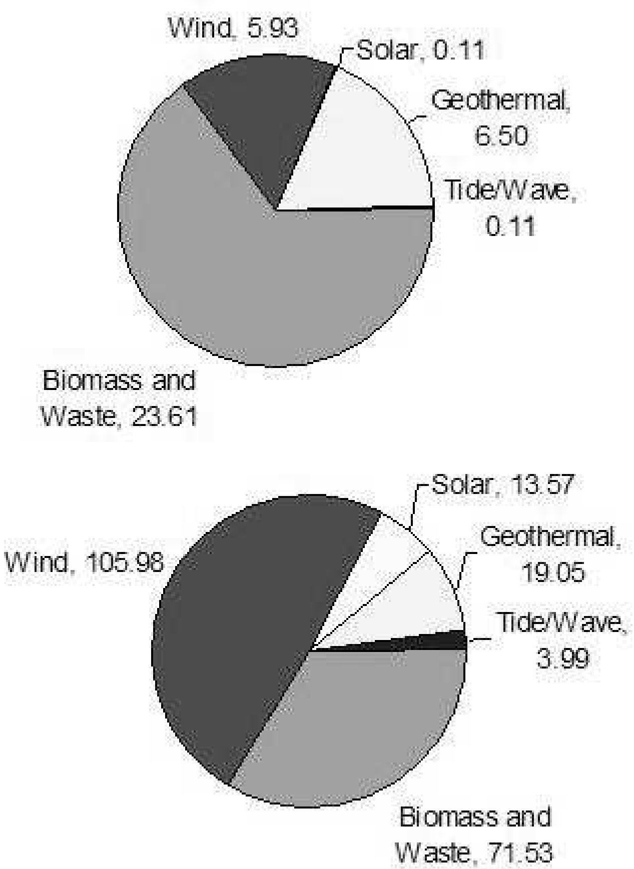

Fig. 3: Current and projected non-hydro renewable electricity production for 2030 (in GW) [1].

The major causes of the slow deployment of solar technologies are:

• The current relative high capital cost per kW installed compared with other fossil fuel based and renewable technologies;

• The intermittent nature of the energy input, and hence the requirement for energy storage systems to match the energy supply with the electricity demand and to decrease the capital cost.

Cost of electricity: The current higher capital cost of PV technologies compared to fossil fuels is a major barrier to large-scale deployment of solar energy. Today's price of electricity from solar energy4, as reported by the IEA, ranges from \$0.35/kWh to \$0.60/kWh for solar PV and from \$0.085/kWh to \$0.135/kWh for solar thermal, compared to \$0.045/kWh - \$0.055/kWh for wind and \$0.040/kWh for natural gas[1]. This large range of cost of solar energy is due to differences in the local insolation and to the estimation of the *Balance Of System* (BOS) cost relative to specific applications (namely stand-alone or grid-connected, ground-mounted or rooftop systems). The price of the active material, the manufacturing, and the BOS components are the main elements determining the total price of PV technologies. Since the 1970's research has been exploring new processes for producing low-cost wafer silicon (both singlecrystal silicon, sc-Si, and polycrystalline silicon, pc-Si), and the use of low-cost materials for thin-film PV applications, such as amorphous silicon (α-Si), III-V compounds (*e.g.* GaAs, InP), CIGS (Cu[In1-xGax][Se1-ySy]2), cadmium telluride (CdTe), and more recently organic materials. The efficiency of thin-film laboratory cells has increased steadily in the last 20 years (**Fig. 4**) and these technologies are believed to have the potential of bringing down the cost of solar energy to \$0.03/kWh - \$0.05/kWh[12]. Manufacturing scale is another key requirement for decreasing the cost of solar technologies since large-scale production lowers the cost of active materials and production. This is demonstrated by the price drop that silicon PV modules (sc-Si, pc-Si, α-Si) experienced since the early 1980's following a *progress ratio5* of ~77% with cumulative production growing from 10MW to more than 1GW in 2000[13]. If the trend continues, the price of \$1/W (~ \$0.06/kWh) will be reached when the cumulative production reaches 100GW [14], which in return will push further the deployment of solar energy systems. Some studies (see for example[15]) suggest that this price can be reached entirely through manufacturing scale, without the need for any significant new invention. However, more research and development will increase competitiveness of solar technologies. Design and technological innovations could also decrease the cost of BOS components, and in particular of energy storage systems that represent a major fraction of the total installation cost of systems where storage is required (up to 70-80% with batteries accounting[16] for 30-40%

CONCLUSION

The deployment of solar technologies for energy production at a large scale requires the involvement of both political and economical players, but also further improvements in the conversion efficiency and reduction of manufacturing cost. A large ongoing research effort aims to find innovative solutions to overcome these barriers. In the last decade, photovoltaic technologies have experienced an astonishing evolution that led to the increase of the efficiency of crystal-silicon solar cells up to 25% and of thin-film devices up to 19%. Recently, nano-technology, innovative deposition and growth techniques, and novel materials opened routes for reaching higher performances (multijunction devices and other 3rd generation photovoltaics) and for developing very low-cost devices such as organic-based PVs. All these technologies face comparable fundamental issues related to the steps involved in the conversion of photon energy into electricity: photon absorption, charge carrier generation, charge separation, and charge transport.

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