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State of the art and future prospects for solar PV development in Chile

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ABSTRACT

The primary goal of this work is to provide an understanding of the state of the art and future prospects for solar PV technology in Chile. Chile is leading the incorporation of this type of energy in Latin America, with a solar PV market that has experienced a dramatic growth in the last years, mainly due to the high solar resource and the favorable conditions of the market to new investors. Main findings of this study are based on the influence of geographical and climate conditions on the Chilean solar resource, the current status of solar PV industry, electric market and further insights to future deployment of PV technology in this country. A literature review about the effect of desert conditions on the performance of PV systems is also presented, including main results of different studies carried out in the Middle East, Africa, Asia, Australia, the United States and Chile, as they represent areas where emerging markets of solar PV are growing. Based on the literature review, this work provides some directions to future research in Chile highlighting the main scientific areas which need more extensive R&D efforts to analyze and improve the reliability of PV installations in Chile.

1. Introduction

Deployment of Renewable Energy (RE) technologies around the world keeps increasing sharply as the effects of climate change demand more attention and concern in the near future. Growth rates of RE differ substantially across regions and nations, however, the renewable power generating capacity experienced its largest annual increase ever in 2016, with an estimated 161 GW of capacity added [1]. That way, solar Photovoltaics (PV) represented 47% of the new installed RE capacity in 2016, which, for the first time, accounted more additional power than any other RE generation technology.

Falling prices and capital expenditures, particularly for modules, have increased the competitiveness of solar PV technologies with traditional power sources. Reduction costs of around 29% were experienced between the first quarter of 2016 and 2017, with an estimated installation cost of 1.03 USD/W_{dc} and 1.11 USD/W_{dc} for fixed-tilt and one-axis-tracking utility-scale systems, respectively [2].

The solar PV market is also diversified with a wide range of commercial and emerging technologies made of different materials with different features and solar cell efficiencies. PV cell technologies are usually classified into three generations depending on the material used and maturity: the first generation uses the wafer-based crystalline silicon technology and they are fully commercial, the second generation is based on thin-film PV technologies with an early market deployment, and the third generation includes technologies under demonstration and novel concepts [3].

By the end of 2016, the accumulated total capacity of PV technology installed around the world reached an estimated of 303 GW, with 75 GW of new addition throughout the year [1]. This uptrend of new installed capacity is expected to be maintained in the years to come as new markets expand, such as those of Latin America, the Middle East, North Africa and Southern Asia [4]. In the case of Latin America, Chile was the region's top installer located 10th globally for newly added capacity during 2016 [1].

These emerging markets are being developed in desert areas which are zones of interest for PV applications due to their high levels of

Abbreviations: 1G, First generation; 2G, Second generation; 3G, Third generation; AM, Air Mass; AOI, Angle of Incidence; ARC, Anti-Reflective Coating; a-Si, Amorphous silicon; AtaMo, Atacama Module; CDEC, Economic Load Dispatch Center; CdTe, Cadmium Tellurium; CIGS, Copper-Indium-Gallium Selenide; CIS, Copper-Indium Selenide; CNE, Electrical National Commission; CO, Carbon monoxide; CO_2, Carbone dioxide; cSi, Crystalline Silicon; DNI, Direct Normal Irradiation; DNO, Distributor Network Operator; EVA, Ethylene-Vinyl Acetate; GDP, Gross Domestic Production; GHG, Greenhouse Gases; GHI, Global Horizontal Irradiation; HIT, Hybrid heterojunction with Intrinsic Thin layer; IBC, Interdigitated Back Contact; IR, Infra-Red; ISC, International Solar Energy Research Center; I_{sc}, Short circuit current; m-cSi, Mono crystalline silicon; NEC, National Electric Coordinator; NOx, Nitrogen oxides; OECD, Organization for Economic Co-Operation and Development; p-cSi, Poly crystalline silicon; PERC, Passivated Emitter and Rear Contact; PPA, Power Purchase Agreement; PSDA, Plataforma Solar de Antofagasta; PV, Photovoltaics; RE, Renewable Energy/ Energies; RM, Metropolitan Region; SAT, Single axis tracking; SEA, Environmental Assessment Service; SIC, Central Interconnected System; SING, Northern Interconnected System; STC, Standard Test Conditions; Std, Standard glass; T, Transmissivity; TF, Thin Film; TM, Thermoplastic; UV, Ultraviolet; Yf, Energy Yield; RE, Renewable Energy/ Energies; RM, Metropolitan Region; SAT, Single axis tracking; SEA, Environmental Assessment Service

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energy density and low-land use. Nevertheless, the performance of PV technologies is highly affected by the environmental conditions, which in deserts implies exposure to higher temperatures and ultraviolet (UV) irradiation, in addition to deposition of dust and low precipitation rates [5,6]. Following this, the overall performance of PV systems is substantially different under desert conditions in comparison to the information given by tests under Standard Test Conditions (STC) by manufacturers.

As it was mentioned before, Chile is the country with the largest addition of solar PV technology in 2016 from Latin America. Since 2014, deployment of solar PV technology in Chile has experienced an exponential growth mainly due to the high solar resource which its territory is endowed with, and the favorable market conditions to new investors. Particularly, the highest levels of solar irradiation in the world have been found in the Atacama Desert located in northern Chile. In this manner, Chilean market represents an exceptional study case for the rest of the world, since its rapid growth on solar PV has occurred without any economic incentive from the government.

Therefore, a comprehensive overview of the current state of PV technology in Chile is presented in this work. Section 2 concerns the current commercial large-scale PV technologies deployed around the world (first and second generation) identifying their main features, advantages and disadvantages of applications. Section 3 concerns a framework about the geographical and climatic conditions of Chile which play an important role in the solar resource of the country, followed by the current electric demand in Chile. Historical development, the current state of the PV industry, and a description of the electric market in Chile are presented in Section 4, with some future projections and perspectives of the PV industry. The impact of desert conditions on PV performance technology is analyzed in Section 5, emphasizing that desert conditions of Atacama are different to the rest of the worldwide deserts. In Section 6 is presented the main conclusions of this literature review; and finally, in Section 7, the scientific gaps to fill in Chile on this research field are presented.

2. Current commercial PV technologies

2.1. Solar cell PV technologies

Up to this date, solar cell technology has gone through three differentiated stages: the first generation (1 G) based on crystalline silicon (cSi), the second (2 G) based on thin film (TF) inorganic semiconductors and the third (3 G) generation of emerging technologies. The silicon (Si) - based products include the monocrystalline (m-cSi) and polycrystalline (p-cSi) technologies; hybrid heterojunction with an intrinsic thin layer (HIT) and bifacial cell technology.

M-cSi solar cells have higher efficiencies than p-cSi, around 5% more, but due to its complicated production process and the involved costs, p-cSi is the dominant Si-based technology in the market (56% p-cSi vs 36% m-cSi)[7]. The HIT cells have a competitive price compared to m-cSi and p-cSi alternatives, with an increased power conversion efficiency up to a record value of 26.6% (the highest among all Si-based technologies) and potential for further improvement [8]. A recent alternative of Si-based products is the bifacial technology, which is based on a special kind of cell that allows light to enter from both the front and back faces of the cell in order to generate current. Some studies have shown that albedo radiation contributions on the back side of the module can be appreciable to the amount of power generation. Different studies about the behavior of this technology can be found in [9–12].

Alternatively, main TF technologies are based on amorphous silicon (a-Si) solar cells, Cadmium-Tellurium (CdTe) and Copper-Indium-Gallium Selenide (CIGS). a-Si was developed as an attempt at lowering costs, however, it has low efficiencies (around 10% for most commercial products) and suffers from light-induced degradation, hence, it has been displaced as a stand-alone product by 2 G alternatives such as CdTe or CIGS cells [7]. The evolution and greatest challenges of these technologies are addressed in [13,14]. Regarding costs, a-Si technology is typically cheaper than CdTe or CIGS modules, and HIT modules are typically more expensive than standard cSi modules. Fig. 1 exemplifies this, as close to 90% of the market is dominated by conventional Si technologies while a-Si is being phased out and TF shows no significant trends towards increasing their market share.

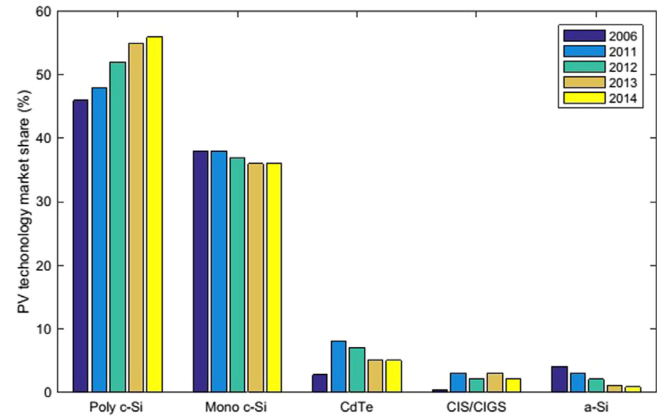

Fig. 1. Market share of different PV technologies from 2006 to 2014 [17].

However, according to PVinsights Solar PV Module Weekly Spot Price [15], p-cSi module average cost is about 0.315 USD/W and TF module cost ranges between 0.29 and 0.42 USD/W with an average cost of 0.336 USD/W. Therefore, it can be discussed that TF technology has lost its competitive advantage over conventional and more commercially successful Si-based products until further developments are made to once again close the gap between these technologies. Yet, Theologitis et al. [16] performed a sensitivity analysis for cell prices founding that cSi and CdTe could be the dominant market of solar PV technologies in the future, considering that CIGS module prices may decline at a slower pace than cSi and CdTe modules.

On the other hand, encapsulation is another critical component of PV modules whose selection is related to the particular conditions where a PV module will operate, in order to ensure significant module lifetime and a reliable performance of the system [18,19]. Its function is to seal and isolate the delicate active layers from external intrusions as humidity and mineral contamination, representing about 40% of the whole PV module cost. Nowadays, the most popular encapsulating material used for PV applications is the Ethylene-Vinyl Acetate (EVA) due to its high-cost performance relationship and durability [20], however, other encapsulating materials are discussed in [21,22]. Coatings development has also emerged in order to reduce performance losses mainly due to solar radiation reflection, soiling and UV degradation. Development of coatings has followed certain requirements as low costs, uniform properties, convenience, and long-term reliability [23]. Main characteristics and advancements of Anti-Reflective Coatings (ARC), anti-soiling and anti-UV coatings are addressed in [23–35].

3. Chilean framework: environmental conditions and energy demand

3.1. Impact of geographical features and climate conditions on solar resource of Chile

Chile is a country endowed with a unique geography. Its territory extends along 4337 km in a latitude range between 17°35'S (from the Altiplano highs) and 56°S (to Tierra del Fuego, the Islas Diego Ramírez and Cape Horn) [36], and exhibits a land configuration that contributes to a variety of climates which gradually change as the country goes over the south with a progressive rise of elevation from west to east [37,38]. These geographical and climate conditions play an important role in the surface solar radiation of Chile. Therefore, when these natural conditions are considered, three large zones of Chile can be found: the extreme north, the central zone, and the extreme south.