Literature Review

Cypress Reed

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Abstract

As governmental and social opinion has shifted in favor of decarbonization, solar energy has become increasingly popular. In particular, photovoltaics (PV) have grown significantly due to their ease of implementation and cost efficiency. Most PV installations use older crystalline silicon (c-Si) technologies. C-Si technologies remain dominant despite newer technologies, such as thin-film and hybrid inorganic cells, meeting or surpassing them in cost and efficiency. While newer technologies can be more cost-effective or efficient at low scales, the high cost of their commercial production inhibits them from becoming a dominant force in the PV market. Improvements of c-Si are the most effective to improve PV technology in the short-term, but long-term development of new technologies is essential to the energy transition.

1. Introduction

According to Osman, C-Si technology is highly efficient[1], in part due to its long-term use and research. Such crystalline photovoltaics are considered first-generation because they were the first commercially available photovoltaic technology[2] and make up 90% of PV production[3]. C-Si PV cells have some intrinsic issues which challenge their long-term effectiveness. In particular, c-Si PV cells use a thick crystalline structure. This thick crystalline structure is rigid, has a high material cost, and tends to be fragile[4]. The thickness of most c-Si panels is due to that fragility; because thinner cells tend to be more fragile, manufacturers have to use thicker cells for outdoor use. Newer second-, third-, and fourth-generation photovoltaic cells offer benefits such as higher efficiency, lower costs, less long-term degradation, or some combination[1]. Some fourth-generation PV cells, such as perovskite cells, have significantly higher efficiencies and lower theoretical costs than first-generation cells, but they have not been commercialized fully. This literature review compares generations of photovoltaic cells to find strengths and weaknesses of each as well as research gaps.

2. PV Cell Generations

Osman and Qureshi defined four major generations of PV technology[1]. Their paper was an overview of the current state of photovoltaics as a whole, so it is a suitable foundation for this literature review.

2.1. First-generation PV cells

First-generation technology, based on crystalline silicon, is well-defined, well-researched, and well-established as an industry. This section of literature review covers articles from Nature and MDPI Crystals, both regarding c-Si's current state and future prospects. C-Si cells begin as raw silicon before being processed into ingots, sliced into wafers, processed into cells, and placed into cell assemblies, or panels. A visual example is pictured in figure 1. C-Si cells have continually improved in efficiency at a rate of about 0.3-0.4% per year, with a theoretical maximum of about 23-24% for consumer-grade c-Si panels[5]. Because so much research effort is placed in c-Si cell improvements, c-Si remains the dominant PV technology, at 95% market share[6]. One way to overcome c-Si's limitations is to stack a silicon-based PV cell with another cell, typically GaAs or GaIn, in what is called a tandem solar cell. This technique has shown efficiencies of up to 36% (dependent upon implementation)[2].

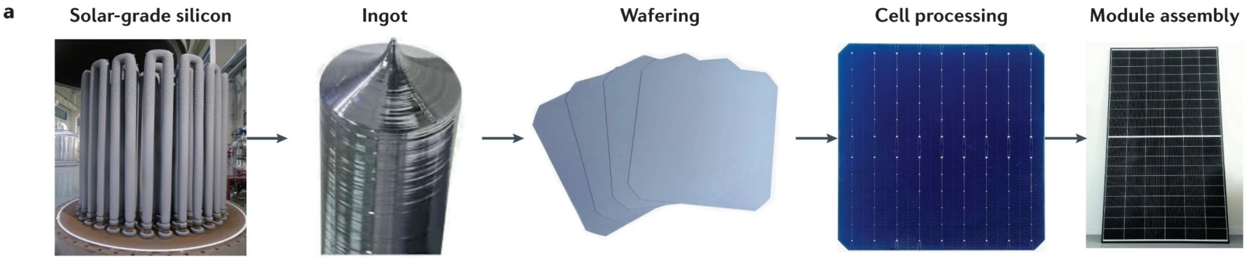

Figure 1: The steps from raw silicon to photovoltaic module[2].

Sabatino et al. state that the advantages of tandem solar cells come from their ability to avoid absorption and thermalization losses[6]. Thermalization losses come from photons below the bandgap of a semiconductor material not absorbing and being kicked off as losses. Absorption losses come from a mismatch in the angle of light in a process known as Boltzmann losses[7]. What alternate technologies have to overcome is c-Si's exceedingly low costs due to its maturity as a technology, which are continuing to decrease. Relative to 2022 prices, Ballif et al. expect c-Si prices to decrease by an additional 30-40% [2]. C-Si cells are a robust technology that is useful today and will likely be useful into the future, but advancing their technology is critical to the energy transition and long-term success of PV-based energy. In some implementations, second-generation PV cells make more sense.

2.2. Second-generation PV cells

The best known second-generation cell types are Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). There are also flexible silicon panels, but they are inefficient and costly, and therefore are not commercially feasible. A large body of research exists in this area. Salhi wrote an overview of CIGS's properties[8]. It shows the structure of CIGS in layers, as in Figure 2.

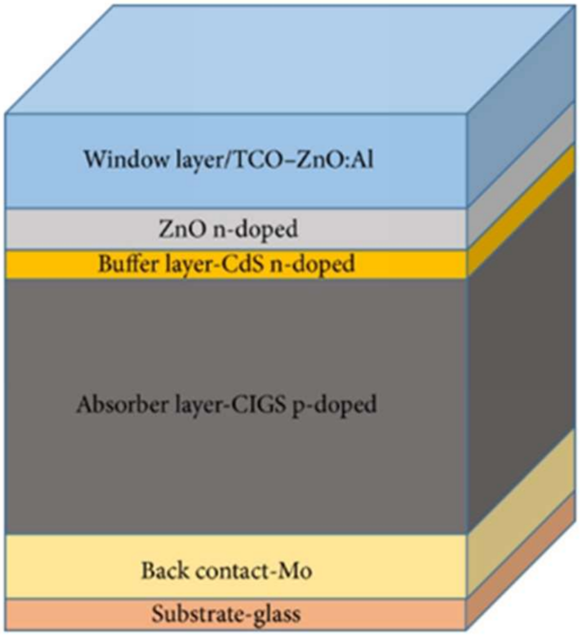

Figure 2: Standard structure of a CIGS solar cell[8].

One promising aspect of thin-film PV cells is that they can be attached to oddly-shaped surfaces, such as roof shingles. Aesthetics are one of the main deterrents of residential PV installations[9], so integrating them into a necessary part of a home's construction could spur additional residential PV installations. Another advantage specific to CIGS cells is that there are newer recycling techniques to recover the critical minerals used in CIGS production[10], which could be massively economically advantageous as CIGS panels could become a cyclical supply chain. Huang et al. recently proposed a recycling method that would allow full metal recovery from degraded CIGS cells[11]. Their proposed strategy would create \$8.34 in revenue per kilogram of CIGS cell. It cycles through different temperatures to control solubility of the component minerals of CIGS cells to selectively remove specific materials, which reduces processing time and energy usage in recycling, improving its economic viability. CIGS, and second-generation PV cells as a whole, are a promising technology for specific applications. When increased durability, improved recyclability, portability, or flexibility are necessary, they are a massive leap forward from c-Si cells. Otherwise, they fall short due to their high production and material costs.

2.3. Third-generation PV cells

Third-generation cells use improved materials and technologies, such as quantum dots and organic wells. They generally focus on efficiency and price[12]. The best-known types from this generation are quantum dot/well- and organic compound-based cells. Third-generation cells are the first cell generation to break past the technical limit that c-Si cells cannot surpass, known as the Shockley-Queisser limit. The most well-known and commercially viable panel type from this generation is perovskite. Perovskite panels have extremely high efficiencies. The highest currently recorded is about 25%[13], but because of advances in coating technology, beyond that is theoretically possible. Most third-generation cells use advanced manufacturing techniques that are prohibitively expensive to commercialize. Because third-generation PV cells are much more recent in development than first- and second-generation cells, research and development are limited. The full extent of their efficiencies, long-term degradation, and possible cost reduction is not fully known, so further research is needed to determine whether they will be effective in the long-term. Long-term degradation is particularly important as a PV cell that is low-cost to purchase is more expensive if it fails significantly sooner than a more expensive cell. Third-generation PV cells are most promising as an addition to c-Si cells. Löper et al. found that perovskite cells stacked on c-Si cells can achieve efficiencies of almost 35%[14]. The advantage of their novelty is that there is likely room for improvement in commercial viability and efficiency. There is also time to address concerns over durability and efficiency. Third-generation cells are extremely promising, but are overshadowed by fourth-generation PV cells.

2.4. Fourth-generation PV cells

Fourth-generation cells have limited research and have not been fully explored. Another name for them is hybrid inorganic cells. They typically combine third-generation cells with nanostructures, with the main nanostructure used being graphene. Graphene in particular is key to the development of fourth-generation PV cells as manufacturing techniques for graphene are not fully developed and different types have yet to be fully explored. Graphene is extremely useful for photovoltaics because it has "unique properties, including high carrier mobility, low resistivity, and excellent optical transmittance," [1]. Graphene's improved mechanical properties are crucial because they improve longevity of the resultant cells, meaning that there is lower likelihood of mechanical failure of resultant panels. Graphene also poses a challenge in that it is the main barrier to implementation of fourth-generation cells.

3. Generation Comparison

Each generation of photovoltaic cells has advantages and disadvantages. C-Si cells have high material cost and are fragile, but are a mature technology with high efficiency and wide commercial adoption. Thin-film cells also have high material cost and haven't been fully commercially realized, but are exceptional for portability and aesthetics. Quantum/organic dot/well cells are efficient and have a potential for lower cost, but have little commercial use. Hybrid inorganic cells have only preliminary research and rely on advanced materials that are currently extremely expensive, but they could become cheaper over time and are extremely efficient. Currently, the best applications for PV are c-Si for most static installations, such as rooftop solar, and CIGS for mobile installations. If a user values aesthetics, CIGS panels could be useful as they can be placed on roof tiles so they blend in better, but this application requires replacing a roof on a house, so it is best for newly built houses. CIGS really shines with mobile installs, particularly with portable solar panels that plug into portable battery units and with vehicle mounts. Because they are thinner and lighter, their portability is enhanced compared to c-Si. They can also be integrated into vehicle roofs, which is useful for people who live out of their vehicle (such as members of the van life movement) and electric vehicles.

4. Conclusion

Crystalline-silicon PV cells remain dominant, but perhaps not for long. Newer technologies and tandem technologies are promising in durability, cost, and efficiency. The main barrier preventing their implementation is a lack of commercially viable production processes. Each of these technologies are promising with enough research, particularly on commercializing existing technologies. Some modern technologies, especially CIGS, have current applications, but broadly are not in a state to displace c-Si. Hybrid inorganic cells are incredibly promising for mass installation, especially when combined with proven c-Si cells in a tandem configuration. Further research for photovoltaics should focus on development of tandem PV technologies to increase efficiency, improvements in coating technology for perovskite cells, and graphene manufacturing.

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