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RESEARCH REPORT

North American Solar PV Copper Content Analysis

Prepared for Copper Development Association

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Section 1
EXECUTIVE SUMMARY

1.1 Introduction

The solar PV market continues to transition from being dependent on government incentives and environmentally conscious wealthy homeowners to a cost-effective source of electricity that is gaining traction across market segments and customer types. The solar PV industry is very mature, and in North America, poised for significant growth over the next ten years.

Copper is a critical element in solar PV hardware and balance of system components, and this will not change over the forecast period. The evolution of the solar PV market in North America and beyond, continues – higher efficiency, lower costs, greater flexibility, and high reliability. While federal and state politics have the potential to accelerate or decelerate solar PV adoption, the overall outlook is positive.

1.2 Methodology

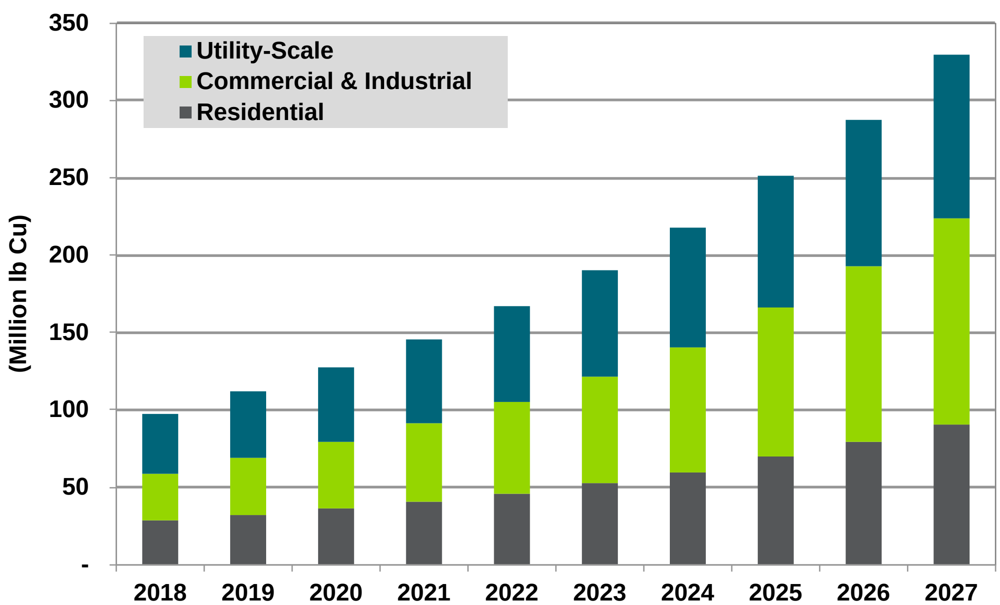
This report presents a forecast for the North American solar PV market through 2027 broken down by segments and countries. Navigant Research's forecast is based on the current regulatory environment, the stage of development of the industry in each of the analyzed markets, and the economics of solar installations compared to retail electricity prices (for distributed solar) or wholesale prices (for utility-scale solar). One of the drivers of solar PV is the variety of system configurations (module chemistry, inverter, balance of system) based on the intended application. Each configuration Navigant analyzed being deployed today, and in the future, would have a modest impact on overall copper content (increase or decrease). We found no significant "threat" to overall copper integration with solar PV systems. In order to be conservative, however, we based on Navigant's assessment, we assumed the copper intensity will decrease slightly as more efficient modules are utilized, but this slight decrease on a per MW basis, will be more than made up for by a growing overall market size across North America due to overall system cost reduction, state-level renewable energy targets, and the increasing adoption of energy storage and other enabling technologies. Therefore, Navigant assumed a constant net copper intensity ratio, which was applied to our forecast of overall solar PV adoption in North America.

1.3 Summary of Results

Between 2018 and 2027, North America is expected to install 137 GW of residential and C&I PV (DSPV) capacity and 125.0 GW of utility-scale solar. The United States will lead with 136 GW of distributed solar to be installed and 122.1 GW of utility-scale solar. Of the distributed capacity, 64.0 GW will be residential systems and the remaining 72.0 GW will be C&I systems.

While the new installed capacity of distributed solar (residential and C&I) and utility-scale solar over the next decade is similar from a MW installed perspective, once we add copper intensity into the equation, DSPV accounts for nearly two-thirds of copper demand. The cumulative ten-year demand for copper is 1.925 billion lbs, led by C&I (713 million lbs) and utility-scale (677 million lbs), followed by residential demand (535 million lbs).

Chart 1.1 Annual Copper Demand from Solar Installations by Segment, North America: 2018-2027



(Source: Navigant Research)

Section 2
INTRODUCTION

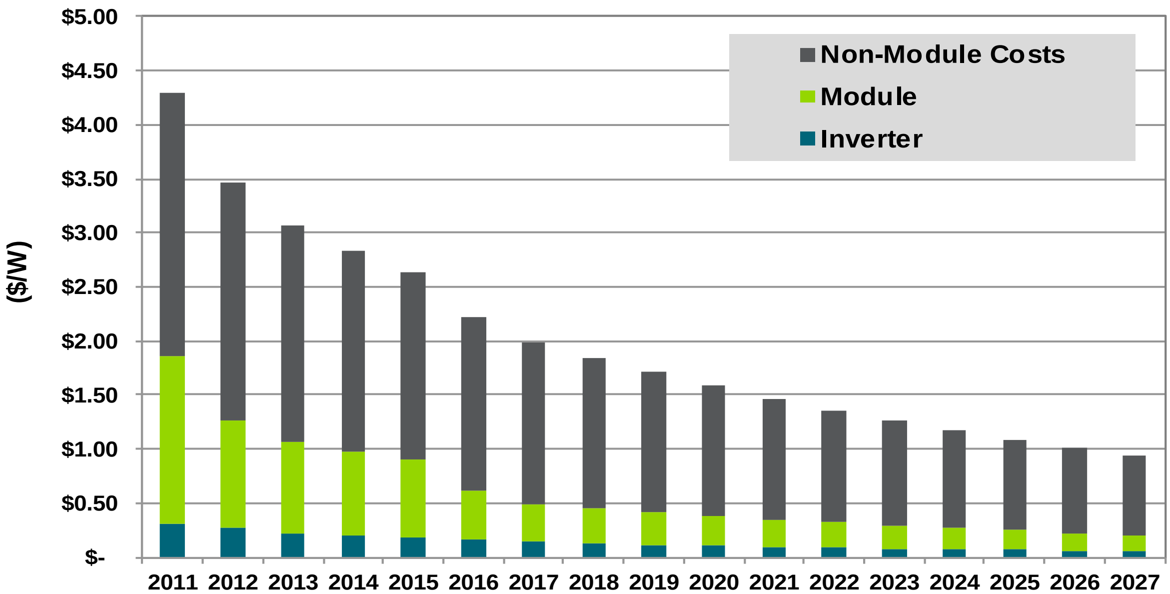
2.1 Cost Reduction Key to Solar PV Success

The solar PV market has transitioned from being dependent on government incentives and environmentally conscious wealthy homeowners to a cost-effective source of electricity that is gaining traction across market segments and customer types. Solar PV hardware manufacturers have largely delivered on ambitious cost reduction targets during the past 5 years, due to scaling up of production in Asia, growing global demand, and the introduction of new high efficiency modules.

Module and inverter manufacturers are increasingly finding themselves squeezed by the trifecta of the growing number of grid requirements, customer demands for increased functionality, and the need for solar to keep reducing costs to achieve grid parity in most of the world. Despite these demands, the learning curve for solar modules shows that their price per watt falls about 26% every time installations double. Meanwhile, inverters, racking, and other Balance of System (BOS) components have historically fallen around 8% per year. Navigant expects these trends to continue for the next 5 years.

The cost structure for distributed solar PV (systems typically installed on a residential property or onsite at commercial and industrial buildings such as big box retailer or manufacturing facility) vary significantly from utility-scale projects, which are installed far from population centers at much larger scale.

Chart 2.1 Distributed Solar PV Installed System Prices (Non-Weighted Average) by Component, North America: 2011- 2027



(Sources: Navigant Research, National Renewable Energy Laboratory)

2.2 Segments

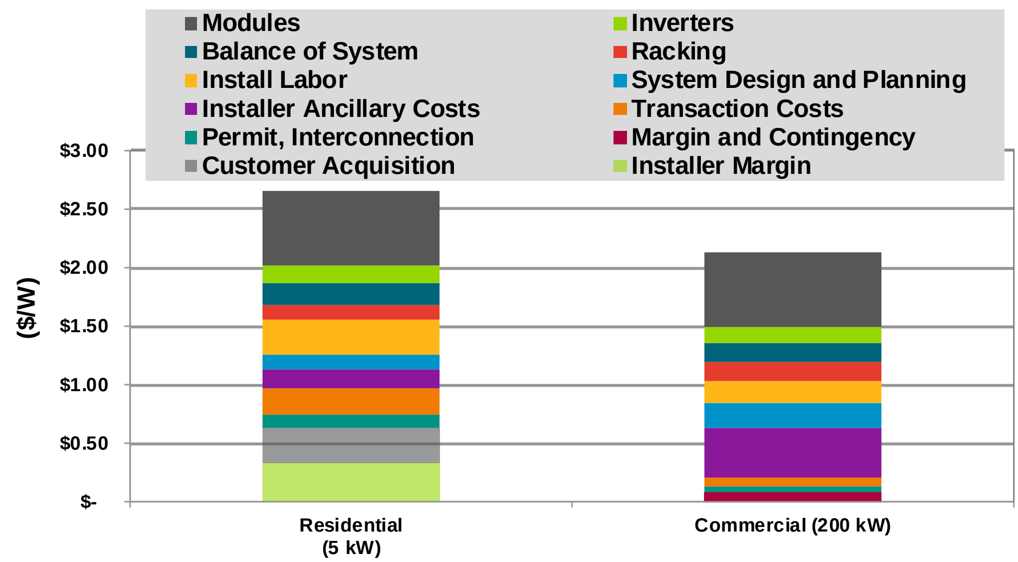
The solar market consists of three different segments that have different economics:

- **Residential:** Solar PV systems (typically less than 10 kW) installed on single- and multi-family homes. These are almost exclusively behind-the-meter/net metered systems. Residential is the second largest annual market segment by capacity.
- **C&I:** Customers such as hospitals, retail, data centers, schools, hotels, manufacturing facilities, warehouses, universities, food processing facilities, and other systems with electricity used onsite and/or net metered. Typical system size ranges from greater than 10 kW to 1 MW, though it can be significantly larger (e.g., data centers). The C&I market is the third largest annual market segment by capacity.
- **Utility-scale:** Utility-scale projects range from greater than 1 MW up to several hundred megawatts in capacity and deliver electricity to the grid, supplying a utility with energy. Nearly every utility-scale solar plant operates via a PPA with a utility. The utility-scale market is the largest annual market segment by capacity.

Installation size has a significant impact on soft costs. The cost of installing a residential system in the United States, including hardware, design, and labor, was $1.41/Watt in 2018, only 9% ($0.12/W) more than for a commercial system with 200 kW capacity.

However, once costs like customer acquisition and other transaction costs are added, the residential cost premium versus the commercial systems grows to 25% ($0.53/W).

Chart 2.2 Residential vs. Commercial Solar PV Installation Costs, United States: 2018



(Sources: Navigant Research, National Renewable Energy Laboratory)

2.3 Copper in the Solar PV Value Chain

Copper is solar installations is used mostly in wiring and power electronics. The copper use in the main sections of the value chain are analysis in the following table.

Table 2.1 Copper use in the Solar PV value chain

	Copper content today	Future	Magnitude of impact
Cells	None	None	None
Modules	Very small, mostly for wiring	Expected drop by about 30% as new technologies are deployed	Low: the current amount is small so the effect of the drop will not cause a significant change in the copper demand in a solar installation
Inverter	Medium	Inverter manufacturers have substituted copper with aluminum in the past depending on commodity prices. More efficient inverters reduce the copper need per W	Medium: Copper demand in inverters fell by about 60% between 2010 and 2017 as inverters became more efficient and new topologies were implemented
Balance of System	High	Electrical Balance of system uses the most copper in a solar installation. Copper is used in wiring and grounding	High: Use of copper reduced by up to 50% per MW installed between 2010 and 2017. Mostly by the adoption of new topologies and higher-powered modules. This impact varies depending of the type of installation

2.4 Innovation in Module and Cell Efficiency

2.4.1 Current Status

Solar PV manufacturers have largely delivered on their promise to drive down costs and scale up production. Between 2008 and 2012, global solar PV installations were not able to keep up with new manufacturing capacity. This created a major imbalance in supply and demand, driving down prices dramatically. The past supply and demand module balance and the fast drop in module prices in the last few years have exhausted most of the low-hanging fruit to reduce module prices and has commoditized the PV market.

Between 2012 and 2015, global solar PV module cumulative capacity remained steady at around 70 GW, but actual production doubled from 32.5 GW to 60 GW, increasing the margins of the top manufacturers and tightening the supply-demand balance for the coming years. As a result, the downward pressure on module prices is expected to ease, allowing manufacturers to reinvest part of their margins to increase capacity. The main players have been deploying capacity expansions since early 2014, but since November 2015, the installed capacity soared. More than 40 GW of new capacity (cells and modules) were installed between 2016 and 2017.

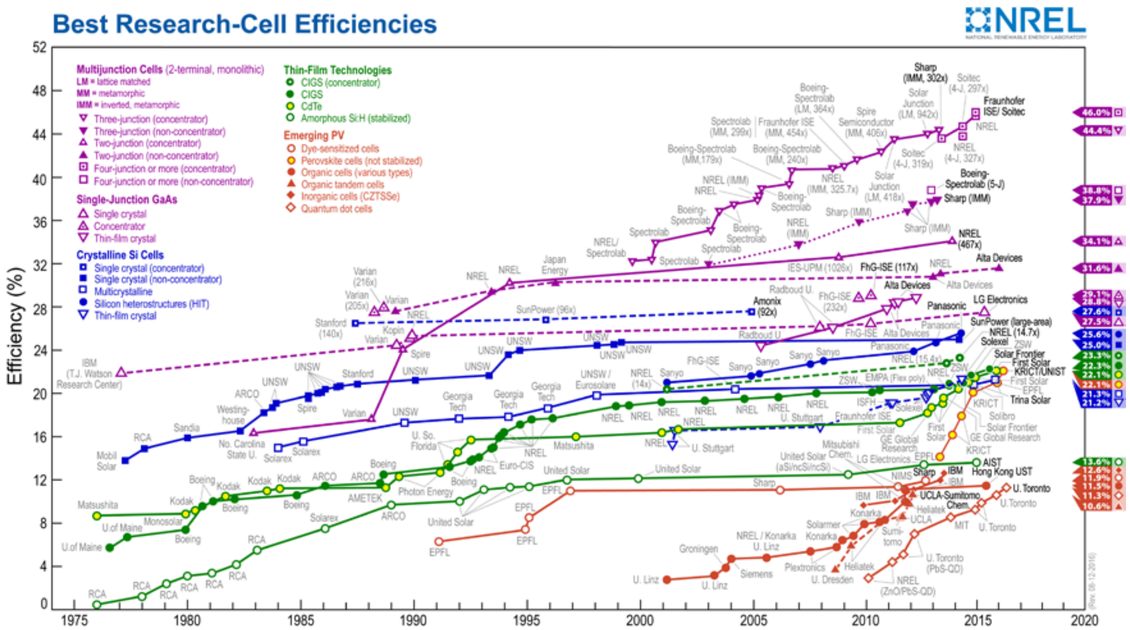
This expansion push caused a drop module and cell prices in 2016, but they stabilized in 2017 and deployments soared. The world installed more than 100 GW in 2017, with China installing 56 GW on its own.

2.4.2 Future Outlook

As they expand capacity, manufacturers are starting to introduce new technologies that could differentiate them from the competition. Many have targeted technologies that allow them to keep similar module prices while reducing other costs in the value chain. P-type passivated emitter rear cell (PERC) modules and direct current (DC) optimizers are well-suited to take over where price competition is fierce, and the installation value chain is already very efficient (such as in utility-scale solar in countries with high labor costs and countries where large-scale installations have to compete in tenders for access). The high-efficiency of PERC modules compared to conventional modules means that bidders could reduce the levelized cost of energy (LCOE) of a project (and with it the tendered price) to outbid other developers.

N-type modules and microinverters are better suited for parts of the market where the installed costs per watt are higher, such as residential and commercial markets. In these markets, a significant part of the final cost is driven by BOS and other installation costs. Manufacturers are also exploring other technologies like concentrated PV (CPV), a higher efficiency version of cadmium telluride (CdTe) thin-film cells, and perovskite cells.

Figure 2.1 Best Cell Efficiencies Achieved For Various PV Technologies in Lab Conditions

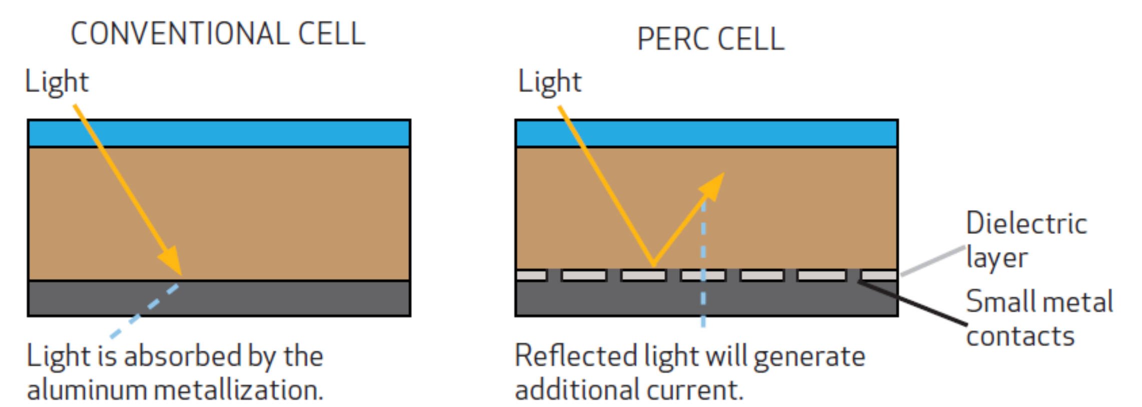


(Source: National Renewable Energy Laboratory)

2.4.3 PERC

In a conventional solar cell, an aluminum metallization layer makes contact across the full area of the back of the cell. PERC technology first coats the backside of the cell with a special dielectric layer that has tiny holes cut by a laser. The aluminum metallization is then applied on top of the dielectric layer and contacts the silicon wafer only through the microscopic holes. This can be done to both monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si) cells.

Figure 2.2 Difference Between Conventional Cells and PERC Cells



(Source: REC Group)

PERC technology increases overall panel performance by increasing a cell's ability to capture light. Shorter wavelengths (blue light) generate more electrons near the front of the cell compared to longer wavelengths (red light), which generate electrons at the back of the cell or even pass through the wafer without generating current. The introduction of PERC technology increases the cell efficiency through a layer that reflects back into the cell any light that has passed through to the rear without generating electrons. Through this reflection, the photons are essentially given a second chance to generate current.[1] The extra energy yield of cells with PERC technology is coupled with an improved ability to capture light at longer wavelengths (e.g., when the sun is at an angle during early mornings and evenings or under cloudy conditions).

2.4.3.1 Trends and Issues

PERC technology has been out of the lab for some time, but it was not until 2012/2013 that cell manufacturers started to add PERC and laser equipment to their production lines. Efficiency gains of PERC products have been increasing rapidly. Multi-Si PERC cells are reaching above 20% efficiency with reactive ion etching (RIE) and 16% without RIE. Maximum Mono-Si cells are already above 22% efficiency, while the average cell efficiency is above 21%.[2]

The main issue concerning PERC manufacturers is the light-induced degradation (LID) of p-type solar cells. LID is a phenomenon seen in silicon solar panels where minor impurities and oxygen concentration in the wafer cause a permanent loss of power upon first exposure to sunlight. Although the panel stabilizes after a few days, the initial loss of power is irreversible. If LID is not controlled appropriately, any efficiency gains obtained using PERC are lost.[3]

In 2015, there were between 6 GW and 8 GW of PERC manufacturing capacity in the market, and this is expected to reach between 12 GW and 15 GW by the end of 2016, with around 55% being mono-Si PERC and the remaining 45% multi-Si PERC. Actual production has yet to follow the increase in capacity. In 2015, only 1 GW of PERC products were shipped, while PERC manufacturing capacity was already between 6 GW and 8 GW. For 2016, between 3 GW and 4 GW capacity additions are expected. LID was still a major concern in 2015, but recent process improvements seem to be solving this issue.[4]

[1] REC Group, http://www.recgroup.com/sites/default/files/documents/whitepaper_perc.pdf, 2014

[2] Trina Solar, http://ir.trinasolar.com/phoenix.zhtml?c=206405&p=irol-newsArticle_Print&ID=2185394, 2016

[3] Kuo-Yi Yen, Shao-Peng Su, Sean H.T. Chen, Li-Wei Cheng, http://ieeexplore.ieee.org/document/7356044/ , Topcell Solar International, 2015

[4] Kuo-Yi Yen, Shao-Peng Su, Sean H.T. Chen, Li-Wei Cheng, http://ieeexplore.ieee.org/document/7356044/ , Topcell Solar International, 2015

Taiwanese manufacturers such as Gintech, Neo Solar Power, and JA Solar were the first adopters of PERC. Taiwanese companies still hold more than 20% of global PERC capacity, although Chinese manufacturers like Trina, Canadian Solar, and Lerri Solar are catching up. Other manufacturers offering PERC products include REC Group, Hanwha Q CELLS, and Solar World.

2.4.4 N-Type Cells

Currently, industrial crystalline silicon (C-Si) solar cell production is still dominated by p-type silicon solar cells. However, the quality of the base material is becoming more important as the industry moves to high-efficiency solar cells. As n-type C-Si cells do not suffer from LID, are less sensitive to prominent metallic impurities, and are less prone to degradation during high-temperature processes—all problems associated with conventional p-type cells—n-type cells have attracted manufacturer's interest.[5] With conversion efficiencies close to 23%[6], n-type C-Si cells offer a material quality allowing them to fully benefit from high-efficiency solar cell architectures. Today, n-type architectures allow the highest conversion efficiencies in the C-Si market, but they suffer from high costs compared to traditional p-type panels due to both the introduction of additional steps in the manufacturing process and to higher wafer prices.

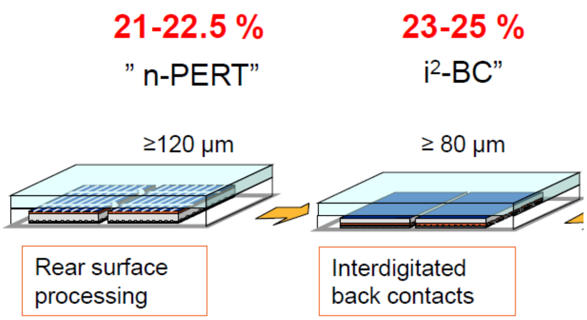
Many former challenges to n-type cells (such as the formation, passivation, and metallization of boron emitters) have more or less been overcome.[7] Recently developed methods for surface passivation and metallization of boron emitters offer the flexibility to process n-type cells in industrial production with high efficiencies in a cost-competitive way. There are two main n-type architectures, a passivated emitter, rear totally diffused (PERT) and interdigitated back contact (IBC). PERT cells are usually less efficient than IBC cells but have higher bifaciality, a key factor if n-type cells are going to take a larger share of the market. IBC's high-efficiency is also matched by an all-black look, a characteristic that has allowed SunPower—the only manufacturer of n-type IBC modules—to sell at a premium in the luxury residential market.

[5] Schmid, http://www.pv-magazine.com/news/details/beitrag/schmid-promotes-pert-over-perc_100018621/ ,

[6] IMEC, http://www2.imec.be/be_en/press/imec-news/crystal-solar-si-pv.html, 2016

[7] Valentin D. Mihailetchi et al. / Energy Procedia 77 (2015) 534 – 539, 535

Figure 2.3 N-PERT and IBC Module Structure and Efficiency Ranges



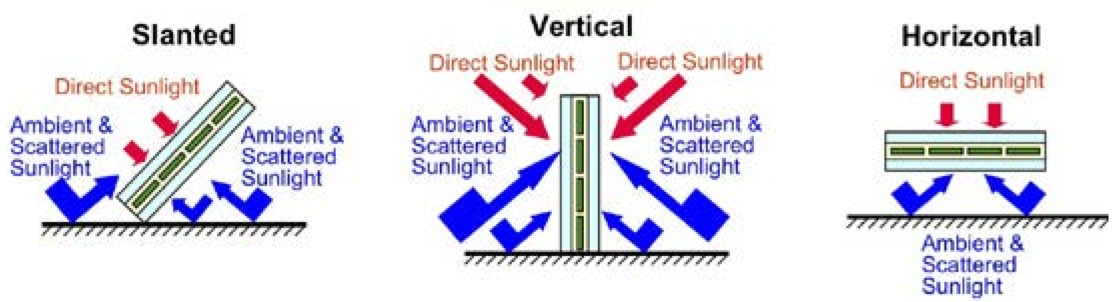
(Source: IMEC)

2.4.4.1 Bifacial Solar Modules

Bifacial solar cells are designed to allow light to reach the solar cells from both the front and rear sides of a solar module. The front side of the cell uses the same design of a conventional C-Si cell, but the rear side uses a grid structure instead of covering the entire back surface with reflective aluminum, which allows sunlight to reach the cells.

Bifacial cells are especially useful in flat roof and ground-mounted installations. While the cost per watt of bifacial panels are not necessarily lower than that of conventional cells, the increase of power helps to minimize the BOS costs and therefore to drive down the cost of each kilowatt-hour generated. Due to their higher bifaciality, n-type PERT cells are especially well-positioned to capture niches in the PV market where bifacial modules have an efficiency advantage.

Figure 2.4 Bifacial Solar Module Installation Options



(Source: Sanyo/Panasonic)

2.4.4.2 Trends and Issues

Companies such as SunPower, Panasonic, Yingli, PVG Solutions, Neo Solar Power, and LG have been producing n-type cells and modules for many years but have failed to capture a significant share of the PV market share until now. There was approximately 4 GW of n-type installed capacity at the beginning of 2016.

Table 2.2 Selected N-Type Cell Manufacturers Installed Capacity

Segment	Units	2016	2020
SunPower	(GW)	1.5	2.3
LG	(GW)	1	3
Silevo	(GW)	0.23	1
MegaCell	(GW)	0.80	0.80
Lerri Solar	(GW)	3	3

(Source: Navigant Research)

2.4.5 CPV

A CPV system converts light energy into electrical energy in the same way that conventional PV technology does but uses an optical system to focus a large area of sunlight onto each cell for maximum efficiency. Although the technology is still very young, CPV solar cells and modules are earning interest from researchers and solar companies alike due to their extremely high conversion efficiencies. CPV can be separated into two different types: high concentration PV (HCPV) and low concentration PV (LCPV).

HCPV systems commonly use multi-junction concentrator cells with III-V semiconductors to achieve the highest efficiencies. Utilizing multiple semiconductor materials with a wide range of bandgaps helps to match the spectral distribution of the sun. Materials that are showing the most promise are Gallium (Ga) and Germanium (Ge) compounds (GaInP/GaInAs/Ge), with cell efficiencies reaching 46%. While the availability of these rarer elements, namely Ge and Ga, are limited, this is not currently holding the technology back because of the low market penetration of HCPV systems. If the technology takes off in the future, then the availability (or lack thereof) of these rare elements will become a significant factor, leading to higher prices. HCPV systems also use dual-axis tracking in order to maximize efficiency and energy output.

LCPV systems use more traditional C-Si cells and single-axis tracking, although dual-axis tracking can be used in these systems as well. HCPV modules currently lead the CPV market, with 90% of installed CPV systems utilizing these cells.

There are a number of drawbacks to CPV technology that are holding it back from large-scale market penetration. The technology is still very young, and thus companies are hesitant to dedicate capital to an industry with so many unknowns. Manufacturing and production for CPV has a very short history and thus a higher associated risk.

Technical drawbacks of CPV include the requirements for very precise tracking and frequent cleaning to maintain high efficiencies. Currently, the main trend that has held the technology back has been the strong cost decreases seen by competing solar industries (namely traditional non-concentrating crystalline and thin-film PV). As it currently stands, CPV is not cost-competitive with traditional flat-plate PV systems. With only one company, Arzon Solar, actively selling CPV modules and a long trail of bankruptcies in the past, it is not expected that the technology will make any market inroads within the next decade.

2.4.6 CdTe and Perovskite Thin-Film Cells

Cadmium telluride (CdTe) thin-film module mass production started in the mid-2000s when the price of C-Si cells spiked, and non-silicon cells gained a cost advantage, but the technology has struggled since then. Currently, only one large CdTe thin-film manufacturer remains, First Solar. The company managed to escape its peers' fate thanks to an early move into project development and large commercial sales.

The technology suffered from lower efficiencies while offering similar or even higher prices than C-Si, but First Solar's R&D activities are starting to succeed. The company's current mass-production modules have efficiencies on par to conventional multi-Si modules (just above 16% on average), and it has achieved more than 22% efficiency in labs.

Another promising thin-film technology is perovskite. Named after prominent Russian mineralogist Lev Perovski, perovskite is a compound that is garnering rapidly increasing interest in the field of solar cells. When originally tested as a potential replacement for traditional silicon-based cells in solar panels, its conversion efficiency tested as low as a measly 3.8% in 2009. However, in the few years since then, perovskite has been able to reach efficiencies approaching 25.5% thanks to dedicated research into the optimal materials that go into the perovskite structure.

In addition to the promising rise in energy conversion efficiency seen in just a few years, perovskite-based solar cells offer other advantages. One of the principle advantages of perovskite is that fabrication is believed to be much cheaper and much quicker than other solar cell technologies according to researchers at the Los Alamos National Laboratory. Methods used to produce perovskite cells involve more standard laboratory equipment than other materials that require sophisticated equipment and procedures. Perovskite fabrication also requires fewer steps than other solar cell materials. Perovskite cells can be manufactured to be thin, flexible, and transparent, which could attract a premium over conventional cells.

Despite these apparent advantages, further research needs to be done to determine if the promising results seen in research laboratories can be effectively translated into large-scale production and implementation in the field. The stability of perovskite cells is a source of concern, as well. The material is an organic-inorganic compound, which means it is water soluble and thus susceptible to moisture degradation. After exposure to moisture, the perovskite cell has shown to significantly degrade in just a short period without any moisture barrier.

2.4.6.1 Trends and Issues

The future of CdTe and perovskite thin-film cells depends largely on the technologies managing to outcompete the more established crystalline industry. In the short term, it is unlikely that CdTe cells will increase their market share (currently at around 5%), as First Solar is already operating at full capacity. (At the end of 2017, the company was running at full capacity and is working on a plant expansion.) Currently, First Solar is reallocating some resources mad available after a decision to close its C-Si production operations, but if the technology is going to capture a higher market share, the company would have to invest in significantly more new production capacity.

In the meantime, perovskite solar cells are gaining plenty of attention from research organizations across the globe. The University of Washington’s Clean Energy Institute has published several articles focused on perovskite technology in solar energy. In addition, Northwestern University’s Institute for Sustainability and Energy has dedicated research to cradle-to-grave lifecycle assessments on perovskite solar cells and is also looking at other materials to replace lead in the perovskite compound; this research is being conducted based on a grant from the US Department of Energy (DOE). In late 2014, Bangor University received a £3.2 million (~$4.9 million) investment from the UK Engineering and Physical Sciences Research Council (EPSRC) to research perovskite technology and applications, as reported by optics.org. Ossila, a company that researches and produces components, materials, and equipment for electronic applications, has also dedicated funds and research into perovskite in solar panels.

Perovskite will need to overcome many current barriers in order to break through into large-scale commercial viability. Increasing solar cell efficiency will remain to be the leading area of research; however, in-depth economic study and analysis needs to be done in order to determine if perovskite can be competitive in both technology and cost with current solar cell materials. Therefore, the market for perovskite is expected to remain very limited in the next 10 years. This does not mean that the material could not one day enter the marketplace, but in the next 10 years, existing technologies are expected to lead the market. Particularly since efficiencies of crystalline and thin-film technologies are still increasing, by the time perovskite enters the marketplace, its efficiency advantage will have been significantly eroded.

2.4.7 Impact in copper use

The use of copper within modules is small. The main minerals used in solar modules are Arsenic (used in semi-conductor chips), Aluminum, Boron minerals (used in semi-conductor chips), Cadmium (used in certain types of cells), Gallium, Indium (used in cells), Iron ore (steel), Molybdenum (used in photovoltaic cells), Phosphorous, Selenium, Silica, Silver, Tellurium, and Titanium.

Wiring is the main use of copper in Crystalline modules – the most common technology and the base for the technologies that are expected to be deployed in the next decade. Copper use per module is not expected to change significantly, but as modules become more efficient, the amount of copper per W will fall. Copper use in modules could fall by up to 30% if there is an increase in efficiency from 16.5% (the efficiency of current modules) to 21% (the most efficient modules currently available in the market).

But the impact of this efficiency gains will be more likely felt in the Balance of System costs, as solar farm sizes of the same capacity will cover a smaller area.

Table 2.3 Module Technology Summary

Technology	Status	Efficiency	Reduction on Copper use	Manufacturers	Production Capacity 2016	Production Capacity 2025
Current Average	Deployment	**Multi-Si**: ~16.5% **Mono-Si**: ~21% production, 22% in the lab				
PERC	Deployment	**Multi-Si**: ~18% production, 20% in the lab **Mono-Si**: ~21% production, 22% in the lab	**9%** **27%**	Gintech, Neo Solar Power, JA Solar, Trina, Canadian Solar, REC Group, Hanwha Q CELLS, Solar World	~6 to 8 GW	68 GW
N-Type	Deployment – small scale	**PERT**: 21.5-22% **IBC**: 23%-25%	**33%** **39%**	SunPower, LG, Silevo, MegaCell, Lerri Solar	~6.5 GW	40 GW
CPV	Halt/Research	29%-30% system efficiency	**75%**	Arzon Solar (Amonix technology)	-	-
Advanced CdTe Thin-Film	Deployment	22% in lab, ~17% top-of-the-range mass production	**33%**	First Solar	2.8 GW	5 GW
Perovskite	Research	25.5% in lab	**54%**	Ossila, Oxford PV	-	-

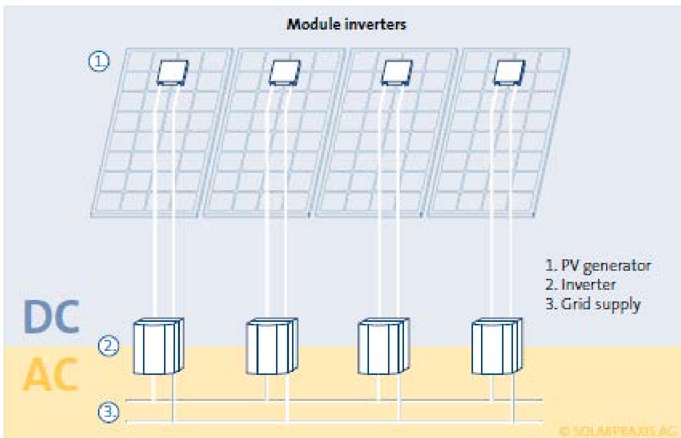
(Source: Navigant Research)

2.5 Module-Level Power Electronics Innovations

The weakness of solar PV has historically been its low efficiency. Even the most efficient mono-Si PV panel has only 25% efficiency, though the majority of modules installed today range from 14% to 16% (compared to wind power at 30% and fossil fuel generators at 80%-95%). However, efficiency is only one factor in determining a solar PV system's overall output; shading, dirt, cabling, voltage drop, inverter efficiency, and heat also affect the overall energy harvest. Microinverters and DC optimizers are two enabling technologies at the module level that are gaining traction in the market. In some cases, microinverters are already being fully integrated to create alternating current (AC) modules. These two technologies are competing to capture the residential and commercial market.

Enphase, SolarEdge, Fronius, SunPower, ABB, and SMA are leading the module-level power electronics (MLPE) market. Enphase is the main proponent of microinverters, while SolarEdge plays the same role for DC optimizers.

Figure 2.5 Module-Level Power Management



(Source: Solarpraxis AG)

2.5.1 Microinverters

Microinverters are installed on the back of each solar PV panel, matching the rated capacity of the panel. Each PV panel's DC power is converted directly to AC (120V or 240V) and is grid-tied. The output of each panel is effectively in parallel, eliminating power losses due to module mismatch and creating a higher energy yield by preventing a single panel's failure from affecting the overall system's energy harvest (as is the case with most string architectures). With microinverters, each panel is effectively individually monitored, providing system owners with a detailed view of solar PV system performance regardless of whether the system is composed of only a few solar modules or more than 1,000.

This architecture distributes the overall risk of failure among the total number of panels in the installation, removes the need for DC cabling, and leverages IT to identify and isolate a problem panel. In contrast, central inverters, though more efficient, have a single point of failure, which can lead to longer periods of downtime.

With maximum power point tracking (MPPT) at the panel rather than the string level, microinverters are ideally suited for the residential and small commercial market segments, as these present a higher risk of shading. Microinverter companies claim their technologies reduce the overall LCOE by 15%-20% compared to string inverters. Individual modules can also be shut down remotely, and with AC electricity, safety is increased for installers.

The downside to microinverters is that they are 30%-50% more expensive than string inverters and have lower efficiencies (though they do typically result in a better overall energy harvest). While the distributed architecture removes the risk of a single point of failure, microinverters introduce many more electronics into the PV system, adding technical risk. Microinverter companies claim better reliability than string inverters because they do not use capacitors. While this makes sense from a technical perspective, microinverters have yet to be in use long enough to test these claims. Furthermore, microinverters on the back of a panel and on a roof could increase the risk of heat damage to the inverter due to higher rooftop temperatures. (String and central inverters are normally housed inside and are rarely placed on rooftops.)

A benefit of microinverters compared to DC optimizers is the reduction in DC BOS components, including the central or string inverter (and its replacement at year 10). In addition, voltages tend to be lower with microinverter systems, which is a safety benefit for rooftop systems.

2.5.1.1 AC Modules

The future of microinverters could possibly involve fully integrated AC panels. Under this architecture, the microinverter is preinstalled on the module, but otherwise provides the same improved energy harvest benefits as a traditional microinverter. The main value-add is a reduction in installation time at the job site. SolarBridge, owned by SunPower, is the leading company in this space. Module manufacturers view the production of AC modules as an attractive means to help differentiate themselves from the competition.

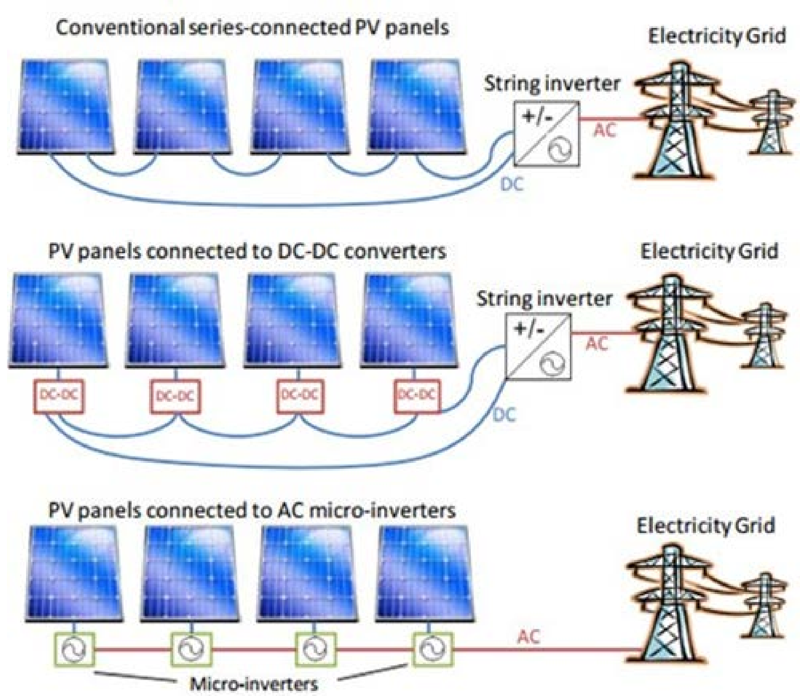
Selling the whole package, perhaps along with cables and racks, could cut a significant amount of assembly and installation time—not to mention cost—for installers. In fact, SolarBridge's own calculations show that system owners can achieve a 20%-30% reduction in LCOE by using panels with pre-installed microinverters. An AC module system also provides a more flexible solution, alleviating the dependence on matching between individual solar panels and making it easier to add panels to a rooftop installation over time without having to resize the entire system.

2.5.2 DC Optimizers

DC optimizers have benefitted from the success of microinverters. Venture dollars, massive marketing budgets, and strong technical performance have won many installers over on the concept of module-level management. Riding the wave of microinverters, DC optimizers represent similar module-level architecture, increasing energy harvest by optimizing operating voltage along each string; however, they still require a string or central inverter.

The main functions of DC-DC power optimizers are to provide MPPT and to harvest the maximum amount of power from each module. The advantages of power optimizers within a string inverter installation are numerous. They standardize the operating voltage of each string, resulting in greater yields at the output of the string inverter(s) and greatly minimize the detrimental effects of module mismatch, soiling, partial shading, and/or snow cover on one or more modules within a string. Optimizers increase yield by approximately 1%-3% when modules are soiled and by 2%-36% when modules are partially shaded. This is when compared to modules with no maximizers. Finally, they allow for web-based module-level monitoring, although not necessarily for module-level control.

Figure 2.6 MLPE Topologies Compared to Conventional String Inverter



(Source: National Renewable Energy Laboratory)

2.5.3 Impact on Copper use

The impact that new power electronics and topology are having in copper demand is moderate. While efficiency gains and new topologies have reduced inverter costs by up to 70% between 2010 and 2017 (with a similar reduction in the use of copper per W of capacity). Power electronics only represented between 10% and 20% of the copper used in a solar installation in 2010. But, like with solar modules, the most significant effect of more efficient technologies and the changes in topology are felt in the wiring and cable demand of the solar installation. This is especially important for microinverters as these change the installation cable demand from DC to AC.

Section 3
MARKET TRENDS AND DYNAMICS

3.1 Market Drivers & Barriers

Historically, renewable energy generation has been a policy-driven industry. In the past, renewables (distributed PV and small wind) were uneconomic in most developed nations when compared to conventional generation technologies. Legislative and regulatory mandates regarding renewable energy development are being driven by increasing concerns for the environment—primarily the amount of greenhouse gases that is emitted by the burning of fossil fuels—and fear that fossil fuels are a limited resource and prices will rise at increasing rates. Additional objectives include achieving greater energy independence for reasons of national security, as well as spurring job growth and entrepreneurial opportunities in emerging sectors of the economy.

The EU was the first group of nations to formally adopt renewable energy targets. It set a goal of 20% of renewable energy by 2020 and has developed aggressive policies and incentives to support this goal. Most other industrialized nations have followed, including China, Japan, and 29 US states. To reach this goal, governments have committed billions of dollars toward research and have developed policies, mandates, and financial incentives (e.g., net metering, interconnection standards, FITs, and rebates).

3.1.1 Financial Incentives, Public Policies, and Trade Wars

Financial incentives and public policies intended to promote domestic manufacturing and larger industry growth in China, Taiwan, the United States, India, Malaysia, the EU, and Canada have resulted in a series of import duties and World Trade Organization filings that effectively amount to a trade war. The central issue is what constitutes legal versus illegal subsidization. The impact of the activities surrounding the trade war has yet to be seen, though it is expected to be limited. Several Chinese manufacturers have rerouted manufacturing through Taiwan, making the import duties ineffective. The following summarizes key developments on this issue to date.

These international trade wars are leading Chinese companies to establish plants or partnerships overseas, although the EU was planning to extend its import duty to Taiwan and Malaysia. They are also acquiring international companies that have established their own reputations, such as BlueStar, which took over REC Solar, and Chint/Astronergy, which acquired Conergy. Overseas capacity can help players avoid trade disputes and penetrate emerging markets with local content requirements, such as Chile or South Africa.

3.1.1.1 Suniva case

On May 24, 2017, the US International Trade Commission (ITC) announced that it will consider a petition by Suniva, a bankrupt solar manufacturer in Atlanta, Georgia, to place tariffs on the most common kind of PV solar cells imported from around the globe. Suniva put forward a petition to set a minimum import price (MIP) to $0.78/W and requested a 4-year tariff schedule on crystalline silicon imports. According to the petition, the floor price would fall to $0.72/W in year 2, $0.69/W in year 3, and $0.68/W in year 4.

On October 31, 2017, the US International Trade Commission (USITC) announced the remedy recommendations that it will forward to President Trump. As we have discussed in previous blogs (here and here), this case has been shaping the future of the US solar industry. Impacts have been felt around the world since May 2017, when Suniva and SolarWorld asked the USITC to investigate.

In summary, they recommended a system involving import quotas, import licenses, and a percentage-based ad valorem tariff of up to 35% in the first year of implementation. The commissioners rejected Suniva's petition to set a minimum import price at $0.74/W; in percentage terms, this would be comparable to a 100% tariff. Like with Suniva's petition, the tariff will be reduced each year and will drop to up to 32% in the fourth year of its implementation (the best case would set the tariff at 15%).

On January 22, 2018, President Trump announced the rates applied to solar modules and cells that resulted from the Section 201 trade case. Modules and cells have a tariff rate of 30% in 2018, to decline 5% in each of the 3 subsequent years, then stay at 15% from 2021. These are just below what the US International Trade Commission (ITC) recommended in October 2017.

3.1.2 Net Metering Policies

For electric customers that generate their own electricity, net metering allows for the flow of electricity both to and from the customer—typically through a single, bidirectional meter. With net metering, electricity from the customer flows back to the grid when generation exceeds use, which has the effect of offsetting electricity consumed by the customer at a different time. Basically, the customer uses excess generation to offset electricity that the customer otherwise would have to purchase at the utility's full retail rate. In the United States, the Energy Policy Act of 2005 requires all public electric utilities to offer net metering to their customers. However, the rates and rules vary depending on state laws and utility policies. Currently, net metering is offered in 44 states and Washington, DC. However, several states like Kansas and Iowa are reviewing their policies and others, like New York, are replacing them with new ways to value the electricity generated by distributed solar systems

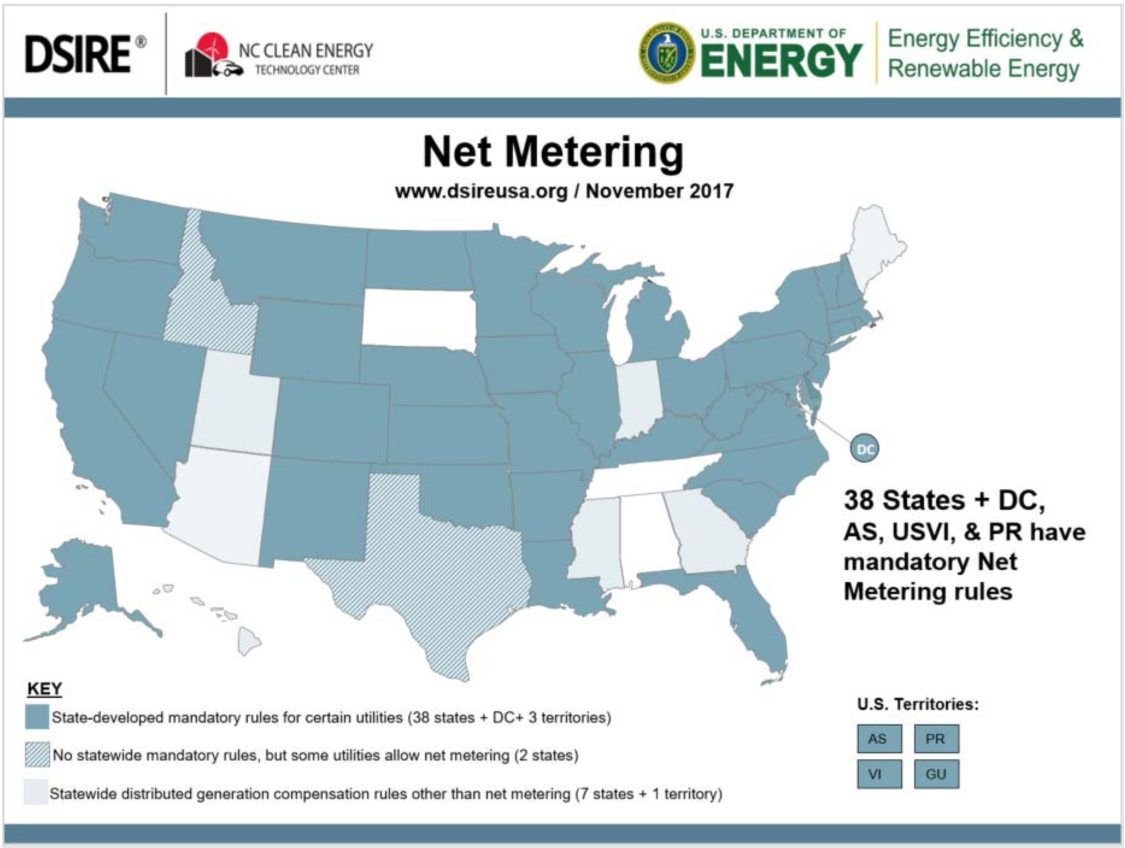
Today, net metering is encountering a series of challenges as solar penetration increases and utilities reach the limits of the amount of electricity that can be fed back into the grid under the rules of the program. Utilities point out that the additional costs required to accommodate net metering are spread among the entire rate base, not just tacked on to homeowners with solar PV on their rooftops. In the United States, some utilities are introducing fixed fees to consumers with solar installations to cover some of their grid costs. Central to this debate is how to ensure the reliability of the electric grid while continuing to revise net metering caps (as a percentage of a utility's highest historical peak load) upward—and how to distribute new costs and benefits across ratepayers fairly.

The first US states to finalize this process were California, Nevada, and Arizona, with each coming up with different answers. On one hand, California introduced a modest interconnection fee and a per kilowatt-hour charge in 2016 while maintaining other benefits like energy offsets, excess electricity banking, renewable energy ownership, and meter aggregation. Customers on the new net metering successor tariff must pay an interconnection fee, estimated at between $75 and $150 for installations under 1 MW and the full interconnection fees for installations above 1 MW. They also have to pay all non-by passable charges (like transition charges, access charges, regional levies and taxes, among others) for all electricity consumed from the grid ($0.02/kWh-0.03/kWh) and go on a time-of-use rate.

On the other hand, Nevada eliminated energy offsets within the same billing cycle and replaced them with a credit for the energy exported to the grid, valued at the utility's avoided cost rate. It also moved net metered customers to a new customer class, with a higher monthly service charge and lower per kilowatt-hour energy charge. The changes in Nevada have virtually killed the local market for distributed renewables for two years, until the State government dialed back some of the new policies in place.

Arizona went for the middle ground. In December 2016, the Arizona Corporation Commission approved significant changes to the state's distributed solar policies, which include lowering the credit residential solar customers receive for excess energy sent back to the grid and limiting how long customers can keep their rates. This will replace Arizona's net metering program with export credits based on short-term valuation methods. In the short term, distributed solar exports will be compensated based on a 5-year average of utility-scale solar PPA pricing. In future rate cases, export rates will be determined either by the Resource Comparison Proxy or by an avoided cost methodology that uses 5-year forecasting to evaluate the costs and values of energy, capacity, and other services delivered to the grid from DG.

Figure 3.1 States with Net Metering



(Source: DSIRE)

3.1.3 US Investment Tax Credit

While the credit was scheduled to decrease to 10% from the current 30% for solar and small wind systems after 2016, the 30% solar Investment Tax Credit (ITC) has officially been extended through 2021. The US Congress agreed on a bill that extends the solar ITC by 5 additional years, as part of a $1.15 trillion spending bill.

For large solar projects (commercial and utility-scale), the ITC was extended from December 31, 2016, stepping down from 30% to 10% until 2024. Projects that start construction by 2019 will receive the current 30% ITC, while projects that begin construction in 2020 and 2021 will receive 26% and 22%, respectively. All projects must be completed by 2024 to obtain these elevated ITC rates.

For residential PV systems, a similar tax credit phaseout applies until December 31, 2021, after which the tax credit scheme ends.

Table 3.1 ITC Phaseout Timetable

Segment	Units	2017-19	2020	2021	2022-
Commercial and Industrial (C&I) and Utility-Scale	(%)	30%	26%	22%	10%
Residential	(%)	30%	26%	22%	0%

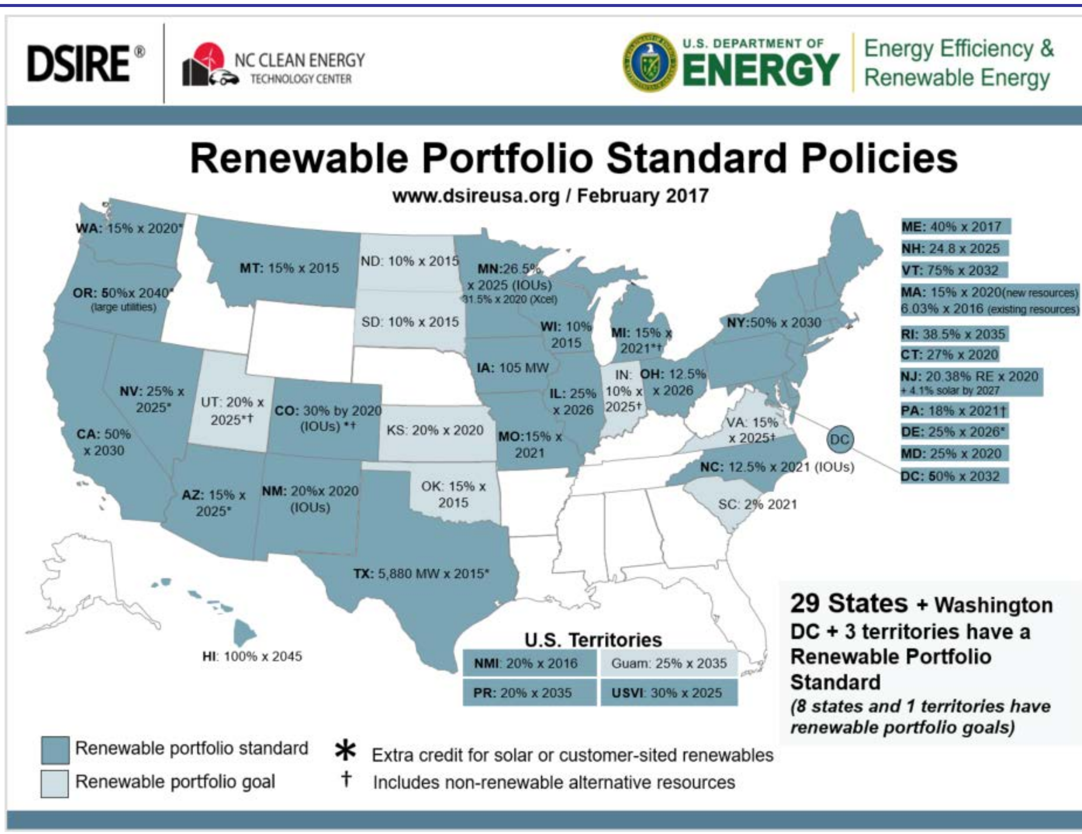
(Source: Navigant Research)

The phaseout of the ITC in the second part of the forecast in this report will have a small effect on the level of solar installations. By 2022, it is expected that the electricity cost from PV will be competitive with retail and, in some cases, wholesale electricity prices.

3.1.4 Renewable Portfolio Standards

In the United States, the compliance markets are set by the states, in what is called Renewable Portfolio Standards (RPSs). If the RPS is 20%, the utilities in that state must hold Renewable Energy Credits (RECs) equal to 20% of their electricity sales. RECs are purchased on the open market or obtained from their own renewable generation assets.

Figure 3.2 States with Renewable Portfolio Standards*



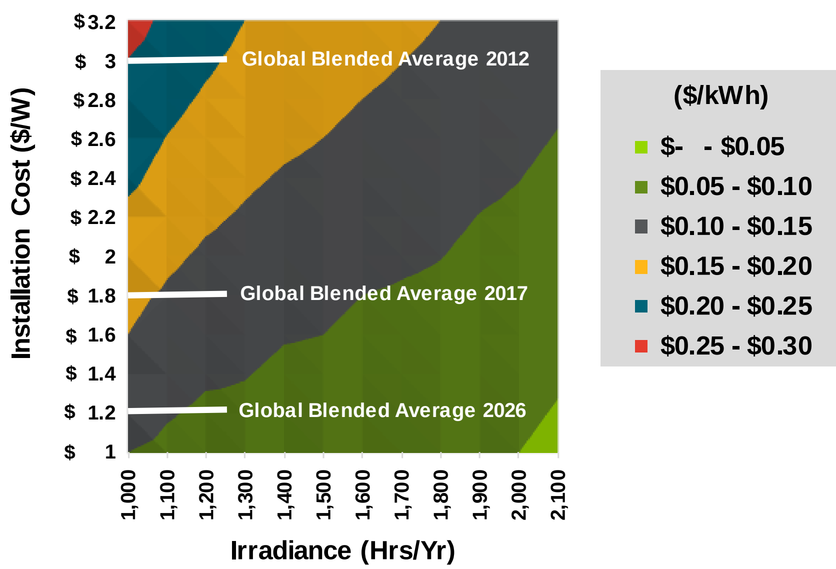
**Note: California increased its RPS to 50% by 2026, 60% by 2030, and 100% by 2045 (Source: DSIRE)*

In order to further stimulate solar PV development, some states count solar RECS (SRECs) as worth 2 or 3 times the amount of regular RECs toward meeting an RPS requirement—despite generating the same amount of electricity as a non-SREC. In a voluntary market, RECs are obtained by corporations or individuals that want to purchase renewable power.

3.2 Grid Parity

Conceptually, grid parity is the point where electricity generated from solar PV is equal to or less than the cost per kWh of electricity sold by the utility to homeowners and commercial and industrial facilities. Reaching this "tipping point" would theoretically enable solar PV to scale even more rapidly as customers would save money on day 1. There are many technical and non-technical factors that improve or weaken prospects for grid parity being achieved, but chief among them is installed cost. Navigant Research's forecast assumes that PV module prices and installation costs will continue to decline at a rate of between 4% and 10% depending on the maturity of the market, reaching a global average in the range of $1.20/W installed anywhere in the world by 2026. With this installed cost, the levelized cost of energy for distributed solar will range from less than $0.05/kWh in sunny regions of the world to less than $0.15/kWh in the least sunny populated regions of the world. If this price is realized, solar PV will largely be at grid parity or better (compared to 2016 retail electricity prices), without subsidies, in all but the cheapest retail electricity markets or in regions with poor irradiance.

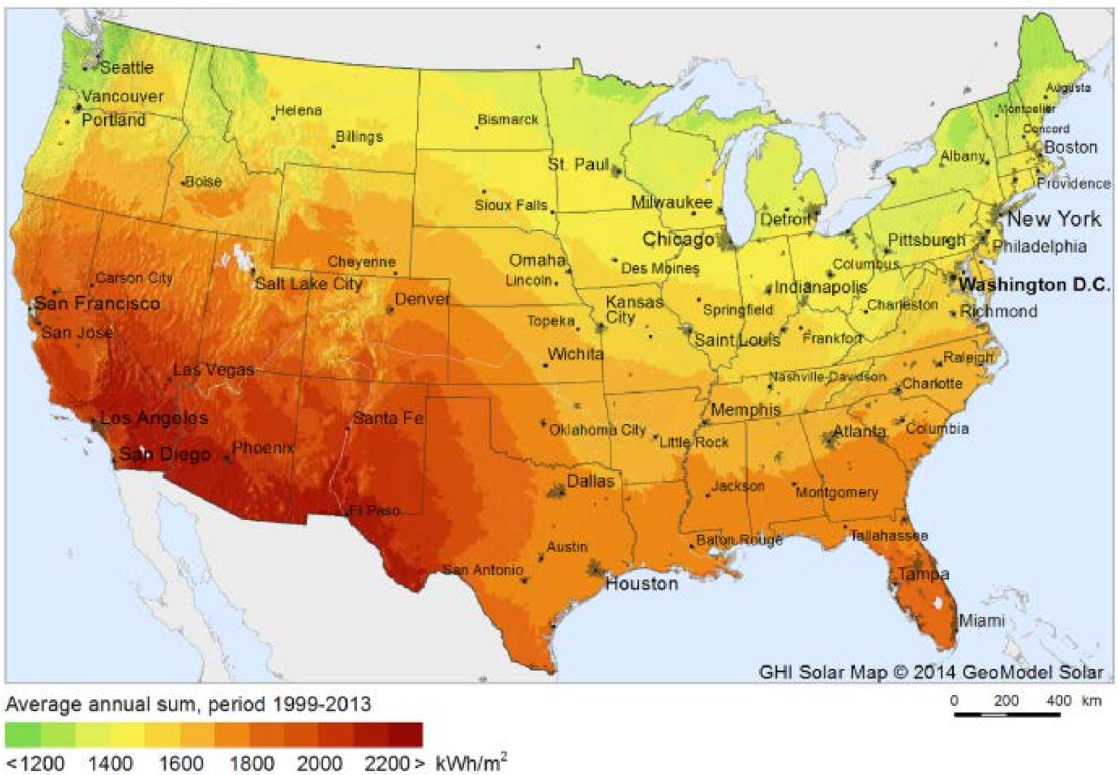
Chart 3.1 Estimated Levelized Cost of Energy and Different System Costs and Irradiance Levels (Pre-Tax)



(Source: Navigant Research)

Most of the US has relatively good irradiance levels, with the minimum levels seen in the Northwest and the maximum levels in the Southwest. The latest public rounds of utility capacity tenders have shown results at between $0.025/kWh and $0.035/kWh in states like Arizona and Colorado, making solar the cheapest source of electricity in those states.

Figure 3.3 US Irradiance map



(Source: SolarGis)

Section 4
METHODOLOGY

4.1 Navigant Research Forecast Methodology & Assumptions

This report presents a forecast for the North American solar PV market through 2027 broken down by segments and countries. Navigant Research's forecast is based on the current regulatory environment, the stage of development of the industry in each of the analyzed markets, and the economics of solar installations compared to retail electricity prices (for distributed solar) or wholesale prices (for utility-scale, or non-distributed, solar).

One of the drivers of solar PV is the variety of system configurations (module chemistry, inverter, balance of system) based on the intended application. Each configuration Navigant analyzed being deployed today, and in the future, would have a modest impact on overall copper content (increase or decrease). We found no significant "threat" to overall copper integration with solar PV systems. In order to be conservative, however, we assumed the copper intensity will decrease slightly as more efficient modules are utilized, but this slight decrease on a per MW basis, will be more than made up for by a growing overall market size across North America due to overall system cost reduction, state-level renewable energy targets, and the increasing adoption of energy storage and other enabling technologies. Therefore, Navigant assumed a constant net copper intensity ratio, which was applied to our forecast of overall solar PV adoption in North America.

4.1.1 Segmentation

Navigant's analysis and forecasts are segmented by the residential, commercial and industrial, and utility-scale as described below:

- **Residential:** Solar PV systems (typically less than 10 kW) installed on single- and multi-family homes. These are almost exclusively behind-the-meter/net metered systems. Residential is the second largest annual market segment by capacity.
- **C&I:** Customers such as hospitals, retail, data centers, schools, hotels, manufacturing facilities, warehouses, universities, food processing facilities, and other systems with electricity used onsite and/or net metered. Typical system size ranges from greater than 10 kW to 1 MW, though it can be significantly larger (e.g., data centers). The C&I market is the third largest annual market segment by capacity.
- **Utility-scale:** Utility-scale projects range from greater than 1 MW up to several hundred megawatts in capacity and deliver electricity to the grid, supplying a utility with energy. Nearly every utility-scale solar plant operates via a PPA with a utility. The utility-scale market is the largest annual market segment by capacity.

4.2 Copper Intensity

Copper intensity varies depending on the type of installation, as the technology. For example, while residential and C&I systems have moved to string inverters or microinverters in the last 5 years, utility-scale projects typically use central inverters. However, the solar PV market continues to evolve in response to rapid technological innovation, meaning the solar PV system of 2027 may be configured quite differently compared to systems today.

- **Residential:** Copper intensity in residential systems is readily scalable, since most copper is used to string together the required number of panels, and, in best-practice designs, to ground them. Distances to inverter/transformers, switchgear and the service entrance do not vary much. Hence a four-kW system will contain approximately twice the copper as a two-kW installation.
- **C&I**: Commercial-scale systems ranging in size from tens of kilowatts to a few megawatts are constructed to more robust standards and more closely resemble utility-scale fields. (Figure 9). They typically contain all-copper grounding systems and up-sized wire gages. Installations include multiple inverters with or without built-in transformers, but generally do not incorporate a single, large transformer since connection to the grid is made at the distribution transformer serving the property.
- **Utility-scale:** A typical utility-scale solar facility comprises acres of panels arranged in rows. DC power is collected from groups of rows and sent to large inverters via a dc disconnect switch. From the inverters, AC current passes to an intermediate-voltage 208 delta-480/277 wye step-up transformer. Groups of such transformers send power to larger 480-step-up transformers for transmission to the grid. Some installations incorporate a massive buried bare copper grounding grid to avoid lightning damage. Such grids are used in some, but not all, utility-scale solar installations.

The following table shows the evolution of copper intensity if the same projects were built in 2010 (actual) vs 2018 (estimated), driven by the changes in installation techniques and module efficiency improvements in each type of project. Based on Navigant's analysis, on a lbs/MW basis, it is estimated that in 2018 utility-scale installations would use 65% less cooper, C&I installations 35% less, and residential installations 30% less.

Table 4.1 Copper Usage Intensity in Photovoltaic Solar Installations, 2010-2018

	Units	Springville, AZ: 6.4 MW Utility-Scale, Grid Connected	Scottsdale, AZ: 12kW Large Residential	Tucson Municipal Water, AZ: 140 kW Commercial-Scale
Total Cable Usage,	lbs Cu	57,670.00	99.23	1,740.87
Power Usage, W&C	lbs Cu	28,033.89	72.37	1,622.58
Ground W&C Usage	lbs Cu	13,416.48	26.86	118.29
Balance-of-System Equipment	lbs Cu	24,880	53.50	369.40
Copper Usage Intensity, 2010	**lbs/MW**	**15,432**	**11,876**	**15,073**
Copper Usage Intensity	*tons/MW*	*7.72*	*5.94*	*7.54*
Solar Industry Efficiency gains 2010-2018	*%*	*65%*	*30%*	*35%*
Copper Usage Intensity, 2018	**lbs/MW**	**5,411**	**8,303**	**9,789.90**

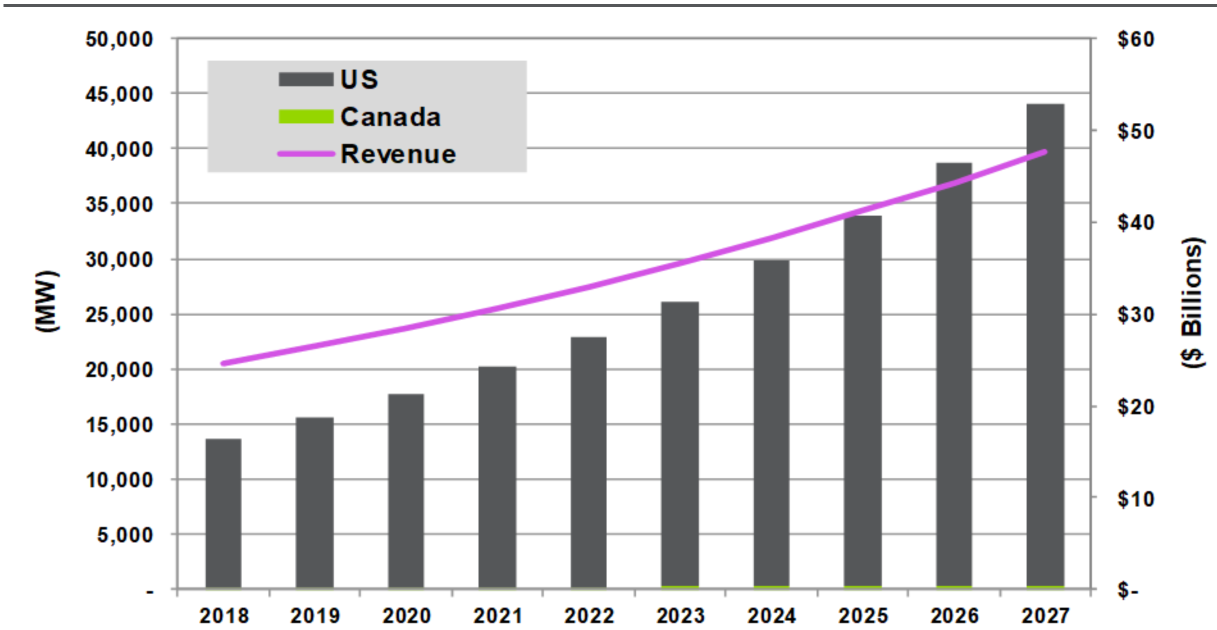
(Source: Copper Alliance, Navigant Research)

Section 5
SOLAR MARKET FORECASTS

5.1 Copper Demand Forecasts by Technology

Between 2018 and 2027, North America is expected to install 137 GW of Residential and C&I PV (DSPV) capacity and 125.0 GW of utility-scale solar. The United States will lead with 136 GW of distributed solar to be installed and 122.1 GW of utility-scale solar. Of the distributed capacity, 64.0 GW will be residential systems and the remaining 72.0 GW will be C&I systems

Chart 5.1 Annual Solar PV Installed Capacity and Revenue by Country, North America: 2018-2027

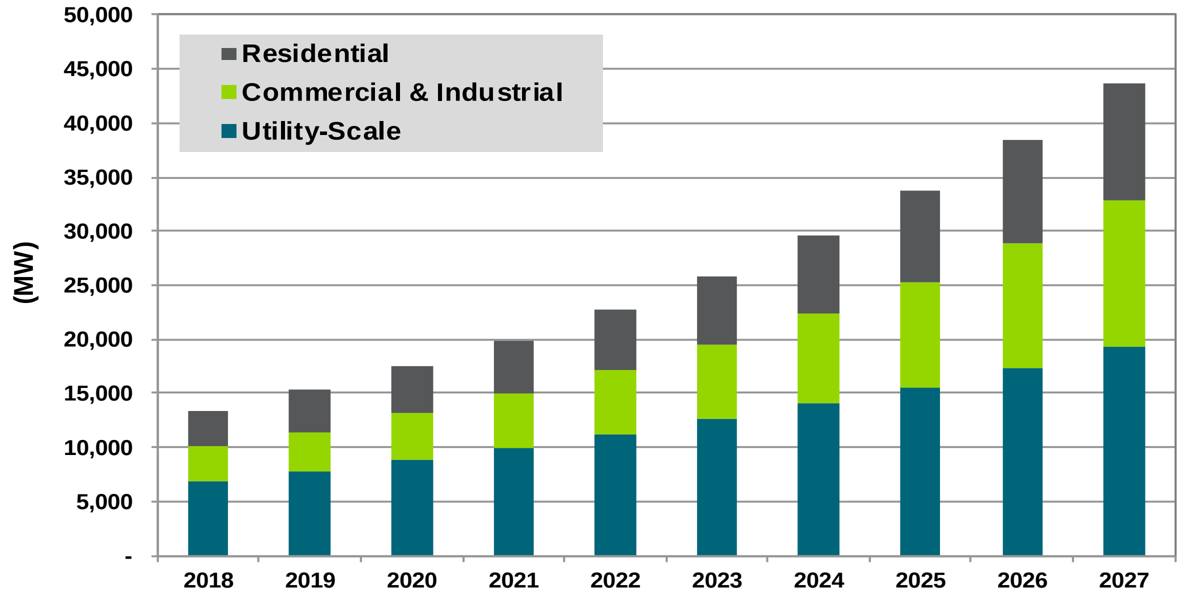


(Source: Navigant Research)

DSPV installations in North America are expected to experience a 15.8% compound annual growth rate (CAGR) between 2018 and 2027. During 2027, 24.5 GW of DSPV is forecast to be installed in the United States—nearly four times the amount installed in 2018. In 2027, 19.2 GW of utility-scale solar PV will be installed that year, nearly three times the forecast 2018 total.

Note that although Navigant Research's forecast already accounts for the drop in the US ITC from 30% to 10% in the next 5 years, it does not include potential policy changes at state level.

Chart 5.2 Annual Solar PV Installed Capacity by Segment, North America: 2018-2027



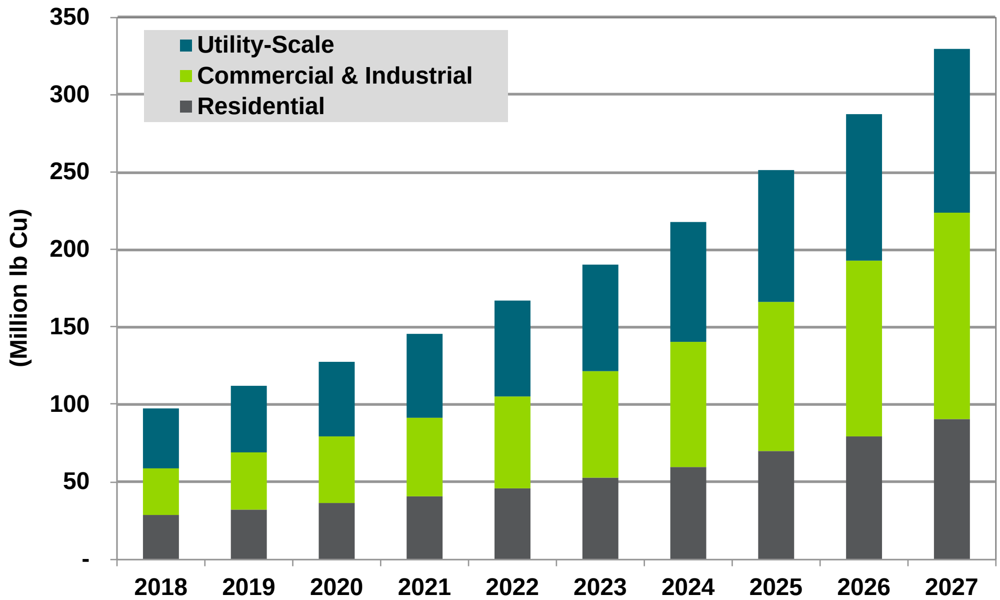
(Source: Navigant Research)

Applying the copper intensity presented in the methodology section to the estimated solar forecast gives us a total demand for copper between 2018 and 2027 of 1.925 billion lb Cu (or 962 Million short tons Cu), with almost 99% coming from the US and the remaining from Canada.

While the new installed capacity of distributed solar (residential and C&I) and utility-scale solar over the next decade is similar, once we add copper intensity into the equation, their shares change significantly. On a ten-year cumulative basis (2018-2027), total copper demand by segment is as follows:

- Residential: 535 million lbs.
- Commercial & Industrial: 713 million lbs.
- Utility-Scale: 677 million lbs.

Chart 5.3 Annual Copper Demand from Solar Installations by Segment, North America: 2018-2027



(Source: Navigant Research)

Section 6
RESULTS OF COPPER DEMAND ANALYSIS

6.1 Summary of findings

The solar PV market continues to transition from being dependent on government incentives and environmentally conscious wealthy homeowners to a cost-effective source of electricity that is gaining traction across market segments and customer types.

Solar PV hardware manufacturers have largely delivered on ambitious cost reduction targets during the past 5 years, and with the introduction of new high efficiency modules, they are now focusing on reducing soft costs like labor, customer acquisition, financing costs, and permitting.

Vertical integration has resulted in market consolidation and the emergence of globally active platform companies. It will also ultimately result in greater potential for long-term growth for the solar sector—as Navigant Research expects these trends to continue over the next decade. Although the amounts of copper used per MW of solar installed capacity has decreased in the last decade do the technology advancements, this decline has been compensated by a significant increase of solar installations. The growth in the solar PV industry is expected to drive significant amounts of copper demand (1.925 billion lb) over the next decade.

6.2 Conclusions and recommendations

The solar industry has grown dramatically over the last decade, becoming the largest source of new electricity capacity around the world. The economics of solar PV now make it one of the cheapest sources of electricity in several US states and close to natural gas plants in others, even when it must compete against established plants.

The next few years, between 2019 and 2022, will see incentives to the solar industry reducing and, in some cases disappearing, but that is not expected to cause a significant change in the growth rate as cost reductions in solar are expected to continue thanks to a healthy number of new technologies coming to improve system efficiency, increasing its competitiveness even without subsidies. The impact of solar PV in the electricity sector goes beyond the price of electricity. Its modularity allows the installation of PV systems beyond the transmission grid and all the way to the electricity consumer premises, changing the way the market operates from a hub and spoke design to a networked one composed of customers that both consume and produce electricity (prosumers).

While the deployment of solar PV will create copper demand due to the new installations, it is expected that it will also affect other copper demand drivers in the electricity market as distributed solar in particular, changes the dynamic between generation, transmission and distribution of electricity.

Section 7
ACRONYM AND ABBREVIATION LIST

BOS .... Balance of System

C&I .... Commercial and Industrial

CAGR .... Compound Annual Growth Rate

CVD .... Countervailing Duty

DG .... Distributed Generation

DOC .... Department of Commerce (United States)

DSPV .... Distributed Solar PV

FIT .... Feed-In Tariff

GW .... Gigawatt

ITC .... Investment Tax Credit

kW .... Kilowatt

kWh .... Kilowatt-Hour

kWp .... Kilowatt-Peak

Mono-Si .... Monocrystalline Silicon

Multi-Si .... Multicrystalline Silicon

MW .... Megawatt

MWh .... Megawatt-Hour

PPA .... Power Purchase Agreement

PV .... Photovoltaics

Q .... Quarter

REC .... Renewable Energy Certificate

RPS .... Renewable Portfolio Standard

SREC ....Solar Renewable Energy Certificate

US .... United States

W...Watt

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Section 10

SCOPE OF STUDY

This report provides an overview of the Solar PV market in North America, with a specific focus on estimating the amount of copper that will be utilized in the industry. The market overview and forecasts focus on the three major market segments for grid-connected Solar PV: utility-scale, commercial & industrial, and residential. This report provides details on the market dynamics including a discussion of the leading solar PV technologies across all three major market segments. Drivers, barriers, and the competitive landscape in the market are explored to provide context on the forecasts for overall deployments and the demand for copper in the industry.

SOURCES AND METHODOLOGY

Navigant Research's industry analysts utilize a variety of research sources in preparing Research Reports. The key component of Navigant Research's analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Navigant Research's analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

These primary and secondary research sources, combined with the analyst's industry expertise, are synthesized into the qualitative and quantitative analysis presented in Navigant Research's reports. Great care is taken in making sure that all analysis is well-supported by facts, but where the facts are unknown, and assumptions must be made, analysts document their assumptions and are prepared to explain their methodology, both within the body of a report and in direct conversations with clients.

Navigant Research is a market research group whose goal is to present an objective, unbiased view of market opportunities within its coverage areas. Navigant Research is not beholden to any special interests and is thus able to offer clear, actionable advice to help clients succeed in the industry, unfettered by technology hype, political agendas, or emotional factors that are inherent in cleantech markets.

NOTES

CAGR refers to compound average annual growth rate, using the formula:

$$CAGR = (\text{End Year Value} \div \text{Start Year Value})^{(1/\text{steps})} - 1.$$

CAGRs presented in the tables are for the entire timeframe in the title. Where data for fewer years are given, the CAGR is for the range presented. Where relevant, CAGRs for shorter timeframes may be given as well.

Figures are based on the best estimates available at the time of calculation. Annual revenues, shipments, and sales are based on end-of-year figures unless otherwise noted. All values are expressed in year 2018 US dollars unless otherwise noted. Percentages may not add up to 100 due to rounding.

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