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RESEARCH REPORT

North American Wind Energy Copper Content Analysis

Prepared for Copper Development Association

Produced 3Q 2018

Jesse Broehl
Senior Research Analyst

Dexter Gauntlett
Principal Research Analyst

Section 1
INTRODUCTION

1.1 Introduction

The global wind industry installed just under 52 gigawatts (GW) in 2017 with 51.9 GW installed. The United States saw over 7 GW installed and reached over 89 GW of cumulative capacity, second only to China. The US is in the early stage of a major acceleration in wind plant construction expected to peak in year 2020 as tax credits are slowly phased out and their value reduced each year, with 2023 the last year that wind plants are eligible for reduced level tax credits. The wind industry is confident that it can survive and be competitive without tax credits in the US. That is most likely true given the rapidly falling Levelized Cost of Energy (LCOE) of wind, which is enabled by relentless advances in wind turbine technology. What the industry likely cannot survive without is the raw material copper used all throughout a wind turbine and the broader wind plant. Copper plays critical roles at a wind plant, beginning with copper wiring coursing through wind turbine control systems that engage operation once minimum speeds are present. Copper plays an indispensable role converting the wind turbine's mechanical energy into electrical energy in the generator. After up-tower power conversion, copper cables transmit electricity from the top of the wind turbine (nacelle) down to the tower base. These are increasingly long distances. The second most popular wind tower size installed in the US in 2017 was 95 meters (311 feet)[1]. Meantime, the Europeans are surpassing 140+ meter hub heights (459 feet) on select projects. Copper cable travels these distances to the tower base where switchgear and step up transformers – both built with copper components – send electricity into a wind plant's miles of interconnecting copper cables. These buried cables eventually reach a centralized copper-enabled step-up transformer and substation where clean inexhaustible renewable energy flows into homes and businesses throughout the electricity grid. This report takes a deep dive at copper's role in the wind power industry and estimates current and projected annual copper demand through year 2027 for the US, Canada, both for the onshore and offshore sectors. The report also provides a brief overview of the global wind power markets, on and offshore along with more detailed analysis of the US and Canadian wind markets.

1.2 Methodology

This report builds upon research conducted by the Copper Development Association (CDA), including detailed analysis of copper intensity used in the various hardware subcategories of a typical wind plant. Multiple sizes of wind plants with different size wind turbines from different wind turbine Original Equipment Manufacturers (OEMs) are used as

[1] US Wind Industry Annual Market Report Year Ending 2017, American Wind Energy Association

part the underlying assumptions. Averaging across these multiple examples provides estimates for lbs. and tons (US tons, not UK tonnes or Metric tons) of copper usage at typical wind plants. Similarly, offshore data from rigorous studies of the UK offshore wind market contribute the offshore content perspective. Numerous aspects of copper usage at wind plants that has been previously described in other CDA reports and insights is included in this report where the content is still accurate and applicable to today's wind market.

This report builds upon CDA's ever-expanding insights of copper usage throughout many industries by including new wind energy market megawatt (MW) / GW forecasts for the U.S, Canada, and North America through partnership with market intelligence firm Navigant Research. This provides multipliers to estimate annual copper content required for the wind power sector in North America. This report's market forecast is for wind energy development over the next 10 years from 2018 to 2027 and includes a separate forecast for offshore wind. Forecasts are based on primary and secondary research and analysis of the wind markets, assessments of policies, incentives, construction activity, wind turbine safe-harbor contracts, and other metrics to measure the wind industry's activity now and in coming years.

The report assumes fixed estimates for copper content lbs. and tons per MW. It does not include escalators or decreases for copper intensity since there is not enough statistically relevant data to back such movements either direction. As wind turbines grow larger in MW nameplate capacity and the larger wind turbines allow for fewer wind turbines to meet the same MW wind plant capacity, there is an assumption that this may require less copper if there are fewer wind turbines. However, there is evidence detailed in section 1.10.3 that these larger turbines may have a net wind plant increase in copper content for the same total wind plant size. This factor and other factors such as substitution of aluminum in some parts of the wind turbine can impact overall copper demand but these factors play a much smaller role than the MW forecast data and therefore the MW forecast is the key data relied on for this report's forecast of copper demand.

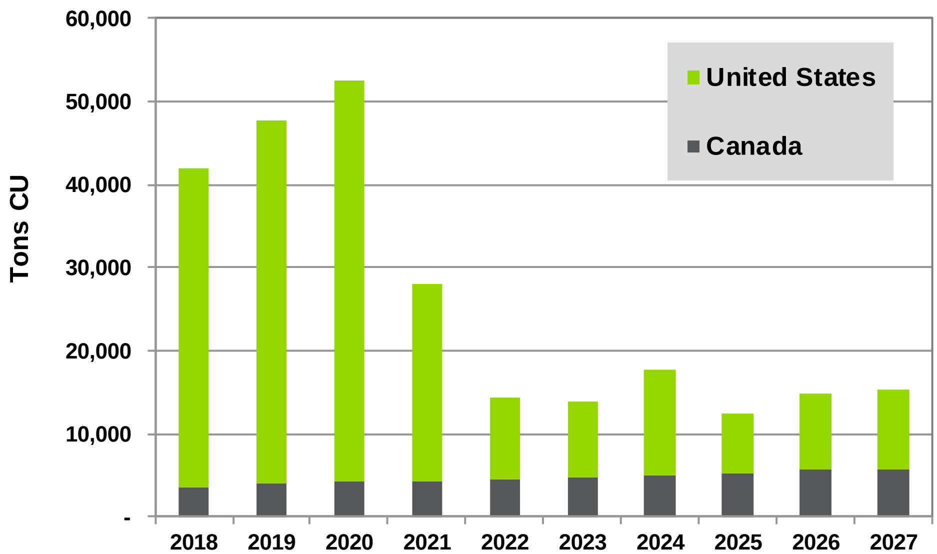
1.3 Summary of Results

Navigant Research is forecasting 48,721 MW (48.7 GW) to be installed between 2018 and 2027 in the US. This is based on analysis of wind plants known to be under construction and an increase in the capacity of so-called safe harbored wind plant expenditures (more explanation in US forecast assumptions chapter). Based on an analysis of Production Tax Credit (PTC) deadlines and construction patterns, Navigant projects that 8-10 GW/year of wind projects will be installed in 2018-2020 and with year 2020 the peak installation year expected to surpass 10 GW and then dropping sharply due to expiring tax credits.

That rate of installation is what drives the copper content usage forecast, exhibiting current high volume of 38,453 tons in the US in 2018 and peaking in 2020 with 48,358 tons. Levels decrease sharply thereafter dropping to 23,763 tons in 2021 and then leveling off at an average of 9,579 tons per year through the remained of the forecast to 2027. This is using the base-case assumption of 4.76 tons/MW which is the average of the copper intensity data for the wind plant examples used in this study.

Canada's wind market will play a relatively negligible role in copper content usage by the wind power industry due to its low installations rates relative to the much larger US market. The forecast for Canada expects just over 10,000 MW installed through the 10-year forecast period. This compares to the 48,721 MW expected to be installed by the US. Canada's wind market will also see no offshore wind installed during the forecast period. Canada's base case scenario assuming 4.76 tons/MW represents 3,570 tons of copper in 2018 and growing at minor CAGR of 5.5% through the forecast period to reach 5,760 tons in 2027. Overall average through the 10-year forecast period is 4,761 tons/annually.

Chart 1.1 Copper Demand, Base Case, Onshore North America

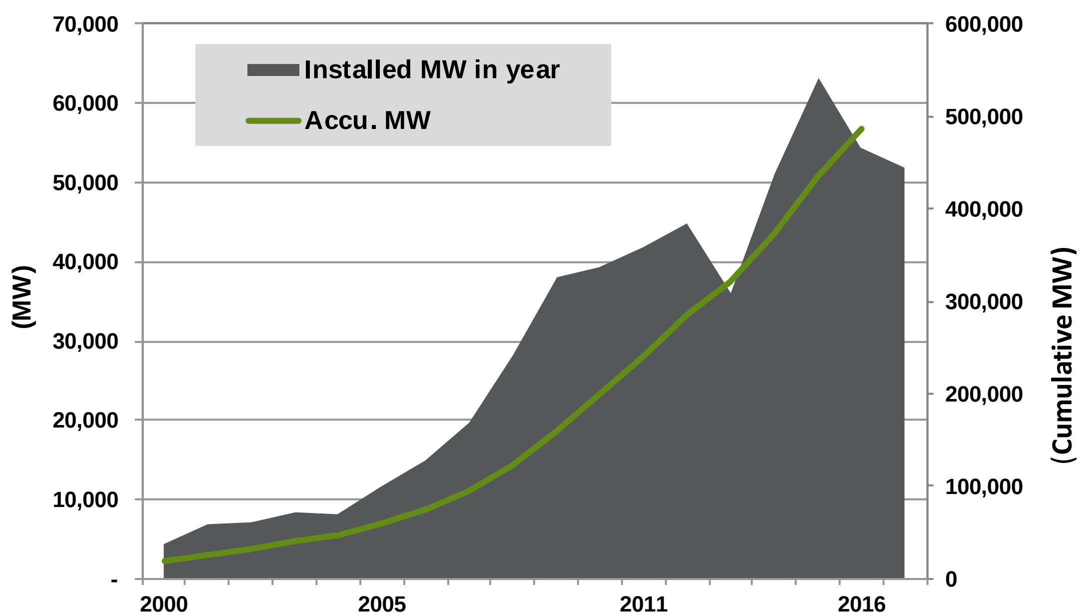


(Source: Navigant Research)

1.4 Global Wind Energy Market Overview

The global wind industry installed just under 52 GW in 2017 with 51,915 MW installed. This was a 4% decrease in installed wind capacity from 2016 when 54,315 MW was built. In 2016 that was itself a decrease of 14% from the record-breaking year prior when 63,135 MW was installed. Two years in a row of decreases does not, however, bode ill for the overall global market. China's massive wind market – China dropped from 23.3 GW installed in 2016 to 19.5 GW installed in 2017 – which is itself a remarkable amount of new annual capacity for one country. The Americas region also decreased, led mostly by the U.S which installed just over 7 GW in 2017, down from 8.2 GW the year before. This represents a temporary drop as the policy driven cyclical market ramps up with expectations of record installations peaking in 2020. Canada also contributed to the declines in the Americas region as it only brought online 341 MW, down from 702 MW the year before, however it should see growth soon as the market in Alberta takes off. Elsewhere, however, installations exhibited healthy growth. The European wind market experienced a year over year increase of 14.6% with 15.9 GW installed up from 13.9 GW the year before. The usual top markets such as Germany, the UK, France and Turkey contributed the most, while smaller but broad-based gains in other European countries contributed. The other smaller regions and countries in Asia and Latin America showed the same rate of installations in 2017 as the year before, and Africa doubled its contributions thanks largely to South Africa. More detailed analysis of wind market activity in the US and Canada is included below in sections 1.6 and 1.7.

Chart 1.2 Annual and Cumulative Wind Power Capacity, World Markets: 2000-2017



(Source: World Wind Energy Market Update 2018, Navigant Research)

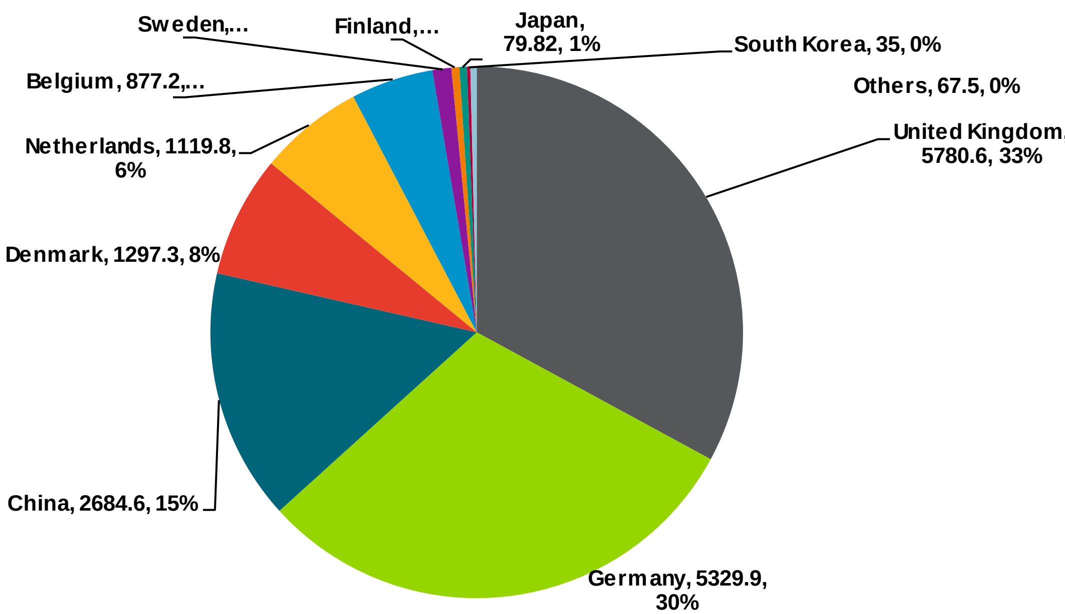
1.5 Global Offshore Wind Energy Market Overview

While the onshore wind market is larger in terms of total megawatt plant capacity added annually, offshore wind is growing more quickly. It is forecast to grow at an 11.1% compound annual growth rate (CAGR) between 2017 and 2022, compared to single-digit growth rates for onshore wind. Approximately 4,246 MW was installed in 2017, bringing total global cumulative capacity to 16,837 MW. Some notably large 2017 installations came from Germany with 1,476 installed, bringing its total cumulative online to 5,329 MW, and 688 MW online in 2017 in the UK, bringing the UK's cumulative total to 5,780 MW. The Netherlands exceeded 1,119 GW with 600 MW coming online in 2017. China installed 1,164 MW in 2017, bringing its cumulative total to 2,678 MW.

There is also a substantial 7,942 MW of wind projects under varying levels of construction. This includes 2,945 MW in China, where the offshore sector is picking up steam. Aside from one 60 MW project under construction South Korea, the remainder of offshore wind under construction is in Europe, with 4,937 MW under construction.

Globally, over 18,776 MW are in advanced planning stages, but this does not guarantee all these projects will proceed to construction. Advanced planning is defined generally as one or more of the following prerequisites in place: site permitting, awarded tender, power purchase agreement (PPA) or other power off-taker arrangement, turbine supply agreement, or project financing. A further 20,094 MW is in early planning, which is more loosely defined as known projects generally without any of the project requirements.

Chart 2-3. Capacity (MW) and Country Share of Offshore Wind Projects Online, World Markets: 2017



(Source: World Wind Energy Market Update 2018, Navigant Research)

1.6 United States Wind Energy Market Overview

The United States installed 7,017 MW in 2017, bringing its cumulative total to 89,077 MW. The tax credits in place for wind energy virtually guarantee a robust market expected to peak in 2020 with over 10 GW annually. This is essentially a cycle of overbuilding while the US market still has tax credit incentives in place. Even with modest new electricity demand in many parts of the US, utilities and large C&I players are motived to purchase wind power while it is still "on sale" as supported by the phasing out tax credits. The boom will be followed by a rapid deceleration after 2020 when wind competes purely at market cost and demand will have been largely met by the previous build cycle. The structure of tax credits has ensured this development and deployment. Wind plants that began construction by the end of 2016 receive 100% PTC value. Projects that started construction in 2017 will receive 80% of the PTC value, and the percentage will continue to decline through 2020 (2018: 60%; 2019: 40%; 2020: 0%). Most importantly, revised guidance in 2016 provided by the US Internal Revenue Service changed the construction window from 2 to 4 years. Therefore, projects on the tail end of the PTC window in 2019, for example, could still be finishing construction through 2023. However, in practice most wind developers seeking the maximum financial return on their wind projects aim to qualify their projects as having started in 2016 or 2017, which underpins the likely peak of annual commissioning in year 2020. Annual installation rates after 2020 are likely to average around 2 GW. No new offshore wind was commissioned in 2017 however several major tenders and policy announcements in 2017 and early 2018 from the states of Massachusetts, New Jersey, New York, and Connecticut show the US market slowly building inevitable momentum to soon see year-over-year steady installations beginning in the mid-2020s.

1.7 Canada Wind Energy Market Overview

Canada saw 341 MW installed in 2017, down from 702 MW installed in 2016, bringing its cumulative total to 12,239 MW. Canada's wind market has steadily dropped since a high point in 2014 when 1,871 MW went online thanks to the Ontario FIT system for large wind plants. Because of that policy scheme disbanded in mid-2013, installations were supported for two more years but began to slide downward in 2016 and 2017. Canada has no central government incentives for wind and relies solely on procurement from its state owned provincial electric utilities that operate in a mostly flat electricity growth demand situation, thereby resulting in few new tenders for projects. Ontario and Quebec have been the primary markets in Canada, but growth lately has been flat. The most promising hope for the Canadian wind market lately has been in the province of Alberta which for years largely shunned wind. A recent realization by provincial government, utility and other stakeholders that Alberta has some of the best wind resources on the North American continent has led to the implementation of a new series of competitive power contract auctions to source up to 5 GW of new renewables capacity, and most of that coming from wind. The first auction was held in December of 2017 procured 600MW for an average C$37/MWh ($30/MWh) for wind plants feeding the grid by the end of 2019. Two more rounds for 2018 are on the way with a first 300 MW Round 2 and 400 MW Round 3. The first Round 2 will include a minimum "Indigenous Equity" component. Canada, like the United States, has many First Nations or indigenous communities. The indigenous equity provisions would require a minimum ownership stake in the projects or a land use agreement.

1.8 Summary of Copper Usage in the Wind Energy Industry

Copper usage intensity for wind generation (pounds needed per megawatt of new capacity, lbs./MW) exceeds that for conventional fossil and nuclear generating facilities by a factor of between two and five. Thus, all new wind capacity added during the coming decades will require significant quantities of copper electrical products. Aggressive development of offshore wind energy will require even more copper owing to the large distances to be spanned with large gauge conductors. Copper's advantage when applied to wind turbines and wind power plants include copper's higher conductivity. This can mean lower losses in the wind turbine step-up transformers, wind plant switchgear, and cables including cables to transmit power down the tower (see section 2.10.1 on taller towers) and the underground buried wind plant collector cables that transmit power from individual wind turbines to centralized switchgear and substation equipment. Advantages also include copper's inherent corrosion resistance (especially relevant in offshore plants), but also relevant onshore since wind turbines are exposed to the elements. Copper also has higher strength and relaxation resistance (especially in connectors, but also in transformers).

1.8.1 Typical Usage of Copper in Wind Turbines and at a Wind Plant

Copper is used throughout a wind plant in significant quantities. Estimates on those quantities will be provided further below in Table 3-1. This section will first describe the areas of copper usage and related market dynamics. Wind farm designs have become somewhat more uniform than in early years, and it has become accepted practice to install a single all-copper grounding system connecting all components (turbines, transformers, substations, etc.). Grounding conductors are usually AWG 4/0 but may be as large as 250 MCM. A survey of more than 100 wind farms revealed that conductor lengths average 25 miles per 100-MW wind farm. Grounding is of paramount importance to ensure uniform ground potential among electrical components. Grounding also serves for lightning protection. There have also been reports of increasing use of copper-clad steel grounding conductors by some utilities in the US to thwart theft, but the practice is not known in the wind industry since copper cables are protected within the locked towers or buried.

Individual turbines in a farm are typically arranged in groups of various sizes. The groups are connected electrically via buried copper-concentric-neutral (aluminum conductor) power collector cables. Power from several groups may then be collected at one or more substations, from which power transitions to overhead aluminum conductors before (in some cases) being stepped up again to grid voltage. An important fraction of copper intensity in such farms is embodied in the buried, large-gage (typically from AWG 4/0 to 250 MCM) bare-copper ring grounds that surround each turbine tower and transformer, and which connect all turbines and substations in the installation to maintain a uniform ground potential.

The use of heavy DLO (Diesel Locomotive) cables, ground based 100% copper transformers and copper-concentric-neutral collector cables, along with robust grounding networks, represents the upper limit of the copper intensity ranges. The lighter, all-aluminum step-up transformers mounted in nacelles along with lighter-gage, high-voltage down-conductors constitute the lower end of the intensity range. There are many variations. In one alternative design, the step-up transformer is located approximately half-way up the turbine tower, with DLO cables above and high voltage cables below. In another variation, the step-up transformer utilizes copper magnet wire on the primary windings and aluminum on the high-voltage secondary. Copper intensity in onshore wind farms is strongly related to the physical size of the installation due to the miles of copper grounding cable and copper-concentric-neutral aluminum-conductor power cable installed over large distances. Other important contributors to copper intensity include magnet wire for generators and transformers, DLO cables, control and communication cables, and busbar for switchgear.

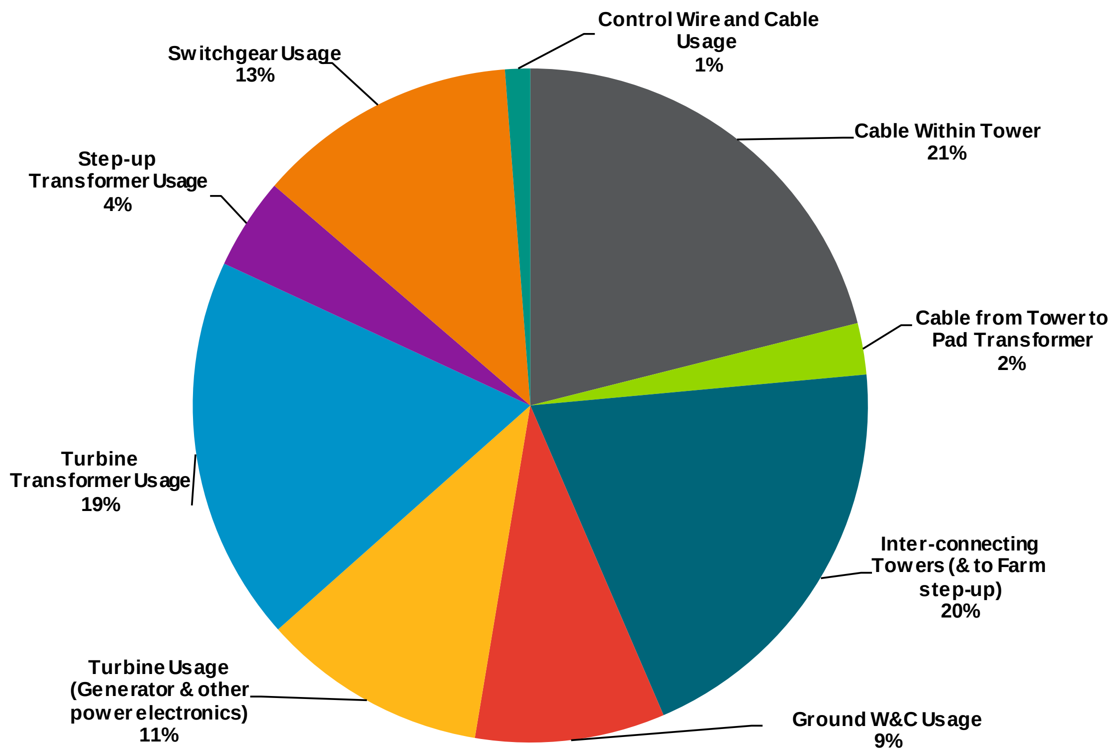
Today's larger turbines utilize copper more efficiently. The latest tower designs reportedly vary in their efficiency of copper usage. Interviews with suppliers and developers indicate that some onshore wind turbines incorporate aluminum selectively, especially in the cast-coil transformer in the nacelle, which, as noted earlier, reduces copper intensity significantly.

In addition, some manufacturers are now considering flexible aluminum cable to transmit power from the nacelle to the tower base. However, these manufacturers uniformly indicate the cabling is and will continue to be all-copper for offshore installations to avoid saltwater corrosion. That having been said, however, Vestas plans to use cast-coil aluminum transformer mounted in the nacelle of its offshore turbines, since, as they said, only copper is exposed outside the transformer because the aluminum-to-copper transition is made within the cast volume surrounding the windings.

1.8.2 Copper Megawatt Intensity as a Percent of Total Wind Plant by Application

The following chart shows an estimate of the proportions of copper used at an onshore wind plant. The estimates are an average of the varying amounts of copper in table 2.1, which includes copper estimates at 5 wind plants using different wind turbine manufacturers and turbine nameplate MW sizes. The estimates compensate for the different total wind plant sizes and the number of wind turbines. The data can therefore provide a reasonable estimation of copper usage in the different parts of the wind turbine and the wind plant. The largest proportions, as could be expected, are for cable usage.

Chart 1.4 Copper Megawatt Intensity as a Percent of Total Wind Plant by Application



(Source: Navigant Research)

1.8.2.1 Copper Megawatt Intensity as a Percent of Total Wind Plant by Application Descriptions:

- Within the cable application, the largest usage at 21% is the cable within the wind turbine tower used to transmit power from the turbine nacelle down to the tower base.
- At 20% usage are the cables needed to interconnect the various wind turbines to centralized balance of plant equipment such as a step-up transformer and substation. A further 2% total usage is represented by cables that transmit power a shorter distance from the tower base to a nearby pad-mounted transformer.
- The next largest application after the various cabling applications is at the wind turbine transformer (19%), which steps up power to transmit to through the wind plant interconnecting cables, usually located outside the tower base.
- Approximately 13% is represented by the switchgear usage. Switch gear is located at every wind turbine and it controls high power electric power circuits. Its work encompasses switching and protecting individual wind turbines. It is also used to isolate a single turbine, so other turbines in a string can continue generating power

while one isolated wind turbine has inspection, maintenance or other downtime work applied.

- At roughly 11% usage, substantial amounts of copper are needed for the generator located within the wind turbine drivetrain in the nacelle. Each wind turbine manufacturer addresses these components slightly differently, such as squirrel cage induction generators or the more common double-fed-induction generators. These first two are relatively compact in size and generate electricity from the high-speed output of a wind turbine gearbox (see second photo below). Wind turbines with direct drive configurations avoid the use of a gearbox and therefore rely on a much larger size rotor-stator generator configuration, such as shown in the following photograph of copper windings being installed during generator production.

Above: Copper windings being installed in a stator/rotor for a low-speed direct drive (no gearbox) Enercon wind turbine generator (source: Enercon.de). Below: copper windings in more common high-speed gearbox-connected generator (Source: rjweng.com)

- Grounding wire and connectors (Ground W&C) follow transformers for the next most copper intensive component of the wind plant at 9%. This simple hardware located throughout the wind turbine and wind plant and serves the duty of electrical grounding of equipment. This includes lightning protection systems.
- Step-up transformer represents 4% of copper use intensity at a wind plant. As opposed to the small decentralized transformers located at each individual wind turbine, the step-up transformer is the larger centralized transformer required to step up wind plant voltage to the grid voltage. Large wind plants can have multiples. Wind plant configurations differ but this is typically located adjacent to the centralized wind plant substation or multiple substations in large wind plants.
- Lastly, control wire and cable usage at around 1% throughout the wind turbine is a smaller but essential part of the wind turbine, providing the wiring for critical control, operations, and diagnostics for the wind turbine among all the wind turbine components. Even the most minor failures in this system while not very copper intensive have major ramifications for overall wind turbine operation and resulting power generation and revenue.

1.8.3 Examples of copper usage in modern wind turbines

The following photo in Figure 1.1 shows one of the major uses of copper in wind turbines via the cables required to transmit power from the nacelle down through the tower. Cables then connect to a down-tower step-up transformer, switchgear, and inter-array wind plant collector cables. These cables constitute a significant contribution to copper intensity. Many manufacturers adhere to this design. However, at least one supplier (Vestas) mounts an aluminum-wound, cast-coil step-up transformer in the nacelle, enabling the transmission of high-voltage power, usually at 34.5 kV, to the base of the tower via lighter-gauge conductors. Copper intensity is thereby reduced.

Figure 1.1 Heavy gauge copper cables within the wind turbine tower

(Source: Wikimedia Commons)

Figure 1.2 Step-up transformer located on the wind tower pad

(Wikimedia Commons)

1.9 Copper Usage in the Offshore Wind Energy Industry

Offshore wind energy presents a large potential opportunity for copper because of significantly higher copper content use. Based on recent experience at British offshore wind farms [Falconer, 2009], copper intensity may be as high as 22,000 lbs./MW. The challenge for copper usage in the North American offshore sector, however, is that the total volume of MW wind plant capacity is relatively small compared to the broader onshore wind industry. In the 10-year forecast provided in this report for the US (see section 3.1), no offshore wind capacity will be installed in Canada and only a few wind plants in the US in the later part of the forecast. Additionally, in this early stage of the offshore wind market in the US, most of the wind turbine equipment will be imported from Europe, which unlike the US has a mature supply chain for offshore wind. Cables, however, would likely be sourced from North America.

Submarine collector and transmission cables are normally 100% copper, unlike those on land. Substitution by aluminum is feasible but has not yet occurred, mainly for reasons of reliability. Collection and transmission distances are longer than those on land and call for larger-gage cables than those used on land. Offsetting that positive is the lack of a need for grounding cables. Direct-current transmission would reduce the number of conductors needed to two.

Developers and other stakeholders in the nascent US offshore wind industry prefer initial development at around eight miles from shore, depending on the project. This presents a balance between shelf depth, transmission cost and acceptable visual impact. By contrast, 25 miles hides the wind turbines below the horizon but raises costs prohibitively. One supplier proposes that collection between and among turbines will likely involve medium-voltage, three-phase ac power, which would be collected at a central substation where large inverters would convert it to high-voltage dc for transmission to shore. According to that supplier, 10 km (6 miles) is the probable breakeven distance beyond which dc transmission is favored. Some German offshore wind farms are connecting beyond 60 kM out and making use of DC transmission but the breakeven point for DC transmission in the most current wind market in Europe is around 50 kM (31 miles). AC is always used under 50 kM. Maintenance and repair costs are significantly higher for offshore turbines and the other balance of plant equipment so the consequent need for high reliability favors copper.

1.10 Market Issues Affecting Copper Demand in the Wind Industry

1.10.1 Taller Towers Increase Copper Demand

Copper use advantages include lower losses in the down-tower cables required and are the most commonplace solution to down-tower cable needs. This is relevant within the context that wind turbines are getting taller to reach higher and steadier wind speeds – although this is more prevalent in Europe than the US. Most of the advances in recent years leading to more efficient wind turbines has been driven by the deployment of longer blades and resulting larger rotor diameters that can capture more wind. This has also played large role in allowing wind turbines to be sited in areas of medium and low wind speed that a decade ago would not have been economical to construct a wind plant.

Second behind rotor diameter, however, has been an accompanying increase in wind tower heights, or typically described as the hub height, which is where the nacelle and rotor hub are located. Wind turbine manufacturers seeking higher energy yield and more efficient and cost-effective wind turbines have used increases in hub height as part of many solutions for improving performance. This also enables wind plants to be sited in lower wind speed locations, which also often happen to be close to population and electricity load centers, which reduces transmission losses. Every additional meter height increase at a wind plant results in incrementally more copper for the down-tower cable needs.

Recent data from AWEA highlights the taller turbine trend.[2] In year 2017, the average wind turbine hub height increased to 86 meters (282 feet). That figure somewhat masks the underlying data, which is that 47% of wind turbines installed in 2017 are on 80-meter (262 feet) towers compared to 79% built just one year earlier. The shift in 2017 to the second most popular tower was to 95-meter (311 feet) towers, or 22% of towers in 2017. Recent National Renewable Energy Laboratory (NREL) research estimates that shifting hub heights from 80 meters to 140 meters could increase energy production in a range from 20% to 45%, depending on the wind profile at a specific wind plant. These heights are no longer a challenge for the wind industry and have become commonplace throughout Europe where land availability can be a challenge and wind speeds are

Taller towers require more copper cable. Example of a Nordex 2.4 MW wind turbine with 117-meter rotor mounted on a concrete and steel 141-meter hybrid tower (source: Nordex)

[2] US Wind Industry Annual Market Report Year Ending 2017, American Wind Energy Association

generally lower than in the US, so rotor diameters and tower heights are increasing along with turbine capacities. The latest battleground in the ever-tightening wind turbine market is with on-shore wind turbines in the 4 MW range, which until now has had very few offerings and only minor commercial deployments. No less than four turbine OEMs announced new 4 MW turbine models over the first two quarters of 2018. Taller towers factor prominently as part of the technology offerings:

- GE Renewable Energy announced its first turbine offering in the 4 MW range with a new 4.8 MW unit that features a 158-meter rotor enabled by carbon blades. Tower heights are 101-meters, 120.9-meters, 149-meters and 161-meters.
- Vestas upgraded and uprated its 3 MW range and added three models in the 4 MW range. Tower heights for its V136-3.45 MW turbine are 82 meters, 112 meters, 132 meters, 142 meters, and 149 meters.
- Nordex is uprating its 3 MW Delta series into a 4.0-4.5MW turbine with a 149-meter rotor for medium wind speeds. Steel towers come in 105 meters and 125 meter hub heights and concrete-hybrid towers offer hub heights of 145 and 164 meters.
- Germany's Enercon is rapidly evolving its 4MW class turbines. Its current EP4 turbines (4-4.2 MW) E-126 and E-141 turbines feature concrete-steel hybrid towers to enable a 159-meter hub height.

1.10.2 Aluminum Substitution by the Wind Industry as a Risk to Copper Demand

Substitution by aluminum is still a relatively minor issue in the US, although it is a threat in on-shore wind. The cost differential between copper and aluminum is seen as an emerging issue by some manufacturers. It has begun to affect copper usage intensity in some wind turbine manufacturer brands. For example, Vestas, which is essentially tied with Siemens Gamesa as the world's number largest manufacturer of wind turbines, has for several years now substituted aluminum for copper in step-up transformers. The supplier also moved the step-up transformers from the tower base to the nacelles, thereby transmitting high-voltage power — over smaller-gauge cables —to the ground-based collection grid, further reducing copper intensity.

Substitution by aluminum can be addressed with proactive promotion based on copper's known benefits of higher energy efficiency (reduction of energy losses) and assurance of long-term reliability. Aluminum is vulnerable here due to its lower strength, relaxation behavior and corrosion resistance. The downstream technical and economic risks associated with "value engineering" copper out of critical components are unknown. And, because the costs or repair, maintenance and downtime are known to be high in wind-energy plants, copper promotion based on reducing life-cycle costs through improved reliability and efficiency should be a worthwhile undertaking. Institutional promotion through the establishment of prudent codes, standards and recommended practices should is also recommended.

1.10.3 Effect on Copper Content of Higher MW Wind Turbine Capacities

The proven and unbroken trend is consistently to see slowly increasing wind turbine capacities, also named wind turbine nameplate ratings. For example, a 2.3 MW wind turbine from GE Renewable Energy was one of the more popular GE wind turbines installed in 2017. Similarly, the Vestas 2.0 MW wind turbine was the most installed by Vestas in the US in 2017. Average wind turbine nameplate sizes are provided in the following table (1000 kW = 1 MW).

Figure 1.3 Average Size of Wind Turbines (kW), Annual Installations 2012-2017, US and Canada

Year	Units	Canada	United States
2012	(kW)	1,921	1,930
2013	(kW)	2,077	1,841
2014	(kW)	2,065	1,970
2015	(kW)	2,177	2,056
2016	(kW)	2,763	2,141
2017	(kW)	3,087	2,371

(Source: World Wind Energy Market Update 2018, Navigant Research)

A question with regards to wind plant copper demand is whether the increase in wind turbine nameplate ratings, which results in fewer wind turbines for the same MW total wind plant capacity, results in less overall copper demand by wind plant. Intuition would suggest that with less wind turbines installed, the resulting less cable needed per towers and site cables would require less copper. Data is very difficult to access in this area because wind turbine OEMs are confidential in this area. However, some data made available from the largest wind turbine OEM, Vestas suggests that the increase in turbine nameplate ratings does not reduce total copper content required but rather increases it due to the copper content increase required for the larger wind turbine and associated subcomponents.

The following chart provides examples of the difference in copper content for a 100 MW wind plant using Vestas V110-2.0 (2 MW) wind turbines versus a 100 MW wind plant using Vestas V126-3.45 (3.45 MW) wind turbines. The results show that the difference in wind plant cabling and balance of plant copper use is negligible, but the wind turbine use increases despite there being fewer overall wind turbines to satisfy the overall 100 MW wind plant capacity. This is partly due to the greater copper needs for wind turbine generator, power converter, transformer, switchgear, and other turbine needs.

This is not to be taken as representative for all wind turbine makes and models, but it is one example from the world's largest wind turbine OEM that the increase in wind turbine nameplate capacities also may represent an overall increase in copper usage. This report's wind forecasts and related copper content estimations cannot account for these nameplate increases since data is so hard to come by, but this example suggests that copper content demand is not likely going to decrease as wind turbines increase nameplate rating and instead they are likely to increase copper demand. The total MW capacity deployed is still by far the largest factor in determining copper usage.

Figure 1.4 Higher Wind Turbine Nameplate Comparison for Copper Usage

Material Breakdown of 100 MW wind plant, Vestas V110-2.0 (2 MW)		Material Breakdown of 100 MW wind plant, Vestas V126-3.45 (3.45 MW)	Difference
Copper / Tonnes			
Turbines	64	188	124
Foundations	2	2	0
Site Cables	82	86	4
Site Switchgear	4	4	0
Site Transformer	22	16	-6
Total	**174**	**296**	**122**

(Source: Vestas, Navigant Research.)

Section 2
COPPER INTENSITY DATA

2.1 Copper Intensity Data Overview

Data on copper intensities were obtained by interviews with developers, designer-installers owners, and by visits to selected installations. This includes those visited for previous market- and case-studies. Data regarding offshore wind were obtained from technical literature, principally as related to offshore development in the UK. Other data were taken from information published for the Cape Wind site in Massachusetts and proposed development off Cape May in New Jersey.

2.2 Wind Plant Examples for Copper Usage Intensity

This report contains data on four operational and one design-stage US wind farm. This demonstrates that copper intensity ranges from 5,600 to 14,900 lbs./MW. The surprisingly large spread is attributable to the difference between copper- and aluminum-wound step-up transformers, furnished in turbines supplied by some suppliers.

The wind farms listed in the table are representative of current turbine designs, containing some newer wind turbine sizes presently installed in the market. Current wind turbine sizes include 2.0 MW, 2.1 MW, 3.0 MW and 3.6 MW. Of the just over 7 GW installed in the US in 2017, the average wind turbine size was 2.37 MW. This reflects a lot of turbines around the 2MW to 2.5 MW and a smaller proportion in the 3 MW+ size class. Canada's average is higher at 3.08 MW in 2017 based partly on developer preferences in the Canadian market.

The wind industry is capable of building much larger machines for the offshore sector but for the onshore sector, there are almost no installations globally of wind turbines above 5 MW in the onshore sector. The most competitive size range for the latest generation multi-MW machines for onshore is in the 4 MW range. A size spread has increasingly appeared between on and offshore. Turbines in the 3 to 5 MW range were previously commonly installed offshore in Europe. However, that pipeline of projects in development is increasingly moving to between 7 MW and 9.5 MW turbines. The larger the wind turbine, the fewer can be installed for the same total wind plant MW size, which lowers the overall project cost due to fewer foundations and the high offshore construction cost. The 9.5 MW V164 Vestas turbine is currently the largest wind turbine available, followed by Siemens Gamesa with its 8 MW SG 8.0-167 DD. GE Renewable Energy says it has committed to developing a 12 MW offshore turbine with a 220-meter rotor diameter.

Table 2-1. Copper Usage Intensity in Current-Generation US Wind Plants

Wind Plant	Meadow Lake, IN 99MW	100MW 50, 2.0MW Vestas (Designed	Rattlesnake Rd, OR 102.9MW	Meridian Way, OR 105MW	Lone Star, TX 400MW 200, 2MW

	66, 1.5MW Acciona	/ not built)	49, 2.1MW Suzlon	35, 3.0MW Vestas	Gamesa
Category	Copper, 1000s of pounds				
Power Cable Usage					
Within tower	443	84	789	59	257
Tower to pad transformer	37	20	35	20	79
Interconnecting wind turbines and to central wind plant step-up transformer	200	200	170	190	790
Ground W&C Usage	170	75	77	73	309
Turbine Usage	106	105	108	98	420
Turbine transformer usage	112	Al cast-coil	147	Al cast-coil	600, Cu cast-coil
Farm Step-up Transformer usage	45	45	55	40	155
Switchgear usage	132	120	138	98	480
Control Wire and Cable Usage	12	11	14	11	45
TOTAL	**1,257**	**660**	**1,533**	**589**	**3,135**
Copper Usage per Tower	19	13	31	17	16
Copper Usage Intensity, 1000s of lbs. per MW	12.7	6.6	14.9	5.6	7.8

(Source: Copper Development Association Inc, Navigant Research)

2.3 Offshore Wind Increases Copper Usage Intensity

In the absence of US offshore wind facilities or sufficiently advanced design parameters for proposed facilities, a literature search was conducted on European and UK offshore wind designs under the assumptions that a future US offshore wind market would be reasonably similar. To this end, a well-researched study of copper usage in British and some European offshore wind farms provided evidence that copper usage intensity per MW should be considerably larger than that in US onshore farms. UK developers guard specific design details more carefully than do the US counterparts that supplied the data shown in Table 2-1 therefore, certain assumptions based on published standards had to be made for the facilities studied. Separately published life-cycle analyses provided additional data.

Based on various sources, copper intensity in generators was rated at 792 lbs./MW. This value corresponds reasonably well with copper intensity in large industrial motors (approx. 1 lb/kW or 1000 lbs./MW). Usage intensity in transformers was given as 2,200 lbs./MW, cabling within the turbine and tower as 673 lbs./MW and copper in gearboxes as 174 lbs./MW.

It was reported that, on average, offshore wind farms require 21,076 lbs./MW installed, an intensity that exceeds the largest value reported in Table 1 by more than 41%. Of the total copper reported for UK offshore turbines, 3,850 lbs. are contained in the turbine generator and its transformer and 13,310 lbs. in the cabling between the turbine and the substation. All farm step-up transformers included in the report were 100% copper wound, as they were large MVA units (manufacturers indicate that transformers above approximately 20 MVA are all-copper); however, the smaller step-up transformers utilized with each wind tower, for example, utilized aluminum in some coils on some farms (usually with low or no efficiency specification) while other farms specified higher efficiencies and/or all-copper transformers, including those not studied but included for projections.

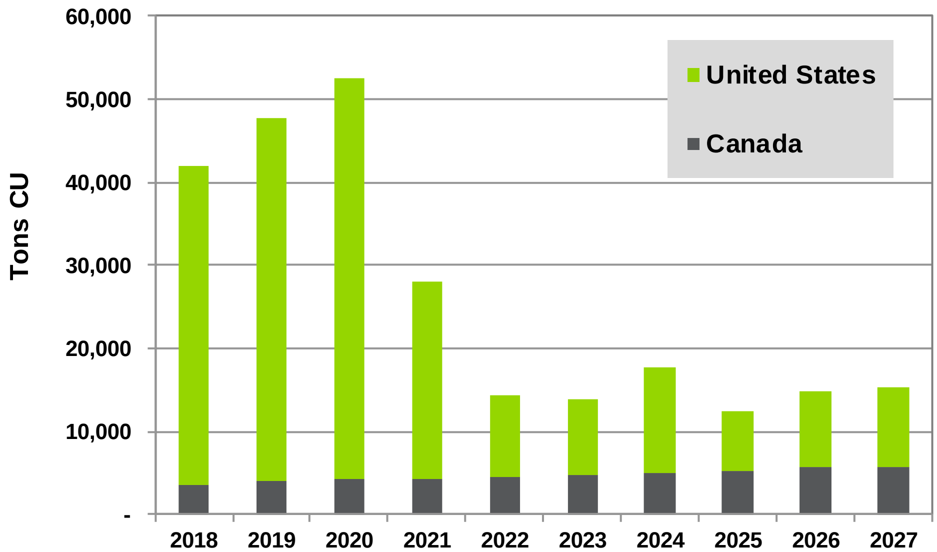
Estimates of copper used to connect to the onshore grid were based on several lifecycle analyses conducted on European offshore farms. The grid interconnection was found to consume, on average, 25,168 lbs. per turbine or 7,766 lbs./MW of nameplate rating. Cabling was found to account for 82% of total copper usage in offshore wind farms or 16,346 lbs./MW. Interestingly, the author concluded that (given the average 2008 price for copper) that metal cost constituted only 3.4% of the total installed cost. This compares favorably with an informal estimate of 3.8% made for this study based on onshore wind farms. Industry sources indicate that copper intensities are expected to be similar to the current European and UK experience, upon which the data cited above were based.

Section 3

RESULTS OF COPPER DEMAND AND FORECAST ANALYSIS

3.1 Summary of findings

Chart 3.1 Copper Demand, Base Case, Onshore North America



(Source: Navigant Research)

3.1.1 Summary Assumptions and Insights on the US Wind Market Forecast

Many particulars to a wind plant such turbine size, wind plant size, if aluminum is substituted for copper in any application, which components are imported, etc. all play a role in adjusting how much copper is needed in a given market. However, the far greater determinant of copper usage is the MW capacity installation in a given market. Navigant Research analyzes all global wind markets and pays especially close attention to the United States since it is Navigant's home market and it is the second largest wind market globally. Copper demand for the US wind market will therefore track closely the MW installation rates. Chart 3.1 shows copper tons needed to satisfy the expected build cycle during the current 10-year forecast 2018-2027. The unusual spike in the near term followed by a rapid deceleration deserves specific explanation.

The United States is in the middle of a large wind plant construction boom driven by the extension in 2015 of the Production Tax Credit (PTC), which provides 2.4 cents per kilowatt hour ($24/MWh) for 10-years. A political compromise was struck in 2015 on the tax credits whereby the wind industry agreed to let the tax subsidy policy phase out in exchange for a long step-down phaseout period from 2016 through 2019, which provides stability to the market for the next few years. The wind industry felt this was preferable to the uncertainty of the typical on and off again yearly cycles that have plagued this policy over the years. There is a mostly consensus view in the wind industry in the United States that toward the end of the phaseout period (2019-2023), wind will be cost-competitive against other fuel sources, so it will no longer need the tax credit subsidies. Current LCOE comparisons suggest wind is already cost-competitive against other power plants in areas with good wind resources, which is much of the central US corridor running from Texas through the Great Plains and upper Midwest.

The PTC was secured from 2016 through 2019 in exchange for allowing its value to drop. Wind plants that began construction by the end of 2016 or achieve “safe harbor” with a minimal 5% investment in project capital will receive 100% tax credit value once the project is commissioned. After 2016, the tax credits were reduced to 80% of their value in 2017 construction starts, 60% for 2018, and 40% in 2019, and zero by 2020. What is most helpful to wind developers is that for each of those PTC years, wind plants have 4 years to complete construction. For example, projects that started in 2016 (100% PTC value) will have until 2020 to complete construction. That explains why year 2020 is the year of peak capacity with over 10 GW expected to come online. Projects that started in 2017 (80% PTC value) have until 2021 to finish construction. Projects starting in 2018 (60% PTC value) will have until 2022. The last year that projects could start construction is in 2019 for 40% PTC value, and they must be completed by 2023. While wind plants could theoretically start construction during the later stages of this PTC phaseout, the reality is that slightly less than half of projects installed by 2020 will be commissioned under a 100% PTC scenario. Exact numbers are unknown, but a very large amount of capacity qualified in 2016 for 100% PTC value through safe harbor because meeting the 5% spending level is relatively easy. For some companies, this involved a deposit on one or more wind turbines or large balance of plant equipment such as step-up transformers.

3.1.2 Summary Assumptions and Insights on the Canada Wind Market Forecast

Canada’s wind market will play a relatively negligible role in copper content usage by the wind power industry due to its low installations rates relative to the much larger US market. There has been a drop in Canada’s wind market in recent years. It is likely to stabilize and begin to notch upwards as activity in the windy province of Alberta picks up. Canada saw 341 MW installed in 2017, down from 702 MW installed in 2016. In its peak year of installations in 2014 Canada saw 1,871 MW installed. The downturn in more recent years is due to the removal of Ontario’s Feed-in-Tariff (FIT) program. Alberta is the next growth engine for wind in Canada. The province implemented a new series of competitive power contract auctions to source up to 5 GW of new renewables capacity, and with most of that coming from wind. The first auction was held in December of 2017 and procured 600 MW for an average C$37/MWh ($28.70/MWh) for wind plants feeding the grid by the end of 2019. Two more rounds for 2018 are on the way with a first 300 MW Round 2 and 400 MW Round 3. Some growth will continue in Ontario and Quebec, and a small amount of additional capacity will be installed in the other provinces. The forecast for Canada expects just over 10,000 MW installed over through the 10-year forecast period. This compares to the 48,721 MW expected to be installed by the US.

3.1.3 Wind Market Copper Content Demand, North America

3.1.3.1 Wind Market Copper Content Demand, United States

Navigant Research is forecasting 48,721 MW (48,7 GW) to be installed between 2018 and 2027 in the US. This is based on analysis of wind plants listed as under construction and an increase in the capacity of safe harbored wind plant expenditures. Based on an analysis of PTC deadlines and construction patterns, Navigant projects that 8-10 GW/year of wind projects will be installed in 2018-2020 and with year 2020 the peak installation year expected to surpass 10 GW.

For the purposes of determining copper demand, the North America forecast is split between the United States and Canada. Within both countries, the forecast is split between on and offshore because the copper content assumptions for offshore are significantly higher per MW at approximately 10.54 tons per MW versus 4.76 tons per MW for onshore base case. No offshore wind capacity is expected in Canada. In the US, some offshore wind capacity will start to be added but at levels that are very low relative to onshore capacities.

That rate of installation is what drives the copper content usage forecast, exhibiting current high volume of 38,453 tons in the US in 2018 and peaking in 2020 with 48,358 tons. Levels decrease sharply thereafter dropping to 23,763 tons in 2021 and then leveling off at an average of 9,579 tons per year through the remained of the forecast to 2027. This is using the base-case assumption of 4.76 tons/MW, which is the average of the copper intensity data for the five wind plant examples used in this study.

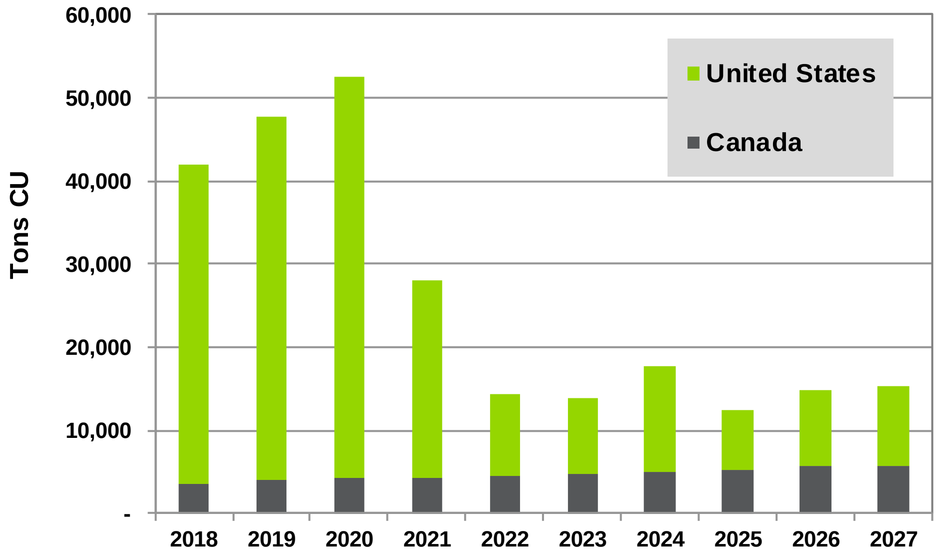
The onshore low-case, which is the lower end of the copper usage range witnessed in the five researched example projects, is 2.8 tons per MW and driven by wind turbine vendors that substitute aluminum in some parts such the turbine step-up transformer and some of the downtower cabling. Charts and tables are also provided for the onshore high-case, which reflects the high end of the copper usage range witnessed in the researched example wind plants. This level is 7.45 tons/MW and is charted to show a range of copper demand but is unlikely to be close to the true market estimate.

3.1.3.2 Wind Market Copper Content Demand, United States

Canada's wind market will play a relatively negligible role in copper content usage by the wind power industry due to its low installations rates relative to the much larger US market. The forecast for Canada expects just over 10,000 MW installed through the 10-year forecast period. This compares to the 48,721 MW expected to be installed by the US. Canada's wind market will also see no offshore wind installed during the forecast period. Canada's base case scenario assuming 4.76 tons/MW represents 3,570 tons of copper in

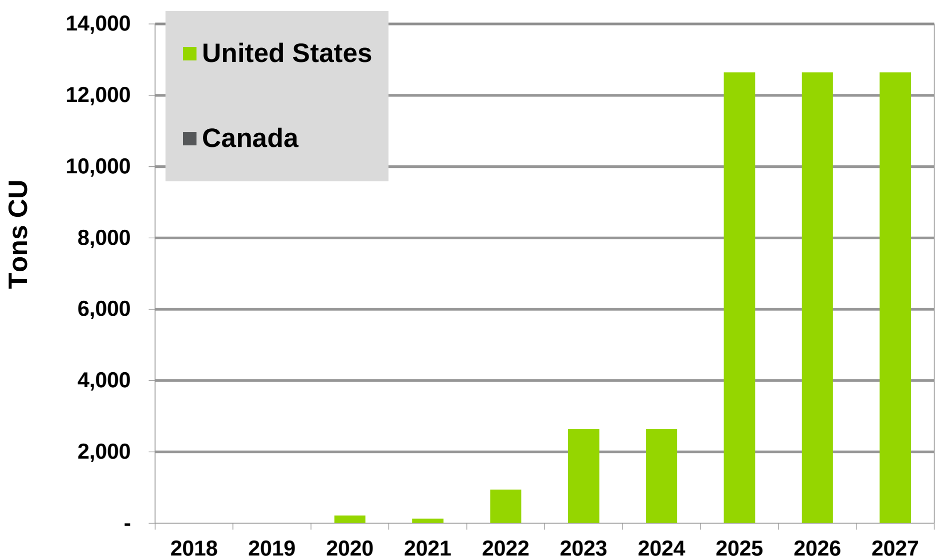
2018 and growing at minor CAGR of 5.5% through the forecast period to reach 5,760 tons in 2027. Overall average through the 10-year forecast period is 4,761 tons/annually.

Chart 3.2 Copper Demand, Base Case, Onshore North America



(Source: Navigant Research)

Chart 3.3 Copper Demand, Offshore Base Case



(Source: Navigant Research)

3.2 Conclusions and recommendations

Navigant Research is forecasting 48.7 GW to be installed between 2018 and 2027 in the US. Navigant projects that 8-10 GW/year of wind projects will be installed in 2018-2020 and with year 2020 the peak installation year expected to surpass 10 GW. Current copper demand levels are at an estimated 38,453 tons in the US in 2018 and peaking in 2020 with 48,358 tons. Levels decrease sharply thereafter dropping to 23,763 tons in 2021 and then leveling off at an average of 9,579 tons per year through the remainder of the forecast to 2027.

Canada's wind market will play a relatively negligible role in copper content usage by the wind power industry due to its low installations rates relative to the much larger US market. The forecast for Canada expects just over 10,000 MW installed over through the 10-year forecast period and some of the wind turbine supply chain will be sourced from the US. Canada's base case scenario assuming 4.76 tons/MW represents 3,570 tons of copper in 2018 and growing at minor CAGR of 5.5% through the forecast period to reach 5,760 tons in 2027.

The reasons for the drop-off in the US market is that the industry is in the early to mid-stages of a major acceleration in wind plant construction expected to peak in year 2020 as tax credits are slowly phased out and their value reduced each year, with 2023 the last year that wind plants are eligible for reduced level tax credits. Since copper usage is so closely tied to the MW installation rate, the reality is that the wind market is not a growth market and will in fact decelerate by -14.4% CAGR through the 2018 to 2027 forecast period.

However, the US remains a very large market in quantity for copper even if growth rates accelerate into 2020 and then taper off. Some copper and copper-enabled components will be imported but most copper will be sourced in North America to be proximate to the highly developed supply chain in the US wind market. Even with a deceleration through the forecast period, the wind power industry is here to stay as technology advances and reductions in cost have made it increasingly competitive with other generation sources. Wind energy will be a key part of the US and Canadian electricity generation markets and copper will play an indispensable material role to enable this technology and marketplace now and in the foreseeable future.

Section 4

ACRONYM AND ABBREVIATION LIST

BOP .... Balance of Plant

C&I .... Commercial and Industrial

CAGR .... Compound Annual Growth Rate

DLO .... Diesel Locomotive (cable)

CDA .... Copper Development Association

DG .... Distributed Generation

FIT .... Feed-In Tariff

GW .... Gigawatt

kW .... Kilowatt

kWh .... Kilowatt-Hour

LCOE .... Levelized Cost of Energy

MW .... Megawatt

MWh .... Megawatt-Hour

OEM .... Original Equipment Manufacturers

PPA .... Power Purchase Agreement

PTC .... Production Tax Credit

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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. This report builds upon research previously conducted by the Copper Development Association, including detailed analysis of copper intensity used in the various hardware subcategories of a typical wind plant. Numerous aspects of copper usage at wind plants that has been previously described in other CDA reports and insights is included in this report where the content is still accurate and applicable to today's wind market.

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.

Published 3Q 2018

1375 Walnut Street, Suite 100
Boulder, CO 80302 USA
Tel: +1.303.997.7609
http://www.navigantresearch.com