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The Asia Pacific renewable supply chain opportunity

Unbundling the value in solar and offshore wind

Grant Hauber, Strategic Energy Finance Advisor, Asia

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Key Findings

The potential for solar photovoltaic (PV) and offshore wind supply chain investments in Asia Pacific presents a US$1.1 trillion opportunity to 2050, of which 75% would be spent on and remain within the countries undertaking these projects.

Solar PV power projects represent the "here and now" opportunity to capitalize on the supply chain, with US$346 billion of potential localized inputs out of US$395 billion of investment through 2050.

Offshore wind is a core growth sector in the Asia Pacific, with US$425 billion of localization potential on US$621 billion of total investment, and shipbuilding opportunities of up to $97 billion to 2050.

Governments looking to tap into the clean energy supply chain need to look beyond panels and turbines. Balance of systems for solar and offshore wind represent 75% and 68%, respectively, of total spend on projects. That is where the greatest business opportunity is for domestic suppliers, manufacturers, and contractors, starting now and running over the next 25 years.

Executive Summary

The Asia Pacific region possesses vast, untapped potential for renewable energy, particularly in solar and wind resources. Harnessing this potential could transform the region's energy economy. There are gigawatts of projects looking for investment with development activities stretching over decades. This sustained regional investment opportunity could potentially drive the development of regional and domestic renewable energy supply chains as core businesses.

This report focuses on two energy transition sectors: solar photovoltaic (PV) projects and offshore wind farms.

Solar PV offers the "here-and-now" opportunity – it already represents the lowest marginal cost of electricity generation globally, with overall prices continuing to decline. This creates an immediate opportunity for governments to achieve dual targets of decarbonizing their grids while providing their consumers with the lowest cost of power.

Offshore wind offers the potential for reliable, predictable, large-scale renewable energy supply. While currently nascent in the Asia Pacific, it represents a promising evolving opportunity over the coming years. Global evidence shows offshore wind rapidly declining in costs with larger scale implementation. Further, wind can complement solar generation, as wind typically produces the most power at night.

Together, solar and offshore wind could significantly contribute to regional energy transition efforts, creating substantial large-scale economic opportunities.

Investments could reach hundreds of billions of dollars over the next twenty-five years, with a large proportion of those capital flows supporting domestic manufacturing, supply, and service sectors. Governments across the region are already contemplating how to capture that value and keep it onshore.

Policymakers, when considering solar and wind energy supply chains, often focus on the most symbolic components of generation facilities: solar PV panels and wind turbines. They are the most visible and seemingly obvious focus for "green technology" investment.

While these are attractive symbols of the sustainable energy transition, the supply chain for solar and wind energy extends far beyond these components. It includes materials, fabrications, infrastructure, logistics, and services that are needed to deliver fully functioning energy projects. These inputs can provide great value to the domestic economy over decades.

Some of these elements are advanced green technology in themselves, while others are more commonplace materials and services. All are essential and some inputs can be equally or even more valuable than the technology they support. Understanding their scope and value is essential to maximizing the renewable energy opportunity.

Beyond solar PV modules, the solar energy supply chain comprises numerous components such as electrical equipment, racking and tracking systems, controls, construction contracting, testing, and operations services.

Offshore wind requires fabricating out of raw steel foundations and towers, creating forgings and fittings, constructing transmission substations, and laying undersea cables between them. These components and fabrications must be lifted, shipped, and installed, requiring fleets of ocean-going vessels equipped with some of the world's largest marine lifting and portside equipment. Additionally, robust port facilities and manufacturing shops are required to support these operations. All of these are supply chain components that complement wind turbines.

When developing national renewable energy technology strategies, countries would benefit from looking beyond panels and turbines. These high-tech components, although crucial, require significant investments, face high competition and low margins.

> **When plotting national renewable energy technology strategies, countries would benefit from looking beyond panels and turbines.**

Nowhere is this more evident than in the Chinese solar supply chain, where China dominates the process of converting raw silica into PV modules. The country produces 83% of the world's polysilicon, 97% of wafers, 83% of cells, and 72% of modules. Additionally, China has over 100% excess manufacturing capacity, sufficient to supply double the projected global demand into the next decade.

For countries attempting to break into the PV market, China's dominance is an extreme challenge. Currently, markets looking to compete with China are producing outputs that are anywhere from 20% to 200% more expensive; meanwhile, China's costs are further dropping while those of other countries are remaining stagnant or are rising.

In contrast, the non-panel, non-turbine supply chain, offers more opportunities. Many of these "balance of system," or BoS, components and services are best provided locally and represent the majority of investment costs in a solar PV project or wind farm.

In solar PV, BoS components account for 60% to 72% of total investment, while in offshore wind farms, they represent about 58% to 68%. These localized costs are typically shared amongst manufacturers, suppliers and service providers, instead of going to a single company. This creates the potential for broader distribution of economic benefits.

Size of the Opportunity

The order-of-magnitude assessments undertaken for this report estimate that from 2025 to 2050, the Asia Pacific region has a combined investment potential of US$1.1 trillion in solar PV and offshore wind energy, creating a potential 873 gigawatts (GW) of clean energy. Of that, US$394 billion supports solar PV projects totaling 634 GW and US$621 billion helps construct 239 GW of offshore wind farms.

Local supply chain development represents the bulk of this opportunity. Over the period 2025 to 2050, 72% of solar PV investment (US$

billion) and 68% of offshore wind investment (US$425 billion) are projected to use local materials, manufacturing, and service providers. In the offshore wind sector, which uses fleets of installation, construction and maintenance vessels, another US$72 to US$97 billion for new fleet construction to 2050 may be required. This will be a boon to regional shipbuilders and to the maritime economies that support and maintain these fleets.

Table 1: Summary of Solar PV and Offshore Wind Supply Chain Potential 2025 to 2050 (USD Billions)

	2025 - 2030				2031 - 2050				Total to 2050			
Investment	Ex-region	Regional	Local	Total	Ex-region	Regional	Local	Total	Ex-region	Regional	Local	Total
Solar PV	$ 2.0	$ 24.9	$ 60.8	**$ 87.7**	$ -	$ 21.6	$ 285.3	**$ 307.0**	$ 2.0	$ 46.6	$ 346.1	**$ 394.6**
Offshore Wind	$ 27.7	$ 14.9	$ 33.7	**$ 76.3**	$ 30.3	$123.5	$ 391.0	**$544.8**	$ 58.0	$ 138.4	$ 424.8	**$ 621.2**
Totals	$ 29.7	$ 39.8	$ 94.5	**$164.0**	$ 29.7	$145.2	$ 676.4	**$ 851.8**	$ 6..0	$ 185.0	$ 770.9	**$1,015.8**
Vessels	**$41.4**				**$56.1**				**$97.5**			
Total	$205				$908				$1,113			
Capacity												
Solar PV	197 GW				437 GW				634 GW			
Offshore Wind	27 GW				212 GW				239 GW			
Totals	223 GW				650 GW				873 GW			

Source: IEEFA estimates.

The estimates in this report are based on nationally announced plans for renewable energy capacity additions over the period to 2030 and onward to 2050. There are varying degrees of policy support and market readiness for implementation. Projects already underway within national frameworks were counted toward near-term 2030 goals. Where programs have yet to be implemented, practical assumptions about timing toward first implementation were made, pushing start dates out. By 2050, it is assumed that these plans will be achieved.

National plans vary, with some being ambitious and others conservative. Collectively, these differences balance out, making the aggregate figures reflect a more average attainment. With continued cost drops and increased experience, there is potential for these plans to evolve.

For example, Indonesia has very modest short-term additions in solar, while Japan has very ambitious goals. Taiwan is already implementing its offshore wind program, whereas other countries are either at a very small scale or yet to begin. Yet all countries in the region can benefit from empirical evidence from their neighbors on what works, what does not, and the associated costs. Offshore wind, in particular, benefits from a regional supply chain sourcing strategy in its early implementation stages. Eventually, some of those components and systems may be better produced locally, but in the meantime, the supply chain can learn and mature.

Taken together, solar PV in the near term and offshore wind in the medium to long term are tremendous growth businesses. The supply chain inputs to solar and wind projects in the Asia Pacific through 2050 are estimated to be worth US$185 billion regionally and US$770 billion in potential localized national sourcing. Additionally, another US$72 billion to US$97 billion needs to be invested in marine vessels to support offshore wind.

These estimates are based on current government policies on targeted capacity additions and current studies using supply chain cost trajectories. If overall lifecycle costs further decrease as predicted, these forms of energy will become even more economically advantageous. With the potential to grow localized solar and wind supply chain content over time, there is a strong incentive for governments and businesses to pursue these industries.

Introduction

Renewable energy technology has experienced a dramatic reduction in the lifecycle cost of energy produced. Solar PV and wind power generation technologies are now among the least expensive energy sources, often cheaper than the lowest-cost fossil fuels.[1]

In 2023, both the International Energy Agency (IEA) in its Annual Energy Outlook and the Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR-6) declared that ramping up the adoption of basic renewable energy is the primary means for the world to achieve rapid and economic decarbonization, in concert with electrification, energy efficiency and methane leak reduction.[2] As a result, and with consensus agreements calling for a global tripling of installed renewable energy capacity arising from the 28th Conference of Parties (COP28) under the United Nations Framework Convention on Climate Change (UNFCCC), the stage is set for PV and wind technologies to experience explosive growth over the coming decade and beyond.[3]

Responding to this call, most governments have set decarbonization targets to 2030 and then further out to 2050. These reflect the goals and expectations set under the 2015 Paris Climate Agreement and the resulting Nationally Determined Contributions (NDCs) each country defined. Countries have translated their NDCs into national energy sector development plans, which include significant targets for renewable energy, and the majority of which foresee large contributions from solar PV and wind energy. Most countries have set renewable capacity addition targets, while select others have set targets for renewable energy generation as a proportion of total supply.

The need for truly zero-emission energy, coupled with the prodigious cost decline of clean energy technology, offers unparalleled investment and employment opportunities across the Asia Pacific energy manufacturing, construction, and power generation markets. More significantly, it can deliver energy to economies in a stable, predictable and low-cost manner. This is the definition of a win-win outcome.

If a government's goal is to minimize the cost of energy to the economy and society, then right now is the best time in history to deliver on that vision. In the solar PV sector, with a glut of Chinese-produced panels flooding global markets and their industry in an overcapacity situation, it is a buyer's market. If governments in the Asia Pacific can implement policy mechanisms that incentivize the mass development of solar power farms and wind installations, they could lock in long-term, very low marginal costs of electricity for the next decade and beyond.

But what if a country wants to take its place amongst the club of global green technology manufacturers? What if a country wants to maximize the domestic content contribution of green technology to its renewable energy farms? Is there any possibility of competing efficiently and economically with China? Are countries fated to ceding investment monies to foreign suppliers?

[1] EY. If every energy transition is different, which course will accelerate yours?. December, 2023.
[2] International Energy Agency (IEA). World Energy Outlook 2023. October 23, 2023.
Intergovernmental Panel on Climate Change. AR-6 Synthesis Report on Climate Change 2023. March 2023.
[3] United Nations Framework Convention on Climate Change. Conference of Parties First Global Stocktake Decision, paragraph 28. December 13, 2023.

Must they be resigned to paying higher costs for energy if they wish to reserve the green market for higher-cost domestic players? Is there some sort of middle ground where these costs and benefits can be shared? How can domestic companies, investors and labor benefit directly from the green revolution and keep a good portion of that money onshore?

Seizing the "Now Opportunity" and Building for the Future

This report focuses on the opportunity of two renewable energy technology applications: solar PV farms and offshore wind farms. The report seeks to comprehensively scope the nature of the supply chain opportunity, disaggregate it into its constituent components, and quantify it.

Scoping identifies the most advantageous elements of the solar and offshore wind supply chains to focus on to maximize the economic benefit within each economy in this study. Quantifying aggregates the potential cash flow to businesses participating in the supply chain.

The report focuses on the high-potential combined solar and wind markets of the Asia Pacific: Japan, South Korea, Malaysia, Taiwan, Vietnam, the Philippines, and Indonesia. These are traditional maritime economies, which have inherent industrial and economic resources dedicated toward offshore opportunities that could be adapted for offshore wind. Nearly all are endowed with good to excellent solar resources.[4]

Solar PV projects offer a here-and-now opportunity. Little technology development is required to maximize the benefit of their deployment today. However, solar performance continues to improve. Evolving solar technologies are increasing their output per square meter, while using less polysilicon, leading to a further drop in unit costs. Design, procurement and construction of solar projects can be done in a matter of months, with generation phased in as portions of a solar project are completed, helping deliver immediate benefits to the grid.

Offshore wind farms represent the future of large-scale sustainable energy. Operationally, consistent wind resources available offshore hold the potential to provide highly reliable energy supply, often at times of day complementary to solar. Developmentally, the scale of offshore wind supply chains creates a large and sustained investment and employment opportunities.

First-mover wind pioneers in Europe and China have worked to rapidly drop unit costs while solving manufacturing and installation challenges. The offshore wind industry will see further cost drops, potentially similar in magnitude to those seen in solar energy. Asia Pacific countries are maritime-oriented economies, most of which are endowed with excellent offshore wind resources, are in a perfect position to ramp up supply chain participation and seize their share of this generational opportunity.

[4] Note that Malaysia is included in the solar PV supply chain assessment but excluded from the offshore wind segment in light of limited offshore wind resources and an absence of government plans to pursue the sector.

Transition Timing: Near-Term and Evolving Opportunities

Solar PV and its supply chain are an immediate opportunity. Countries seeking to lean into the deployment of solar energy can do so within the year if they choose. Solar represents an immediate opportunity for countries to reduce their cost of energy, almost universally undercutting the cost of the fossil-fueled equivalent. At the same time, they can grow domestic businesses and services supporting the green energy market at great scale.

With solar PV technology experiencing an ongoing evolution – higher sunlight conversion efficiencies and optimized manufacturing processes – there is a near-term promise of delivered energy costs decreasing even further. These conditions create an immediate opportunity to deploy solar energy services at all scales – utility, commercial, residential – from large-scale farms down to individual consumer applications, whether through public auctions or private developments.

Solar, by its nature, operates during the peak hours of the day when demand is the highest in most Asia Pacific economies. In large quantities, solar can offset the need for expensive, fossil-fueled peak-load generation, creating immediate economic benefits. The distributed nature of solar supply inputs, depending on where they are connected to the grid, can even contribute to greater system stability.[5,6]

Solar panels have become commoditized. The falling costs of PV panels mean that the remaining costs for implementing a solar farm, or balance of system costs, are of greater importance.

As this report demonstrates, balance of system costs, depending on the market where the project is being implemented, can account for 65% to 90% of the cost of a solar farm. Taking advantage of the low-cost solar opportunity thus becomes a matter of how projects are designed and implemented domestically. The future of low cost clean energy is in each country’s hands; governments can create the conditions to maximize that benefit at the least cost.

Offshore wind is a rapidly evolving, medium-term prospect for large-scale energy generation. Offshore wind encompasses an array of available, accessible technology elements that must be efficiently brought together to achieve cost-effectiveness. To achieve scale economy from offshore wind supply chains, projects must be implemented at large scale. Achieving that requires a range of up-front investments in port infrastructure, manufacturing facilities, marine vessels, and human resources. However, the prospective payoffs from those investments are large and decades in duration. Policy frameworks, preliminary investments and good planning are needed to implement it effectively.

There are two aspects of offshore wind farms that hold potential value: their value as substantial energy sources and the economic value of the goods and services that go into them.

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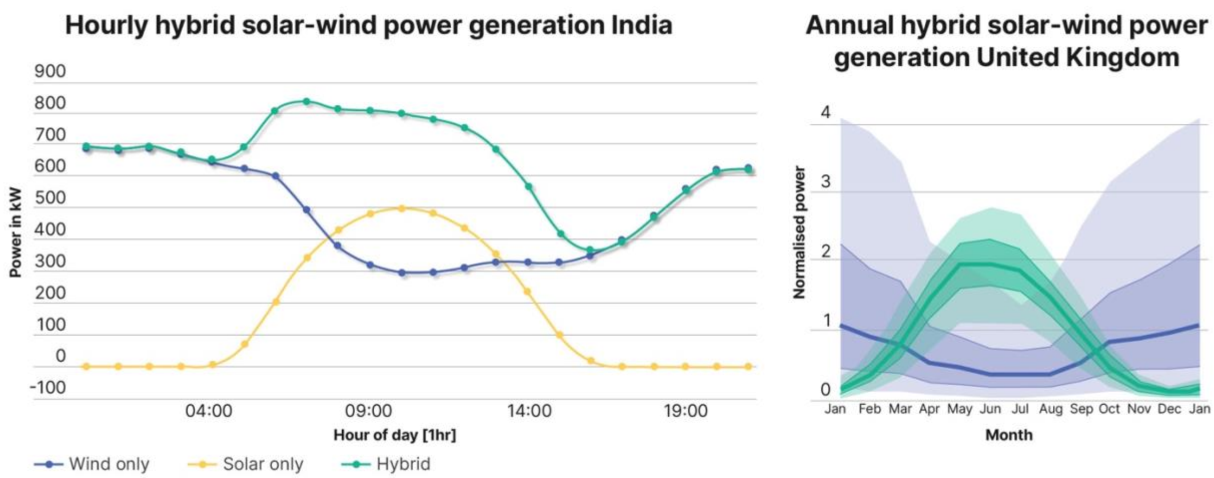
[5] National Renewable Energy Laboratory. Grid-integrated distributed solar: addressing challenges for operations and planning. March 2016.
[6] Wood Mackenzie. Tiny drops create mighty oceans: how distributed solar keeps the Puerto Rico grid afloat. March 12, 2024.

Firstly, as an energy resource, offshore wind has the potential to provide complementary and sustained energy supply at hours of the day when solar power is not available and/or at times of the year when solar irradiance may be diminished.

In most regions of the world, offshore wind resources have prominence at night, counterbalancing the daytime solar availability. Wind and sun also show seasonal counterbalances across the year. While resources in a given location need to be verified through measurement, this general principle of complementarity can be leveraged to provide large quantities of predictably firm power from renewable energy sources, year-round. A number of studies globally have demonstrated this complementarity, two samples of which covering hourly and annually are shown in Figure 1.

Figure 1: Wind-Solar Complementarity



Sources: Left: Agarwal, V.K. et al. Wind-Solar Hybrid System – An Innovative and Smart Approach to Augment Renewable Generation and Moderate Variability to the Grid. IEEE 7th Power India International Conference. November 2016. Right: Bett, P and Thornton, H. The climatological relationships between wind and solar energy supply in Britain. Renewable Energy, Volume 87, Part 1. March 2016.

Business-wise, offshore wind is a potential boon to domestic maritime economies because it requires a wide variety of suppliers and service providers, marine vessels and the operating services that accompany them, components, and equipment, delivered both onshore and offshore. Given the massive scale of the equipment and infrastructure involved, being in reasonable physical proximity to their installation location can offer significant benefits. In the Asia Pacific, the near limitless availability of offshore wind resources, coupled with steadily decreasing costs, mean that this industry may be one that can be sustained for decades to come.

While domestic supply chains for offshore wind may take time and effort to evolve, they benefit from being based on known, available technology. It involves steel fabrications, marine logistics, component integration, and project management, aspects of which can be directly borrowed from the offshore oil and gas industry.

Taking advantage of the offshore wind opportunity foremost comes down to a political economic decision: whether or not to pursue it, rather than whether or not the science and engineering behind it will work.

This paper estimates the order of magnitude of the upstream supply chain investment and downstream project application opportunities presented by solar PV and offshore wind projects in key Asian markets.

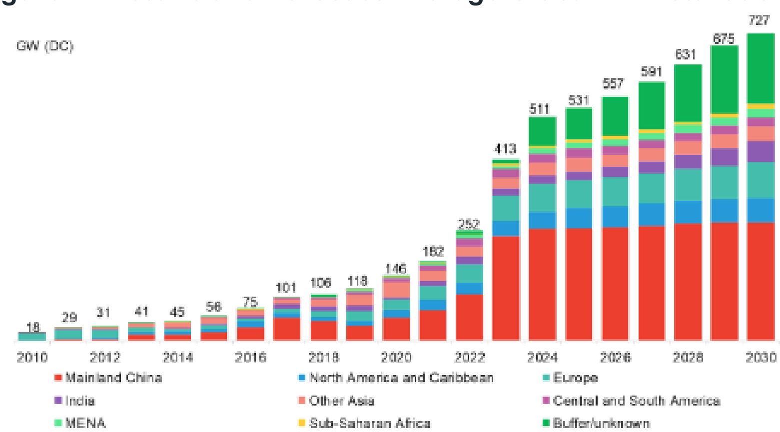
We first present an overview of the PV and offshore wind supply chains, reviewing key inputs, components and services that lead to an installed and operating electricity production facility. Based on an array of research reports and industry projections, we then determine the potential for each solar PV and offshore wind energy technology in core countries in the Asia Pacific. From these potentials, we assess what proportion of those installations could be sourced domestically in each country projects are being implemented, which elements could be sourced regionally amongst core players in the supply chain, and which components would likely have to be sourced from key countries of manufacture outside the Asia Pacific.

The aim is to not only demonstrate the substantial value of downstream investment in power generation. Equally importantly, Asian investors and constituencies can benefit from long-term employment in the green technology sector brought by the upstream manufacturing, fabrication, supply and logistics opportunities. However, as this report will demonstrate, the bulk of the value of this opportunity comes from products and services *other than* solar modules and wind turbines.

Solar Photovoltaic

Globally, the aggregate solar photovoltaic market exceeded US$320 billion in new investment in 2022, accounting for 45% of all electricity sector investment.[7] Between 2022 and 2023, solar additions grew an incredible 64%, jumping from 252 GW to 413 GW. Over 500 GW of installations are projected for 2024, another 20% year-on-year growth.[8] While 2023's growth rate was exceptional, a more conservative view of future demand growth, 5%-6% annually, will still see the world adding over 500 GW annually for the foreseeable future.

Figure 2: Historic and Forecast Average Global PV Installations

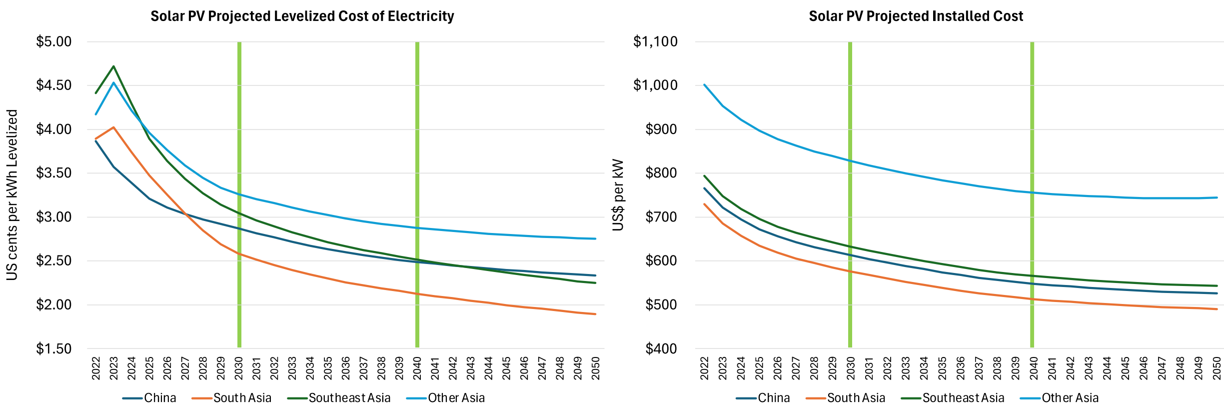


Source: Bloomberg NEF. Global PV Market Outlook, 4Q 2023. November 29, 2023. MENA = Middle East and North Africa.

The global uptake in solar PV energy has been driven by a precipitous drop in solar PV costs across all aspects of the production value chain. Between 2010 and 2020, PV panel costs dropped 89%. Since 2020, panel prices have dropped a further 42%. As a result, the average global levelized cost of electricity (LCOE) made from those panels has reached US$40-45 per MWh. At this level, on a lifecycle basis, solar is the cheapest source of electricity in almost every market worldwide. Further, input costs for PV panels are continuing to fall. S&P projects that LCOE is heading towards a range of US$25 to $28 per MWh by 2028.

[7] International Energy Agency. Solar PV.
[8] S&P Global. Over 500 GW of solar PV installations globally in 2024, with robust demand from mainland China. February 26, 2024.

Figure 3: Solar PV Historic and Forecast LCOE and Installed Cost



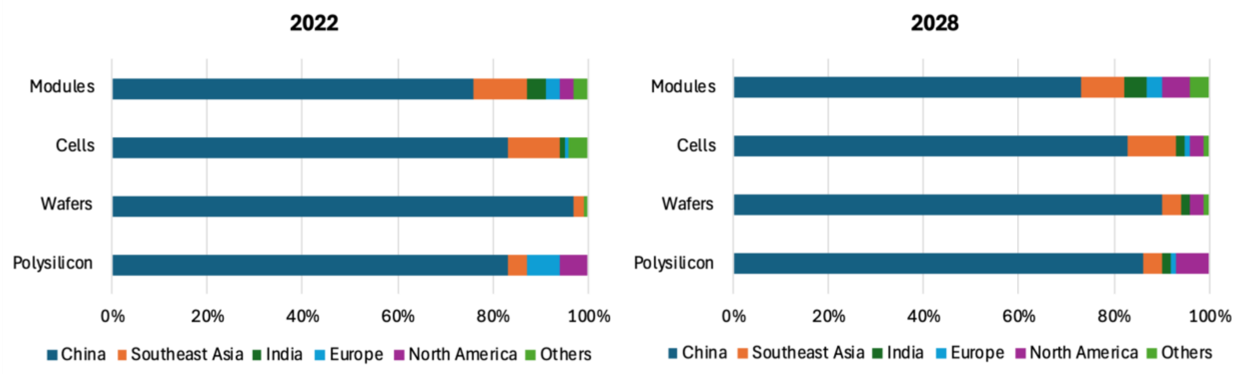
Source: Data adapted from DNV. Energy Transition Outlook 2023. October 11, 2023.

Governments in many countries want to claim a share of the upstream market in the solar PV manufacturing sector. Green tech is seen as “hot” and for many governments, having a manufacturing base in their country could be perceived as placing them at the cutting edge of the revolution, whether economically or psychologically. Given the global demand growth cited above, it would seem possible that many countries could get a share of the pie. There is only one major challenge to that thinking: China.

China dominates the global supply chain for solar PV, with a vertically integrated industrial complex that converts raw silica sources into panels ready for installation. A 2023 report from the Sustainable Energy for All coalition showed how panel production costs in both existing and hypothetical new-build manufacturing capacity in Southeast Asia would be 15% to 35% higher than in China.[9] However, that report was using 2022 data; since the report was published, Chinese panel prices have dropped by more than 50%, thus putting Southeast Asian costs in the range of 25% to 50% above China. With gigawatts of new manufacturing capacity coming online using the latest, most efficient PV production technology, China is expected to continue to dominate global PV supplies.

[9] Asian Development Bank, Bloomberg Philanthropies, ClimateWorks Foundation and Sustainable Energy for All. Renewable Energy Manufacturing Opportunities for Southeast Asia. August 2023.

Figure 4: Projected Share of PV Value Chain 2020 Versus 2028



Source: IEA. Renewable Energy 2023. October 2023.

Despite China's currently robust claim over the upstream elements of PV module production, there remains huge opportunity for countries to participate in the overall solar PV project supply chain. Where the green energy transition really matters – the delivery of affordable, sustainable energy to economies in the form of kilowatt-hours – current solar panel prices could be seen as a boon.

Firstly, the drop in panel costs is a windfall for governments, utilities and industry looking to source the cheapest power possible with the lowest lifecycle costs. It is a period where there should be a prolonged boom in solar PV project development that provides a counterbalance to the historically volatile and money-consuming business of using fossil fuels for power generation. The win-win is that affordable energy also addresses the massive task of decarbonizing the economy, making doing so less of a burden and more of a solution.

For the domestic supply chain, a push for solar generation should mean there are opportunities to participate in the boom as installations of solar panels continue to accelerate. But if not in the PV panel value chain, then where? Enter the balance of systems and project installation value chain.

What a PV boom means is that all forms of installations, whether utility-scale farms, community-level plants, industrial or even residential rooftop installations, require large numbers of inputs from a wide variety of suppliers, contractors and investors to see the solar vision realized. That creates large-scale opportunities for investments in manufacturing, fabrication, bundling and services, much of which can be captured domestically in each country pursuing solar.

To understand the solar supply chain investment opportunity, it is important to identify its components. While much emphasis is placed on the value chain associated with solar panel manufacturing, there are a significant number of non-panel key components and services required to complete and operate solar farms. This perspective is important to keep in mind when countries are looking for their niche in solar farms, given China's dominance of the PV panel supply chain.

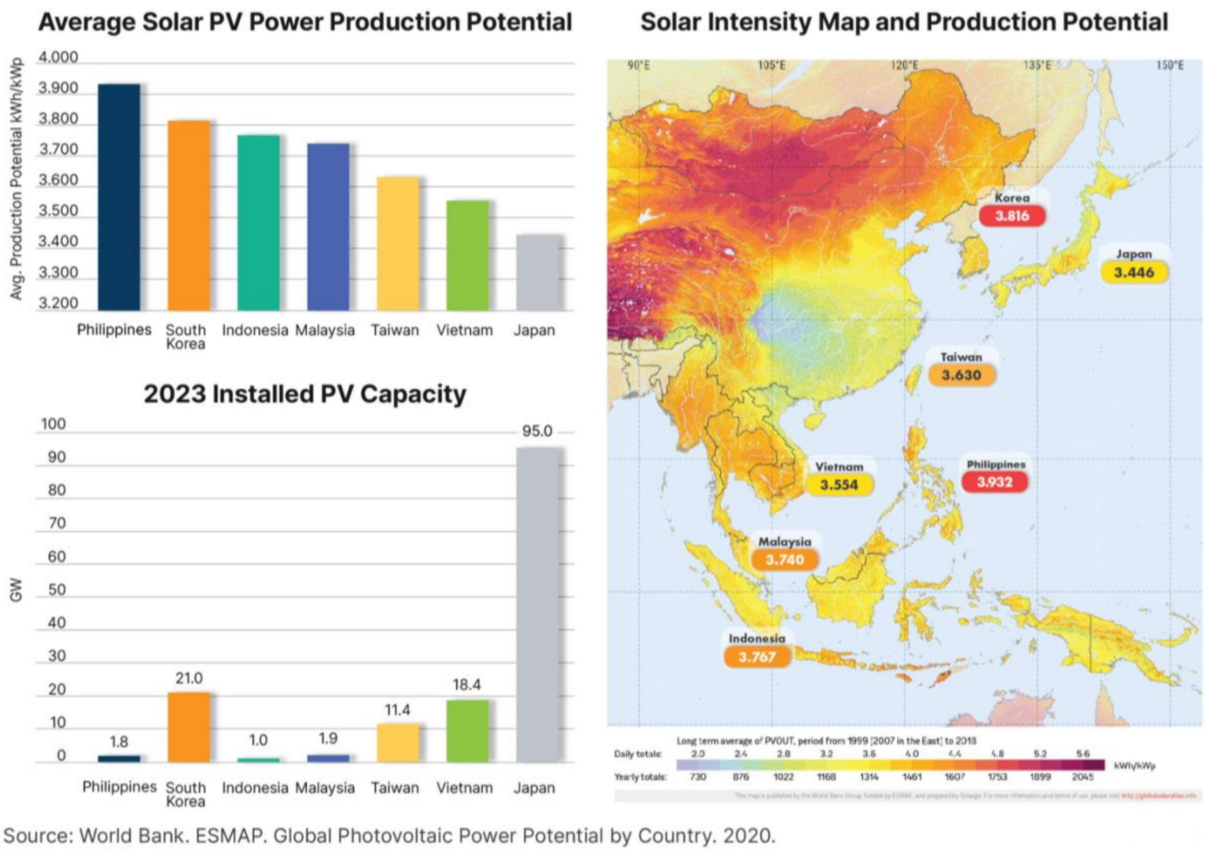
Opportunity from Increasing Solar Ambitions in Asia Pacific

In 2024, solar PV is the lowest cost energy option in nearly every market worldwide, and prices for solar PV modules keep dropping. Paradoxically, despite the region being endowed with high-quality solar resources and despite the promise of low lifecycle costs achievable with solar PV, many Asia Pacific countries' near-term national ambitions for adopting solar remain extremely low.

The figure below shows the solar irradiance and corresponding power production potential for solar PV in key Asia Pacific economies, ex-China. The map, prepared by Solargis and the Energy Sector Management Assistance Program (ESMAP) of the World Bank, shows the average electricity output per kilowatt of PV installed, adjusted for both maximum solar resource intensity and the practical matters of availability of space to install solar.

The Philippines and South Korea have the highest solar potential, while Japan has the lowest. Despite this, Japan already has some of the highest rates of solar penetration globally, totaling over 22% of the country's installed capacity. Meanwhile, Indonesia, ranked third in the region for solar potential, has almost no installed solar capacity, at less than 2% of total generation. This not only means that Indonesia has the lowest rate of solar use in the Asia Pacific, but also places it among the lowest globally.[10]

Figure 5: Asia Pacific Solar PV Electricity Production Potential

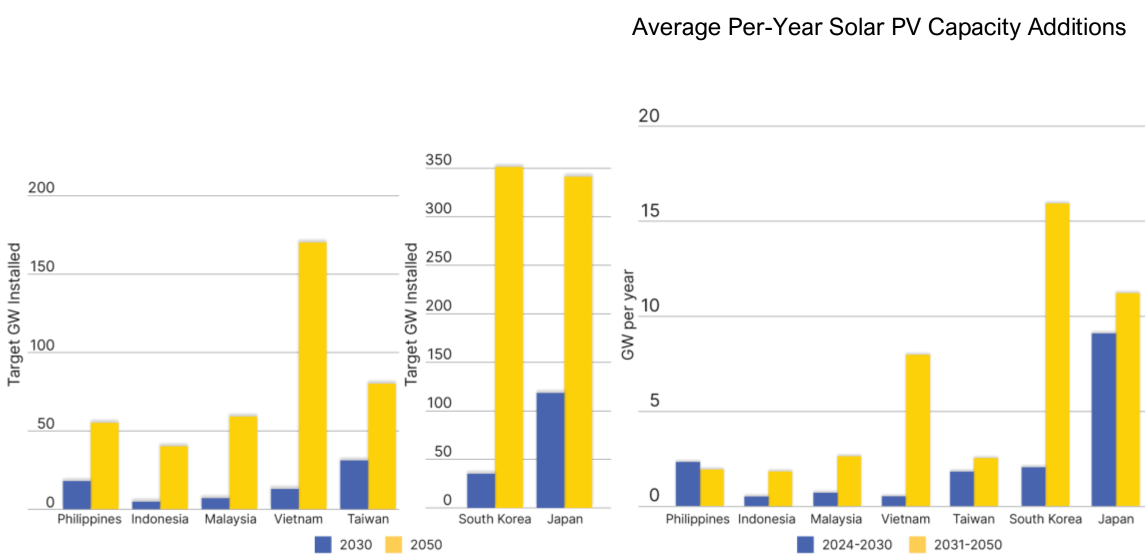


Source: World Bank. ESMAP. Global Photovoltaic Power Potential by Country. 2020

[10] Refers to the 96-country dataset tracked by EMBER where Indonesia ranked last. EMBER. Year Electricity Data. April 17, 2024.

Despite solar's highly competitive cost, it appears few countries in the region are concertedly embracing the opportunity to lock in lower, non-volatile energy prices for their economies for the long term. This is particularly affecting energy sector planning for the current decade. Looking at the official targets for solar additions, shown in Figure 6, nearly every government has effectively deferred thinking about solar until after 2030. The exception to this is Japan, which is targeting over 110 GW of installations during this near-term period. Such low levels of adoption will negatively impact experience in implementing projects and keep supply chain participation minimal, leaving countries less prepared to rise to their proposed burst in solar activity toward 2050.

Figure 6: Comparison of Government Solar PV Addition Targets, 2030 and 2050



Source: Compendium of national plans, IEEFA estimates.

In contrast, in 2023, China added a record-breaking 216.9 GW of solar capacity,[11] an amount equal to the total installed electricity generation capacity from *all* sources in Indonesia, Malaysia, the Philippines and Vietnam combined. That equates to China commissioning 594 MW of capacity every day, a number greater than some countries proposed annual solar addition targets over this decade. Overall, China's effort in solar PV alone added 7.5% to the country's total installed capacity in just one year. China is clearly taking advantage of having the lowest marginal cost source of energy to help reduce its electricity costs while simultaneously addressing some of its decarbonization commitments.

It is unclear why many governments in the Asia Pacific are delaying the adoption of solar, particularly when other parts of the world are proving that it is not only cost-effective but also able to shave expensive mid-day peaking demand from fossil fuels. Historically dire, and now outdated, predictions

[11] Reuters. China's installed solar power capacity rises 55.2% in 2023. January 26, 2024.

of grid collapse have not occurred anywhere. Indeed, grids both large and small have been reliably operating on large proportions of daytime solar power.[12]

Now is the time to put programs in place to procure solar capacity and use competitive forces to drive costs down. This sets the stage for the proportionally larger additions that most Asia Pacific countries have set for themselves beyond 2030. Scale economies and learning curves require time and experience to develop; efforts must be made now to create procurement paradigms and participants that drive those positive changes seen elsewhere globally.

Pragmatism Needed for Local Content Requirements

Governments are concerned that committing to solar in large amounts means ceding money to technology suppliers in other countries. This provides an impetus for local content requirements (LCRs) that seek to shelter the emerging domestic solar PV sector. However, countries do not necessarily need to locally manufacture every component of a solar farm system to derive greater domestic benefit. There are a wide array of inputs and services required to implement a solar project, many of which can be source domestically.

Using data from a variety of industry, government and academic estimates, IEEFA estimates that solar PV modules represent only about 20%-27% of the total cost of a utility-scale solar PV farm.[13] As noted earlier, given the rate at which PV panel prices are dropping, their proportion of total installed cost is expected to fall further as panel-related supply chain competition continues. The remaining 70%-80% cost of equipment and services needed to commission a fully operating solar farm is not dropping anywhere near the rate of PV modules, as those costs are less affected by panel production price dynamics. That creates potential for local manufacturers and service providers to capture a part of supply chain value.

The next section examines the elements of the PV supply chain to better understand where competition or technology creates barriers to entry and where there are clear opportunities for domestic companies to participate.

Solar PV Supply Chain Overview

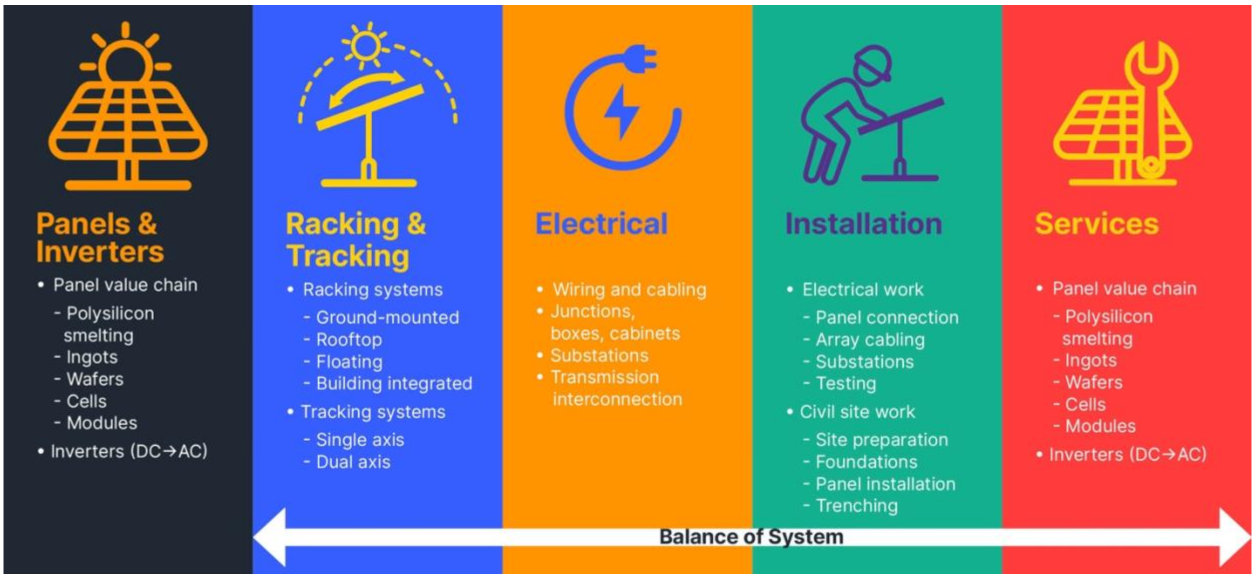
Figure 7 below lists the general categories of components, products, equipment, infrastructure, and services needed to implement a solar farm project. Solar panels and inverters – the electric devices that convert the direct current (DC) produced from a panel to alternating current (AC) used in power grids – are the primary technology components of the solar farm supply chain. Everything else

[12] As an example, on November 21, 2021, the grid in South Australia produced 104% of demand from a combination of solar and wind resources. Since that date, during spring and autumn seasons, the South Australia grid has been regularly repeating this production surplus of renewable energy. Source: Australia Energy Market Operator. Grid Data.

[13] IEEFA drew upon data on supply chain component-wise balance of system cost allocations from a number of industry data source and from cost allocation datasets from DNV, Energy Transition Outlook 2023, April 2024; Wood Mackenzie, US Solar Market Insight Annual Report 2023; US National Renewable Energy Laboratory, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks Q1-2023, September 2023; and IRENA, Renewable Power Generation Costs in 2022, August 29, 2023.

needed to create, install and operate a solar farm is bundled into the category of balance of system, or BOS.

Figure 7: Elements of the Solar PV Farm Supply Chain



Source: IEEFA.

First, the solar PV module production process will be assessed to better understand the constraints to effective competition. Then, the BOS value chain components will be examined to show their proportional contribution to the total project value.

For a more detailed view of what makes up each of the non-panel supply chain elements, refer to Appendix A.

Solar PV Manufacturing Background

China dominates the global supply chain for solar PV panels, delivering nearly 85% of demand. Governments worldwide are talking about getting involved in domestic solar panel manufacturing; this is seen to diversify dependence away from China while placing their country at the cutting edge of green technology. The pros and cons of this approach need to be weighed carefully.

The attraction of solar as an energy source is that it has the lowest LCOE globally. This low cost is driven by the constantly falling price of PV modules, and the inputs used to make them, and, coming out of China, they are a product of extreme domestic market competition. Attempting to recreate these production value chains in other countries will come at great cost. Non-Chinese production will be more expensive, ranging anywhere from 29% to 200% greater, according to an analysis of potential supply chain costs undertaken by the IEA.[14]

First, to understand the constraints and competition in the PV market, let's establish the nature of the PV panel manufacturing value chain. The process from raw silica to finished PV panels has five primary steps:

Figure 8: Photovoltaic Panel Supply Chain Overview

Source: IEEFA.

State of the Panel Market

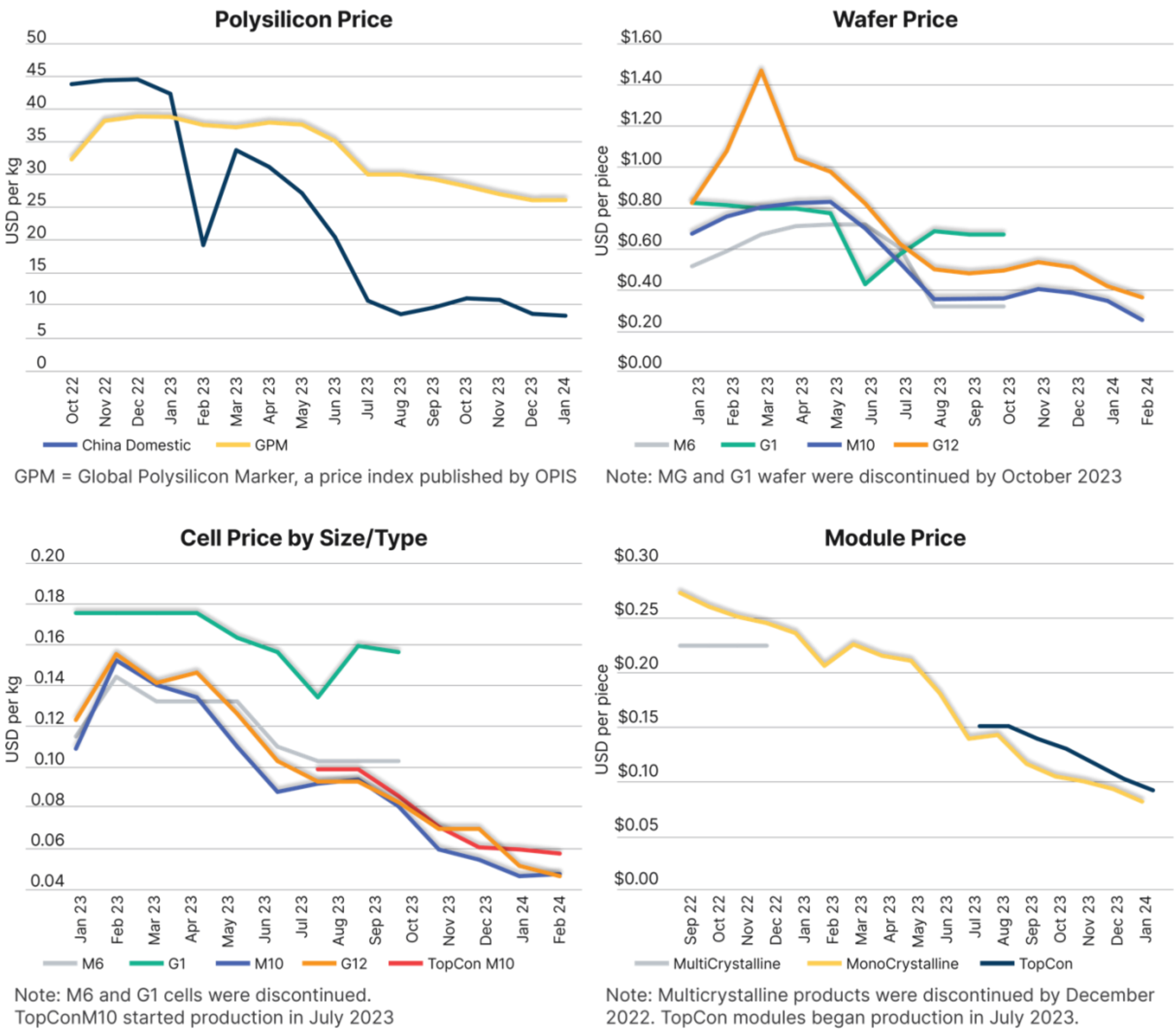
The world is currently in a state of oversupply of PV panel supply chain inputs, driven almost exclusively by China. Utilization rates for Chinese plants averaged about 60% at the end of 2023.[15] Global solar installations totaled 417 GW in 2023, a new record. By contrast, optimistic scenarios place global demand between 450 GW and 650 GW per year over the remainder of this decade.[16]

China already has PV plant capacity additions planned for 2024 that could increase global panel manufacturing capacity to between1.0 TW and 1.2 TW.[17] This persistent overcapacity in manufacturing has had the effect of pushing down global prices of PV panels, dropping costs in 2023

[14] International Energy Agency. Solar PV Global Supply Chains. July 2022.
[15] Reuters. China solar industry faces shakeout, but rock-bottom prices to persist. April 3, 2024.
[16] BNEF. 1Q 2024 Global PV Market Outlook. March 4, 2024.
[17] PV Magazine. A terawatt of solar module capacity expected within 16 months. September 14, 2023.

by 50% versus 2022 prices. In April 2024, PV module prices stood around US$0.11-$0.12 per watt.[18] With more manufacturing capacity additions already in the pipeline, prices are likely to fall below US$0.10 per watt.[19] This bodes extremely well for any countries, companies, or communities that want to integrate solar PV into their energy supply mix. Prospects are financially more challenging for any group looking to newly invest in any part of the panel manufacturing process as a market entrant.

Figure 9: Solar PV Value Chain Price Drops 2022-2024

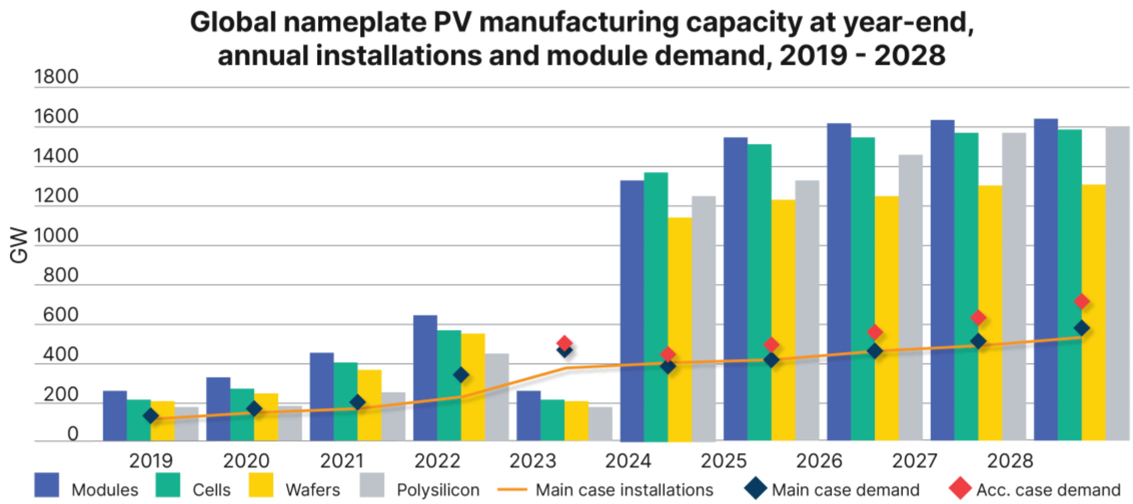


Source: OPIS. APAC Solar Weekly. January 24, 2024

[18] OPIS. APAC solar weekly. April 2, 2024.
[19] S&P Global. World stuck in major solar panel 'supply glut'; module prices plummet: IEA. January 12, 2024.

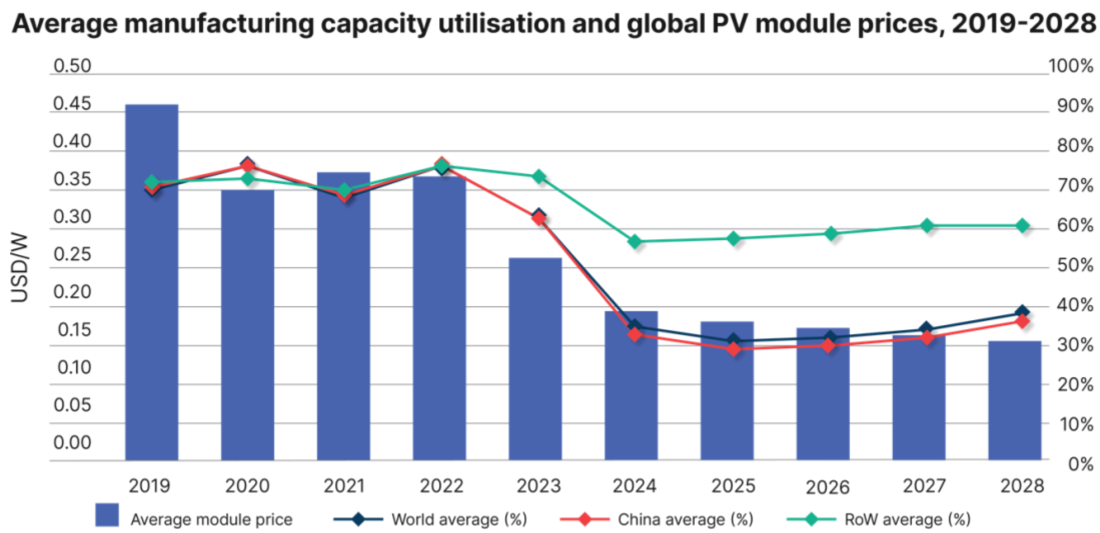
As Figure 10 shows, manufacturing capacity across the PV panel supply chain is projected to greatly exceed projected demand through the rest of the decade. This is corroborated by current and project plant capacity utilization rates shown in Figure 11. This is driven by what in 2024 is likely to become in excess of 1 TW of panel manufacturing capacity in China, well exceeding projected global demand for modules of around 500 GW.

Figure 10: Projected Manufacturing Capacity Versus Projected Global PV Demand



Note: Acc. Case = accelerated case.
Source: IEA. Renewables 2023. January 2024.

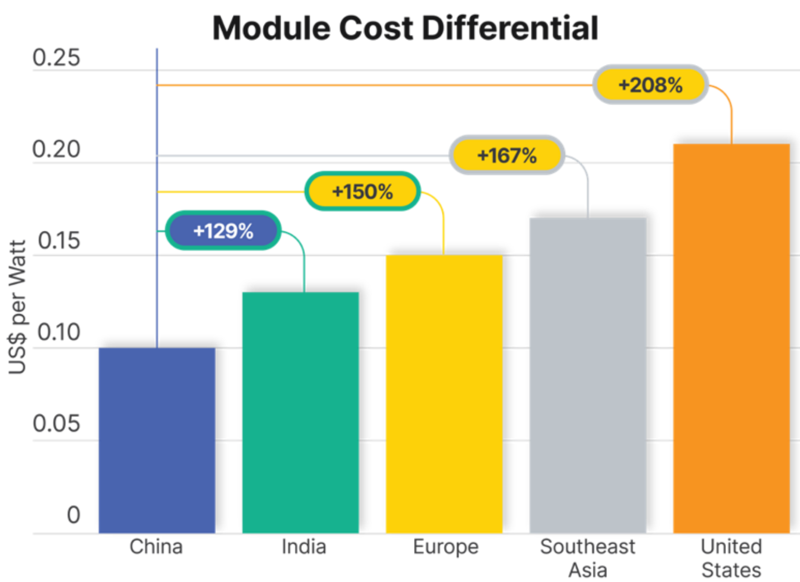
Figure 11: Current and Projected PV Plant Utilization Rates



Note: RoW = rest of world
Source: IEA. Renewables 2023. January 2024.

China's manufacturing cost and, therefore, sales price advantage has been sustained. Recent data on these differentials is presented in Figure 12. Currently, Southeast Asia manufacturing costs are 167% above those of China.

Figure 12: PV Module Manufacturing Cost Differentials by Region



Note: Price is for 182mm-based PERC mono-silicon-based modules as of March 29, 2024. Regional manufacturing cost differentials are as of December 31, 2023.
Sources: Manufacturing differentials: S&P Capital IQ. Squeeze on European solar manufacturers curbs innovation, cementing China's lead. April 15, 2024. Module market Price: OPIS. APAC Solar Weekly. April 2, 2024.

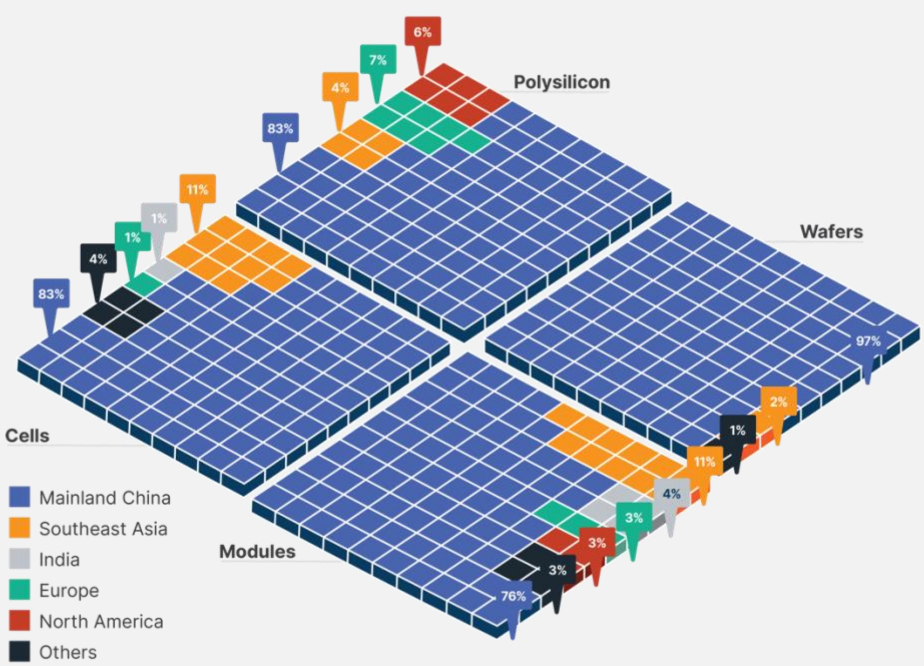
Box 1 – China's Dominance of the PV Module Production Chain

China dominates all aspects of solar PV panel development, from the creation of silicon from raw materials all the way through to panel modules. China supplies over 80% of the polysilicon used for making wafers. However, when it comes to converting that polysilicon into ingots and then slicing those ingots into wafers, China effectively controls the entire market, supplying over 97% of wafers. This means that despite around 17% of polysilicon being smelted elsewhere in the world, nearly 85% of that third country production amount winds up being used in China.

Wafers then need to be converted into PV cells, where again China controls over 83% of that market. Modules, the final product in the PV supply chain, are where things become moderately more diverse, with about 22% of panel output coming from markets outside China. Southeast Asian countries, primarily Malaysia and Vietnam, account for over 11% of the global market, with most of their output being exported to North America and Europe. This is also the one segment of the market which is adding capacity and competition globally. The module segment does for the most part, however, still rely on inputs from Chinese suppliers.

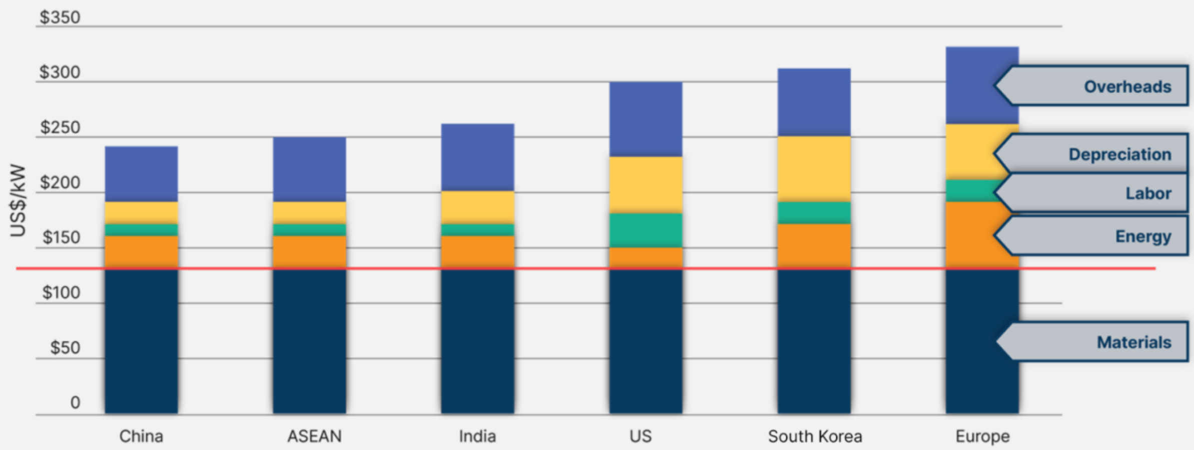
China Dominates Solar Value Chain

Global Solar Module Production Capacity by Value Chain Step in 2022 (%)



Source: S&P Global Commodity Insights.

An interesting observation on the PV panel supply chain competition is that, for the most part, the raw material input costs are roughly the same across all markets. In large part, this is due to China's domination of all panel input materials production. Export markups are small, and panel producers in most countries make use of Chinese inputs. The differences in finished panel prices come from plant development costs, labor, energy inputs, approvals and financing cost specific to each country. China has streamlined or minimized all those other costs, and, as such, has a large advantage. The chart below shows the cost differentials as of the end of 2022. However, since then, China's costs have plunged further, dropping cell costs per watt from $0.24 in 2022 to $0.12 currently in 2024. At that price, most non-Chinese companies are priced out of the market. Indeed, Europe has seen production facilities shutter during the first quarter of 2024 due to an inability to meet such pricing.[20] In the United States (US), subsidies for domestic production and tariff barriers against Chinese-made panels are the only measures protecting domestic producers from this price pressure; even then, US' final to-market prices remain above China's.



Source: IEA. Solar PV Global Supply Chains. July 2022.

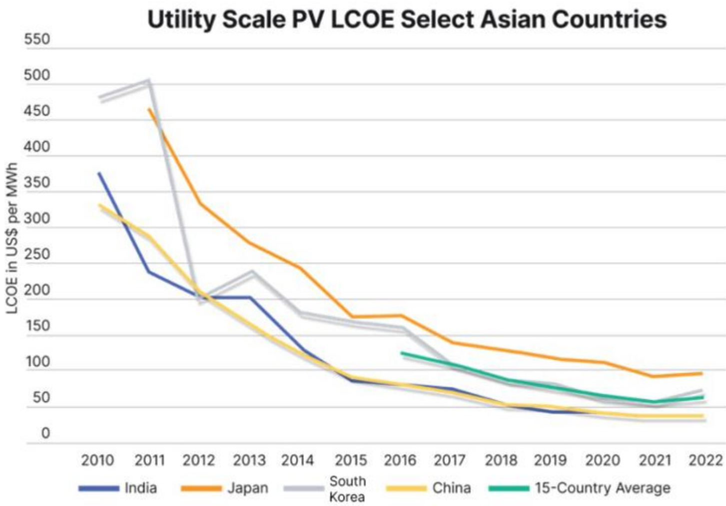
Reduced PV Panel Costs Drive Down Delivered Power Costs

Most relevantly to the Asia Pacific, drops in PV module prices have driven down the capital costs of fully functioning solar farms. Globally, LCOEs have fallen consistently for the past 15 years. The only exception was the period of widespread global inflation experienced in 2022-2023. Since then, costs have stabilized as have LCOEs. In 2022, LCOE levels globally ranged from a low of US$35 per MWh to an average of US$63 per MWh.[21] Currently, markets like Japan and South Korea are outliers, with LCOEs in the US$74 to US$95 per MWh range. Shared factors driving higher costs in both countries are the cost of land and more complicated permitting processes. In Japan, uniquely worldwide,

[20] S&P Capital IQ. Squeeze on European solar manufacturers curbs innovation, cementing China's lead. April 15, 2024.
[21] IRENA. Renewable Power Generation Costs in 2022. August 29, 2023.

installation costs account for the largest proportion of cost, equating to 44% of total project cost, compared to a rest-of-world average of 16%.[22]

Figure 13: Levelized Cost of Electricity for Solar is Falling in Step with Drops in PV Prices



Source: IRENA. Renewable Power Generation Costs in 2022. August 29, 2023. IRENA data for 15-country sample was limited to 2016 to 2022.

What is the impact of continuously falling solar panel prices? That depends on how you define and look at the PV supply chain.

- If you are a project developer, this is an excellent prospect. Decreasing panel prices means you can either lower your tariff price to be more competitive or build in an extra buffer to cover project implementation risks.
- If you are a utility electricity supplier, you can decrease costs to consumers while eliminating input price volatility associated with fuel payments.
- If you are a supplier of any complementary equipment needed to complete a fully functioning solar farm, there are great prospects for your products being taken up because the main input has become commoditized.
- However, if you are a PV panel value chain participant, you are fighting to survive on ever-shrinking margins.

This latter situation is where the challenge comes for solar technology providers. As the input commodities and technological transformation services become ever cheaper, their profit margins shrink. It, therefore, becomes harder for new entrants to compete with established players who have optimized their processes with experience and know inherently where savings opportunities lie.

The majority of solar farm construction costs are particular to the country in which the farm is situated. Local conditions impact solar farm cost: terrain, soil, site access and distance to the grid are all site-specific. Grid conditions may dictate the choice of inverters and switchgear, while distance to

[22] Ibid 21.

that interconnection has a great impact on investment cost. Labor costs vary widely, particularly across regions within larger countries.

Thus, the balance of system costs, labor inputs and regulatory and operational characteristics will have a greater impact on the financial viability of solar farms than panel costs, given that panel modules will be a decreasing proportion of total project cost (absent some sort of similar scale economy learning curve in the balance of systems).

The implication is that, increasingly, local supply and service chains will govern the final price for solar power on the grid. This makes it incumbent on national policymakers, in partnership with the domestic industrial-commercial supply chain market, to create the conditions that optimize the balance of systems costs, allowing their country to benefit from the unprecedented economic opportunity provided by cheap solar PV modules.

Allocation of Costs for a Solar Farm

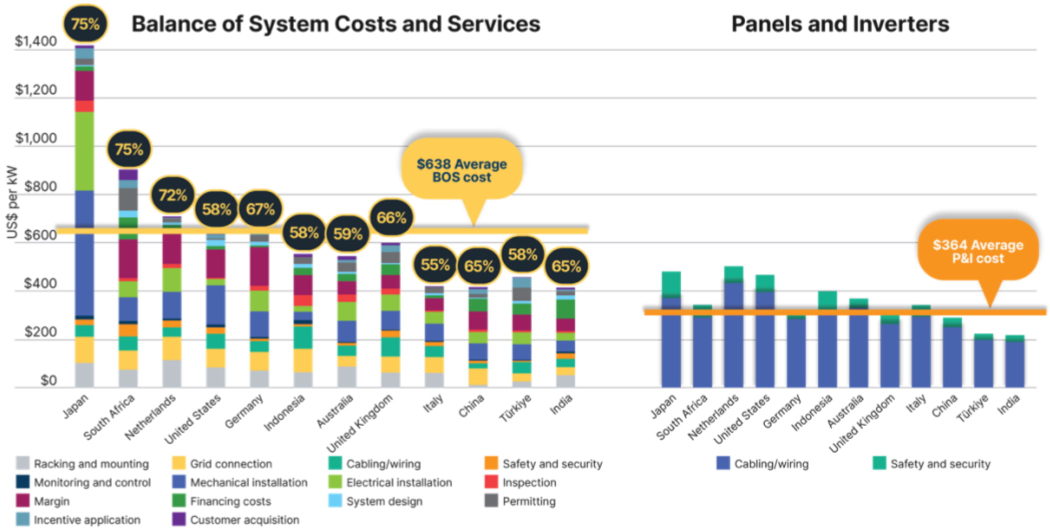
At the coarsest level, a solar farm's cost can be broken up into two major categories: (1) panels and inverters and (2) balance of systems.

Panels and inverters are dominated by Chinese suppliers in the Asia Pacific, where it is challenging to compete on cost and quality. Although there may be niche players for inverters or domestic manufacturers of panels in a given country's market which may hold some competitive advantage. Globally, panels and inverters account for about 25% to 45% of total project cost, depending on the country, with an average of 33%.

The balance of system, or BOS, therefore, comprises the majority portion of PV farm costs, ranging from 55% to 75% of total project costs. BOS is made up of hard costs for equipment, such as inverters, transformers, racking, cabling, switchgear, and enclosures; site work including costs for equipment rentals, labor, and the services they provide, as well as so-called 'soft costs' like studies, design, permits, interconnection permissions, and financing costs for a project. Nearly all of the project development and financing costs are locally incurred, and potentially half or more of the balance of system costs could be domestically incurred.

Figure 14 below illustrates how large BOS costs are and how much they can vary from country to country. This figure is derived from a study led by the International Renewable Energy Agency (IRENA), which looked at solar farms in 33 countries that demonstrated a wide range of total installed costs. Costs for solar PV panels and their respective inverters averaged US$364 per kW. BOS costs, which include racking, grid interconnection, and all site development and permitting costs, showed a wider range, averaging $638 per kW. Overall balance of system and implementation costs ranged from 55% to 75% of total project cost with an average across countries of 64%. It is notable that the IRENA study used 2022 cost numbers. Since then, over the course of 2023, module costs dropped by nearly 50%, while many of the BOS costs remained similar to those in the study. What this means is that BOS expenses and investments for a solar farm now likely account for about 75% of total delivered costs.

Figure 14: Comparison of Balance of System Costs to PV Panels + Inverter Cost for Solar Farms in 2022, Select Countries



Source: Adapted from IRENA. Renewable Power Generation Costs in 2022. August 29, 2023.

Unlike panels, which trade in a comparatively tight band globally, the value of BOS costs varies widely. With all-in installed costs of utility-scale solar farms ranging from $650 per kW to $1,900 per kW, and the wholesale price of PV modules ranging from $120 to $200 per kW, domestic market players can still provide material value.

While the cost of capital can be a factor depending on the country and the structure of the financing package, it is not a material driver of these cost variations. In particular, debt interest during construction is very low due to solar projects' short implementation timeframe. Given the modular and scalable nature of solar projects, project sizes can be designed to match the financial capabilities of domestic developers and local lenders.

With the focus then on materials and services costs, there is potential for domestic companies – service providers, constructors, designers, and equipment suppliers – to participate in a greater share of solar farm development and operations and derive value from participating in the solar PV supply chain.

For Asia Pacific governments, this means that the greater economic opportunity arising from solar PV lies in the development and outfitting of solar farms, rather than from the PV panels that go in them.

PV Supply Chain Opportunities

Beyond solar PV panels, there is an array of components, systems and services needed to realize a solar farm. These are summarized below. These categories are used to estimate the market opportunity allocation in this assessment. For more details on the utility solar farm BOS components, please refer to Appendix A.

Balance of System Elements

Inverter systems. Inverters are at the heart of power supply from farm to grid. They convert the direct current outputs from the PV panels to alternating current on the transmission grid. Inverters must match the voltage and frequency of the grid to ensure output power meets the transmission system operator's requirements. Inverter technology and design have advanced in recent years to perform "grid forming" services, which help solar farms become more beneficial, active participants in keeping the grid stable. Inverters, therefore, are adopting more advanced circuitry and control systems to be able to perform that role. This has served to narrow the range of companies manufacturing and competing in the inverter space.

Transformers and switchgear. The primary electrical systems are commonly sold as skid-mounted packages. Assembled and tested at the factory, they can be placed in enclosures and delivered to the site as a fully functioning unit, ready for connection. The primary suppliers of the equipment are limited to North Asian, European, and North American providers, such as Siemens, ABB, Hitachi, Toshiba, and about a dozen Chinese suppliers, the largest of which have 20-year plus track records.

Potential opportunity lies in working with these established suppliers to create the containerized or skid-mounted systems as integrators. Integrators can become trusted suppliers to solar farm developers in a country or even regionally. Decisions can be taken as to whether package systems are delivered ex-factory or if responsibilities include transportation, insurance, site delivery and installation.

Electrical systems and components. The on-farm, behind-the-inverter electrical systems comprise cabling, connections, collector boxes, breakers and the enclosures that house them. There are solar-specific cabling formats that allow for ease of connecting hundreds or thousands of panels on a farm, and sorting those cables into junctions and trunk lines that lead to the inverters. Cable management systems are important to keep connections organized and to protect the links.

Racking systems. Mounted to the ground or affixed to a roof or other structure, racking is the structural system that holds the panel. Systems are typically modular to facilitate both their transport and their assembly by individual workers. Framing, made of aluminum or steel, is designed for minimal use of materials but with maximum strength to withstand high winds and other natural events while keeping the panels aligned. There are numerous jointing and fastening hardware systems that accompany racking. Foundation piles for in-ground, fixed-bottom applications can vary in design based on the type of ground condition on site. Sometimes, the piles are machine-driven, drilled, and grouted in the case of rock, or can even be hand-placed.

Tracking systems. There are much greater seasonal solar movements at higher latitudes, along with reduced outputs in winter. Tracking systems integrate with the racking system and rotate the panels with the sun's movement such that the angle of incidence between the sun's rays and the panel face is kept perpendicular. Tracking systems require higher quality metals, called torque tubes, upon which the panels rotate. Motors drive the torque tubes. Dampening systems attached can reduce vibrations that rotation might induce. Sensors and control systems are needed to coordinate the tracker, typically sold bundled as proprietary systems.

Electrical contractors. Electrical contractors provide all the labor and skills needed to install the solar farm, connect it to the substation, and make onward connections to the transmission grid. They will set up the control systems and both site and remote monitoring software. The contractors will conduct testing services to make certain all systems are functional.

Civil construction and site works. Solar farms must prepare their sites with cleared and level areas for installation. They may be graded for drainage. Trenching may be required for cabling systems. Foundations are provided for electrical substations, other major poles and equipment and site buildings. Access roads are also within the scope of civil works.

Site security. Contractors provide site fencing, perimeter sensing, and camera security systems. These can be bundled with security operations services.

Operations management. An operating contractor can be retained to monitor day-to-day system generation and operations. They conduct periodic site inspections, checking connections, wiring, panel integrity, and electrical systems performance. They can provide panel cleaning services to remove fouling and keep them operating at top efficiency. Panel replacements can be executed if needed. Vegetation management services keep the panels and their connections free of ground cover plants.

Development. Solar farms only come into existence with the help of planners, managers and financiers. Utilities or independent companies that focus on solar arrange for all site surveys, studies, engineering designs, and permits. They obtain the land rights, create the specifications for the farm, and bid out for all of the supplies and services listed above. They are responsible for arranging power sales contracts, legal agreements and financing.

Assessment of the PV Supply Chain Opportunity

Beyond the Panel

Deployment of solar PV in utility-scale projects, community solar suppliers and private rooftop applications holds the potential to transform access to and the cost of energy across the Asia Pacific. Countries looking to take advantage of solar energy at all-time low costs will need long-term solar projects at scale. To cash in on domestic supply of materials, components and services while keeping investment money local, many governments immediately jump to domestic manufacturing of solar PV modules.

This report highlights that China currently dominates the supply chain for modules, particularly the upstream inputs of polysilicon, wafers and cells, which are available at the world's lowest costs by wide margins. China's effective 100% overcapacity in PV manufacturing capability means that open market prices for modules will continue to drop as existing Chinese producers fight to maintain cash flow. Potentially, only those companies with the best technology at the lowest cost will survive. However, driven by Chinese government policy and support, this depressed price environment will likely continue to flood the global markets with high-quality, low-price PV products into the 2030s.

Attempts to replicate China's supply chain will likely be met with higher end-unit costs. That undermines the premise of providing low marginal cost, widely available clean energy. Most countries in the Asia Pacific are awash in fossil fueled energy sources, in many cases at high cost, and late to realizing their decarbonization commitments under the Paris Climate Agreement.[23] Adding time, complexity, and cost by requiring the development of domestic production capabilities of solar PV components where they will not be competitive in the medium term, diverts precious resources – human, policy, capital and time – away from readily achievable energy transition progress.

Non-Panel Solar PV Supply Chain Market

The continuously decreasing costs of the primary technology input for solar farms, which already has the lowest long-run marginal cost, reduce the all-in project deployment cost. This can stimulate its demand and those of all of the other materials, components, and services required for solar generation.

The market quantification exercise presented below is predicated on that decreasing cost pricing dynamic. Imposition of import duties on Chinese PV products and/or mandatory domestic panel manufacturing at sub-par scale or quality will increase the costs of solar systems. The absence of sustained subsidies/tariff support will reduce the demand for solar and, therefore, negatively impact the non-panel supply and service market.

The solar capacity additions used in this estimate are based on announced national energy plans. These plans typically look at targets to 2030 and 2050.

These analyses were performed assuming an unfettered evolution of solar supply chains, driven by domestic demand in each country. Excessively restrictive market rules or onerous local content requirements were ignored for the purposes of the analysis. Thus, the numbers here are the unconstrained market potential for each government's proposed policy-based capacity additions or renewable energy contribution targets.

Other assumptions used in calculating prospective costs trends, balance of system cost trends and estimates used in arriving at total investment sizes are described in Appendix B.

[23] Countries in the Asia Pacific rank from "Insufficient" to "Critically Insufficient" on Climate Action Tracker's index of decarbonization progress. This means they either lack targets for decarbonization, those targets will not allow the country to meet its commitments and/or selected actions in energy sectors will not allow countries to meet their targets. For more details refer to each country's assessment page on Climate Action Tracker's website (Accessed April 18, 2024).

Solar PV Project Market Value to 2050

Based on stated national development plans for solar capacity additions in each Asia Pacific country, order-of-magnitude assessments have been made for the annual need for input of products, materials and services to the solar sector. The assessment of what is required to develop and deliver fully operational and grid-connected solar farms is broken down into supply chain and service components specific to each solar project.

“Extra-regional” is defined as the proportion of supplies originating from outside Asia Pacific, whereas “regional” means primarily inputs sourced from China and from amongst the countries in this study. Localization was progressively applied over time. Most solar PV modules were initially sourced from China. In markets with current PV module manufacturing, it was assumed that, as the scale of domestic market demand increased, manufacturing capacity would be diverted to serve the home market. Over time, all markets would manufacture their own modules. The balance of systems in most countries were locally sourced, except for inverters and substation transformers; however, with demand, those components were more rapidly localized.

Summary of Solar PV Investment

The investment potential for solar PV in the Asia Pacific is estimated to be US$394 billion through 2050. About US$88 billion is developed to 2030, but the bulk of investment follows with US$306 billion occurring between 2031 and 2050. The non-solar module proportion is US$296 billion by 2050, or nearly 75% of total investment, with local content rising 6 percentage points between 2030 and 2050.

Table 2: Asia Pacific Estimated Solar PV Market 2025 to 2050 (USD Billions)

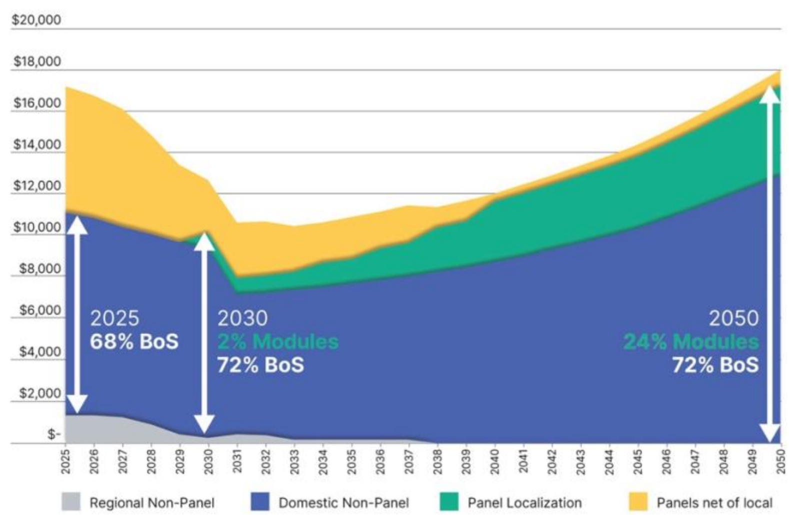
	2025 - 2030			2031 - 2050			Total to 2050		
	Ex-region	Regional	Local	Ex-region	Regional	Local	Ex-region	Regional	Local
Investment	$ 2,011	$ 24,918	$ 60,751	$ -	$ 21,649	$ 285,315	$ 2,011	$ 46,568	$ 346,066
		$87,680			$306,965			$394,645	
Capacity		197 GW			437 GW			634 GW	

Source: IEEFA estimates.

IEEFA’s estimate for localization potential includes provisions for long-run domestic production of PV modules. Chinese over-capacity is expected to run through at least 2030, keeping prices low. It is assumed that nearly all panel sourcing in the Asia Pacific through 2030 uses low-cost Chinese products. However, eventually, with the presumed success of Asia Pacific domestic solar addition programs as announced, combined with continuing global demand for panels, it is assumed that current countries with some domestic panel manufacturing will ramp up domestic sales of PV modules. This would phase in slowly over the period 2031 to 2040, whereafter domestic markets could become majority locally supplied.

It is important to emphasize, however, that most investment potential and benefit is derived from the balance of system business throughout the assessment period, capturing 75% of ever-increasing annual investment in solar projects. The total cumulative market value of the balance of system supply and services from 2025 to 2030 is US$67.2 billion, rising to a cumulative US$229 billion from 2031 to 2050, totaling US$296 billion over the period 2025 to 2050.

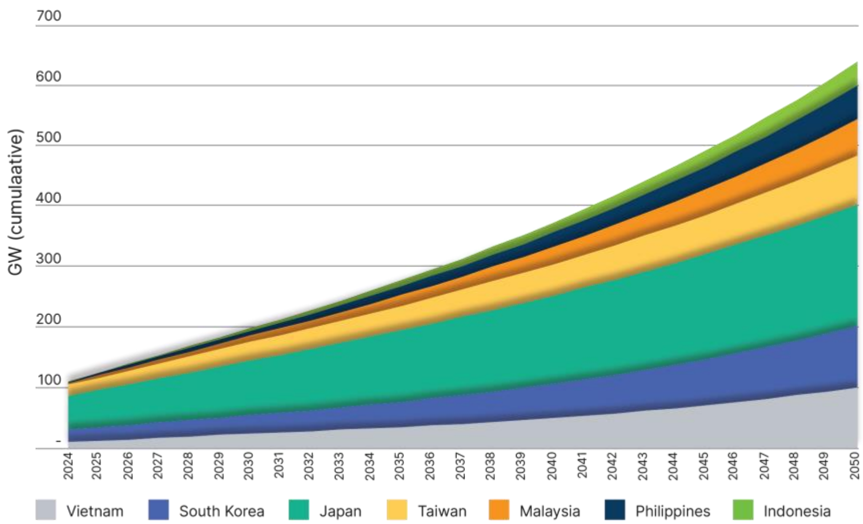
Figure 15: Estimated Regional Solar PV Investment Value 2025 to 2050



BoS = Balance of systems. Source: IEEFA estimates based on current national plans modified for current progress against targets.

The additions underlying the investment in the chart above are taken from each country's energy sector development plans and decarbonization targets. The indicated dip after 2030 is driven by Japan's goal to double its solar capacity by 2030, from 55 GW to between 108 GW and 118 GW. IEEFA's estimate for Japan scales back that addition rate to about 88 GW given the current status of the initiative, but still that level of investment is aggressive and inflates the overall regional growth. After 2030, Japan rejoins the rest of the region in the envisioned trend of steady but upward addition trend. Whatever the strategy, over the period to 2050, these additions accumulate to over 634 GW of installed solar capacity across the Asia Pacific.

Figure 16: Asia Pacific Cumulative Projected Solar PV Capacity to 2050



Source: IEEFA estimates. Solar additions based on stated development national plans from each country, adjusted by IEEFA market assumptions and projections.

Solar opportunity by market

Figure 17 shows the projected market values for solar capacity additions by country included in this study. These investment amounts are divided into panels, inverters, and balance of system components. The balance of system category is further broken down into essential supplies, components, and services needed to create fully operational solar parks.

Market values are based on targeted solar capacity additions outlined in national renewable energy plans. They do not reflect the far greater solar potential of each country as noted in the section above.

The projected investment amounts account for increasing rates of capacity addition in each country. Simultaneously, they apply a declining cost curve for capital investment requirements, as prices for modules and balance of system components are projected to decrease over time. Figure 17 breaks down costs by supply chain component.

Figure 18 illustrates the potential for localization over time within each country. This figure highlights the slender contribution of solar PV modules to total project costs. BOS aggregate costs range from 67% in South Korea to 85% in Japan.

South Korea has both the potential and ambition to grow its solar industry. It has the capability to localize almost all aspects of the supply chain. However, the main challenge is finding the space required for large-scale solar projects. Industrial rooftops and floating projects could provide solutions. Government plans call for hundreds of gigawatts of additions, but the focus is beyond 2040, with an emphasis on maintaining fossil fuels in the near-term electricity mix. Consequently, IEEFA has constrained additions to 100 GW by 2050. This figure is significant for the region but lower than government targets would suggest. This leads to a potential investment of US$51 billion, with about US$36 billion coming from the domestic supply chain.

Japan is a world leader in solar installations, ranking third in generating capacity behind China and the US. With plans to further grow its solar resources, Japan's market potential could reach US$126 billion by 2050. However, Japan has some of the highest installation costs in the world, accounting for nearly half of the total system costs. This helps keep the majority of the project value local, estimated at US$108 billion. Industrial players may see continued capacity additions as a signal to invest in expanded module manufacturing, which could increase domestic costs. However, this would also raise system costs, as domestic manufacturing expenses are likely higher than those for panels sourced abroad.

Malaysia is currently one of the top PV module manufacturers outside of China, with nearly all of its production destined for export. This creates an opportunity for Malaysian manufacturers to redirect a portion of that capacity to serve the domestic power market. However, the country has yet to embrace its natural solar potential. National plans currently include minimal solar additions by 2030, with plans to grow that capacity ten-fold thereafter. It is currently unclear how energy sector policies will be modified to stimulate this targeted growth. If achieved, this could create an investment potential of US$42 billion, with nearly US$30 billion from domestic sources. This figure could be even higher if module export capacity were redirected inward.

Vietnam, like Malaysia, is a key non-Chinese PV module manufacturer serving the global solar export market. Following the pattern of other Asia Pacific countries, Vietnam's current energy plan includes modest solar capacity additions through 2030, followed by significant growth targeting 170 GW of installations. If conditions allow, this would provide a low marginal cost of energy to support the economy. A promising development is the advancement of a policy allowing direct power purchase agreements (DPPAs) between private solar power project developers and industrial consumers. Many multinational companies operating in Vietnam have global corporate renewable energy mandates and have faced material challenges meeting those requirements in the country. The DPPA policy would help address this challenge and could spur gigawatts of installations. Overall, national targets imply an investment potential of US$60.6 billion by 2050, with a localization prospect of US$43.6 billion.

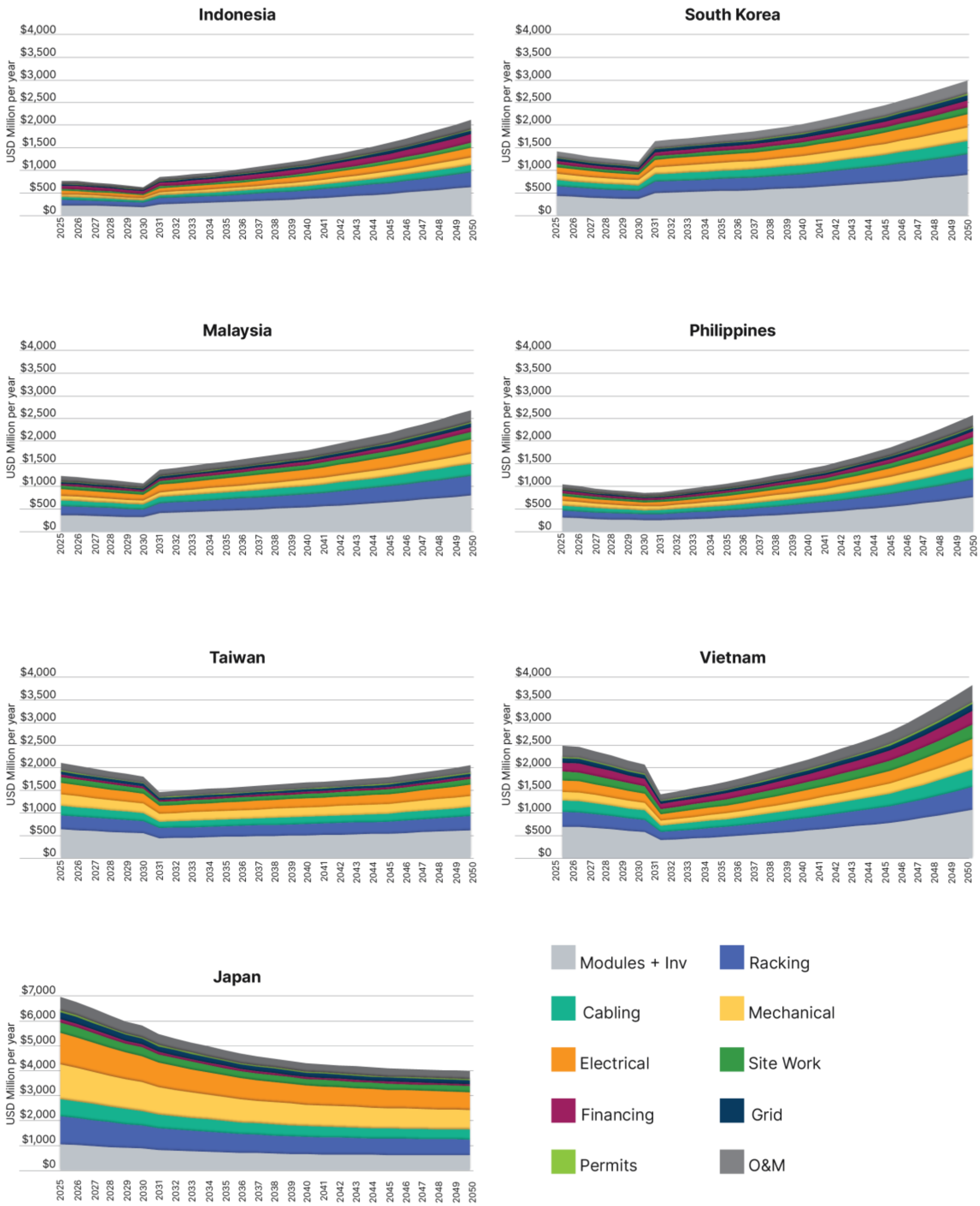
Taiwan has a moderate solar power development plan through 2050 that seeks to add about 2.0 GW to 2.5 GW per year over the 25-year period. Geographically, Taiwan has relatively level plains on its western coast, including material portions of which is agricultural land. The relative development density on the island means that transmission access is rarely far distant. This combination of land and proximity creates great potential for agrivoltaic installations, or solar farms that are installed adjacent to or above existing cropland. Certain crop species benefit from the partial shading from the PV modules. This symbiosis of power generation and crop production benefits can create additional cash flows for farmers during and between growing seasons. In addition to agrivoltaics, utility-scale farms are also possible. There is currently over 440MW of floating solar projects in shallow coastal waters, with the potential to add to those installations. In an innovation for the domestic solar supply chain, some of these floating farms use a proprietary anchorage system developed in Taiwan to protect against the impacts of cyclones.[24] Together, the investment prospects for solar power farms in Taiwan total US$45 billion through 2050 with a localization potential of US$31.5 billion for non-panel content. A transition to a proportion of domestic panel sourcing towards the end of the projection period could see an additional US$6.8 billion in local content.

The Philippines has established a strong procurement program for renewables with solar performing well in auctions to date. This process has resulted in proposals for projects with low marginal costs of power. With plans to continue renewable energy auctions, there will be sustained demand for the solar supply chain, particularly for balance of system components. However, this demand is unlikely to drive significant investment in panel manufacturing capacity, so market projections conservatively assume continued imports. The local content potential in the Philippines could reach US$25.8 billion by 2050.

Indonesia's energy plan has the least quantity of planned near-term solar energy additions in the region, despite the country's very high solar generation potential. This is due to a policy environment that favors "dispatchable renewables" like hydro, biomass, and geothermal, which the state-owned utility PLN can control, albeit at higher marginal costs. While there has been recent success with a 145 MW floating solar project commissioned in 2023, overall plans remain small. Indonesia has the potential for a world-class utility-scale solar industry if policy conditions would be amended to permit it. Currently, stringent local content requirements, disadvantageous interconnection requirements, and the small scale of proposed capacity additions are hindering industry development. Some domestic module manufacturing facilities primarily focused on exports could supply the domestic market. However, due to the policy-constrained lack of demand, there are minimal balance of systems suppliers, manufacturers, and contractors. This means that initial system costs in Indonesia will be significantly higher than global market averages. Assuming some of these issues are resolved, and the solar market is allowed to evolve like others globally, Indonesia's longer-term plans could see an investment of US$31 billion, with US$22 billion remaining domestic.

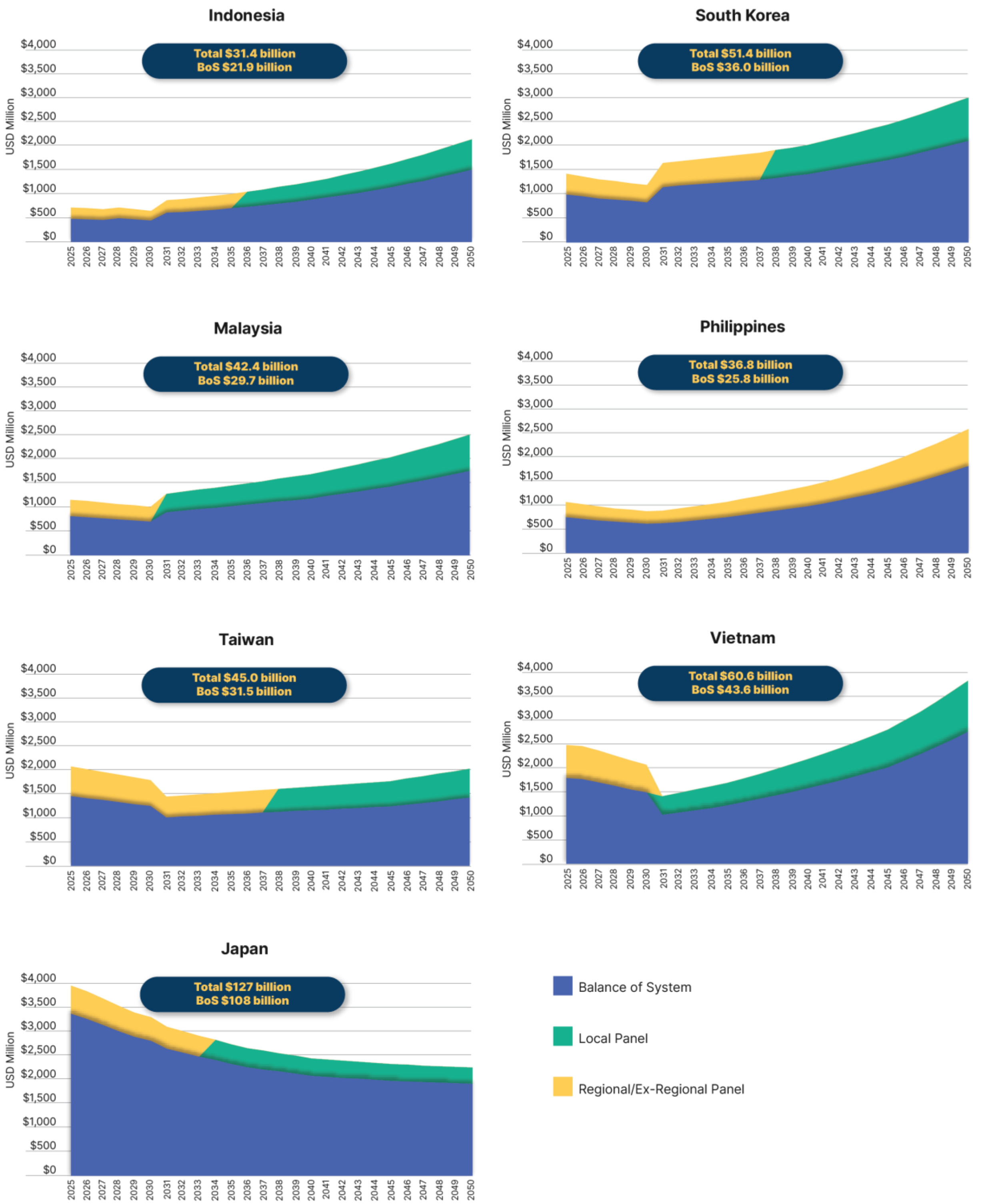
[24] Offshore Energy. One of Taiwan's largest near-shore floating solar projects completes. February 22, 2024.

Figure 17: Projected Solar Park Spend by Cost Component for each Study Country, 2025 to 2050



Source: IEEFA estimates.

Figure 18: Projected Localization of Solar PV Supply Chain 2025 to 2050



Source: IEEFA estimates.

Table 3: Summary of Panel and Balance of System Values by Study Country 2025-2030, 2031-2050 (USD Billions)

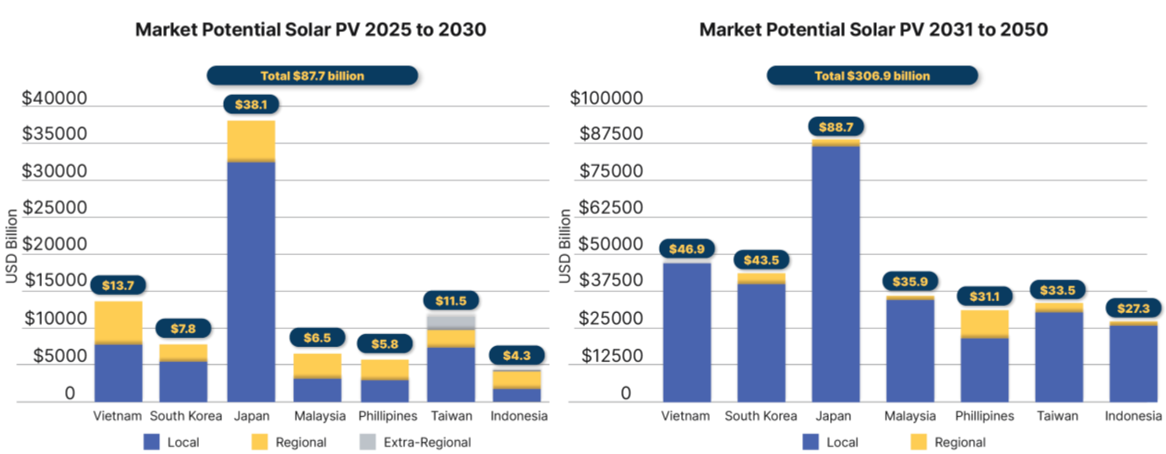
	2025 - 2030			2031 - 2050			Total to 2050		
Investment	Panel	BoS	Total	Panel	BoS	Total	Panel	BoS	Total
Indonesia	$ 1,295	$ 2,816	$ 4,112	$ 8,191	$ 19,112	$ 27,303	$ 9,486	$ 21,928	$ 31,414
Japan	$ 5,710	$ 32,358	$ 38,068	$ 13,310	$ 75,423	$ 88,732	$ 19,020	$ 107,780	$ 126,800
South Korea	$ 2,348	$ 5,479	$ 7,827	$ 15,409	$ 30,475	$ 45,883	$ 17,757	$ 35,953	$ 53,710
Malaysia	$ 1,953	$ 4,556	$ 6,508	$ 10,781	$ 25,156	$ 35,938	$ 12,734	$ 29,712	$ 42,446
Philippines	$ 1,733	$ 4,043	$ 5,776	$ 9320	$ 21,748	$ 31,068	$ 11053	$ 25,791	$ 36,844
Taiwan	$ 3,451	$ 8,053	$ 11,504	$ 10,044	$ 23,437	$ 33,481	$ 13,496	$ 31,490	$ 44,986
Vietnam	$ 3,830	$ 9,849	$ 13,679	$ 13,134	$ 33,773	$ 46,907	$ 16,964	$ 43,622	$ 60,586
Total	$ 20,320	$ 67,154	$ 87,4744	$ 80,189	$ 229,123	$ 309,313	$ 100,510	$ 296,277	$ 396,786

Source: IEEFA estimates.

Solar PV features as a national energy diversification and decarbonization strategy in every Asia Pacific market. However, through 2030, except for Japan's proposed large-scale additions, the remainder of the Asia Pacific's ambitions for adding PV are modest. There is a step change in capacity growth proposed for the period from 2031 to 2050, with increased spending ranging from 300% in the Philippines to 1700% in South Korea per year as compared to the period 2025 to 2030. Should this level of investment materialize, there will be tremendous benefits to domestic supply chain participants, requiring a great ramp-up in supply chain outputs and an increase in human resource requirements.

Figure 19: Country-wise Solar PV Investment Value, 2025 to 2030 and 2031 to 2050

Total Investment Potential 2025 to 2025: US$394 billion



Source: IEEFA estimates. Country capacity additions based on national plan targets, adjusted outward in time based on current state of solar program implementation. Dollar values based on estimates of individual country localization curves.

Asia Pacific Solar PV Market Taken Together

In all, in the Asia Pacific, there are great prospects for solar PV project supply chain participation. A total of US$394 billion in investment is required to realize capacity additions of 617 GW through 2050. Approximately US$296 billion, or nearly 75% of the total, is focused on domestic non-panel, balance of system opportunities. That percentage share of the balance of system is consistent across the study period. Such a large proportion of value creates both immediate and long-term sustained opportunities for domestic solar BOS players. All that is needed to unlock this potential is positive, progressive, and supply chain-aware domestic policy.

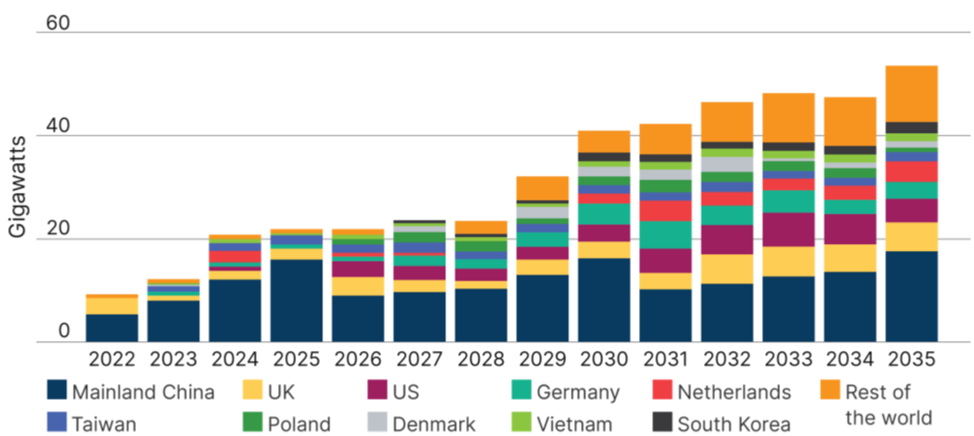
Offshore Wind

Offshore wind holds the potential to be the future of stable renewable energy supply. In most parts of the world, it is complementary to solar energy, available at night or, in certain parts of the world, available all day long. It is typically a highly reliable source of energy as wind speeds and occurrences offshore are more predictable and consistent than terrestrial wind power.

Growth of Offshore Wind

Figure 20 illustrates the projected growth of wind farms globally through the middle of the next decade. Offshore developments are projected to add about 20GW per year to 2030, whereafter annual additions are set to double into the mid 2030s. Currently, momentum is decidedly building as trailblazing large-scale offshore farms reach commissioning, while the next round of wind farms reach their final investment decisions and deploy hardware. With this momentum comes the refinement of outputs from supply chain participants, improved practical experience, and, in turn, refinement of costs.

Figure 20: Projected Global Annual Offshore Wind Farm Additions to 2035

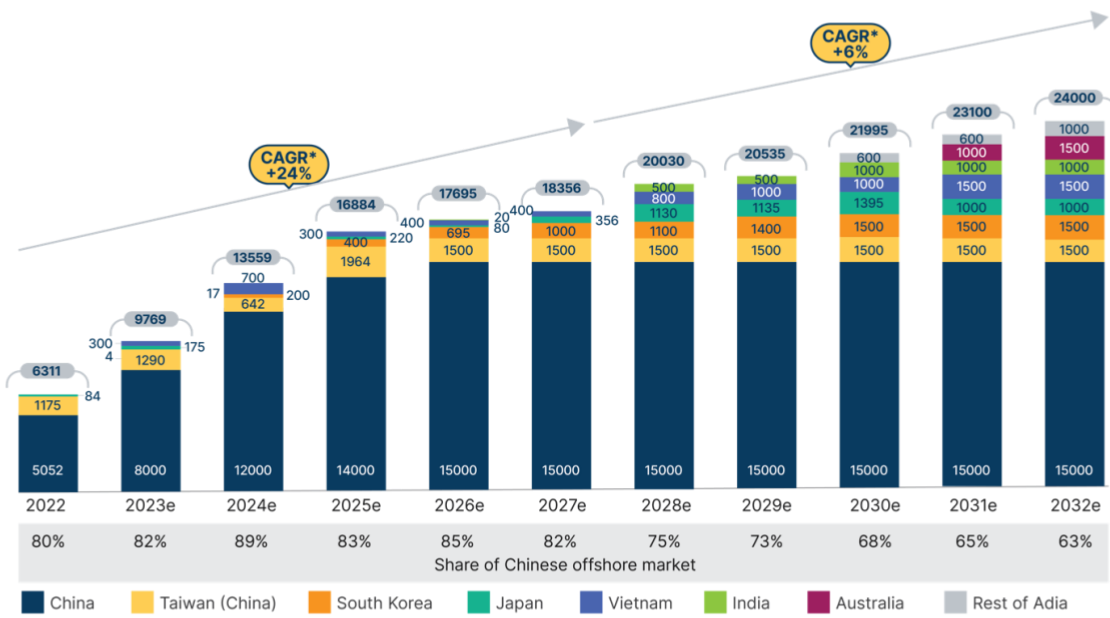


Source: Bloomberg Green. Offshore Wind's Next Big Problem: Not Enough Ships. March 18, 2024.

China has been steadily developing and deploying offshore wind farms over the past few years. The country has developed a fully vertically integrated supply chain for the sector, from domestically developed wind turbines to foundation fabrication to shipyards proficient in constructing the highly specialized vessels required to install facilities. However, nearly all this capacity has remained domestically focused as part of China's massive renewable energy build-out. The Chinese wind industry is currently at a practical equilibrium between national supply and demand for all components of the offshore system. China represents about 60% of the global installations for offshore and this is reflective of their roughly 60% average share of the supply chain. Such a self-serving balance creates, in the short-run, potential opportunities for non-China players to develop roles in the offshore supply chain and services ecosystem. It seems unlikely, given China's success in other key energy infrastructure supply sectors, that this equipment and the knowhow behind it will remain domestically contained for long.

At the same time, a limited number offshore wind developments in the rest of the Asia Pacific have been progressing. Taiwan has the largest program currently in implementation. At the end of 2023, Taiwan had 2,250 MW of offshore wind commissioned, with additions near 2,000 MW financed and entering construction; those farms have rolling completion dates through 2024-2026.[25] While smaller installations between 100 MW and 3000 MW are currently in development in South Korea and Japan, looking ahead, there are larger plans being put in place throughout the Asia Pacific region.

Figure 21: Asia Pacific Projected Offshore Wind Turbine Demand



**Compound Annual Growth Rate.*
Source: Global Wind Energy Council. Offshore Wind Report 2023. August 28, 2023

Price Projections

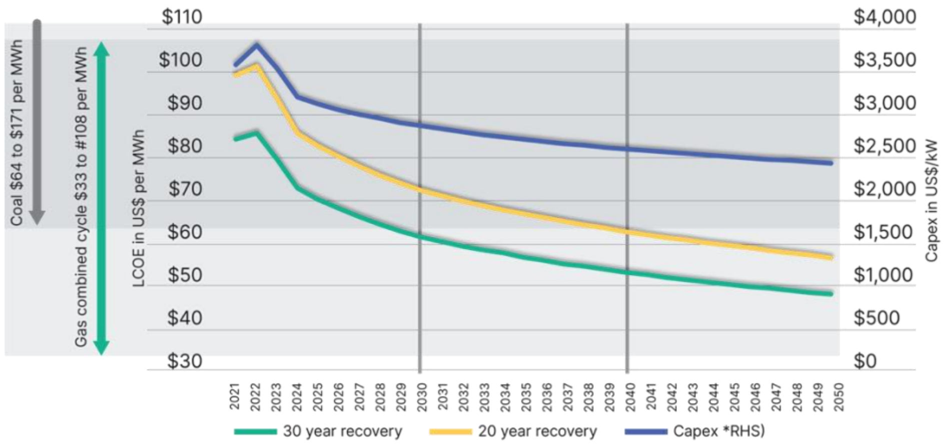
As momentum for offshore wind project implementation builds, so too does the development of supply chains to support it. This has led to decreasing costs for offshore wind, following trends set by onshore wind before it. According to the IEA, over the period from 2010 to 2022, the capital cost per kW installed for offshore wind dropped nearly 75% to about $3,460.[26] The corresponding levelized cost of electricity from those projects also plummeted, dropping from over $200 per MWh in 2021 to $81 per MWh in 2022. This begins to place offshore wind within the price bands of traditional fossil

[25] Ministry of Economic Affairs. Taiwan's offshore wind power installation exceeds 2GW to lead the Asia-Pacific region in 2023. March 13, 2024.
[26] IEA. Renewables 2023. January 11, 2024.

fueled electricity sources of coal and natural gas. Costs are slated to continue to drop as GW-scale wind farms in Europe, Taiwan, and the United States ramp up their installations.

According to estimates from the US National Renewable Energy Laboratory (NREL), offshore wind costs for the United States are expected to drop from US$62-US$72 per MWh in 2030, to US$53 to US$63 per MWh in 2040, and are projected to end up in a range of US$48 to US$57 per MWh by 2050 (See Figure 22). It is notable that NREL's projected costs are potentially at the higher end of the range as US costs for materials and labor are about 25%-30% greater than those in the Asia Pacific. These ranges of costs position offshore wind competitively with both coal and natural gas combined-cycle generation. Should any form of carbon tax or carbon pricing be applied in a given market, then offshore wind would move lower than its fossil fuel competitors. Even in 2023, absent a carbon price, and depending on the configuration of an offshore wind project and the locations and use cases of fossil fuel power plants, offshore wind was competitive with both gas and coal in a range of $72-100 per MWh.[27]

Figure 22: Projected LCOE for Fixed-Bottom Offshore Wind to 2050

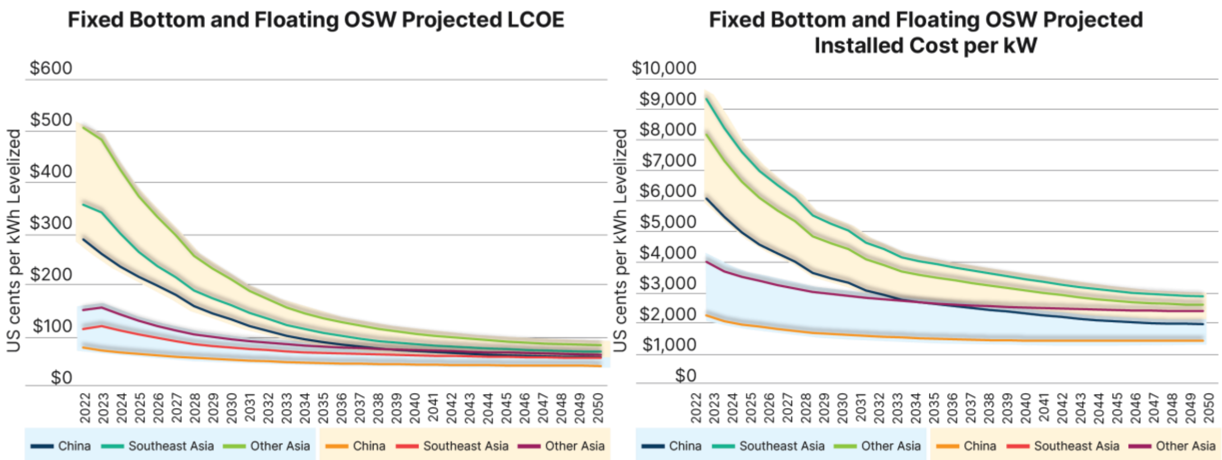


Source: IEEFA adapted from the following: LCOE, Capex – NREL Annual Technical Baseline – Offshore Wind 2023. July 15, 2023. LCOE range for Gas and Coal – Lazard. Levelized Cost of Energy Analysis, Version 16.0. April 2023.
Note: From the NREL model, costs for the wind farm assume 1,000 MW farm size, 9.2m/s average wind speed, fixed bottom installation, and 7.2% learning rate. Ranges for gas combined cycle on the low end assume Henry Hub gas price of $2.60 to $4.30 per mmbtu; price ranges for gas in the Asia Pacific are closer to US$9 per mmbtu, average.

For a comparison of trends between fixed-bottom and floating offshore wind modalities, Det Norske Veritas (DNV), in its annual Energy Technology Outlook, calculated some even more aggressive price drops for fixed-bottom offshore wind, reaching levels of US$39 to US$64 per MWh by 2050 (See Figure 23.) DNV's outlook also takes a pragmatic view of near-term offshore wind farm investments currently, with costs double to triple that of fixed-bottom wind. However, they also forecast a dramatic learning curve and scaling for the floating sub-sector, with costs dropping 40% by 2030 and by two-thirds of today's costs by 2050.

[27] Refers to Lazard's Levelized Cost of Energy Analysis v16.0. August 2023.

Figure 23: Offshore Wind Historic and Forecast LCOE and Installed Cost

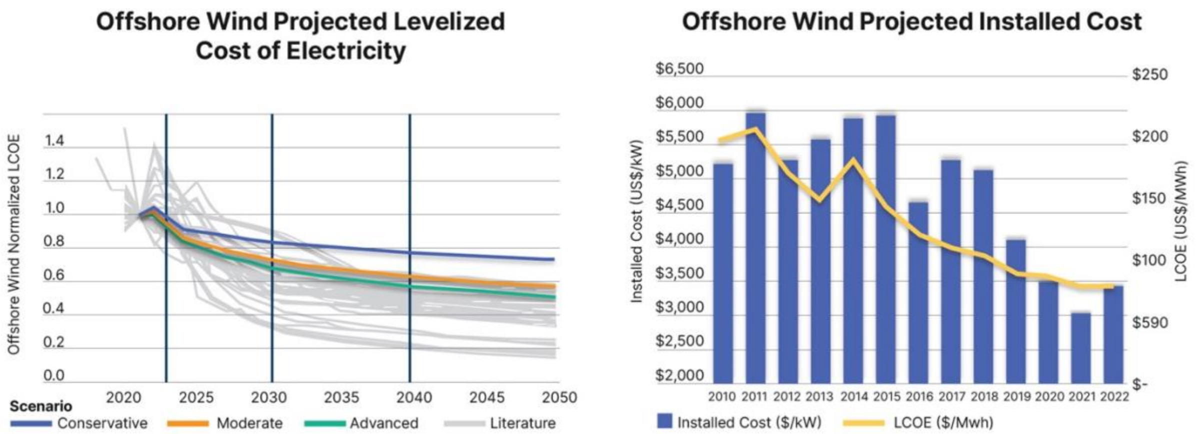


Source: Data adapted from DNV. Energy Transition Outlook 2023. October 11, 2023.

The bottom line with these projections is that, with the coming advances in wind turbine size, efficiency and reliability, wind turbine prices per MW will drop. Further, large-scale offshore wind farm LCOEs in Asia will plummet as deployments of offshore wind farms advance, and with the learning and economies of scale from non-turbine supply chain refinements discussed in this paper.

The biggest implication of these forecasts is that wind farms are moving into a position to undercut imported natural gas and coal, even in markets where those prices are subsidized, and in the absence of carbon pricing. This is particularly the case with natural gas combined cycle power plants in the Asia Pacific that are reliant on liquefied natural gas (LNG) imports. Typical supplied gas costs in the LNG import markets of Asia rise to anywhere between US$7 per million British thermal units (MMBtu) and $11 per MMBtu under long-term contracts, with spot cargo rates potentially higher, as seen in 2022-2023. With gas accounting for about two-thirds of the operating cost for combined cycle gas turbine (CCGT) plants, in most cases, in most Asian markets, such gas prices would set up offshore wind to be competitive with natural gas by 2030.

Figure 24: Offshore Wind Projected Costs



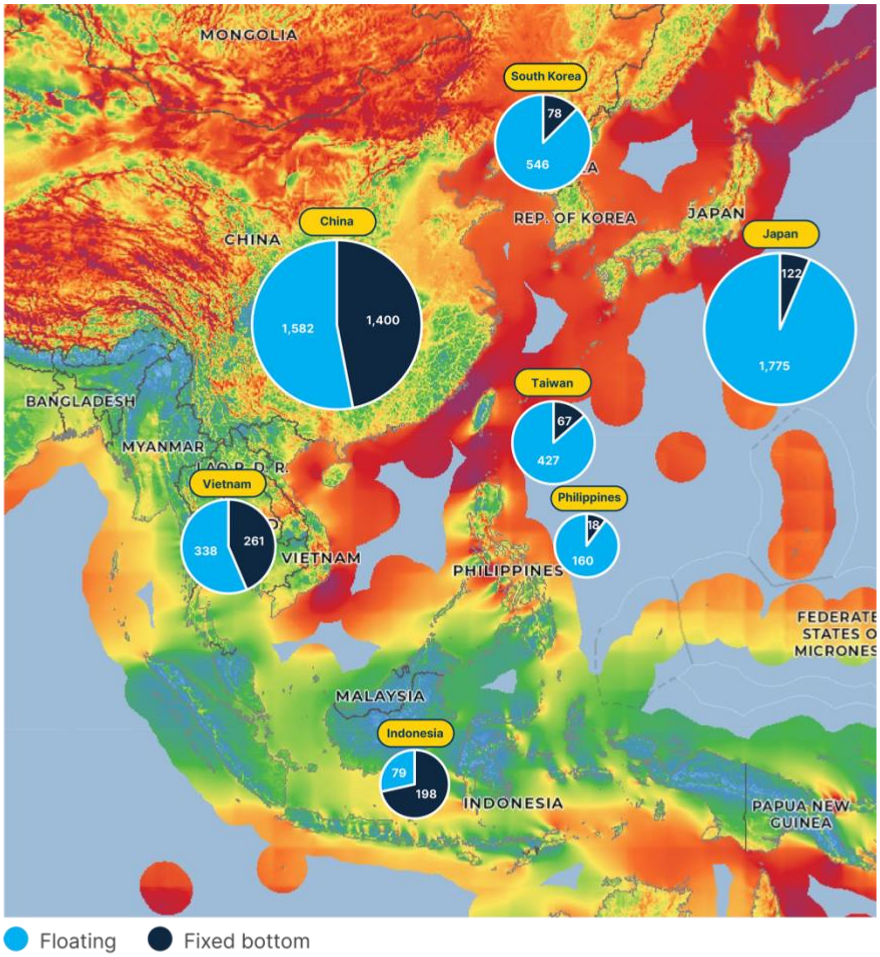
Sources: Left – NREL. Annual Technology Baseline for Offshore Wind, 2023. Right – IEA. Renewable Energy Costs 2023. August 2023.Offshore Wind Resources Available in the Asia Pacific

Offshore Wind Resources Available in the Asia Pacific

The allure of offshore wind is that it typically blows at moderate to high velocities, in the range of 7 meters per second (m/s) to 10m/s, in predictable patterns year-round. In the Asia Pacific, most countries possess areas of good to excellent wind resources. The resource potentials for countries have been estimated based on the Energy Sector Management Assistance Program of the World Bank. The capacity potentials far exceed even their largest energy need projections for most countries (See Figure 25).

For most countries, the farther offshore a wind turbine, the greater and more constant the wind speeds, thus resulting in the greatest generation capacity potential. However, this comes with the challenge of being in deeper water, likely requiring a floating solution. Indonesia appears to be an exception due to its island topography featuring shore proximity in the more limited windy areas. Further, in countries like China and Vietnam, extensive shallower continental shelf areas combined with strong coastal winds create greater potential for fixed-bottom installations, which bodes well for cost of these projects.

Figure 25: Offshore Wind Capacity Development Potential for Fixed Foundation and Floating Turbines

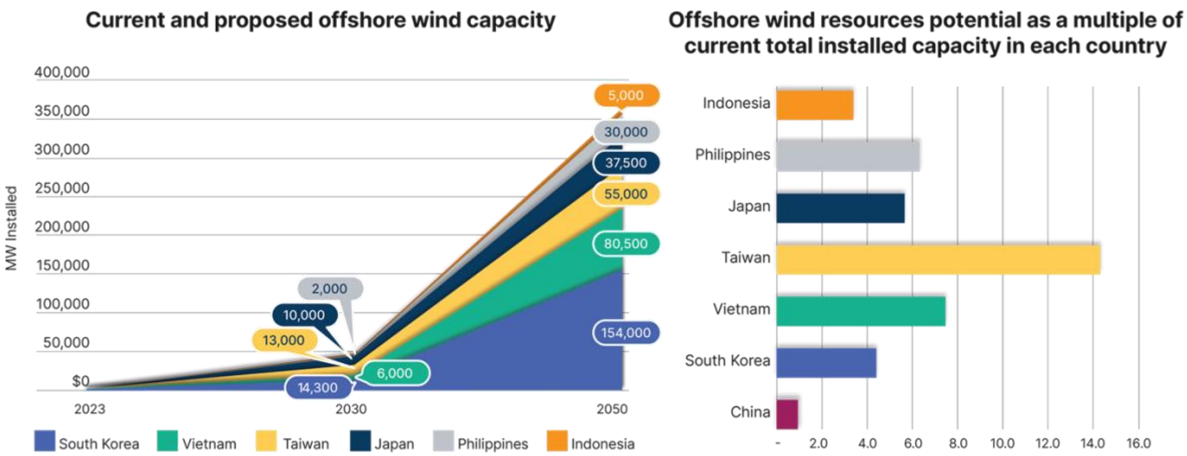


Sources: Adapted from Bulletin of the American Meteorological Society, Volume 104: Issue 8, Pages E1507-E1525. The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. August 2023. Link to the Global Wind Atlas application can be accessed here. Fixed foundation versus floating capacity potential is from World Bank Group Energy Sector Management Assistance Program. Offshore Wind Technical Potential.

In concert with these wind resource quantifications, offshore wind has been incorporated into national decarbonization plans as part of each country's Nationally Determined Contribution (NDC) targets under the 2015 Paris Climate Agreement. The current offshore wind capacity targets for the countries are shown in Figure 26. Most countries' plans represent only fractions of their potential offshore wind build-out. China is the most ambitious, whose current plans seek to exploit about 34% of the theoretical wind resources available in practical territorial waters. At the other end of the spectrum, Japan is currently looking at making use of only about 2% of its offshore wind resource potential.

In almost every major Asia Pacific economy, the potential offshore wind capacity available exceeds the total installed capacity of each country's grid by multiples. Even in the case of China, offshore wind capacity potential is roughly equal to the country's current total installed capacity. Of course, for practical reasons, exploiting full offshore capacity is impossible due to the existence of shipping lanes, protected marine sanctuaries, fishing grounds, and constraints on interconnection to the land-based grid. However, even accounting for these limitations, the magnitude of resources available could satisfy material portions of grid demand, even after accounting for areas that lack practical development potential.

Figure 26: Asia Pacific Regional Offshore Wind Capacity Targets

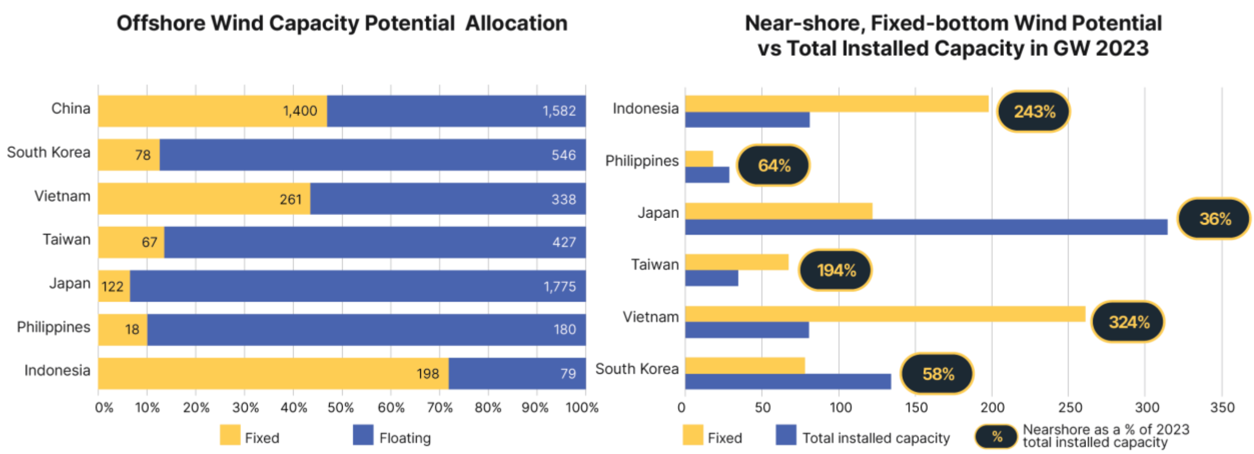


Source: World Bank Group, Energy Sector Management Assistance Program. Offshore Wind Technical Potential.

Nearshore, fixed-bottom wind turbine installations are far more numerous and are proven to be cost-effective globally. Floating offshore farms are currently under construction but have yet to ramp up to scale in operation. However, floating wind is a fast-emerging sector where the learning curve will bring great efficiencies and cost reductions in the coming years.

Nearshore versus deep water opportunities vary by country across the Asia Pacific. In Vietnam and China, there are nearly equal resources available in shallow and deep water; in Indonesia, the majority of the opportunity is in shallow water. In these countries, shallow water wind resources are sufficiently generous that they can be the preferred means of development for the foreseeable future. In some countries, however, such as Japan, the Philippines and South Korea, the majority of the wind resources opportunity is in deep water. However, these steep biases towards deep water should not put off wind farm development, as the capacity potentials tell a bigger story. In the medium term, there appears to be enough nearshore developable wind resources to provide material inputs to each country's decarbonization efforts. The chart to the right in Figure 27 shows that even in Japan, where shallow water locations are far fewer than deep water, the country could add an equivalent of 36% of today's total installed generation capacity in shallow waters before having to move to more challenging locations.

Figure 27: Allocation of Shallow Water and Deepwater Potential for Offshore Wind



Source: World Bank ESMAP. Global Wind Atlas. August 2023.[28]

Lower cost, nearshore development potential could meet material percentages of national energy needs in almost every country in the region.

With the combination of wind resource potential and national government plans to tap it, there is a growing regional critical mass of offshore wind activity. China, which is adding about 10 GW of offshore wind per year, is well underway to secure a diversified energy supply portfolio based on wind. Elsewhere in the Asia Pacific region, the most active market is Taiwan, which is currently implementing offshore wind at a large scale. To their 2.25GW base, Taiwan is adding about a gigawatt per year to 2030. Vietnam, which granted generous feed-in tariffs to renewables of all varieties through 2021, saw a swift addition of 1 GW of offshore wind. That activity has now calmed while the government considers a revised tariff regime. Elsewhere in the region, efforts remain nascent, and are still in the planning stage. However, offshore development areas and development licenses have been issued in Japan, South Korea and the Philippines, which are critical steps in advancing projects.

As seen in the European offshore market, scale is key to lower prices and faster realization. Yet offshore wind infrastructure and services in the Asia Pacific remain limited, mostly concentrated in China, and those resources are focused almost exclusively on Chinese projects. The offshore wind builds outside of China are making use of regional fabrication services in ports spread across Singapore, Vietnam, and to a limited extent, Taiwan for domestic farms.

For scale economies to be achieved, and prices to truly drop within the region, more of the Asia Pacific maritime economy needs to be engaged. If the offshore wind sector is to rise to meet the targets that countries have proclaimed, creating the necessary policy and infrastructure conditions

[28] Data obtained from the Global Wind Atlas version 3.3, Technical University of Denmark (DTU) and the World Bank Group Energy Sector Management Assistance Program (ESMAP). August 2023.

for investment to flow – whether to ports, vessels, manufacturing or offshore services – requires attention. There is major potential for supply chain development and active participation at scale in almost every country in the Asia Pacific.

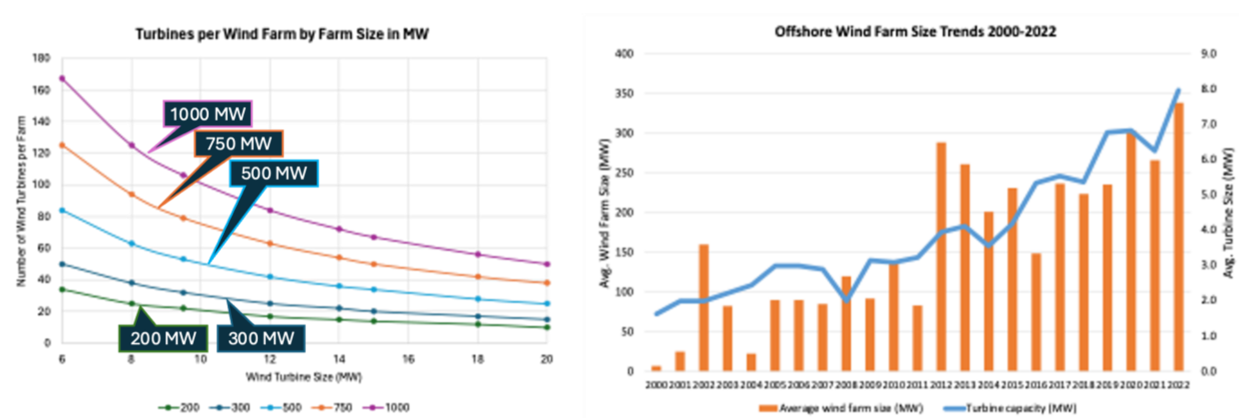
Evolving Offshore Scale Economies

Offshore wind farms are tending towards configurations with fewer wind turbines but far larger generating capacity. The initial wind farms in the United Kingdom, starting in 2003 and running through the 2010s, used 3-6 MW turbines. Thus a 1 GW wind farm, even using 6 MW technology, would require 167 wind turbines and foundations.

In the 2020s larger turbines have become available. Now European wind farms are employing 9.5-10 MW turbines, with the next phase of the UK's Dogger Bank currently installing 12 MW units. A 1 GW wind farm using a 9.5 MW turbine requires 106 turbines, towers and foundation elements. Increasing the turbine size to 15 MW, now under consideration for large-scale wind farms, reduces that number to 67. As a result, globally, the total capacities of offshore wind farms are getting larger. In the 2010s, most wind farms were in the 100 MW to 300 MW range; the latest wind farms approved in 2024 are around 1 GW capacity. Figure 29 shows the tradeoffs of turbine size and wind farm capacity, while Figure 30 tracks the growth of average turbine size available over the years.

The next generation of Asian wind farms will likely be able to skip the smaller scale turbines altogether and look exclusively at 9 MW and larger machines. This saves greatly on the number of foundations required, the number of vessels required to move those foundations and install the turbines, and reduces cabling connections amongst the turbine arrays.

Figure 28: Number of Turbines and Foundations Based on Turbine Capacity and Wind Farm Size



Source: Left – IEEFA. Right –NREL. 2022 Cost of Wind Energy Review. December 2023.

Figure 29: Wind Turbine Size Trends and Comparison

Source: Van Oord. Van Oord Orders Mega-Ship. October 1, 2021.

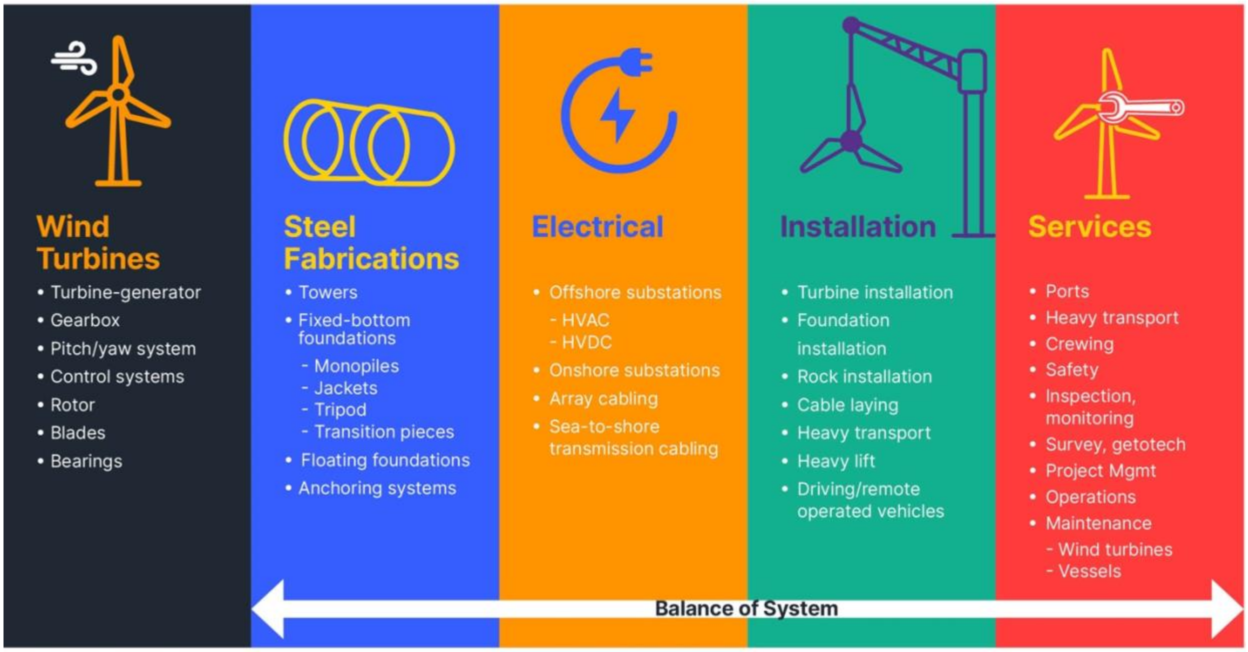
Offshore Wind Supply Chain Elements

Offshore wind farms hold the potential to tap a material amount of domestic and regionally sourced inputs. The turbine itself accounts for about 37% of the total project cost for fixed foundation wind farms, dropping to 27% of total project costs for wind farms with floating foundations. Thus, the bulk of offshore wind farm costs focus on foundations, transmission systems, and installation logistics. While most high-technology key components in the wind turbines are sourced from a limited number of original equipment manufacturers (OEMs), a number of key components need to be integrated nearer to the final location of installation due to their size and mass. Towers, blades, and rotor hubs are the most apparent. When combined with the massive fabrications for their foundations and the construction logistics needed to install them, offshore wind presents a large opportunity.

Offshore Wind Supply Chain Overview

Figure 30 below lists the general categories of components, products, equipment, infrastructure, and services needed to implement an offshore wind farm project.

Figure 30: Elements of the Offshore Wind Farm Supply Chain



Source: IEEFA.

The offshore wind turbine supply market has a limited number of players, with China having about two-thirds of the global total and Europe, the US and South Korea accounting for the ex-China market. Siemens-Gamesa, Vestas, and GE Vernova are the mainstream Western offshore turbine suppliers. South Korean companies have been investing in turbine development, with Doosan Enerbility commissioning its prototype 8 MW turbine in October 2023. Samsung has validated a 9.5 MW design while Hyosung is currently developing a 10 MW turbine.

Until recently, Chinese manufacturers almost exclusively served their domestic offshore wind market, with manufacturing capacity nearly matching installation rates. Now, however, the first cross-border deals are commencing, with Shanghai Electric and Mingyang venturing into Korean waters. Chinese turbine manufacturers are also in a race to announce increasingly larger wind turbine capacities, offered with a variety of blade lengths to more efficiently cover mid-speed to high-speed wind resources.

Figure 31: Offshore Wind Turbine Offerings

Size Offshore Turbine produced *MW Class*

Company	4	5	6	7	8	9	10	11	12	13	14	15	16	18	20
ex-China															
Vestas						9.5						15			
Siemens Gamesa					8			11			14				
GE Vernova			6						12		13.6				
Samsung						9.5									
Doosan	5.6				8										
China															
Mingyang		5.5		7.25	8			11			14			18	20
CSSC Haizhuang			6.2		8		10		12					18	
Dongfang										13				18	
Windey						9	10					15	16		
Goldwind			6	7	8					13					
CRRC		5	6	7			10								
Sany						9									
Shanghai Electric	4				8.5										
Envision			6												
Sinovel			6												

Source: Manufacturers' websites, press releases, accessed March 2024.

Port Infrastructure. Offshore wind requires sizeable marine infrastructure including appropriate port facilities and a wide variety of specialized vessels. Landside port facilities require large fabrication and marshalling yards for heavy, large-scale components, with ideally a minimum area of 20 hectares. Quaysides need to extend from at least 200m for fixed-bottom supports to over 500m for floating farms to accommodate berthing of the types of vessels for carrying the massive components. Port quaysides need to be level with the cargo area of the ships that will transport the components to facilitate roll-on roll-off operations. Drafts of up to 20m can be required, potentially deeper, if floating offshore foundation structures are to be outfitted quayside.

Portside facilities require highly reinforced quays and assembly areas, provisions for heavy lift cranes, and the space for stockpiling input materials, received components, fabrications in process, and completed sets. When a wind farm is under construction, there could be dozens of piles, foundation assemblies, and towers present in these yards simultaneously.

When nacelles, the enclosures that contain the turbine gearing and generation systems, arrive at port, they can have a mass in excess of 750t for the largest turbines. This machinery will ultimately need to be lifted to heights of 200m to the top of the combined tower-foundation structure upon which it will rest once out at sea. Foundation elements, whether for fixed or floating turbines can have assemblies standing 100m tall and weighing up to 5,000t. Offshore transmission system substations, which are assembled as a single-piece unit and placed atop a foundation platform at sea, can weigh up to 20,000t.

Specialized equipment is needed to move these massive fabrications around the port site. Multi-wheeled, self-propelled, synchronized moving platforms to roll components around yards and massive heavy lift cranes are required, along with expertise in specialized logistics operations.

Appendix C provides a more detailed overview of the full range of equipment, vessels, yards and fabrication facilities required for offshore wind farms.

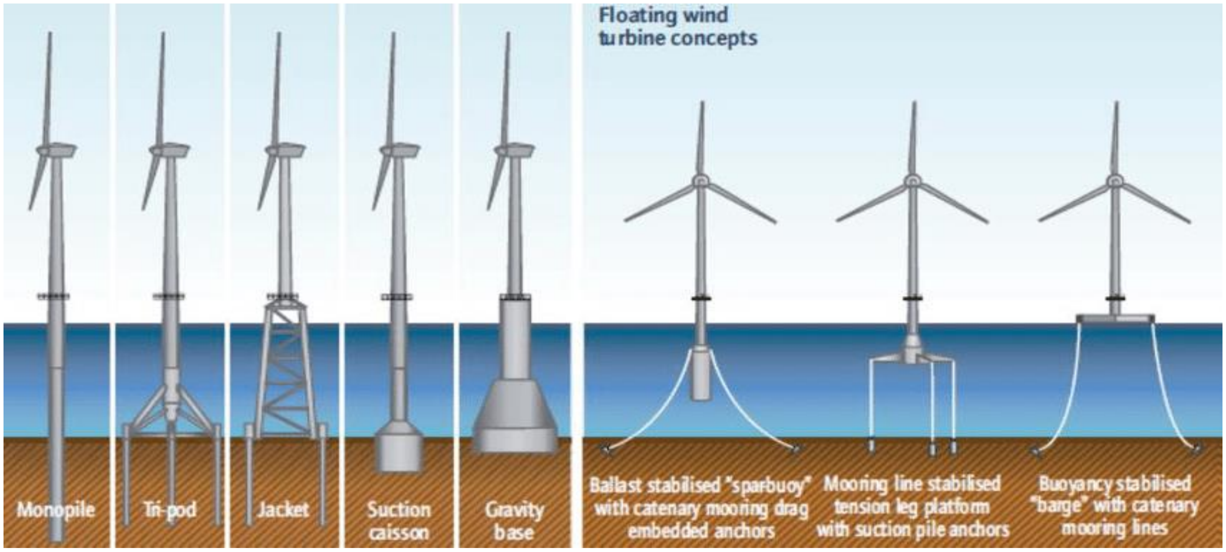
Specialty material suppliers. There are many steel forgings, castings and fabrications required for offshore wind. These components go into the foundations, the joints between the foundation and the tower, the towers themselves, as well as the connections between the tower and the nacelle. Creating these components requires high-quality forgings or steel plate, along with advanced cutting, shaping and welding equipment and skills. These fabrications must be finished to high tolerances, painted and coated to resist the corrosive forces out at sea. All this work must be done in appropriately designed and outfitted facilities to assure the highest quality. Ideally, given the size of the piecework produced, the facilities should be located near ports to enable the smooth transfer and integration of the output.

Specially designed subsea cables are needed for the transfer of generated electricity from the turbine to the shore via the substation. These are accompanied by protection systems to deal with harsh sea conditions and protect against ship anchor strikes. Substations for power conversion and transfer can be either high voltage alternating current (HVAC) or high voltage direct current (HVDC) depending on how far offshore the station is situated. Integrated substation topsides are delivered as fully assembled and tested units to be placed offshore.

Fabrication yards. Nearly all major foundation fabrication could be done in the destination market for the wind farm if countries move on the opportunity. The risk is that existing marine service centers could move to corner this market. There are very similar skill sets and fabrication scales between offshore wind and the offshore oil and gas industry. Thus, fabrication centers used to working on oil and gas, like Singapore; Vung Tau, Hai Phong and Khanh Hoa in Vietnam; Batam in Indonesia; or various Chinese yards, hold the potential to capture market share. The tradeoff between regional fabrication and local fabrication comes down to the ability and the cost of moving completed components by towing or carrying them on heavy transport vessels to destination markets. Open ocean-going heavy lift vessels are in development that could permit longer distance transport of completed large-scale components. This is currently, however, an expensive – and potentially risky – alternative to localized assembly. Risk arises when valuable completed components have to be transported across open waters, subject to the vagaries of sea and wind conditions. The chance of fabrications being lost or damaged rises as the scale of the offshore wind farms increases. Thus, developing a localized high-quality fabrication capability holds strong competitive potential.

Foundation structural systems for offshore come in a wide array of sizes and types, designed to match the seabed geological conditions, and the size and sweep of the wind turbine. At times, with changing subsurface conditions, more than one type of foundation might be used on one wind farm. Figure 32 below illustrates the range of fabrications that yards might possibly produce.

Figure 32: Range of Offshore Wind Foundations, Fixed and Floating



Source: Konstantinidis, E and Botsaris P. Wind turbines: current status, obstacles, trends and technologies. IOP Science. November 2016.

Personnel. Skilled workforces are necessary for implementing each component and each phase of these facilities. Offshore installation and maintenance is highly specialized. Fabrication requires high-quality welding and finishing labor. All equipment, marine or onshore, requires skilled operations and maintenance personnel. Shipyards and marine services are required for day-to-day vessel support. The offshore wind industry feeds into and can leverage the maritime economy elements that already exist in most of the Asia Pacific.

According to the Global Wind Energy Council, an offshore wind farm requires about 50% more labor hours per megawatt than the equivalent onshore wind farm. By their example, a 500 MW offshore wind farm demands an estimated 2.1 million person-days to implement over its life, with 70% of those hours occurring during fabrication and installation. Over 40% of those hours are allocated to highly skilled professionals.[29]

Where Value is Created in the Offshore Wind Supply Chain

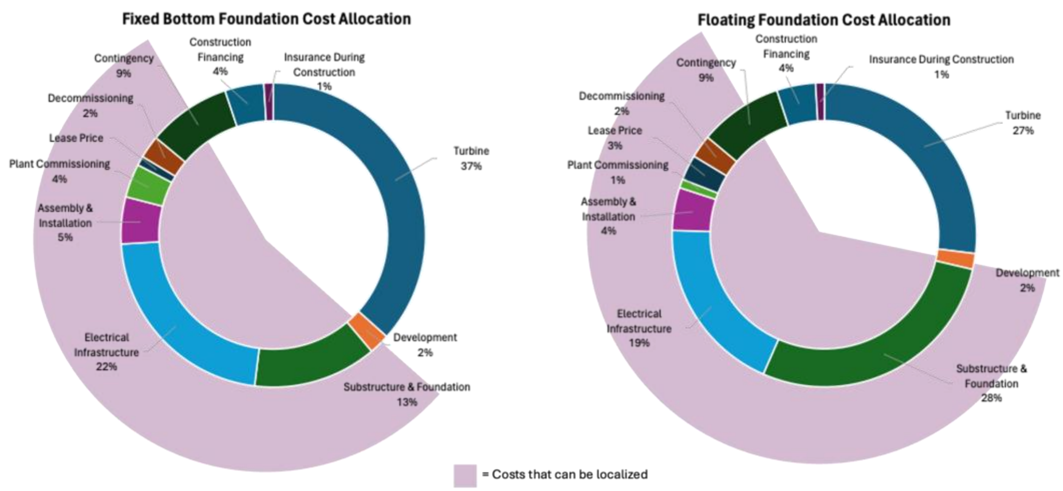
Offshore wind, by the nature of project design and components, holds great potential to spread benefits of supply and participation across a wide array of participants. While there are a limited number of wind turbine manufactures, there can be many suppliers of materials, fabrication services, logistics and handling, a majority of which need to be sourced within the country where the wind farm is being developed. Turbines are among the few pieces of equipment for wind farms that currently must be sourced from a limited number of established manufacturers.

Figure 33 provides a breakout of the cost category of expenditure for both fixed-bottom and floating wind farms. Given the higher fabrication requirements of floating wind farms, the share of non-turbine costs is higher. Using numbers from the US National Renewable Energy Laboratory (NREL),

[29] Global Wind Energy Council. Global Wind Report 2024. April 2024.

the amount of budget the wind turbine absorbs is between 27% and 37% of total project cost, depending on whether an offshore wind farm is fixed to the sea floor or floating. After subtracting out financing costs and insurance, local and/or regional suppliers and service providers have between 55% and 65% of the total budget available for their participation. If domestic financing and insurance coverage are added in, those totals can reach a range of 60%-70%. With over 64 GW of offshore wind currently in operation and another 380 GW proposed globally over the next 10 years, there are huge opportunities to participate in the supply chain.

Figure 33: Typical Break Out of Offshore Wind Costs by Foundation Type



Source: NREL. 2022 Cost of Wind Energy Review. December 2023. Local content potential: IEEFA estimates.

In the Asia Pacific, it is still the early days of offshore wind farm development, and supply chains are evolving. Taiwan provides an excellent illustration of how sourcing is addressed: despite its preference for local content in its bidding structures, only a subset of wind farm components can be sourced domestically. Wind farms there draw on a wide range of suppliers, fabricators and service providers globally. This diversity is illustrated in Box 2, which provides an overview of the Changhua Wind Farm in Taiwan. There, 27 contractors from a dozen countries have been brought together to deliver the wind farm. Ten of those contractors are from Taiwan, but some of the major fabrications, like the turbine foundations, are being sourced regionally from yards in Vietnam.

Box 2 - Greater Changhua Wind Farm, Taiwan

Greater Changhua is in located in the Taiwan Strait Phase 1 is 605 MW and Phase 2a of 295 MW, totaling 900 MW. Construction commenced in November 2019 and was commissioned progressively over a period from April 2022 to December 2023. The two phases are now fully operational. Power is sold to national electric utility, Taiwan Power Company (Taipower), under a 20-year power purchase agreement (PPA), based on a feed-in-tariff. Scoring for the consortium's selection had weighting towards local content to encourage the development of domestic suppliers and service providers.

The farm is near shore, 35-60km, fixed bottom, 34m to 44m water depth. It uses 112 Siemens 8MW SG 8.0-167 DD, 167m rotor diameter with 81.4m long blades. Two offshore substations are connected to the shore by two 55km HVAC transmission cables.

Equity sponsors: Ørsted, Denmark holds 100% of Phase 1, and is partnered on Phase 2a with two financial investors, 25% Caisse de dépot et placement du Québec and 25% Cathay Private Equity, with Ørsted holding the remaining 50%. Debt financing raised $2.76 billion of export credit from four different agencies and commercial debt facilities with tenors of 18 to 20 years.

Phase 2b 337MW and Phase 4 of 583MW, totaling 920 MW, achieved financial close in October 2023 and construction commenced immediately. Final completion will be in 2026, thus a 24-to-32-month implementation period. These phases were competitively awarded (no FIT) and as such have no local content requirements. 100% of the power output is being sold to Taiwan Semiconductor Manufacturing Company under a fixed-price corporate PPA over 20 years.

There is an optional 600MW stage, Phase 3, where no investment decision has yet been made.

The Phase 1 and Phase 2a projects have 27 subcontractors working to complete various aspects of supply, fabrication, installation, and commissioning works. There are 10 Taiwanese contractors, 5 from the Asia Pacific, and 12 from Europe.

Engineering	Demark, Taiwan
Ocean Survey	UK, Taiwan
Turbines, blades, towers	Spain/Germany
Steel fabrications	Taiwan, Vietnam
Shipbuilding	Taiwan, Japan, Singapore
Heavy Lift/Transport	Germany, Netherlands
Specialty concrete products	Germany
Pumps and mechanical	Norway
Cable manufacturing	Netherlands
Cable Laying	Netherlands, Taiwan
Subsea foundation monitoring	UK
Specialty coatings and sealants	Sweden
Dredging/seabed preparation	Belgium

References: Power Technology. Greater Changhua Offshore Wind Farms, Taiwan. December 1, 2023. TXF intelligence. Changhua 1 and 2a Offshore Wind Farm - EKF/UKEF/Atradius Covered Loan. October 2021. Ørsted, March 30, 2023.

Offshore Wind Supply Chain Opportunities

Market size estimate assumptions

The estimated value of supply chain opportunities in wind was based on each regional government's stated target portfolio contribution from offshore wind. This mostly consists of capacity targets in megawatts for 2030 and 2050. IEEFA adjusted the 2030 targets to account for the extent of progress achieved to date with offshore programs, resulting in most countries' initial projects being pushed back in time. The surest sign of imminent progress is the achievement of financial close on a project; that means money will be spent. Ahead of that point there are many details on permits, approvals, composition of the engineering, procurement and construction contracts, and the final investment decisions from the developers that need to take place. Challenges or uncertainties with any of those elements could lead to delays.

As of early April 2024, only Taiwan has projects that have reached financial close within the last 6 months. Development rights have been awarded in Japan, South Korea, and the Philippines. Based on current progress reports, however, the implementation date for those projects remains uncertain. There has been no action on offshore wind taken in Indonesia to date. Vietnam has extremely high ambition in its offshore wind plans, based on official targets to 2050, but it appears unlikely that the first rounds of projects would be completed in any volume ahead of 2030. Bankability of power purchase agreements, along with unresolved issues on tariff structures, bidding procedures, and transmission interconnect signals are known issues cited amongst foreign investors. It may take some time before conditions are ripe to resume their wind program.

The greatest unknown in each country is connectivity to the national transmission grid. Where landfall will be, what strengthening and improvements are required to accept those concentrated inputs, and how those costs will be borne are all still open considerations in project approvals.

Further, a general consideration across the region is the need for appropriate port and fabrication yard infrastructure to be in place. In the Philippines, where nearly 60 GW of offshore development rights have been handed out, the current port infrastructure in the country is insufficient to handle the type of fabrications and component movements required for offshore structures of the type that will be required; that situation would be exacerbated if multiple projects were implemented concurrently. It is unclear when such port upgrades might be implemented. By contrast, South Korea, with its world-class shipbuilding and fabrication yards, backed by heavy industry, is more immediately adaptable to the demands of the offshore wind supply chain should the country decide to focus on it. In general, regional shipbuilding and oil and gas fabrication service centers in Singapore, Batam in Indonesia, Vietnam, South Korea and China can all serve as initial supply points for regional offshore wind development. While fabrications will need transport to their final destination, such a regional sourcing approach has proven feasible so far for Taiwan.

Offshore Wind Farm Market Value to 2050

Based on the stated national development plans for offshore wind farms in each Asia Pacific country, order-of-magnitude assessments have been made to estimate the annual needs for materials and services. The evaluation looks at fabrications, supplies, and services specific to each wind farm. Vessels needed for installations and maintenance are pooled for the Asia Pacific region and estimated separately in the next section below. IEEFA made assumptions on the degree of local, regional, and extra-regional procurement spend based on the current state of manufacturing, fabrication, marine logistics, and related capabilities in each market.

“Extra-regional” is defined as supply proportions coming from non-Asia Pacific origins, whereas “regional” means primarily inputs source from China and from amongst the countries in this study. Localization was progressively applied over time, such that, except for wind turbines, in most cases the majority of supply chain and services would eventually be brought into domestic markets, presuming the size of the market was large enough and sufficiently consistent to warrant that. A consistent market was defined as one that assures at least 1 GW wind farm build-out per year through 2050. For wind turbines, a notable localization exception is South Korea, where domestic development of offshore-scale wind turbines is advancing toward deployment. This would mean that South Korea could become another regional supply competitor to China over the course of the assessment period. That potential is considered when allocating costs to regional suppliers.

Summary of Offshore Wind Investment

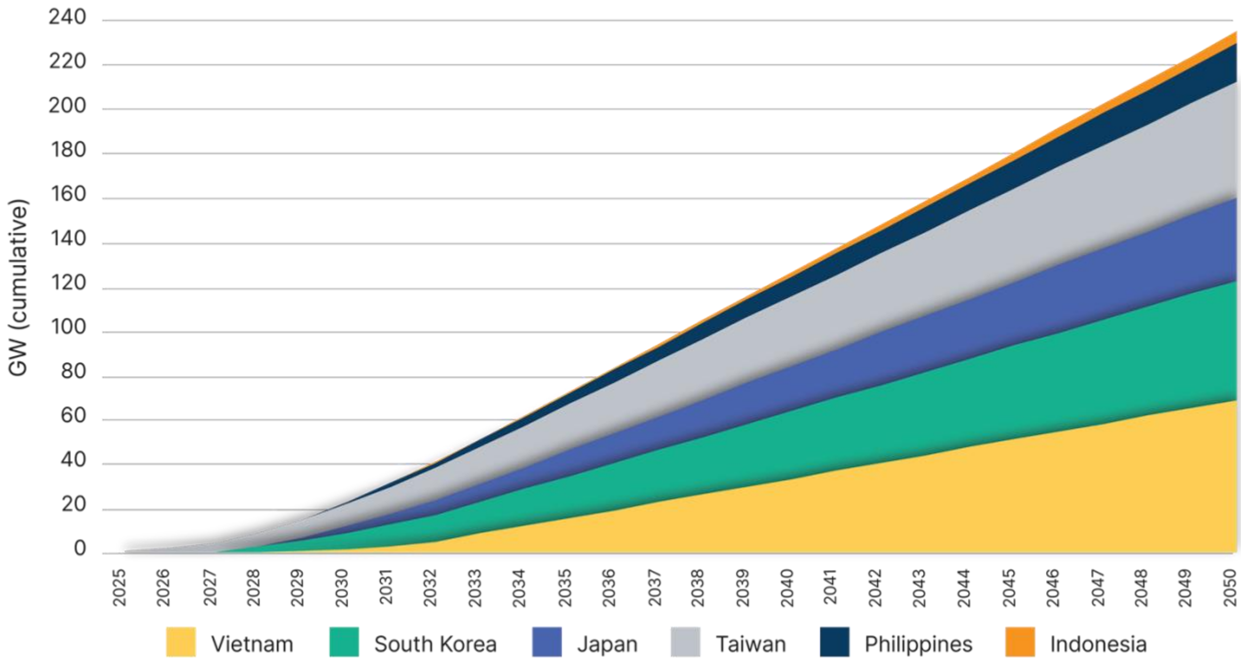
The investment potential for offshore wind in the Asia Pacific is estimated to be US$621 billion through 2050, helping to create over 239 GW of capacity. About US$76 billion worth of wind farms are developed by 2030, enabling 27 GW of offshore capacity. However, the bulk of offshore wind development follows between 2031 and 2050 with an investment of US$545 billion driving the addition of 212 GW. The total non-wind turbine proportion of this spend is US$360 billion by 2050 or nearly 60% of total investment, with local content rising nearly 20 percentage points between 2030 and 2050.

Table 4: Asia Pacific Estimated Offshore Wind Market 2025 to 2050 (USD Billions)

	2025 - 2030			2031 - 2050			Total to 2050		
	Ex-region	Regional	Local	Ex-region	Regional	Local	Ex-region	Regional	Local
Investment	$ 17,309	$ 25,259	$ 33,747	$ 12,144	$ 141,478	$ 384,256	$ 29,453	$ 166,737	$ 418,003
	$76,315			$537,877			$614,192		
Capacity	26,760 MW			212,306 MW			239,065 MW		

Source: IEEFA estimates.

Figure 34: Cumulative Offshore Wind Additions 2025 to 2050

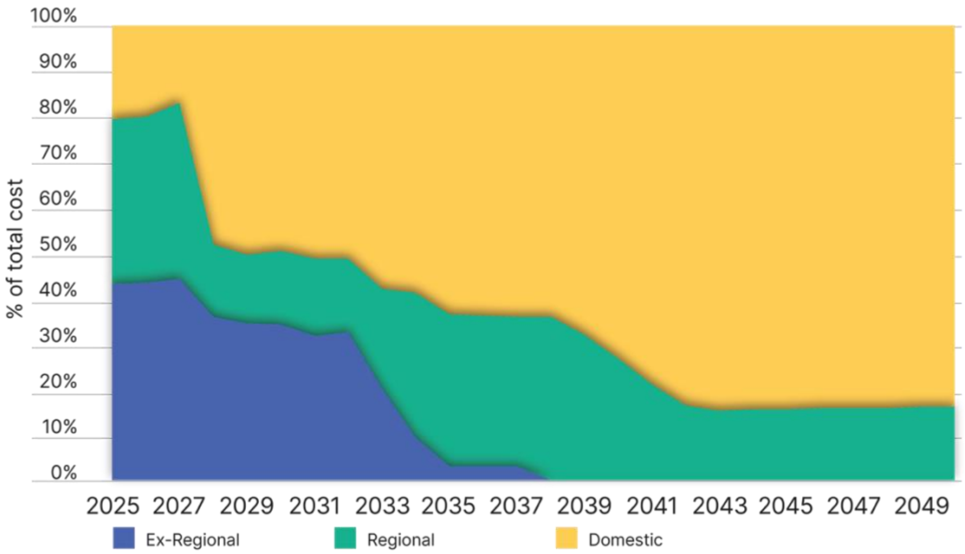


Source: IEEFA estimates. Above is the aggregate of each country's individual growth in additions based on national plans, adjusted for current state of offshore wind program implementation.

The dollar values in this estimate account for investment in wind farms only and do not include investments in port infrastructure or shore-side facilities that might occur through government, private sector, or public-private partnerships. While port investment and fabrication facilities are a necessary part of the offshore wind industry, specifics of needed investment are not included here due to the wide variability of existing port facility characteristics in the region as well as their geographic spread. The figures here also exclude marine vessels required to construct and maintain these wind farms; however, that estimated investment is provided in the section that follows.

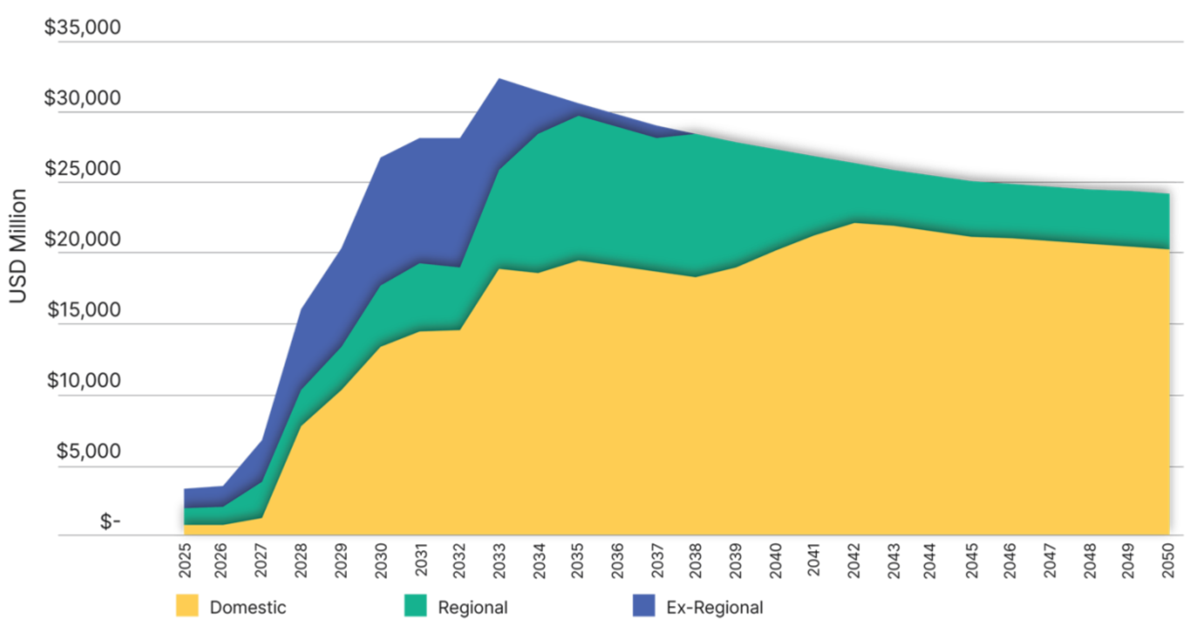
With regional implementation at such a scale, it is projected that, over time, a sustained level of activity will drive most components of the offshore wind supply chain to be localized. Current assumptions already see supply chain localization of 50% by 2030 for projects in implementation or development, increasing to about 80% by 2050. Based on projections in this study, that would capture US$391 billion of project investment.

Figure 35: Asia Pacific OSW Localization Trend to 2050



Source: IEEFA estimates. Above is the aggregate of individually determined country localization curves.

Figure 36: Regional Estimated Offshore Wind Investment Value 2025 to 2050



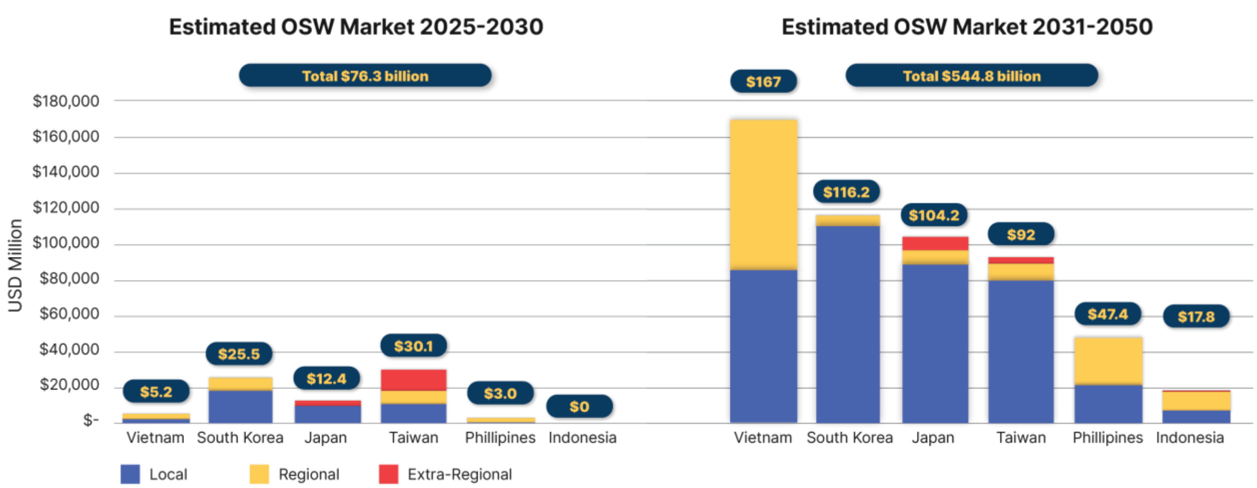
Source: IEEFA estimates. Estimates are linked to currently stated national offshore wind development targets, adjusted outward in time based on current status of each national program.

Despite the large long-term prospects for offshore, near-term estimates of wind farm build-out are projected to be very low. IEEFA assumes that unless a government is currently, in 2024, actively engaged in bidding, negotiating, and finalizing contracts and/or approvals for wind farms, it would be a challenge for a wind farm to reach its financial close and start construction before 2030.

First-of-their-kind infrastructure projects will always take longer due to unforeseen complications. For offshore wind, there are many extra technical, economic, environmental, and social considerations to sort through before a government can approve a project and before the investor on the other side of that approval can close on its contracting and financing arrangements. Port infrastructure, fabrication yards, and manufacturing facilities must be in place in advance of construction. Many of those facilities can have preparation lead times stretching from one to three years. Accordingly, IEEFA estimates push out the commencement of a country's offshore wind program based on where progress sits today. Below, nearly all contemplated wind farm realizations take place after 2030.

Taiwan has the most active offshore program, with tangible targets, and it is assumed that the policy conditions will be kept in place for that build-out to continue. Programs are ramping up in South Korea and the Philippines such that wind farms of scale may start construction before the end of the decade, presuming issues on transmission access are proactively addressed. Prospects are higher in South Korea for a pre-2030 start, as their port, shipbuilding, and fabrication infrastructure are in advanced states. Japan's trajectory is tentative, given issues on fishing grounds and similar transmission access issues as South Korea and the Philippines. To date, offshore wind farms in Japan have been implemented at small scale – below 100 MW each, keeping per-MW costs high. Recent development area allocations hold the promise that Japan may be able to start realizing scale economies from offshore wind, though the industry remains in a "first generation" state of development.

Figure 37: Country-wise Offshore Wind Investment Value, 2025 to 2030 and 2031 to 2050

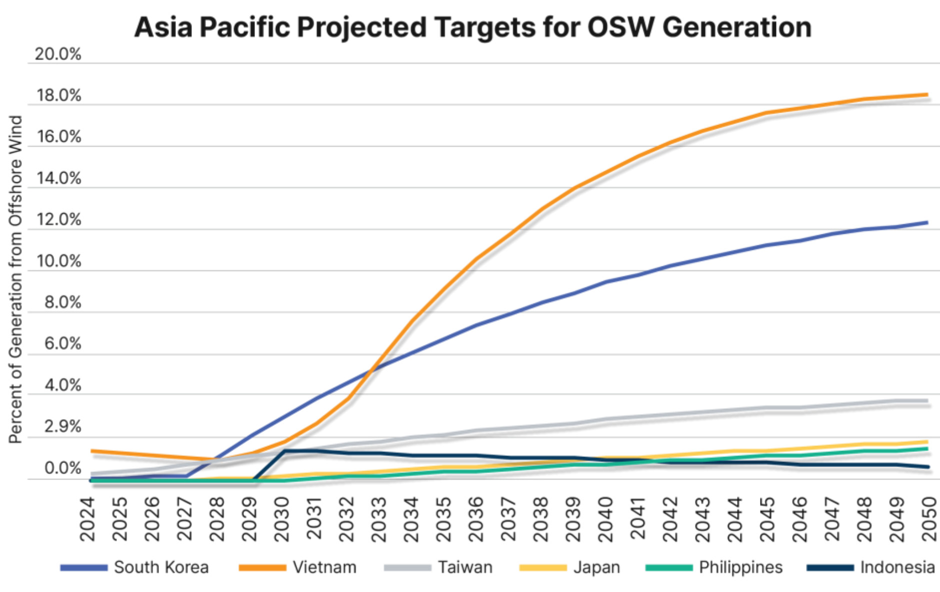


Source: IEEFA estimates. Country capacity additions based on national plan targets, adjusted outward in time based on current state of wind program implementation. Dollar values based on estimates of individual country localization curves linked to starting industrial manufacturing and port infrastructure base.

The projected proportion of total wind farm costs that were allocated to component procurements and services obtained domestically, regionally or from outside the Asia Pacific evolved over time. Progressive localization of key wind farm components was assumed, based on the proposed size of each country's wind program and how sustained that implementation was. Generally, IEEFA assumed growing rates of localization if the annual addition was consistently over 1 GW. Lower rates of project implementation increased the proportion of regional and extra-regional sourcing and increased the time period over which that sourcing persisted.

Certainly, the installed capacity numbers proposed are sizeable. But how does this investment measure up to the overall decarbonization contribution for each country? Development plans under energy policy from Vietnam claim bold percentages from offshore wind, albeit pushed out toward 2050. Vietnam's plan implies that offshore wind's contribution to generation could approach 20% by 2050, even with the country's high electricity demand growth trajectory. South Korea's targeted capacity additions imply wind energy supply between 10% and 12% of 2050 generation. In other markets, while the total GW numbers may appear sizeable, the targeted proportion of energy contributed from offshore wind is comparatively diminutive. For Japan, Indonesia, Philippines and Taiwan, IEEFA estimates that the currently planned offshore wind capacity targets yield kilowatt-hour contributions to the grid of 4% of national demand or lower. This stands in stark contrast to the scale of wind resource potential highlighted earlier in Figure 27.

Figure 38: Percentage of Projected Generation Supplied by Offshore Wind to 2050



Source: National development plans to 2030, 2035. IEEFA estimates of offshore wind capacity additions over time, adjusted outward for current offshore wind program status.

This indicates that if the offshore wind market is successful in reducing costs and increasing scale, there is substantial room for growth in nearly every Asia Pacific market. As was demonstrated at the start of this chapter, the available wind energy capacity for nearly every country in the Asia Pacific is larger than their current total installed capacity from all sources of generation. The current national targets, therefore, represent a considerably conservative lower end of investment potential.

Country-Wise Projected Offshore Wind Market

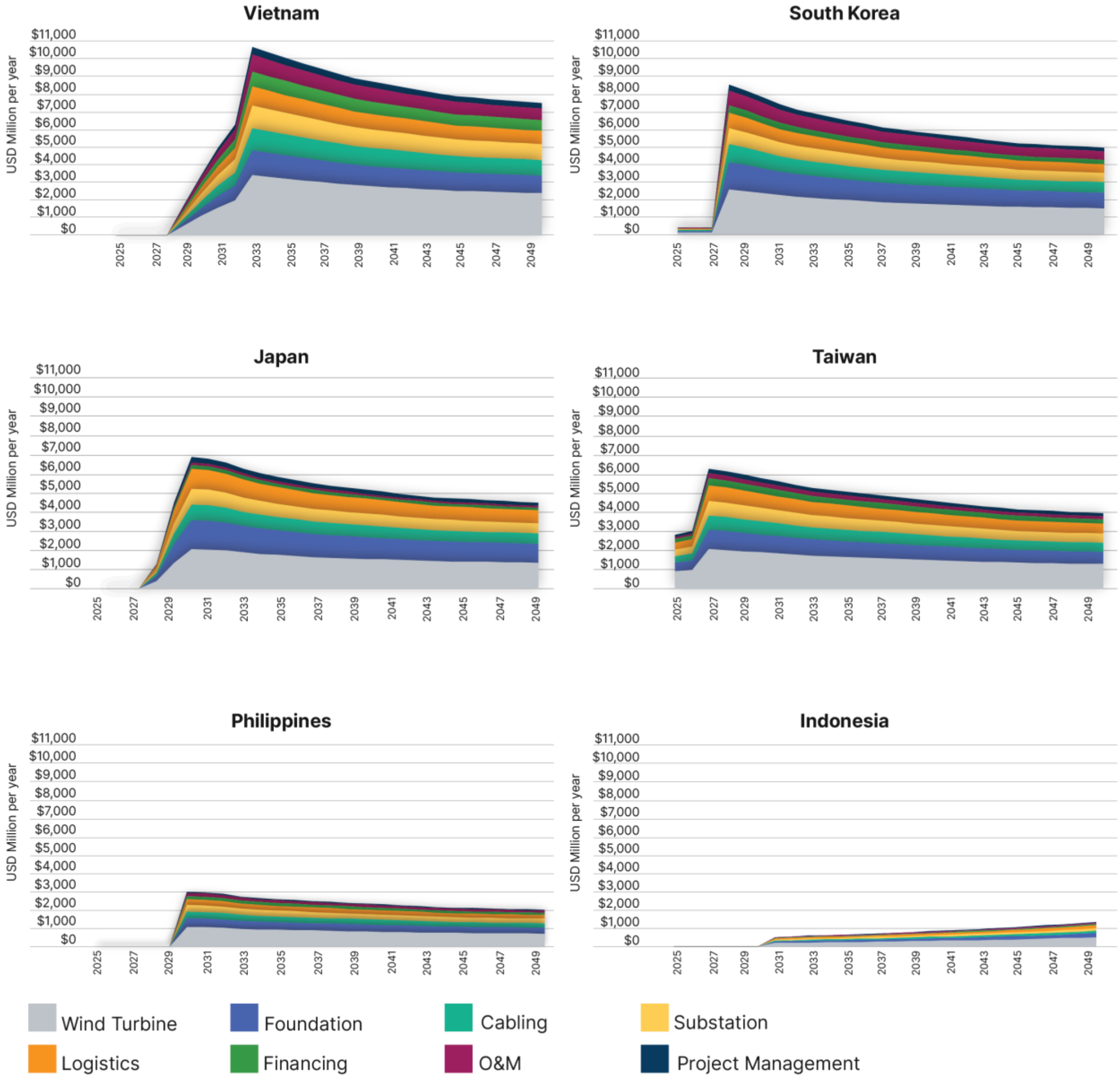
Each country in the Asia Pacific region is charting its own course for offshore wind, reflected in target contributions from the energy source over time. While almost all jurisdictions have some form of wind plan, their development scale and timings vastly vary. Taiwan is already constructing large-scale offshore wind farms, with the latest financial closings each looking to add about a gigawatt of capacity per year for the rest of the decade. Meanwhile, Japan and South Korea appear to be stepping slowly into offshore developments with initial forays taking place on comparatively small scales. While rights allocations have been granted in the Philippines, Vietnam currently has paused their development despite initial success in nearshore wind installations. Indonesia has yet to pursue the resource.

IEEFA's analysis took into account these varied levels of progress, planning and processes to determine the timing of prospective investments and supply chain development. Allocation of development rights is a positive step but is considered too early stage for immediate project implementations. Projects need to be in the financial closing stage to be considered for a near-term start. For countries that have not yet closed on a large-scale wind farm development, it was presumed that any construction start would be at least three years out. If no firm plan for a large-scale program is in place currently, that progress is assumed to be pushed out at least five years.

It is assumed that once a country implements an offshore development program, it will continue that process in 500 MW to 1000 MW increments over sustained periods. This assumption drives the development of supply chains to serve the sector and to evolve the localization potential of the offshore wind sector. Localization is not immediate but evolves over years. The fabrication of foundation and tower components comes first, while more specialized manufacturing of equipment like cables or electrical systems follows later. Consistent demand has to underpin investment in specialized aspects of the supply chain. For those specialized components, current suppliers are considered; many of these manufacturers are in Europe. However, as currently seen in Taiwan and with progressing partnership agreements amongst European suppliers with companies in South Korea and China, these specialty suppliers are looking to establish regional hubs in the Asia Pacific. Thus, supply chain opportunities first move from extra-regional to regional bases before becoming more localized to individual countries. This pace of localization is based on a consistent rollout of wind farms year after year.

Wind turbines and related original equipment manufacturers' systems comprise between 30% to 40% of total project cost, dependent on the country. Figure 40 graphs the evolution of spend on wind farms and the associated breakout of supply chain components by dollar value.

Figure 39: Projected Offshore Wind Farm Spend by Cost Component for Each Study Country, 2025 to 2050



Source: IEEFA Estimates.

Localization Potential

Aggregating extra-regional, regional and localized components gives a better idea of how localization adds up across supply chain elements. Figure 41 illustrates how localization evolves over time.

Taiwan has a head start in the region with 2.25 GW of operating capacity and an immediate implementation pipeline of 3 GW. It is helping the region chart a course for offshore wind supply chains by addressing practical aspects such as sourcing, skills development, and localization challenges. Currently, Taiwan has localized a portion of foundation fabrication, onshore transmission substations, a cable manufacturing plan, and several localized design, construction, and management support service sectors. IEEFA estimates that Taiwan's local component of offshore wind could reach US$81.6 billion by 2050 based on projected additions.

South Korea is projected to rapidly localize its offshore wind industry due to its extensive existing steel, heavy industrial fabrication, and shipbuilding yards. These facilities would need only modest modifications or expansions to accommodate the needs of offshore wind. The country's offshore program could achieve faster growth if the government can address seabed licensing, power contracting procedures, and transmission interconnection challenges. Its heavy industry is currently developing large scale indigenous offshore wind turbine designs (8 MW to 10 MW), creating a reasonable possibility for local turbine sourcing at scale. All elements of the offshore wind supply chain could eventually be sourced from within South Korea, establishing a new core industry that is not reliant on foreign currency-denominated fossil fuel imports. South Korea has the potential to develop US$130 billion in supply chain benefits from offshore wind by 2050.

Japan has tremendous offshore wind resources awaiting exploitation. The country boasts a legacy of vertically integrated heavy industrial infrastructure, world class ports, and a strong maritime economy orientation. Offshore wind should align well with Japan's industrial strengths, but these potentials remain largely untapped and underdeveloped. Despite a domestic perception of high costs, offshore wind's costs are lower, more manageable, and more certain than speculative, less mature alternatives like hydrogen, ammonia, or technologies that depend on continued fossil fuel reliance. Upfront Investment in facilitating grid interconnections for offshore would make use of Japanese companies' unique and considerable expertise in HVAC and HVDC transmission technologies, a key contribution from the domestic supply chain that most other countries lack. However, current offshore licensing, bidding, and pricing create uncertainty for developers. To date this has led to suboptimal size wind projects where scale economies are difficult to achieve. Japan needs to carefully optimize these regimes to improve incentives and outcomes. If Japan meets even its modest offshore wind targets, it could realize an estimated US$82 billion in investment. The market potential could be an order of magnitude greater if offshore wind becomes a primary component of Japan's decarbonized energy supply.

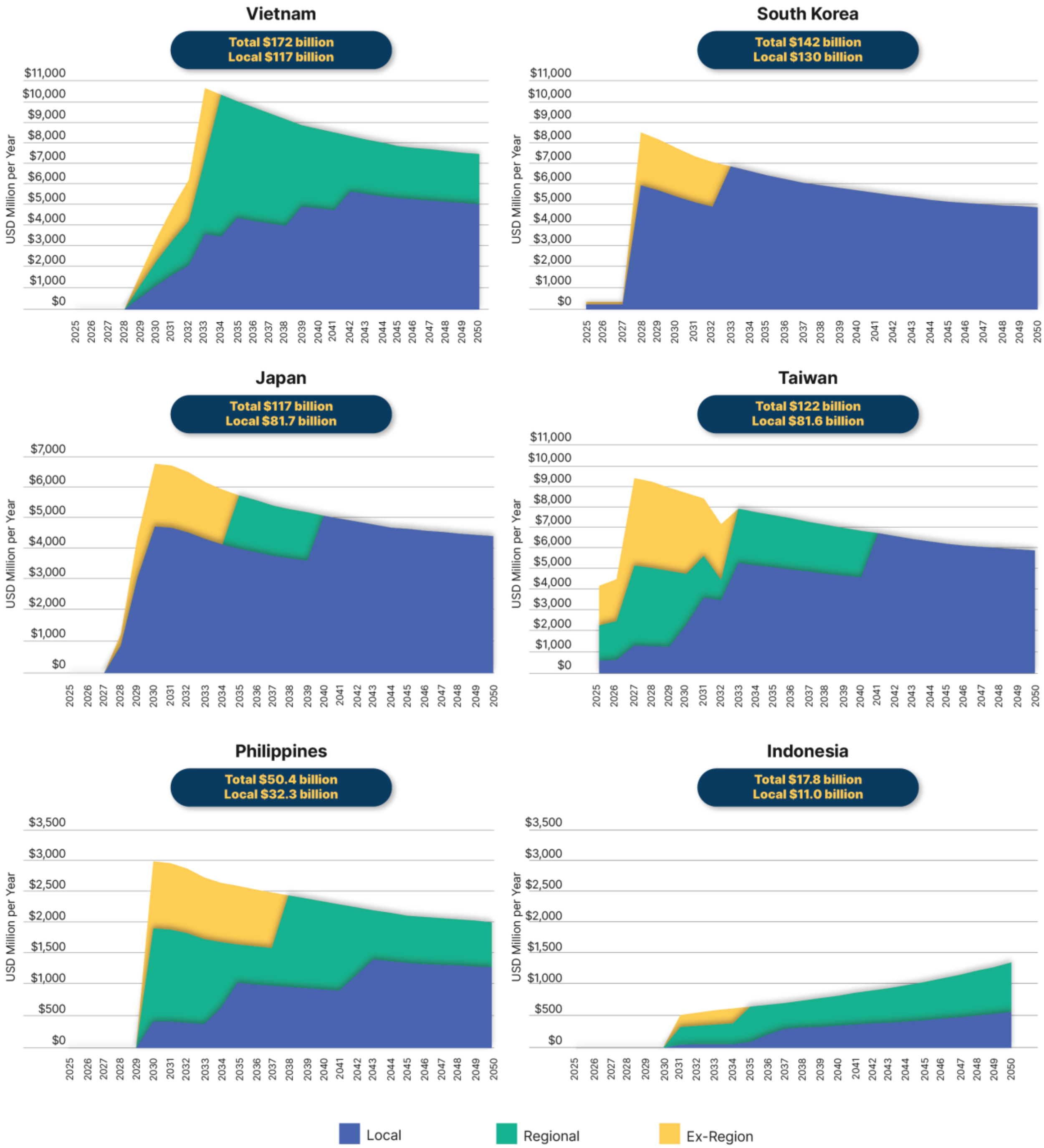
Vietnam is projected to experience an even split between regional technical component suppliers and the localization of fabrication inputs. Vietnamese yards already supply foundation fabrications to offshore projects in Taiwan, giving them a competitive edge. With more than 60% of Vietnam's offshore wind potential located in shallow waters, the country has an excellent opportunity to address critical demand growth at lower cost. This provides clear, economic options for electricity supply growth without the need to manage the costs associated with foreign currency-denominated fossil fuels. If the country can revise its renewables procurement framework to foster genuine competitive bidding instead of feed-in tariffs, it can harness the benefits offshore wind's decreasing cost curve. Vietnam's aggressive offshore wind targets to 2050 could foster the development of a substantial local supply chain worth US$117 billion.

The Philippines has significant wind resource potential, attracting considerable investment interest as shown by the high uptake of licenses. However, the country's current port infrastructure is insufficient for the offshore sector, necessitating large-scale port investments. Geographic constraints and the need for proximity to materials supplies limit the number of locations suitable for developing port-side facilities, a number of which are already congested. The prospective domestic value chain potential is estimated to be US$32.3 billion. If the Philippines can align its offshore ambitions with its infrastructure development, it could significantly increase its localization level.

Indonesia's currently proposed offshore wind program, targeting 5 GW by 2050, is currently too small to develop a large proportion of localization. Indonesia's oil and gas sector fabrication yards, particularly those in Batam near Singapore, are well suited to offshore wind work, although they are geographically distant from the most promising offshore wind areas. These yards could also contribute to development of the specialized vessels required regionally for wind farm logistics and installation. Indonesia could consider a more consistent and larger-scale offshore program to achieve larger capacities at lower costs. Even with modest plans for 5 GW, Indonesia could develop a local market worth US$11 billion for supply chain elements.

Figure 40 summarizes the estimated localization potential for wind farms according to stated national development plans, while Table 5 shows the split between turbine and non-turbine spending for projects in 2030 and through 2050.

Figure 40: Projected Localization of Offshore Wind Farm Supply Chain 2025 to 2050



Source: IEEFA estimates.

Table 5: Breakout of Non-Turbine Investment Potential by Country (USD Billions)

	2025 - 2030			2031 - 2050			Total 2025 to 2050		
	Turbines	Non-Turbine	Total	Turbines	Non-Turbine	Total	Turbines	Non-Turbine	Total
Vietnam	$ 1,652	$ 3,511	$ 5,163	$53,532	$113,756	$167,288	$ 55,184	$117,267	$172,451
South Korea	$ 7,664	$ 17,882	$ 25,545	$34,856	$ 81,331	$ 116,187	$ 42,520	$ 99,212	$141,732
Japan	$ 3,734	$ 8,712	$ 12,445	$ 31,266	$ 72,953	$104,218	$ 34,999	$ 81,664	$116,663
Taiwan	$ 9,955	$ 20,212	$ 30,167	$ 30,573	$ 61,415	$ 91,988	$ 40,528	$ 81,627	$122,155
Philippines	$ 1,078	$ 1,917	$ 2,995	$ 17,065	$30,338	$ 47,403	$ 18,143	$32,255	$ 50,398
Indonesia	-	-	-	$ 6,748	$ 11,010	$ 17,758	$ 6.748	$ 11,010	$ 17,758
Totals	$ 24,083	$ 52,233	$ 76,351	$ 174,039	$ 370,802	$ 544,842	$ 198,122	$ 423,035	$ 621,157

Source: IEEFA estimates.

Offshore Wind Installation and Service Vessels

Currently, there is an acute shortage of the number and types of specialty vessels required to install and maintain offshore wind farms. There are a limited number of niche shipyards constructing these vessels, particularly in Norway and China, with smaller participation from Vietnam, South Korea and Singapore. Most needed are the specialized wind turbine installation vessels (WTIVs), as there are only a few that can install the largest of this generation's 12 MW+ turbines. There are only two ships currently under development that can handle the largest 20 MW turbines.

Regionally, specialized marine vessels are needed to ramp up wind farm construction activity across multiple markets and projects simultaneously. Vessels have flexibility in destination of use, as they can be built in fleets and leased to projects on an as-needed basis, especially for WTIVs. On the other end of the spectrum, general use vessels ranging from massive heavy lifts to small crew transfer vessels can serve other purposes beyond wind farm service.

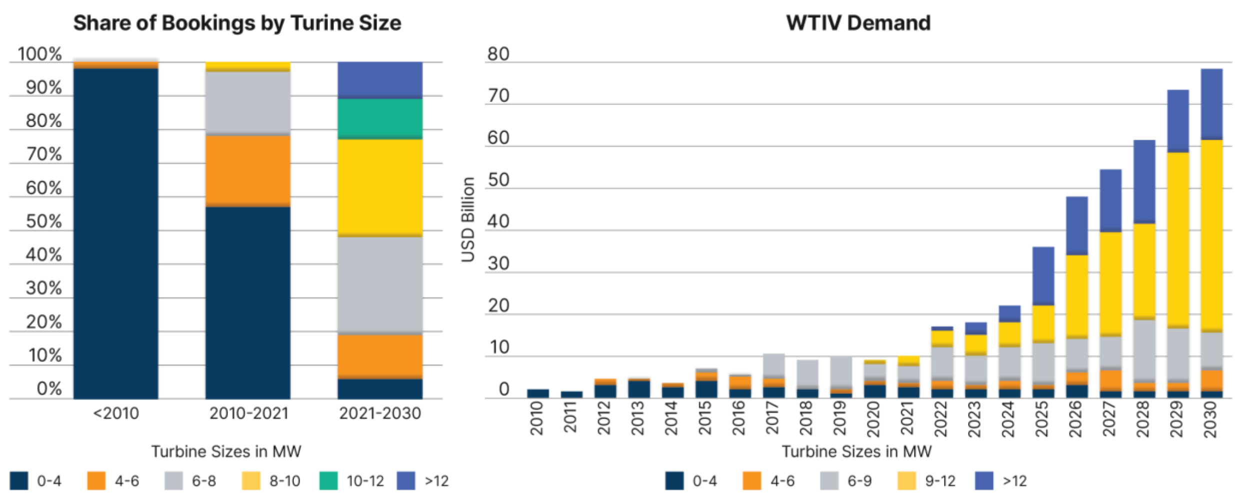
In some cases, developers may seek to build vessels dedicated to serving their wind farms. One of the most needed are service operations vessels, or SOVs. These multipurpose vessels serve both the construction and operations phases of wind farm development. Apart from transferring parts, equipment and crew to turbine and transmission platform sites, they can remain at sea for weeks at a time until works complete. The largest and most modern SOVs are equipped with dynamic positioning systems and adjustable gangways that allow them to stay stationary, permitting the safe transfer of critical equipment. If equipped with walk-to-work gangways, SOVs can allow crew to safely walk to the offshore platform even in rough seas.

A wide array of types and sizes of vessel are needed in adequate numbers to serve the growing offshore wind sector. According to the foundations upon which they must rest, all vessels need to be sized and outfitted appropriately to handle the growing scale of wind turbines. Currently, fleet additions have not been keeping pace with the evolution in size of turbines; this creates large-scale opportunity for shipyards throughout the Asia Pacific to help meet these needs. Figure 41 shows the growing requirement for vessels that can handle 9 MW and greater turbine installations from now to 2030.

Given the lead time required to slot vessel constructions, it is important that yards take views now on the segments of the shipbuilding sector in which they want to participate, consider whether their yards are adequately equipped to handle specialized construction, and whether there is a need to create partnerships with specialty ship outfitting suppliers. Installation vessels may need jack-up systems or dynamic positioning systems which keep vessels in one place during operations. They may need specialty lifting rigs, integrated GPS guidance, or special deck-top handling equipment for dealing with turbine towers or foundation elements.

The range of vessels needed to support offshore wind development, operations and maintenance are shown in Appendix D.

Figure 41: Wind Turbine Installation Vessel Demand by Turbine Size



Source: Rystad Energy Offshore Wind Cube, 2022, via Offshore Magazine. More installation vessels needed to meet offshore wind demand. February 2, 2022.

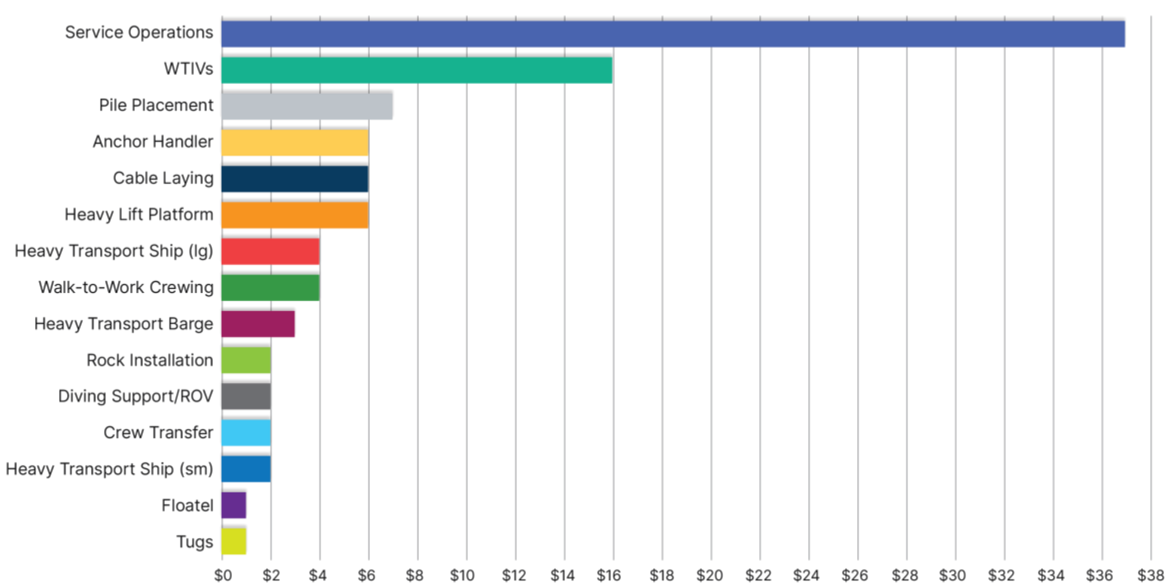
Estimated Investment Value of New-Build Offshore Wind Vessels

The build-out of wind construction and service fleets will be front-end loaded in time, primarily in the 2026 to 2035 period, and particularly so if several countries ramp up their offshore wind programs simultaneously. The analysis in this paper assumes that the most specialized of the vessels will be leased and used within the Asia Pacific region to serve multiple wind farm clients. These would include WTIVs, cable laying vessels, rock installation vessels, and heavy lift transport ships. Crew transfer vessels, tugs, and barges are expected to remain local to each country. In the analysis, SOVs are assumed to be assigned to an individual wind farm, given their roles in construction, operations and maintenance. It is expected that as the timeline extends beyond 2035, most new-build WTIVs will be sized to handle the largest wind turbines. A larger, next-generation vessel will presumably replace a WTIV at the end of its service life. Estimates also assume that beyond 2040, there will be a shift towards a larger proportion of floating offshore wind farms: they will rely more on heavy lift vessels and anchor handlers than WTIVs.

The overall market size for vessels through 2050 is estimated to be between US$74 billion to US$97 billion. About a quarter of the vessels required for offshore wind are general purpose, with many being similar to those used in the offshore oil and gas sector. Thus, the range of building slot bookings depends on whether offshore wind projects will be taking vessels from the oil and gas sector or demanding additional vessels. Bookings for new builds are biased toward the first 5 to 10 years of wind farm development, starting from 2025. Projected vessel investment through 2030 is approximately US$41.4 billion. The level of ship construction is dependent on the timing, scale and success trajectory of each national offshore wind program.

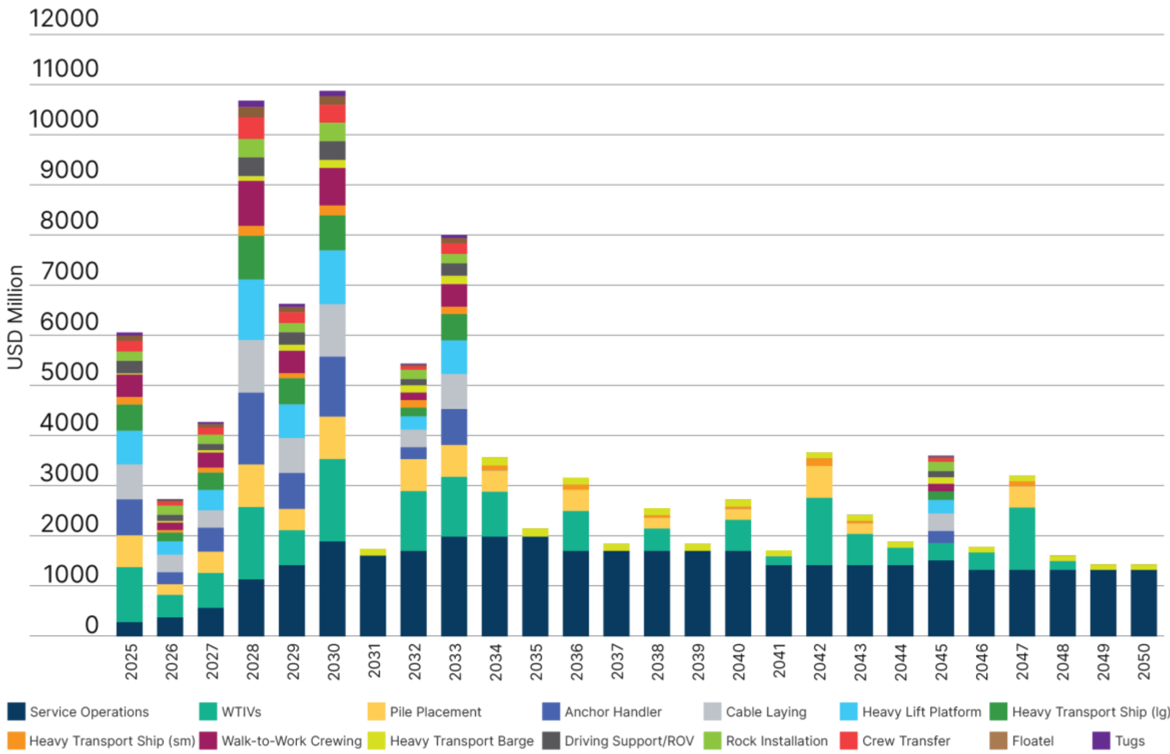
It should be noted that the estimated value is only for vessel construction, excluding the ongoing operational costs such as crews, fuel, berthing, ordinary maintenance and periodic overhauls. While these services provide material economic benefit to the maritime economy, wind farm construction and installation costs effectively embed such operating expenses in vessels' day-rate charters, thus become part of the capital investment cost of a wind farm. Also, the estimated shipbuilding values are gross investment costs, and do not assume a breakdown of country-of-origin sourcing for the various components that go into fully outfitting a vessel. For the more advanced technology ships, specialty supply costs can account for a material proportion of the vessel's value. Currently, regardless of whether a vessel is being built in Singapore, South Korea or China, components like the turbine hoist, geopositioning controls, dynamic ballasting systems, and their integration with thrusters come primarily from specialty suppliers in Europe.

Figure 42: Estimated Shipbuilding Investment Requirements by Vessel Type 2025-2050



Source IEEFA estimates. Vessel demand is linked to current Asia Pacific country offshore wind development plans.

Figure 43: Estimated Vessel Investment by Year, 2025-2050



Source: IEEFA estimates. Timing of vessel demand is linked to the timing of national offshore wind program implementation.

Offshore Wind and Vessel Market Taken Together

This analysis provides an order-of-magnitude estimate of investment potential for offshore wind in the Asia Pacific. It is based on the stated proposed offshore wind build in each Asia Pacific country in this study. Thus, these figures are subject to change. These totals and the required investment time could change due to any delay, advance, increase or scaling back of the national programs. IEEFA notes that some countries' offshore wind program targets are modest by comparison to their wind resource availability. Japan notably has build targets amounting to less than 5% of total demand by 2050. Should offshore wind performance and costs prove advantageous, a scale-up in demand for offshore wind could follow to push these estimates higher. IEEFA considers these demand numbers conservative based on current program implementation assumptions. Regardless of how this market is viewed, it creates large-scale, high-value opportunities for supply chain participants in the region.

Taken together, the offshore wind farm market and the offshore installation and service vessel sector combine to create an investment opportunity of around US$719 billion through 2050. An estimated US$118 billion may be required in the early years of the regional sector through 2030, but, with success, that would increase to near US$601 billion between 2031 and 2050. This level of investment would support the addition of 239 GW of capacity over the 25-year period, at a rate of 4.6 GW per year to 2030, increasing to an average of 10.9 GW per year to 2050.

Table 6: Summary of Projected Investment in Offshore Wind 2025 to 2050 (USD Billions)

	2025 - 2030			2031 - 2050			Total to 2050		
	Ex-region	Regional	Local	Ex-region	Regional	Local	Ex-region	Regional	Local
Investment	$ 17,309	$ 25,259	$ 33,747	$ 12,144	$ 143,706	$ 388,962	$ 29,453	$ 168,966	$ 422,739
Total OSW		**$76,315**			**$544,842**			**$621,157**	
Vessels		**$41,440**			**$56,062**			**$97,502**	
OSW+Vessels		**$117,755**			**$600,904**			**$718,659**	
Capacity		**27 GW**			**212 GW**			**239 GW**	

Recommendations and Conclusion

The accelerating pace of the energy transition is driven by the rapid reduction in the cost of mainstream renewable energy. As renewable energy costs continue to decline, countries have the opportunity to minimize and stabilize energy costs for their economies, reduce reliance on fossil fuels denominated in foreign currencies, and simultaneously achieve decarbonization. Renewables are the most affordable, reliable, and time-efficient means for countries to meet their Paris Agreement commitments.

Additionally, the large-scale requirements of renewable energy projects present significant economic development opportunities for industry and labor, domestically and regionally. This report estimates that the investment potential in the Asia Pacific alone, based on current plans, exceeds US$1.1 trillion by 2050. There is also potential to exceed this figure beyond the limits of current plans.

This paper aims to demonstrate that success in solar and wind energy does not necessarily depend on manufacturing solar PV panels and turbines. There is tremendous value to be created and capitalized upon – indeed, the vast majority of it – from the myriad of other components and services within the supply chain. Opportunities for domestic investment and national benefits exist in both solar PV and offshore wind across nearly the entire supply chain, provided there is a clear national demand for these projects.

Solar Balance of System Supply Chain Considerations

The solar PV module manufacturing market, dominated by China, is likely going to experience significant oversupply for rest of this decade. With available production capacities exceeding 1,000 GW annually and projected demand between 500 GW and 600 GW, panel prices are expected to remain low. The price depression creates an unparalleled opportunity for governments across the Asia Pacific to capitalize on ever-lower-cost solar generating capacity and deliver more stable electricity costs.

While the Chinese oversupply may dampen individual countries' ambitions to produce PV panels, the low costs provide ample opportunity to grow the complementary components and services needed to develop and operate solar farms. As detailed in this report, depending on domestic market conditions, these balance of system costs can account for 62% to 85% of total project implementation cost. This creates substantial opportunities for investing in complementary components, systems, and services to capitalize on the solar PV farm market while keeping revenues within the country.

Solar PV offers an immediate opportunity for national-level energy supply diversification and business opportunities in solar farm development and the supporting supply chain. Although the initial years of adoption may not include the full value chain of solar panel development, targeted aspects of the supply chain can be developed where there is competitive advantage:

- Domestic production of racking, tracking, fastening systems, cabling systems, controls, and substation infrastructure, as appropriate and competitive
- Project development services
- Construction and installation services – civil, electrical, mechanical
- Operation and maintenance services
- Domestic financing of capital and operating costs

Based on capacity or energy addition targets and evolving price trends, IEEFA estimates that the regional solar PV market represents a US$394 billion opportunity through 2050. Of this, US$296 billion, or 75%, is associated with non-panel, balance of systems investment, nearly all of which can be localized in the countries where the solar projects are being built. If solar project demand materializes and becomes a mainstream energy source in a given country, there is potential to gradually localize more components of the value chain. This could include many aspects of PV module production, leading to an aggregate opportunity of US$346 billion.

Offshore Wind Supply Chain Considerations

Offshore wind resources are abundant, sustained, high-quality, and predictable. Wind farms in the Asia Pacific can achieve high capacity factors that drive reliable output, especially during times when solar output is reduced. Combined with increasing scale economies from wind turbines and their decreasing costs, there is significant growth potential.

Between 58% and 72% of total project spend on an offshore wind project is on components, fabrications, and services beyond the wind turbine. Many of these inputs are massive in size and more advantageous if produced locally, offering greater economies when sourced in the country where the wind farm is being built. The Asia Pacific's maritime economies have advantages in this regard, with deepwater ports, shipbuilding industries, operations and maintenance expertise, and, in some cases, transferrable experience in fabricating large-scale components for industries like offshore oil and gas.

Pioneer markets in Europe, North America, and select markets in Asia – especially Mainland China and Taiwan – have made major progress with their offshore wind programs. These markets have demonstrated that gigawatt-scale offshore wind farms are feasible and that, with experience, offshore wind will see the same decreasing cost curve as their onshore counterparts. The advancements made by these trailblazing markets provide valuable lessons for the Asia Pacific, illustrating the necessary policy measures and infrastructure to successfully develop offshore wind. For Asia Pacific countries looking to enter the offshore wind sector, they now benefit from a "second mover advantage."

Offshore wind represents a long-term opportunity with significant supply chain prospects for domestic and regional benefits. It engages maritime economies through:

- Landside fabrication of towers, foundation elements, platforms, and substation packages
- Port infrastructure development, construction, operations and management, including quayside and seaborne services
- Localized production of blades, cabling, and certain components
- Transportation, logistics, and movements services
- Vessel construction, fleet operation, crewing, berthing, and maintenance
- Offshore wind farm maintenance services, which include landside workshops, warehousing and machining/fabrication facilities, as well as offshore skilled trades and services
- Large-scale skilled labor development in fabrication, construction, logistics, seafaring, and mechanical maintenance

Based on stated capacity or energy addition targets and evolving price trends, IEEFA estimates that the regional offshore wind market represents a US$621 billion opportunity through 2050. Of this, US$423 billion, or 68%, is associated with non-turbine supply, fabrication, logistics and services markets. Eventually, US$346 billion in non-turbine supply chain activities can be localized to the markets where offshore wind farms are being built.

Conclusion on the Market for Solar PV and Offshore Wind in the Asia Pacific

This report shows that even with the current targets for solar and offshore wind set by governments, the prospective market exceeds US$1.1 trillion through 2050. Excluding solar panel manufacturing and wind turbine production, the remaining supply chain opportunities total US$771 billion. Of this, US$346 billion, or 88% of the solar PV project supply chain requirements, can be localized, while US$425 billion, or 68%, of the offshore wind supply chain, can become domestically sourced. Additionally, the market for constructing vessels to support offshore wind farm installation and operational services ranges from US$74 billion to US$97 billion.

Table 7: Investment Potentials for Solar and Offshore Wind in Asia Pacific Through 2050 (USD Billions)

	2025 - 2030		2031 - 2050		Total to 2050	
Solar PV	$88	197 GW	$307	437 GW	$346	634 GW
Offshore Wind	$76	27 GW	$544	212 GW	$621	239 GW
Vessels for Wind	**$41**		**$56**		**$97**	
Totals	**$205**	**223 GW**	**$908**	**650 GW**	**$1,113**	**873 GW**

Source: IEEFA estimates.

Solar PV presents an immediate opportunity due to its extremely short procurement and construction timeframes, and its lifecycle costs are already lower than any other form of energy. IEEFA estimates that, given current regional targets, there is an US$88 billion market for balance of system components and services to 2030, and a massive US$307 billion market from 2030 to 2050.

Table 8: Solar PV Market to 2025 to 2050 (USD Billions)

	2025 - 2030	2031 - 2050	Total to 2050
Solar PV	$88	$307	$395
Of which non-panel BOS	*$67*	*$229*	*$296*

Source: IEEFA estimates.

Offshore wind holds tremendous potential for Asia Pacific's maritime economies. While there is a ramp-up period from the time a government decides to pursue the sector at scale to the moment components start being fabricated regionally and then locally, the total market potential to 2050 is about US$621 billion. Regional and domestic ex-turbine fabrication, supply, and services represent a substantial US$423 billion share of that total. Vessel construction to support this offshore wind growth represents an additional US$74 billion to US$97 billion opportunity for the Asia Pacific. Taken together, wind farms and the vessels that serve them account for an investment of about US$719 billion through 2050.

Table 9: Offshore Wind Turbine Market 2025 to 2050 (USD Billions)

	2025 - 2030	2031 - 2050	Total to 2050
Offshore Wind	$76	$545	$621
Of which non-panel BOS	*$53*	*$370*	$423
Vessels	$41	$56	$97
Total	**$118**	**$601**	**$719**

Source: IEEFA estimates.

Over time, as the scale within each country grows, there will likely be a shift, moving ex-Asia Pacific components into the region, and regional fabricators and producers into more local supply roles. Thus, the numbers indicated here represent a base starting point. If the capital investment cost and corresponding LCOEs for solar PV and offshore wind fall as predicted, it is highly likely that target quotas for these energy sources will expand to capture that economic potential. This is a win for power consumers, suppliers, and decarbonization efforts, making solar PV and offshore wind Asia Pacific's US$1 trillion opportunity.

Appendix A: Solar Photovoltaic (PV) Supply Chain

Silicon-based PV Panels

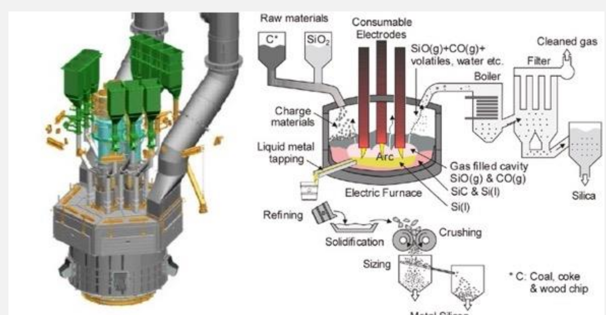
Silicon is currently the most widely used material for solar photovoltaic systems. Raw quartzite or silica-containing materials are converted into metallurgical-grade silicon ore. The silicon is melted and then cast or drawn into crystalline form in standard-sized ingots, which are sliced into wafer form using thin wire saws, then surfaced and polished to prepare them for doping and etching to make photovoltaic cells. Cells are arranged in frames and combined with backing, busbar wiring, glass, and coatings to create a final solar panel or module. A mostly automated and highly controlled process ensures a consistent high-quality end product. The scale of production has become of paramount importance, with most plants in China scaled at multiple gigawatts of annual output, leading to fierce competition that has served to consistently drive prices down across the production value chain.

Polysilicon Refining

Silica is the base material for creating silicon. Its sources vary including sand, quartzite and even from organic materials like the ash of burnt rice husks. Regardless, the silica must undergo smelting to remove impurities and inerts and convert it into a metallic form. Metallurgical-grade silicon has a purity of 99.99999% or above. Higher purity enables better performance, thus the highest purity silicon is used for electronics. PV panels are not as demanding, but still use high-purity silicon.

Polysilicon is comprised of multiple silicon crystals melted together in a heating process and then drawn into an ingot. When used in PV cells, polysilicon takes on a characteristic bluish-purple hue and the mix of crystals is visible. Monocrystalline silicon, as its name suggests, is made from a single silicon crystal. The black crystal is uniform without visible flakes or flecks. Growing monosilicon crystals requires a higher purity metallurgical grade silicon, which makes it more expensive to produce. Monosilicon, when used in PV panels, more efficiently converts sunlight to energy due to its uniformity

Source: https://www.pv-magazine.com/2024/02/08/rec-silicon-to-shut-down-polysilicon-business-in-montana/



Source: https://dhhi-ctgs.en.made-in-china.com/product/JBSnDGbPvXrE/China-China-Best-Silicon-Metal-Smelting-Plant-Si-Metal-Smelting-Furnace.html
https://j-kirr.or.kr/articles/xml/q27r/

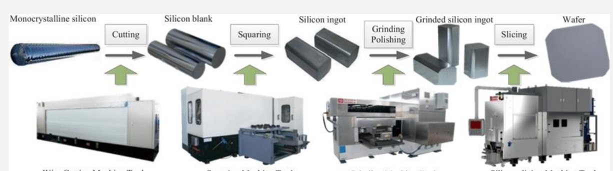
Ingots

Ingots are essentially grown crystals of uniform diameter. Whether it is monosilicon or polysilicon depends on the pool of silicon from which the crystals are grown.

Polysilicon ingots are drawn from a crucible which is densely packed with pure silica crystals of different sizes, then heated to high temperature to blend together.

A high purity “seed” crystal is affixed to the top of the ingot furnace. Crystals are grown in a high temperature, high purity, vacuum environment. Molten silica attaches to the seed crystal, aligning with the atoms of the seed. The process, known as pulling, draws feedstock silica at a highly controlled, constant rate. Crystal growth takes about a week wherein the temperature must be maintained within very tight tolerances.
Ingots are tending towards larger diameters, because this yields wafer of larger sizes with less waste. The latest industry standard is moving from 200mm ingot diameter to 300mm.

Wafers

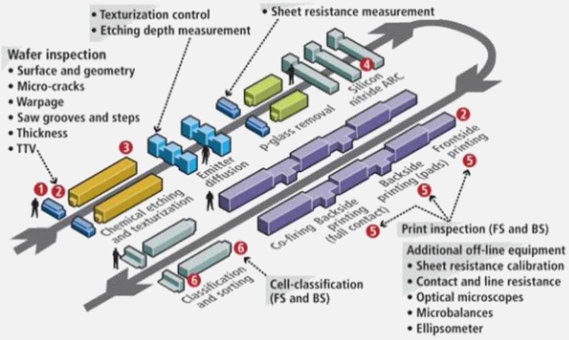


Round ingots need to be trimmed lengthwise into square or rectangular shapes, and then are sliced into the thin wafers that will ultimately become PV cells. Thin diamond and tungsten wire saws are used to slice the silicon material into standard thickness wafers. Wafers are either square, “pseudo-square”, or rectangular. Square and rectangular wafers are cut from fused polysilicon ingots. For monocrystalline ingots, the so-called “pseudo-square” wafers are octagonal, mostly square but with corners trimmed at 45-degree angles. This maximizes the wafer area taken from a circular cross-section monocrystalline ingot.

Cells

Cells are etched from polysilicon or monosilicon wafers through a process of doping. This allows the creation of positive or negative charges on the wafer to generate electricity. The automated cell production occurs in a cleanroom environment to assure uniformity and consistency in production while minimizing flaws.

Image source: https://cetcsolarenergy.com/products/solar_pv_production_equipments.html



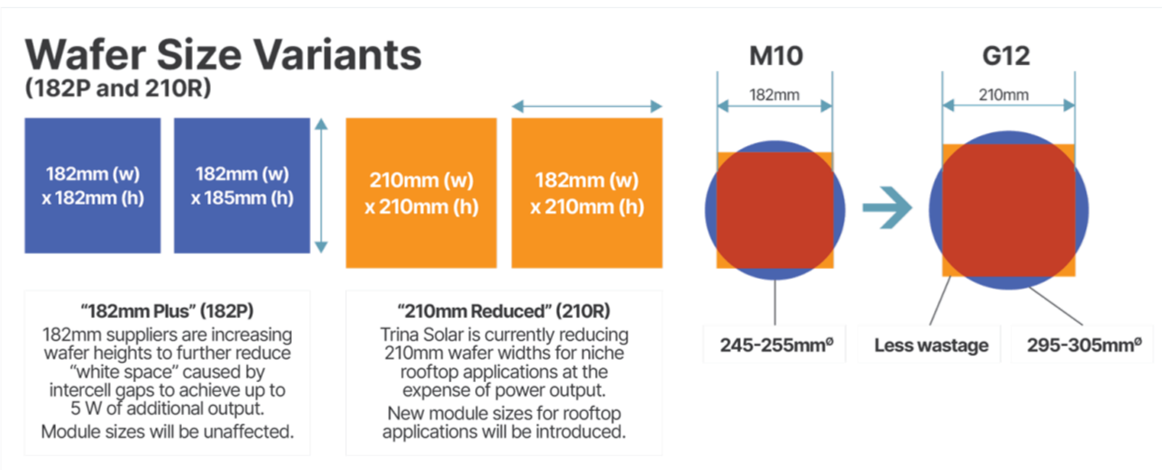
Panels/Modules

Modules are the final assembled product that mounts to racks or roofs, typically called PV panels. The panel is a combination of individual PV cells arranged next to each other, with connections amongst the cells to aggregate current to connection points. The cells are sandwiched between layers of glass, protective coating and backing plates, enclosed in a frame. The cells need to be interconnected through joints for electric current to flow across the panel to connection points. Modules are tending towards uniform sizes such that mounting points can be standardized, to help ease installation and reduce costs. Panels are typically around 1,100mm by 2,100mm, and are targeted for a maximum weight that would allow a single person to pick up and handle.

Appendix B: Key Trends – The Solar PV Module Production Chain

Wafer sizes are increasing, allowing for more efficient use of ingot production processes and leaves less waste from the offcuts, or kerf, that occur when ingots are sliced into wafers. At the same time, each wafer is becoming thinner, dropping from 225 microns (µm) in 2020 to 130-150µm through 2023 to a new low of 40-50µm today. There is, therefore, more wafer yield per ingot, thus, again, reducing costs.[30] Wafers are also being cut into both squares and rectangles for use in different form factor applications. Rectangular cells can be more tightly fitted within rooftop solar frames, thus increasing wattage output for the same panel frame size.

Figure 44: Wafer Size Variants



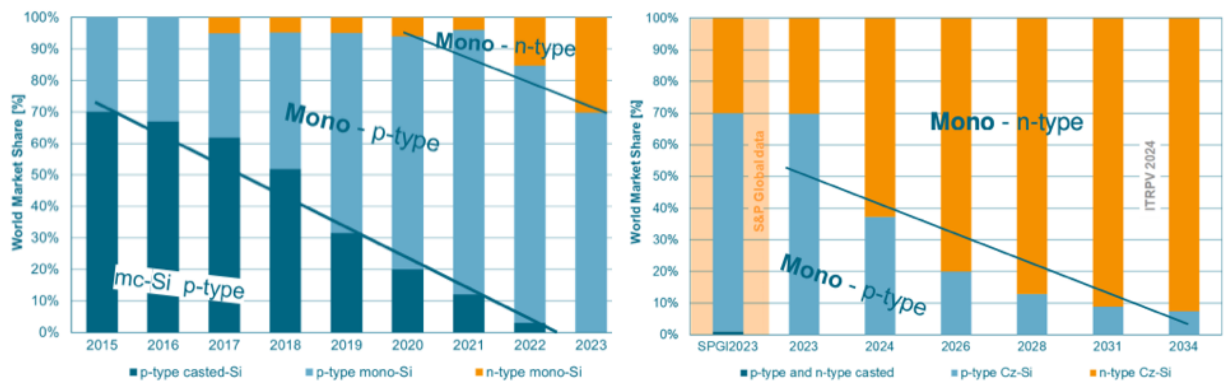
Source: Left – Solar World Online. Report maps the latest global trends in solar panel manufacturing. October 2022. Right – IEEFA.

Cell technology is moving from entire genres of design into new typologies. Multi-crystalline silicon cells, dominant in global markets less than 10 years ago, stopped production at the end of 2022. They have been replaced by monocrystalline "p-type" cells, ramping up from 30% of the market in 2015 to nearly 80% in 2021. However, preferences – along with the scale and costs that go with them – have shifted once again, now to monocrystalline "n-type" cells, which had a 30% market share in 2023, rising from less than 5% of the market only two years prior. Projected to account for 60% of the market in 2024, they will push p-type cells out of the market imminently. Tandem cell technology is the next up, expected to ramp up production in the next year or two, and start to assert a leading role around 2030.

[30] Rethink Energy. Solar industry 'involution' produces 40 micron wafer. April 4, 2024.

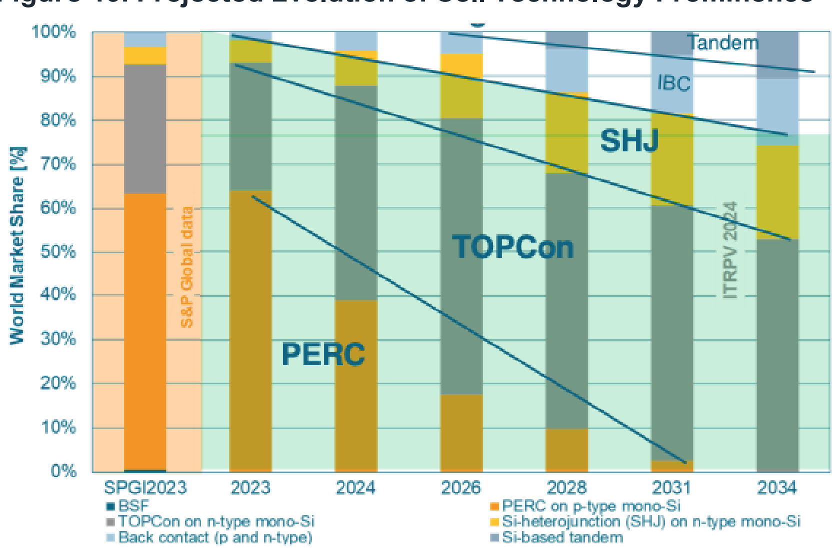
For companies investing in a certain type of cell production based on a particular chemistry or design, their plants remain viable for under seven years on average. They will then likely have to abandon those lines and invest in the next generation technology to remain relevant and competitive. Chinese manufacturers, led by government policy and supported by permissive financing, have pursued the marginal efficiency gains such investment brings as part of a pitched battle for technological superiority. For governments that are contemplating providing incentives or subsidies to upstream cell production segments of the business, this should provide a clear message: for their domestic players to remain relevant and anywhere near cost-effective, recurrent rounds of financial support will be required for production line retooling and overhauls.

Figure 45: Evolution of Silicon Typology 2015-2034



Source: VDMA. ITRPV 2024 15th Edition Presentation. Frankfurt, Germany. March 15, 2024.

Figure 46: Projected Evolution of Cell Technology Prominence



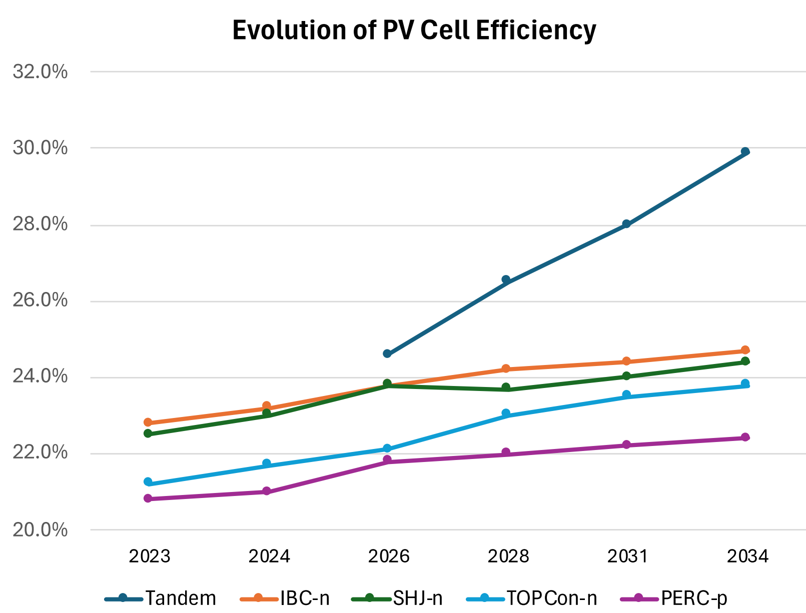
Source: VDMA. ITRPV 2024 15th Edition Presentation. Frankfurt, Germany. March 15, 2024.

Bifacial panels are going to dominate the market. Despite their notionally higher cost, a flood of production has overcome this disadvantage, such that today, bifacial panels represent 70% of deliveries. There are therefore more options for installation geometries to pick up reflective light. This is a boon for farther northern or southern latitudes, agrivoltaic and floating solar applications, or novel installations like vertical panel orientation.

Bifacial panels are less relevant for countries near the Equator, where optimal angles of incidence are closer to 90 degrees. This means that, for the next two to three years, while monofacial panel production is phasing down, prices for these panels will be at a discount, creating a lower levelized cost of electricity (LCOE) opportunity.

Efficiencies are trending higher, both in solar cell light conversion efficiency and in the physical panel design itself. This means more watt output for the same installed panel area, lowering LCOE.

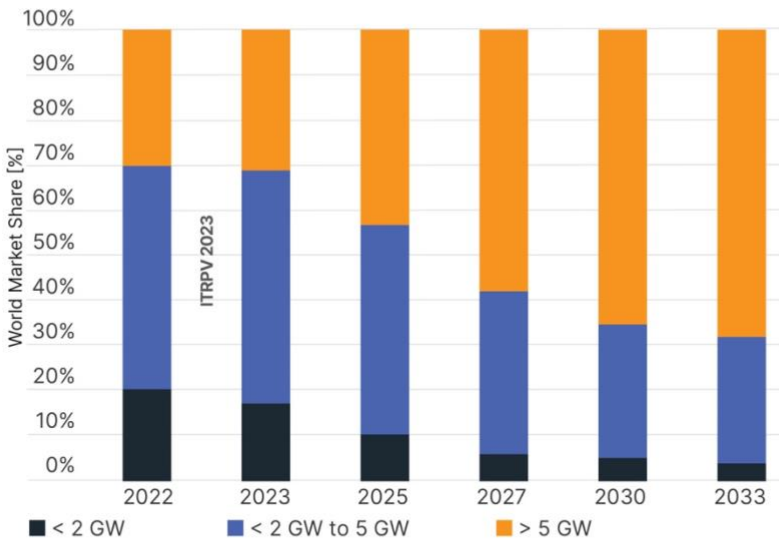
Figure 47: PV Cell Efficiencies – Current and Projected



Source: VDMA. ITRPV 2024 15th Edition Presentation. Frankfurt, Germany. March 15, 2024. IBC-n= Back contact cells, n-type monocrystalline. SHJ-n = Silicon heterojunction n-type monocrystalline. TOPCon-n = Tunnel oxide passivated contact n-type.

Overall, manufacturing capacities and the capacity per plant are increasing. This is all about achieving scale economies. At the same time, the technology being deployed is rapidly evolving, meaning that plant owners need to be constantly thinking about their investing in their next retooling or upgrades. Entire chemistries, ingot sizes, and cell configurations have come and gone in the past decade, with non-stop evolution. This has fostered an environment of cutthroat competition, leaving smaller-scale producers struggling. This has implications for countries that are attempting to diversify away from Chinese supply chains by localizing production of solar PV cells: unless each facility is at a multi-GW scale, it is unlikely to be cost-effective.

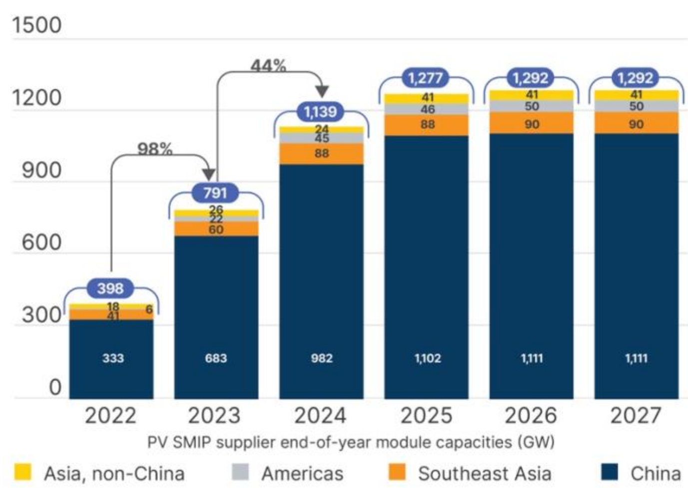
Figure 48: Share of Global Cell Market by Scale of Production Facilities



Source: VDMA. ITRPV 2024 15th Edition Presentation. Frankfurt, Germany. March 15, 2024.

Meanwhile, China continues to add silicon-based PV panel manufacturing capacity. The country is projected to have nearly 1 TW of output capacity by early 2025. At the same time, global demand is projected to be between 500 GW to 600 GW.

Figure 49: Module Manufacturing Capacity



Source: Clean Energy Associates. PV supplier market intelligence report, Q4 2023. January 31, 2024.

Emerging Solar Technologies

There are still new realms of solar technology that have not yet been dominated by China. In general, the entire category of thin films remains open and competitive. Thin films use three primary technologies, copper indium gallium selenide (CIGS), Amorphous silicon (a-Si), and cadmium telluride (CdTe). Most production most occurs in the North American market. These thin films are lighter and more competitive to produce, currently seeing applications in building-integrated PV and large-scale industrial installations.

A highly promising technology is single-molecule layer photoreactors based on perovskites and deposited directly onto PV-grade glass. Theoretically, they have a maximum conversion efficiency of around 43%: bench tests have achieved rates in the mid-30% range, while current reproducible prototypes achieve around 26%.[31] The lowest end of that range already delivers performance that would put them marginally ahead of the most advanced silicon-based PV technology. Combined with other PV technologies (including those that are silicon-based), perovskites demonstrate that they could achieve efficiencies above 30% on a reproducible commercial basis. It is worth noting that the maximum theoretical output of today's standard silicon-based technology caps out at 29%. Thus, perovskite-derived cells, whether solo or tandem, appear to be a promising future solar technology beyond silicon.

While it is tempting for prospective domestic market producers of solar products to jump into the market, significant research and development investment remains before they can be rolled out at a commercial scale. Countries would need to be willing to fund and/or support research and commercialization for several years before they become more established.

[31] The American Ceramic Society. Perovskite solar cells charge ahead to record-breaking efficiencies. July 21, 2023.

Appendix C: Solar and Wind Calculation Assumptions

Context

Overall, this analysis attempts to create an order-of-magnitude assessment of the market potential for completed solar PV utility-scale projects and offshore wind farms connected to the grid within each country of study. Global export markets for these goods and services are not considered. The focus is on the entire project lifecycle within a country, from the initial studies and development phases through commercial operations. Each element of that process and lifecycle contributes to the overall supply chain.

Solar Methodology

Annual Solar Capacity Additions

IEEFA estimated the projected growth of solar investment in each country based on stated national targets for renewable energy. Solar additions were estimated based on either announced capacity additions or the percentage of generation targets linked to years expected to be achieved.

For countries with stated capacity targets, those additions were evenly spread annually over the period.

Where countries targeted percentage of energy supply by solar, IEEFA used the distribution of annual power generation potentials derived from insolation rates to calculate the panel capacity needed to reach the targeted generation.

Most national plans were split between 2030 and 2050 targets for either capacity or generation. The section on solar resource potential below shows the rates used. Power demand growth rates were input as per national energy plans through 2030. Where published rates were available, longer growth periods were included. Thereafter, modest growth rates were applied out to 2050.

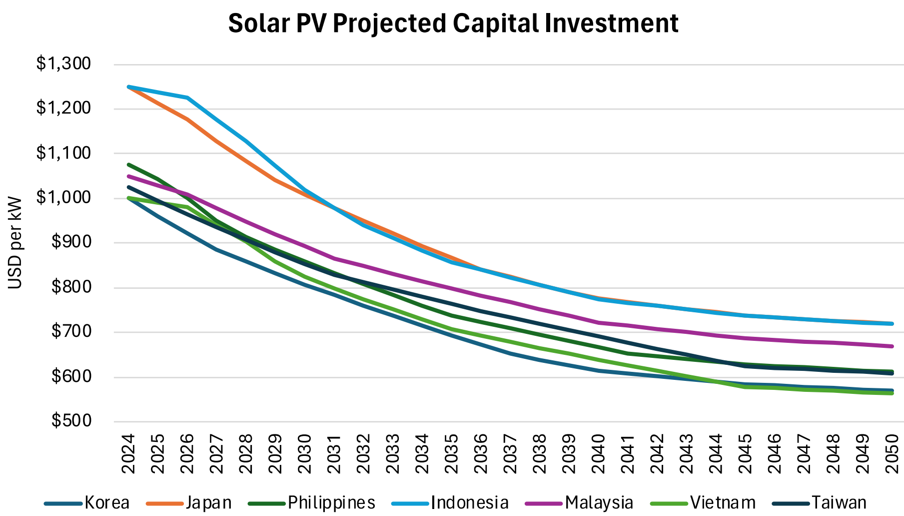
Solar Capital Costs and Supply Chain Disaggregation

Capital costs were applied on a per-kW installed basis. IEEFA derived cost reduction curves based on a blending of projections obtained from the National Renewable Energy Laboratory (NREL),[32] Det Norske Veritas (DNV),[33] the Solar Energy Industries Association (SEIA)/Wood Mackenzie,[34] and the International Renewable Energy Agency (IRENA).[35]

Those curves were adjusted for regional costs, looking at the available empirical data for current solar park installations in study countries, and adjusted for cost indices linked to purchasing power parity as of the first quarter of 2024.

[32] NREL. Annual Technology Baseline 2023, Utility-scale PV. July 15, 2023.
[33] DNV. Energy Transition Outlook 2023. October 2023.
[34] Solar Energy Industries Association and Wood Mackenzie. Solar Market Insight Report. March 6, 2024.
[35] IRENA. Renewable Power Generation Costs in 2022. August 2023.

Figure 50: Solar Project Cost Curves Applied by Country



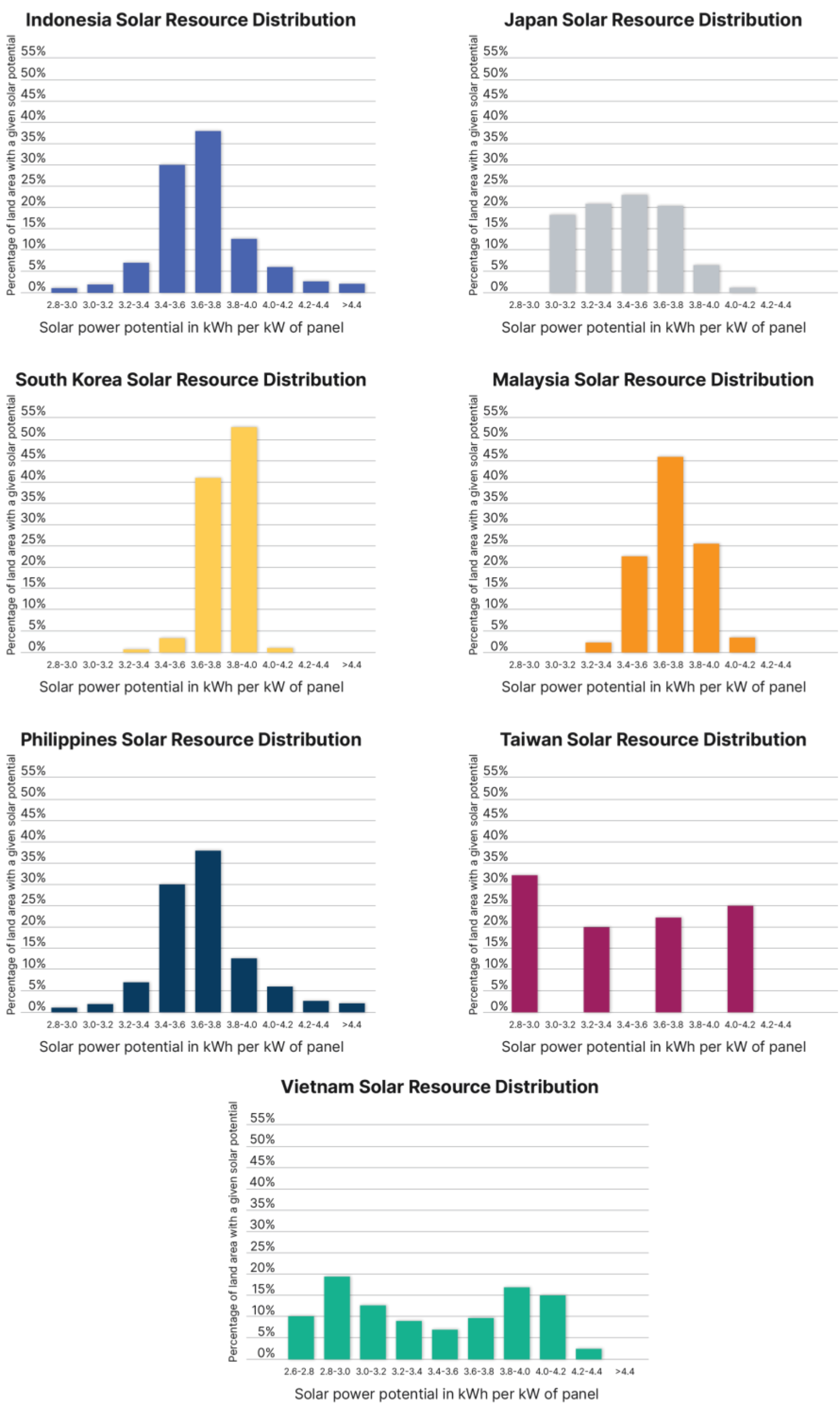
The same sources were used to estimate the breakout share of costs for each supply chain and service component. Localization of supply chain components was assumed to evolve based on the scale of cumulative proposed installations over time. This included panel manufacturing localization; however, this was assumed to evolve after 2030 due to the current overcapacity in the PV module production chain. Regardless of assumptions on panel localization, that did not impact the balance of system localization projections.

Solar Resource Potential

The prospective solar energy that can be captured and converted into electricity was estimated based on the production values from the World Bank ESMAP Global Solar Atlas 2020 (GSA). The GSA converts insolation to electricity output in kilowatt-hours per kilowatt of panel installed. Not all areas of a given geography have the same insolation rates, thus the GSA adjusts for those variations. Further, the GSA's methodology also restricts production potential to those geographic areas where panel installation is feasible. The GSA therefore provides a realistic assessment of a country's solar potential. The histogram of power potentials for each country is provided below.

Note that the estimates for Taiwan were not included in the main publication for the region. These were taken from a separate GSA database that did not include the same level of detailed breakout of resource rates, thus the more distributed data in the histogram.

Figure 51: Solar Resource Potential



Offshore Wind Methodology

Annual Offshore Wind Capacity Additions

IEEFA examined each country's proposed offshore wind capacity additions between 2025 and 2030. For a country that has yet to initiate formal bidding for wind farms, the start date for their program was pushed to later in time, typically beyond 2030. While many countries have begun allocating development rights or seabed space, this is too early a stage to rely upon to determine when a wind farm would be realized. Only once bidding for specific wind farm capacities, tariffs and contracts has stated is a program considered "initiated". Once a program was initiated, the annual rates of additions were assumed to be such that their total add up to each country's proposed targets by 2050.

Offshore Wind Capital Costs and Supply Chain Disaggregation

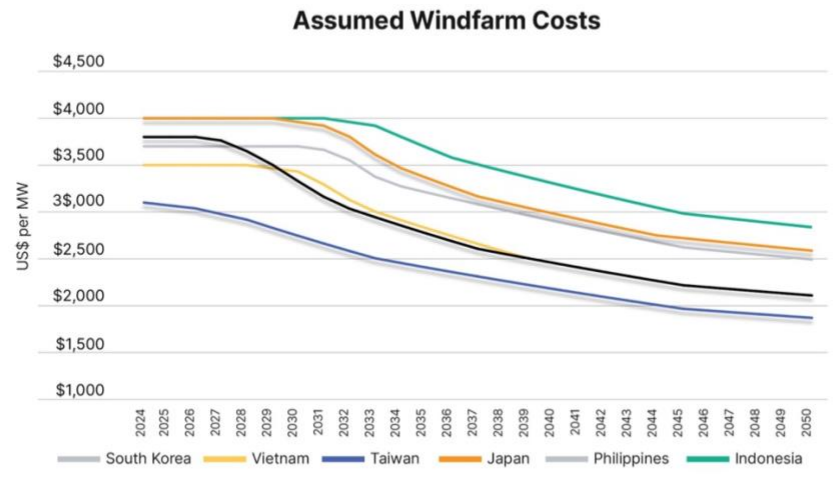
Capital costs were applied on a per-kW installed basis. IEEFA derived cost reduction curves based on a blending of projections obtained from US NREL's Annual Technology Baseline,[36] DNV,[37] and IRENA.[38] Those cost curves were adjusted for regional cost bases, linked to purchasing power parity as of the first quarter of 2024. The initial wind farm developments are assumed to have higher percentages of foreign-sourced components and inputs. As repeat wind farm developments are executed, we assumed this demand will drive, at first, the regionalization of inputs, and then, over time, their localization. Where available, reported contract costs for wind farms under construction in European waters and in Taiwan were used to check numbers.

Due to the higher start-up costs each country market globally has so far incurred with their first-of-a-kind offshore developments, the costs used in this analysis are high for the first two rounds of wind farm developments. Thereafter, project costs assume a declining trend. The rate of decline is linked to two key characteristics within each market: (1) the scale of proposed additions and (2) the starting industrial supply and fabrication endowment. For example, South Korea and Vietnam will have faster localization and learning rates as they already have facilities that support offshore fabrications regionally, as well as shipbuilding yards all of which support the offshore oil and gas sector in the Asia Pacific. Given the current infrastructure and services, a country like the Philippines has a flatter cost reduction curve as local fabrication facilities need longer development time frames.

It was assumed that the countries would first concentrate development efforts on nearer shore, fixed-bottom foundation wind farms, as fixed-bottomed developments incur lower costs. Given the large available quantity of wind generation capacity at fixed-bottom sites, compared to the relatively low capacity target for in each national plan, near-shore sites for the proposed capacity additions are largely sufficient through 2050. From a market size estimation perspective, this assumption leads to lower overall projected market values, given that floating offshore wind farms have higher input cost requirements. Accordingly, the estimates in this analysis could be considered conservative.

[36] NREL. Annual Technology Baseline 2023, Offshore Wind. July 15, 2023.
[37] Ibid footnote 33.
[38] Ibid footnote 35.

Figure 52: Offshore Wind Farm Project Cost Curves Applied by Country



Source: IEEFA estimates based on a blended cost outlooks from NREL, DOE, GWEC.

The supply chain costs for offshore wind projects were disaggregated using indicators from the Global Wind Energy Council (GWEC), NREL and US Department of Energy (DOE) studies listed below:

- NREL. 2022 Cost of Wind Energy Review. December 2023.
- US DOE Office of Energy Efficiency and Renewable Energy. Offshore Wind Market Report: 2023 Edition. May 31, 2023.
- GWEC. Global Offshore Wind Report 2022. June 2022.
- US DOE. Wind Energy Supply Chain Deep Dive Assessment. February 24, 2022.
- GWEC and Ocean Renewable Energy Action Coalition. Offshore Wind Technical Potential in Taiwan. June 2021.

A progressive localization rate was applied to each country's blend of supply chain costs, seeing greater percentages of first, the regionalization, and then, the localization over time. The later a country was assumed to begin its offshore wind program in earnest, the later its localization would occur.

For wind turbine sourcing, it was assumed that projects to at least 2030 would source non-regional turbines, predominantly the European and US providers. Thereafter, more competition would arise from China, thus regionalizing turbine procurements. A unique case is that of South Korea where three domestic companies are either currently testing offshore prototypes or have them under development. This leads to the prospect of a leap to domestic turbine sourcing in the Korean market within the medium term. Should those turbines perform well, they would become candidates for regional supply in competition with Chinese manufacturers.

The analysis assumes that scale economies and reduced balance of systems costs will enable the rapid adoption of larger-scale wind turbines in the Asia Pacific. Wind farms to 2030 are assumed to use 9-10MW turbines, with sizes averaging upward towards 15MW thereafter.

Appendix D: Offshore Wind Supply Chain

Offshore Wind Marine Vessels

There are over a dozen different types of vessels required to design, construct, and maintain offshore wind farms. While some vessels are borrowed from other offshore uses, some are created specifically for wind farms and their unique requirements, such as WTIVs. Estimates vary on vessel needs, but the vessel market through the coming decade could range from US$75 billion to US$97 billion.

Wind Turbine Installation Vessel

Heavy lift crane with high reach is necessary to handle nacelles exceeding 750t and hub heights over 180m.

Requires jack-up capability for waters up to 75m in depth. Onboard storage for up to 4 turbine-tower sets.

US$300-$400 million each and increasing with turbine size requirements. These are the vessels in the shortest supply.

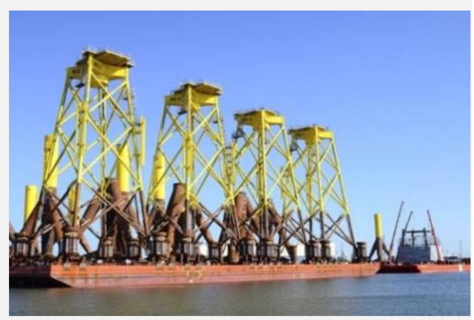
Heavy Transport Vessel

Capable of transporting multiple units of towers or monopile foundations. Needs low deck height with dynamic deck height ballasting to facilitate quayside to ship transfers of components weighing between 300t and 3,000t.

US$30-$40 million

Heavy Transport Barges

Reinforced, level-deck barges are a workhorse of offshore wind turbine installations, particularly for near-shore developments. These must be constructed to handle tens of thousands of tons of deck loading and may also be equipped with pitch and roll compensation to keep steady, level decks.



Pile Placement Vessel

Ship with heavy lift capability up to 500t and fitted with monopile grasping and driving machinery. Larger vessels have deck storage space for piles or work in tandem with heavy transport vessels.

US$200-$225 million

Heavy Lift Vessel

General purpose, sheer leg, floating heavy cranes with capacities between 2,000t and 5,000t, depending on installation needs. Used to handle topsides placement of offshore transmission substations and monopile topsides for fixed-bottom turbines.

US$130-$160 million

Cable Laying Vessel

Highly specialized ships that can spool great lengths of transmission cable needed to interconnect arrays of towers to substations and substations to shore.

US$200-$400 million

Trenching Robots

Remotely operated machinery for burying cable below the seafloor. Often launched from cable-laying vessels or from construction support vessels. These are typically supplied with cable-laying vessels.

Image source: https://www.jandenul.com/fleet/trenchers

Construction Support Operations Vessels

Highly versatile ships with materials transport/storage, moderate tonnage lifting, geopositioning, and wave stabilization capabilities, along with crew accommodations for extended operations away from harbor.

US$90-$100 million

Dive Support Vessel

Underwater construction, inspection and maintenance operations support where remote-operated vehicles and/or divers are deployed to work on foundation and anchorage elements. These specially designed ships have one or more through-hull portals internally to lower equipment or diving bells.

US$100-$125 million

Rock Installation Vessels

Barge-like vessels that carry and place rock armoring around wind turbine fixed foundations and atop buried transmission cables to protect them from anchor strikes and scour.

US$175-$200 million

Image source:

https://www.huismanequipment.com/en/media_centre/press_releases/163-174_Huisman-awarded-contract-for-rock-installation-equipment

Anchor Handling Vessels

General purpose, heavy pull power vessels used to tow and place large offshore assemblies like floating foundations in open water. Come in capacity categories of around 55t, 150t, and 200t. Thus, for very heavy moves, multiple vessels are required.

US$50-$70 million

Walk-to-Work Vessel

Specialized vessels for transporting construction and maintenance crews to turbines and substations. Designed to remain geopositioned and at constant/stable vertical position even in rough seas, such that crew can safely walk to their work platform. Used for far-offshore locations and/or in heavy seas areas.

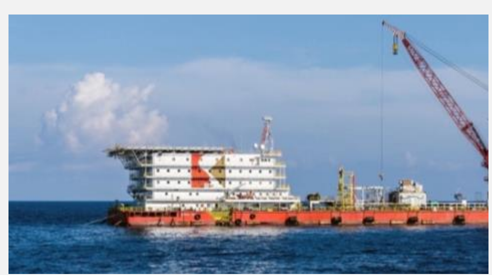
US$80-$100 million

Crew Transfer Vessels

These are general purpose, workhorse craft meant for speedy conveyance of construction, operations and maintenance crews from shore to ship or platform. They may have small hoists and cargo space to provide supply of small parts/components.

US$5-$7 million

Crew Accommodation Vessels (Floatels)



For offshore wind farm installations where distances involved are too far for practical daily crew movements. Sized from 50 crew to hundreds depending on need.

US$30-$40 million

Tugs

Harbor logistics operations need to be supported by fleets of ordinary tug vessels. They help to safely position larger vessels quayside as well as support stabilized, safe movement of large assemblies being towed by anchor handling vessels.

US$2-5 million depending on size

Seabed Survey Vessel

Specially equipped vessels that use seismic and sonar soundings and receivers to map seabed floor topography. Typically contracted from survey service providers on a day-rate basis or per job.

Geological Survey Vessel

These are ships equipped with geopositioning systems that keep them static and allow for floating drilling of sample rock cores from the seabed. This is used to determine the geotechnical characteristics of areas where foundations will be driven, helping inform engineers about the best design for their farm foundations.

Port Infrastructure

Offshore wind farms require significant port infrastructure to support construction and residual capacity to undertake maintenance services:

- The fabrication of towers and foundation systems – whether monopile, jacket, or floating – requires significant yard space, typically a minimum of 10 hectares, but preferably more to provide logistical flexibility.
- Ports must be able to receive deliveries of wind turbine nacelles weighing up to 750t, and transfer completed fabrications from the yard to quayside in increments up to 3,000t. Quaysides should have a minimum berthing length of 500m.
- The landside area should be reinforced to handle the heavy concentration of loads imposed by the fabrications and components.
- Inventory areas are required for the steel plate and tubing to fabricate foundations and towers, along with ancillary cranes and gantries to move raw material and sub-assemblies around the yard.

- Space should be allocated to marshalling, accounting for the multi-axle, self-propelled modular transport platforms needed to shift completed assemblies to ships. Heavy lift cranes are also needed port-side.

Given the significant fleets of specialized vessels wind farms use, amongst the ships themselves there are ongoing requirements for berthing, crewing, regular operations, and overhaul maintenance services. This is particularly important if a country/market has a sustained campaign of wind farm development.

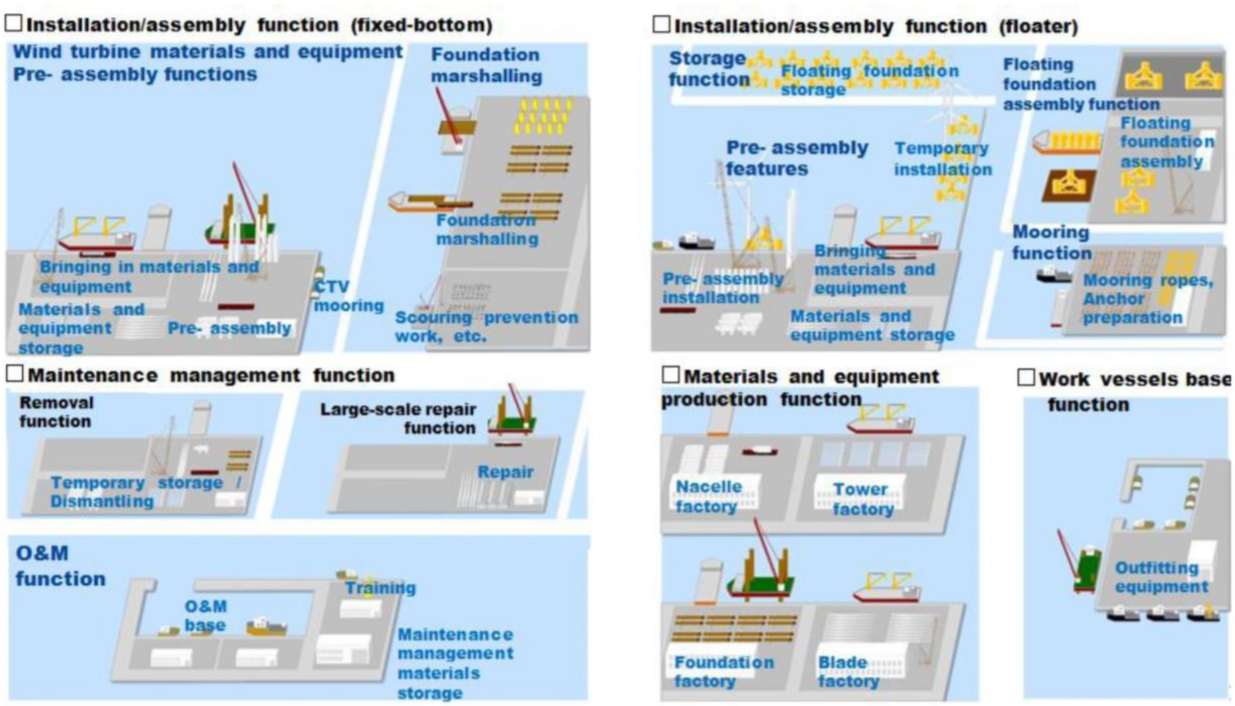
Below is a helpful illustration of the various types of port services required across the implementation and operational life of offshore wind farms, courtesy of the Renewable Energy Institute, Japan.

Modifying and upgrading existing ports can incur costs of US$50-$100 million per location; new-build facilities, depending on location and configuration, can require investments over US$200 million. As illustrated in the figure below, multiple port facilities with similar design requirements and investment costs could be needed depending on how many components are fabricated or manufactured in-country.

Port Functions for Offshore Wind Farm Supply, Construction, Operations and Maintenance

Sufficient port-side areas are needed for materials receiving, handling, fabrications and load-out for installation. Indoor fabrication areas may be required for assembling components that require controlled environments and/or precision fabrication. Wind farms both under construction and operating need warehousing for parts and components. All of these facilities need to be located portside with highly reinforced quays and staging areas since components can weigh hundreds to thousands of tonnes. These port facilities will see peak use during initial installation of the wind farm, however, their use does not end once a project is commissioned. Port areas will serve as day-to-day operations bases for projects. They will house spare parts and back up equipment. Eventually there will be need for major overhaul maintenance on the wind turbines, which will once again see the use of massive lifting and oceangoing vessels needed to conduct the work.

Example of the types of port facilities and the functions they serve:



Source: Ports and Harbors Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan. Study group on ports and harbors to promote the introduction of offshore wind power generation. May 31, 2023. Translation by Renewable Energy Institute, Japan.

Quayside Special Equipment and Services

Special equipment is needed for handling the extremely heavy components, fabrications and assemblies required for offshore wind farms. Quayside areas must be heavily reinforced to handle the multi-thousand-tonne loads imposed by these structures and equipment. Fabrication yards and their port facilities are significant investments, depending on the starting point of the infrastructure.

Temporary Quayside Heavy Lift Cranes

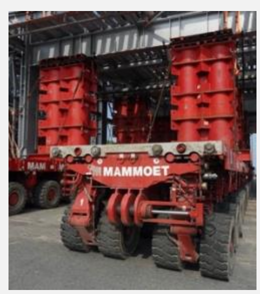
Ground mounted cranes can be installed for medium-term yard and port work, allowing them to be removed once construction activities are completed. Lifting capacities can be upward of 3,200t, suitable for handling completed offshore wind foundation fabrications.

Fixed Quayside Crane

A permanent quayside lifting solution is suitable in areas where multiple offshore wind farms are going to be developed over many years, or at ports where fabrication is being done for many regional customers. Fixed track and permanent cranes can provide flexibility for handling a wide variety of cargoes and lifting situations.

Self-Propelled Modular Transport Platforms

Given the massive size of fabrications in yards and the need to work on multiple foundations, piles or towers at once, there is a need to transport completed fabrications from layout area to quayside. Highly specialized ground transport vehicles are required for areas where cranes cannot reach and/or lifting mass is too great.



Array and sea-to-shore transmission cables

Highly specialized machinery braids and layers cables and protective materials to create durable, high-quality cabling. Depending on the design and installation requirements, cables can range from US$800 to US$1,200 per meter.

Manufacturing Components

Blades

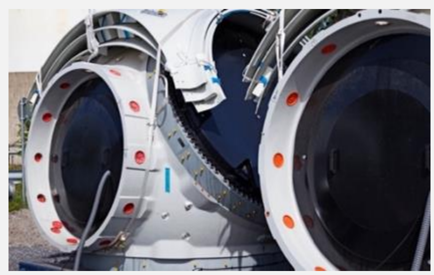
Composites of fiberglass, carbon fiber, balsa wood, and plastics laid-up in specialized facilities with high quality control, ventilation/filtration. Blades for offshore wind farms can range from 80m to 130m, thus facilities need to be able to handle logistics for multiple sets.

Anchoring Systems

For floating foundations, specialty vendors create the systems used to tether the assembles to the ocean floor. A multitude of designs, configurations and techniques are used depending on seabed and oceanographic conditions. Anchor system vendors can work in close coordination with steel fabricators if they wish to outsource certain components.

Castings and Bearings

Specialty metals castings are required for high stress, critical connections such as where the blades attach to the hub and all rotating bearing connections – like between rotor and nacelle and nacelle to tower. These must be machined to exacting specifications and tolerances.



Towers, Monopiles, Transition Pieces

Fabrication facilities contain equipment to bend and roll steel plate into desired shapes. Automated welding machines provide high-quality, full penetration welds to assure strengths. Welds are X-ray inspected for integrity. Final assemblies can weigh over 3,000t.

Exterior fabrication yards are used to assemble larger, more complex foundation elements such as jackets and floating bases.

Transmission Substations

Offshore array cables are fed into offshore transmission substations before heading onshore. Depending on the total load gathered and the distance that needs to be traveled to shore, these can be high voltage alternating current (HVAC) for projects closer to shore and smaller loads or high voltage direct current (HVDC) for longer distances and larger loads. HVDC equipment is more complex and expensive than HVAC, but the savings from line losses over long distances more than make up for that investment.

These are fabricated at onshore manufacturing facilities, loaded onto heavy transport vessels and placed atop foundations by a heavy lift vessel. These assemblies can weigh between 5,000t to 20,000t.

Fixed bottom, offshore HVAC substations run from US$150,000 to US$200,000 per MW. HVDC fixed-bottom offshore substations can cost between US$300,000 to US$500,000 per MW. Moving to a floating offshore configuration can, currently, increase those costs by 50%.

Onshore substations range between US$50,000-US$100,000 per MW (HVAC) and US$170,000-$220,000 per MW (HVDC).

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Author

Grant Hauber

Grant's experience spans over 30 years in 30 different countries, covering energy markets and infrastructure public-private partnerships (PPP). Across Asia, he has garnered expertise as a project developer in both renewable and conventional electricity, a project finance investment banker, and energy asset strategist. More recently, he served as a Principal at the Asian Development Bank in Manila, spearheading creation of the bank's PPP Operational Plan and advising governments across South and Southeast Asia how to integrate PPP principles into their public investment planning.

Grant holds a Bachelor of Science in Civil Engineering from Carnegie-Mellon University and an MBA from the Yale School of Management. He is currently based in Buffalo, New York.

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