International Renewable Energy Agency

RENEWABLE POWER GENERATION COSTS IN 2018

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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FOREWORD

The costs for renewable energy technologies reached new lows again last year. Solar and wind power have emerged as the most affordable power source for many locations and markets, with cost reductions set to continue into the next decade.

Cost declines across the board in 2018 have reconfirmed the status of renewable power as a highly cost-effective energy source. New solar photovoltaic (PV) and onshore wind power are on the verge of costing less than the marginal operating cost of existing coal-fired plants. Steadily improving competitiveness has made renewables the backbone of the world's energy transformation.

The International Renewable Energy Agency (IRENA) has tracked and analysed the cost evolution of renewable power since 2012. Combining the latest data with global coverage and a transparent methodology has helped to shed light on the accelerating momentum of renewables, not only as a key climate solution but also as a strong business proposition.

Within IRENA's database, for instance, over three-quarters of the onshore wind and four-fifths of the solar PV project capacity due to be commissioned in 2020 should produce cheaper electricity than any coal, oil or natural gas option. Crucially, they are set to do so without financial assistance.

The competitiveness of renewable power generation options was not always widely recognised. However, the past decade has seen governments, industry, financing institutions, investors and project developers work together to drive down costs and improve performance. Solar and wind power – once seen as an expensive way to address economic, environmental and social-development goals – are now a cost-competitive way to meet energy demand.

To fully harness the economic opportunity of renewables, IRENA will work closely with countries to develop concerted action on the ground. Electrification with renewables offers a low-cost decarbonisation solution to meet the climate goals set out in the Paris Agreement. Any development aiming to be sustainable needs to tap into renewable power.

Francesco La Camera
Director-General
International Renewable Energy Agency

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

CSP	Concentrated solar power
CO_2	Carbon dioxide
DCF	Discounted cash flow
DNI	Direct normal irradiance
GW	Gigawatt
GWh	Gigawatt-hour
IRENA	International Renewable Energy Agency
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelised cost of electricity
MW	Megawatt (electric)
MWh	Megawatt-hour
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
PPA	Power Purchase Agreement
PV	Photovoltaics
TWh	Terawatt-hour
USD	United States Dollar
VRE	Variable renewable electricity
WACC	Weighted Average Cost of Capital

KEY FINDINGS

In most parts of the world today, renewables are the lowest-cost source of new power generation. As costs for solar and wind technologies continue falling, this will become the case in even more countries. The cost of electricity from bioenergy, hydropower, geothermal, onshore and offshore wind was within the range of fossil fuel-fired power generation costs between 2010 and 2018. Since 2014, the global-weighted average cost of electricity of solar photovoltaics (PV) has also fallen into the fossil-fuel cost range.

Onshore wind and solar PV are set by 2020 to consistently offer a less expensive source of new electricity than the least-cost fossil fuel alternative, without financial assistance. Among projects due to be commissioned in 2020, 77% of the onshore wind and 83% of the utility-scale solar PV project capacity in the IRENA Auction and PPA Database have electricity prices that are lower than the cheapest fossil fuel-fired power generation option for new generation.

New solar PV and onshore wind are expected to increasingly cost less than the marginal operating cost of existing coal fired power plants. In 2020, the weighted average PPA or auction price for solar PV from projects in the IRENA database – USD 0.048 per kilowatt-hour (kWh) – is expected to be less than the marginal operating costs for around 700 gigawatts (GW) of operational coal-fired capacity at the same time. Onshore wind – at USD 0.045/kWh – should fall below the marginal operating costs of almost 900 GW of coal capacity potentially online in 2020.

The global weighted-average cost of electricity from all commercially available renewable power generation technologies declined in 2018. The cost of electricity from CSP declined 26% year-on-year in 2018, followed by bioenergy (-14%), solar PV and onshore wind, both declined by 13%, hydropower (-11%), geothermal and offshore (-1%). Individual bioenergy, hydropower, onshore wind and solar PV projects now commonly undercut fossil fuel-fired power generation, without financial assistance.

Cost reductions for solar and wind power technologies are set to continue to 2020 and beyond. Data from IRENA's Auction and power purchase agreement (PPA) Database show that by 2020–2022, all existing available renewable power generation options will compete-head-to-head with incumbents. As the share of variable renewables increases, the importance of looking beyond generation costs to total system costs becomes more important. Integration costs could be minimal if a systemic approach to the power system transformation is applied, but could rise if opportunities for flexibility options are confined narrowly to the electricity sector.

Expectations about future cost reductions for solar PV and onshore wind are once again being continually beaten by lower values as new data becomes available. At the beginning of 2018, IRENA's analysis of auction and PPA data suggested that the global weighted-average cost of electricity could fall to USD 0.049/kWh for onshore wind and USD 0.055/kWh for solar PV in 2020. A year later, the potential value for onshore wind in 2020 has dropped a further 8%, to USD 0.045/kWh, while that of solar PV drops 13%, to USD 0.048/kWh.

Very low, and falling, costs of electricity for solar PV and onshore wind, as well as cost reductions for CSP and offshore wind until 2020 and beyond, make renewable power the competitive backbone of the global energy sector transformation. Beside making the decarbonisation of the electricity sector economically attractive, these cost decreases unlock low-cost decarbonisation in the end-uses sectors of industry, transport and buildings as the costs of electric end-use technologies such as electric vehicles and heat pumps. IRENA's latest analysis of the world's pathway to a sustainable energy sector[1] therefore sees an increase in electrification, with the share of electricity growing from less than a fifth of final energy demand to nearly half in 2050, on the back of cost-competitive renewables.

Table 1 Global electricity costs in 2018

	GLOBAL WEIGHTED-AVERAGE COST OF ELECTRICITY (USD/KWH) 2018	COST OF ELECTRICITY: 5TH AND 95TH PERCENTILES (USD/KWH) 2018	CHANGE IN THE COST OF ELECTRICITY 2017–2018
Bioenergy	0.062	0.048–0.243	−14%
Geothermal	0.072	0.060–0.143	−1%
Hydro	0.047	0.030–0.136	−11%
Solar photovoltaics	0.085	0.058–0.219	−13%
Concentrating solar power	0.185	0.109–0.272	−26%
Offshore wind	0.127	0.102–0.198	−1%
Onshore wind	0.056	0.044–0.100	−13%

1 See IRENA (2019), Global Energy Transformation: A Roadmap to 2050, IRENA, Abu Dhabi.

SUMMARY

1.1 RENEWABLE POWER GENERATION: THE COMPETITIVE BACKBONE OF THE GLOBAL ENERGY TRANSFORMATION

In most parts of the world today, renewables have become the lowest-cost source of new power generation. As costs continue to fall for solar and wind technologies, this will be true in a growing number of countries.

Data from the IRENA Renewable Cost Database[2] shows that since 2010, the global weighted-average levelised cost of electricity (LCOE)[3] from bioenergy, geothermal, hydropower, onshore and offshore wind projects have all been within the range of fossil fuel-fired power generation costs[4]. Since 2014, the global-weighted average LCOE of solar photovoltaics (PV) has also fallen into the fossil-fuel cost range. The global weighted-average LCOE of the newer solar and wind power technologies – concentrating solar power (CSP), utility-scale solar PV, onshore and offshore wind have all fallen between 2010 and 2018.

In 2018, the global weighted-average LCOE for hydropower, onshore wind, bioenergy and geothermal projects commissioned were all at the lower-end of the fossil-fuel cost range, so that those technologies competed head-to-head with fossil fuels, even in the absence of financial support (Figure S.1). With continued cost reductions, solar PV power has also started to compete directly with fossil fuels. Offshore wind and concentrating solar power (CSP) are less widely deployed, and their global weighted-average electricity costs are in the top half of the fossil fuel cost range. Their costs, however, continue to fall, with auction and Power Purchase Agreement (PPA) results suggesting that by 2020 or 2022, they will also be highly competitive.

Where economic resources remain to be developed, the more mature renewable power generation technologies – bioenergy, geothermal and hydropower – have provided a competitive source of new electricity for many decades. In 2018, the global weighted-average LCOE from newly commissioned bioenergy, geothermal and hydropower facilities amounted to USD 0.062 per kilowatt hour (kWh), USD 0.072/kWh and USD 0.047/kWh, respectively (Figure S.1).

The global-weighted average LCOE of hydropower projects was the same or lower than the cost of the *cheapest* fossil fuel-fired option in all but two years between 2010 and 2018. As a result, the bulk of the deployment of hydropower between 2010 and 2018 has cost less than the cheapest fossil fuel alternative.

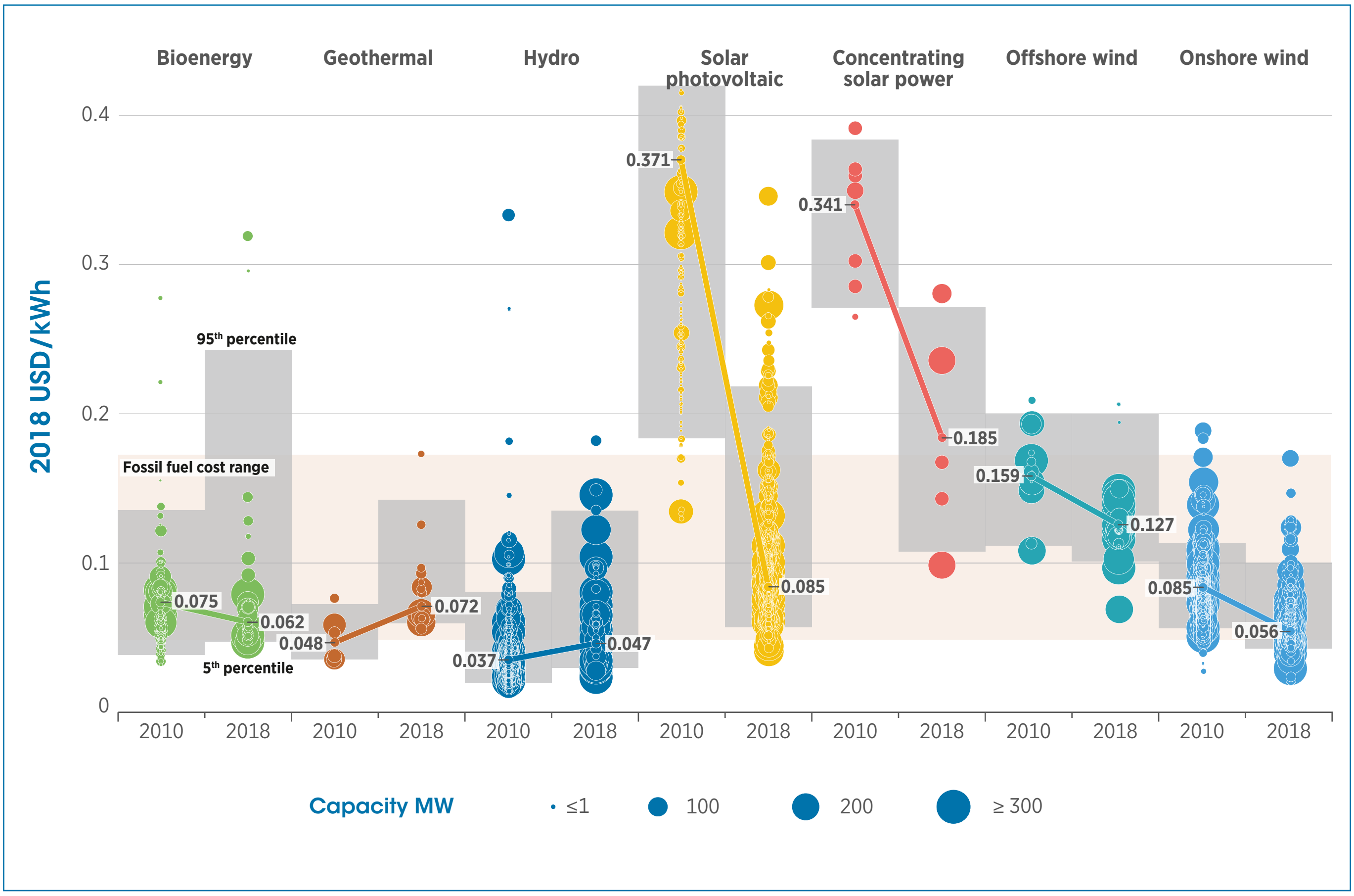
Hydropower is not alone in providing cheaper electricity than fossil fuels in recent years, either, as the global weighted-average LCOE of newly commissioned onshore wind projects in 2018 was USD 0.056/kWh, with significant numbers of projects having costs below that of fossil fuel-fired power generation options.

2 The IRENA Renewable Cost Database contains cost and performance data for around 17 000 renewable power generation projects with a total capacity of around 1 700 GW. It has data on around half of all renewable power generation projects commissioned by the end of 2018.

3 The LCOE of a given technology is the ratio of lifetime costs to lifetime electricity generation, both of which are discounted back to a common year using a discount rate that reflects the average cost of capital. In this report, all LCOE results are in real 2018 USD (that is to say, taking into account inflation) calculated excluding any financial support and using a fixed assumption of a real cost of capital of 7.5% in OECD countries and China, and 10% in the rest of the world, unless explicitly mentioned. All LCOE calculations exclude the impact of any financial support. All data presented here is for the year of commissioning. Planning, development and construction can take 2–3 years for solar PV and onshore wind, but can take 5 years or more for CSP, fossil fuels, hydropower and offshore wind.

4 The fossil fuel-fired power generation cost range by country and fuel is estimated to be between USD 0.049 and USD 0.174/kWh. All cost data in this report is expressed in real 2018 United States dollars (USD), that is to say taking into account inflation.

Figure S.1 Global LCOE of utility-scale renewable power generation technologies, 2010–2018



Note: This data is for the year of commissioning. The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE value for plants commissioned in each year. Real weighted average cost of capital (WACC) is 7.5% for OECD countries and China and 10% for the rest of the world. The single band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 95th percentile bands for renewable projects.

The global weighted-average cost of electricity from all commercially available renewable power generation technologies experienced declines in 2018, with CSP, bioenergy, solar PV and onshore wind experiencing the largest declines.

In 2018, with new CSP capacity commissioned in the People's Republic of China, Morocco and South Africa, the global weighted average LCOE for CSP fell by 26%, compared to 2017. Given the relatively thin market for CSP, this rapid drop in 2018 should be treated with caution. Yet, with a number of Chinese projects likely to be commissioned in 2019, a rebound in costs is unlikely. The global weighted-average LCOE of CSP has fallen by 46% between 2010 and 2018.

In 2018, around 60 GW of new utility-scale solar PV was commissioned (with another 34 GW of residential and commercial rooftop solar PV added). The utility-scale solar PV projects commissioned in 2018 had a global-weighted-average LCOE of USD 0.085/kWh, which was around 13% lower than the equivalent figure for 2017. The global weighted-average LCOE of utility-scale solar PV has fallen by 77% between 2010 and 2018.

Cost reductions continue to be driven by both declines in solar PV module prices and balance of system costs. The former have fallen by over 90% since the end of 2009, with a reduction of around one-third between 2017 and 2018, although much of this reduction will predominantly flow into projects commissioned in 2019. The global weighted-average total installed cost of utility-scale projects fell by 13% to USD 1 210/kW in 2018 compared to 2017 (Figure S.2).

In addition, onshore wind now represents a competitive source of electricity in most parts of the world. In 2018, around 45 GW (IRENA, 2019a) of new capacity was commissioned at a global weighted-average LCOE of USD 0.056/kWh, which was 13% lower than the value for 2017. This reflects both falling turbine and balance of project costs, and improving performance as higher hub heights and larger swept areas harvest more electricity from a given resource than older technologies.

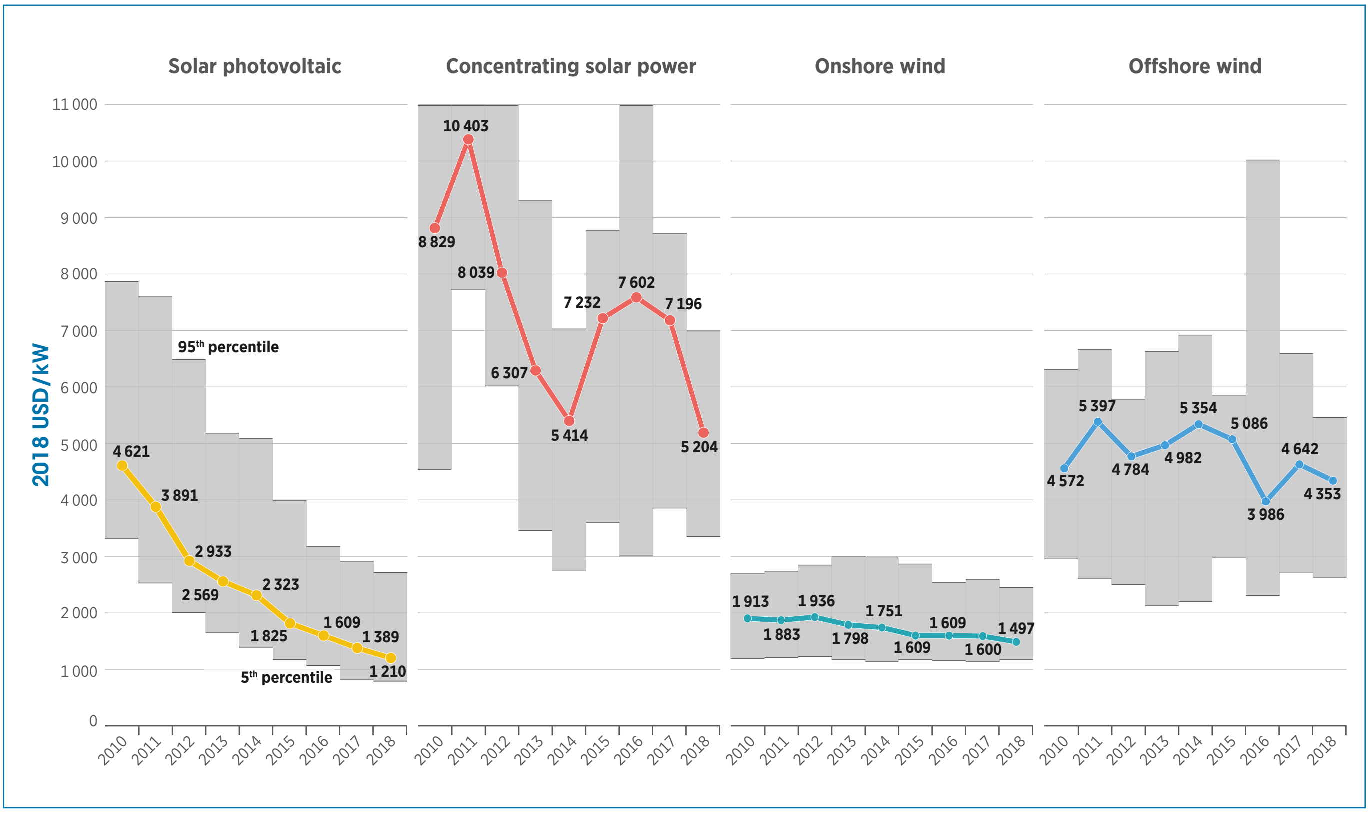
For hydropower projects, after two years of increasing, the global weighted-average cost of electricity from those commissioned in 2018 fell 11%, compared to 2017, to USD 0.047/kWh. This was because the 21 GW of new projects commissioned had total installed costs that were around 15% lower than those of 2017. The major driver was projects commissioned in Asia, where installed costs fell between 2017 and 2018.

Meanwhile, the global weighted average LCOE of bioenergy projects fell by around 14% between 2017 and 2018, as a result of deployment shifting towards some of the less capital intensive technologies used for the combustion of agriculture and forestry residues.

The cost of electricity from both geothermal and offshore wind projects declined slightly (around 1%, year-on-year) in 2018. Only 540 MW of geothermal power generation capacity was added in 2018, however, making cost trends difficult to discern with confidence. The offshore wind sector saw around 4.5 GW of capacity commissioned in 2018, around the same as in 2017, with a global weighted-average LCOE of USD 0.127/kWh.

As the share of variable renewable electricity (VRE) grows, the importance of examining total system costs, not just generation costs increases. IRENA analysis of a pathway consistent with meeting the Paris Agreement goals (IRENA, 2019b) highlights that planning for these high shares is crucial to minimising overall costs. A systemic approach to the creation of markets for flexibility, in the power sector and beyond, can unlock a range of low-cost flexibility options. IRENA's Innovation Landscape for a Renewable-Powered Future (IRENA, 2019c) examined 30 current and emerging innovations across the categories of enabling technologies, business models, market design and system operation that can offer low-cost solutions to higher shares of VRE. Experience from Germany, Spain and Scandinavia shows that low-cost integration is possible, while the continued growth in operating experience, development of new markets for flexibility and emerging innovations are constantly reducing the expected costs and difficulty of integrating ever higher shares of VRE in the system. This is an area were knowledge is evolving rapidly. Indeed, IRENA's 2019 analysis of the global investment needs in grids, flexibility and storage for achieving 86% renewable power generation fell 30% compared to last year's analysis (IRENA, 2019b).

Figure S.2 Global weighted average total installed costs and project percentile ranges for CSP, solar PV, onshore and offshore wind, 2010–2018



Cost reductions for solar and wind power technologies are set to continue to 2020 and beyond. Current auction and PPA data suggests that by 2020, onshore wind and solar PV will consistently offer less expensive electricity than the least-cost fossil fuel alternative, while by then, offshore wind and CSP will offer electricity in the USD 0.06 to US 0.10/kWh range.

IRENA's database of PPA and auction results for around 393 GW of capacity from around 9 850 projects or programmes[5] suggests that costs will continue to fall, out to 2020 and 2022, depending on the technology.

Although care must be taken in comparing PPA and auction results to LCOE calculations[6], for onshore wind, the global weighted-average price of electricity from PPA and auction results could fall to USD 0.045/kWh by 2020 (Figure S.3). This would represent a reduction of around 20% compared to the global weighted-average cost of electricity from onshore wind projects commissioned in 2018, or a decline of around 10% per year.

For utility-scale solar PV, the auction data suggests that the average price of electricity could fall to USD 0.048/kWh in 2020, a reduction of 44% compared to the global weighted-average LCOE of

5 Only the average value for the entire capacity contracted for is reported in some auction rounds or solicitations for generating capacity. As a result, the number of individual projects covered by the database exceeds this value.

6 For a detailed discussion of the challenges of comparing PPA and auction data to LCOE calculations and how IRENA corrects or excludes data for the comparison in Figure S.3, see IRENA, 2018.

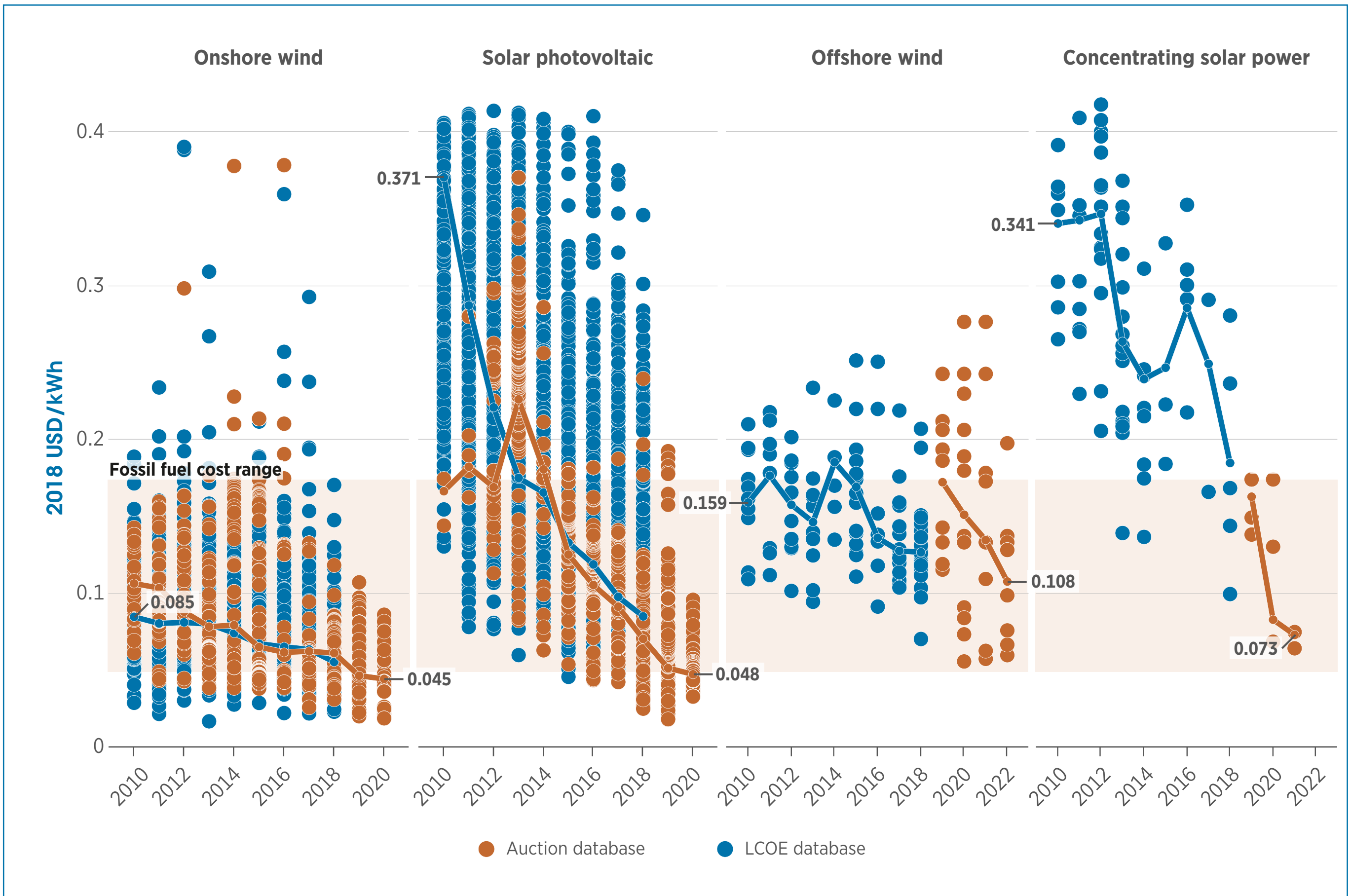
projects commissioned in 2018. At a rate of 25% per year, this represents an acceleration over recent cost reduction trends.

This acceleration is being driven by three factors. First, there are the benefits of competitive procurement in reducing the cost of electricity in markets that previously had higher installed costs than the benchmark competitive cost structure. Second, there is the shift to deploying solar PV in sunnier regions with higher capacity factors, and third, there is the reduced cost of financing.

For offshore wind, the average cost of electricity could fall by 15% to USD 0.108/kWh, or 4% per year, by 2022. Projects in 2022 would predominantly span the range USD 0.06 to USD 0.14/kWh, with projects in Europe in the range of USD 0.06 to USD 0.10/kWh, with some exceptions.

CSP will experience a real step-change in costs, as auction and PPA results suggest the price of electricity will fall by 61% between 2018 and 2021, or 27% per year. This data should be treated with caution, however, as this is based on just five data points for 2020 to 2021.

Figure S.3 The LCOE for projects and global weighted average values for CSP, solar PV, onshore and offshore wind, 2010–2022



Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

For projects to be commissioned in 2020, 77% of the onshore wind project capacity and 83% of the utility-scale solar PV in the IRENA auction and PPA database have costs that are lower than the cheapest fossil fuel-fired power generation option for new generation.

Although care must be taken in comparing the results in the PPA and auction database – as an auction price is not necessarily directly comparable to an LCOE calculation[7] – these percentages highlight the continued rapid improvement of the competitiveness of solar PV and onshore wind, as costs continue to fall.

With the right regulatory and institutional frameworks in place, recent record low auction prices for solar PV in Dubai, Mexico, Peru, Chile, Abu Dhabi and Saudi Arabia have shown that an LCOE of USD 0.03/kWh is possible in a wide variety of national contexts. This very low value is possible when installed costs and operations and maintenance (O&M) are low, the solar resource is excellent and financing costs are low.

Indeed, very competitive total installed costs for solar PV are now possible around the world, even in markets with little previous experience with solar PV. This is because international project developers can bring their experience in project development into partnerships with local stakeholders to take advantage of the low – and falling – equipment costs for this technology. At the same time, the very low risks involved in solar PV project development, when coupled with low offtake risks and a strong, local civil engineering base in the current low interest rate environment, has led to a very low weighted average cost of capital for many of these projects (IRENA, 2017). Stable local currencies, or contracts denominated in United States dollars, also reduce exchange rate risks. Continued improvements and optimisation of O&M practices, coupled with the low cost of land in some of these countries have also helped to minimise O&M costs.

Similarly, there have been very competitive auction results for onshore wind in countries that stretch from Brazil to Canada and India to Morocco, Mexico and Germany. These have shone a spotlight on just how competitive onshore wind is today, as the higher installed costs of this technology compared to solar PV today are offset by their higher capacity factors.

New solar PV and onshore wind will increasingly be cheaper than the marginal operating cost of existing coal-fired power plants.

In 2020, the weighted average PPA, or auction price, for solar PV – USD 0.048/kWh – from the IRENA database is expected to be less than the marginal operating costs[8] of around 700 GW of the coal-fired capacity operational at that time based on analysis from Carbon Tracker on marginal operating costs for coal plants (Carbon Tracker, 2018).[9] In 2020, the weighted average PPA or auction price for onshore wind – USD 0.045/kWh – is less than the marginal operating costs of almost 900 GW of the operational coal-fired capacity potentially online in 2020.

7 See IRENA, 2018 for a detailed discussion of the caveats that apply when comparing data from the PPA and auction database to LCOE data.

8 Marginal operating costs include those for fuel (delivered to the power station), fixed and variable O&M costs and any carbon costs, if such apply to the power plant.

9 This is based on the data on marginal operating costs of coal-fired power plants in 2020 undertaken by Carbon Tracker when compared to the PPA and auction data in the IRENA database anticipated to be commissioned in 2020.

The profitability of existing coal-fired power plants, especially in the presence of carbon pricing, could therefore deteriorate rapidly in the near future. These stresses are already evident in certain markets, such as the United Kingdom, where a carbon price floor has seen coal-fired generation fall from 40% of generation in 2013 to an estimated 6% in 2018. At the same time, renewables have increased from 12% to 28% (BEIS, 2019), with natural gas power generation also growing. In the United States a combination of cheaper natural gas and renewables saw coal retirements of around 61 GW between January 2012 and June 2018.[10]

With global cumulative installed coal-fired generation capacity likely to reach around 2 100 GW by 2020, the prices registered in auction and PPA contracts for onshore wind and solar PV suggest that in 2020, perhaps up to 40% of the existing coal fleet could be outcompeted by new renewable deployment. Further analysis would be required to identify with confidence the proportion of the global coal fleet at risk in 2020 by analysing existing coal plants and new renewable costs at a country level. The figures presented here, however, do give an idea of the order of magnitude of the assets at risk.[11]

Expectations about future cost reductions for solar PV and onshore wind are once again being continually beaten by lower values as new data becomes available.

In January 2018, the data on auction and PPA prices for solar PV and onshore wind suggested that the global weighted-average value for the projects in the IRENA database would fall to USD 0.049/kWh for onshore wind and USD 0.055/kWh for solar PV in 2020. One year later, additional data for projects totalling 33% more capacity for onshore wind and more than twice as much for solar PV, saw the expected value for onshore wind in 2020 drop 8%, to USD 0.045/kWh, and that of solar PV drop 13%, to USD 0.048/kWh.

Falling and very low costs of electricity for solar PV and onshore wind, as well as the cost reductions for CSP and offshore wind to 2020 and beyond mean that renewable power is becoming the competitive backbone of the global energy sector transformation.

The continued cost declines for solar PV and onshore wind, to the point where they will be substantially undercutting even the cheapest new source of fossil fuel-fired electricity by 2020, complemented by declines in the cost of dispatchable CSP and battery storage technologies, improvements in grid operation and an emerging suite of electrification technologies in end-uses (from electric vehicles to heat pumps) will see low-cost renewable electricity generation underpin an energy sector transformation to 2050.

These costs declines and the advances in the ability to securely operate the grid with high shares of variable renewables are not only decarbonising the electricity sector, but are unlocking low-cost decarbonisation in the end-use sectors in conjunction with increased electrification. IRENA's analysis of the Global Energy Transformation: A Roadmap to 2050 (IRENA, 2019b) shows that electrification of end-uses will accelerate in a scenario that is consistent with meeting the Paris Agreement goals. By 2050, electricity's share of total final energy consumption could reach 49%, up from around 19% today. With falling battery costs, electrification of passanger transport reaches 70% by 2050, and electricity will provide 43% of total energy consumption in the transport sector. With the extensive electrification of space and water heating in buildings, electricity accounts for 68% of energy use in 2050. The falling cost of renewable power is therefore also helping to reduce the cost of decarbonising end-use sectors. IRENA's analysis of the investment needs to meet the Paris Agreement goals has fallen by 40% in 2019, compared to the previous estimate.

10 See the Economist Intelligence Unit analysis for a useful summary (accessed 13/4/2019 http://www.eiu.com/industry/article/1277120111/us-coal-plant-retirements-to-continue/2018-09-07) or the EIA reports "Preliminary monthly electric generator inventory" for the raw data (https://www.eia.gov/electricity/data/eia860m/).

11 An IRENA analysis looking at the cost reduction potential for solar and wind out to 2030 for the G20 countries, due for publication in late 2019, will look at this issue in more detail.

1.2 ONSHORE WIND POWER

The global weighted-average LCOE of onshore wind projects commissioned in 2018, at USD 0.056/kWh, was 13% lower than in 2017 and 35% lower than in 2010, when it was USD 0.085/kWh. Costs of electricity from onshore wind are now at the lower end of the fossil fuel cost range.

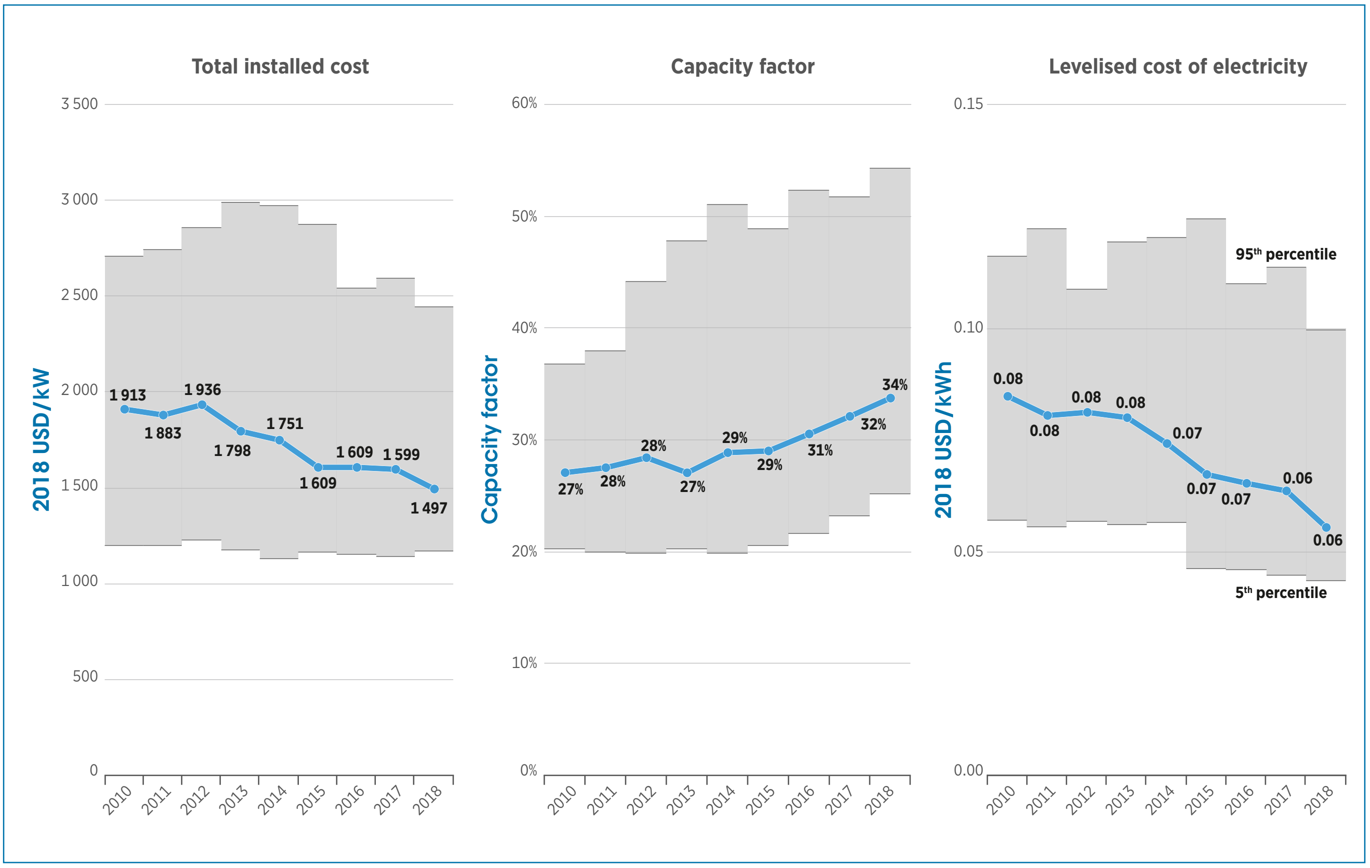
The lower cost of electricity for onshore wind in 2018 was driven by continued reductions in total installed costs, as well as by improvements in the average capacity factor (Figure S.4). The factors driving this trend include continued improvements in turbine design and manufacturing; more competitive global supply chains; and an increasing range of turbines designed to minimise LCOE in a range of operating conditions.

In 2018, China and the United States accounted for most of the expansion in onshore wind power, with increases of 18.5 GW and 6.8 GW respectively (IRENA, 2019a). Deployment was supported by GW or higher new capacity additions in Brazil (2.1 GW), France (1.6 GW), Germany (2.7 GW) and India (2.4 GW). The global weighted average decline in the LCOE of onshore wind by 13% in 2018 compared to 2017 is the culmination of a wide range of country experiences. The weighted average LCOE of newly commissioned onshore wind farms in 2018 in China and the United States was 4% lower than in 2017 (Figure 1.10). Both India and Brazil experienced slight increases in the weighted-average LCOE of projects commissioned in 2018, however, in part due to weaknesses in their currencies in recent years. These increases were also driven by a slightly lower weighted average estimated lifetime capacity factor for projects commissioned in 2018.

The weighted-average LCOE of onshore wind farms commissioned in 2018 in China and the United States were identical, at USD 0.048/kWh. Although China has lower capacity factors than the United States, this is offset by lower installed costs. In 2018, the weighted-average LCOE of onshore wind farms commissioned was USD 0.061/kWh in Brazil, USD 0.076/kWh in France, USD 0.075/kWh in Germany, USD 0.062/kWh in India, and USD 0.063/kWh in the United Kingdom.

Since 2014, there have been an increasing number of projects commissioned with an LCOE of between USD 0.03 and USD 0.04/kWh. These projects, combining competitive installed costs in areas with excellent wind resources are, in some markets, becoming a growing proportion of new deployment. These projects are significantly cheaper than even the cheapest fossil fuel-fired options for new electricity generation and will be undercutting the variable operating costs of some existing fossil fuel-fired generators.

Figure S.4 Global weighted average total installed costs, capacity factors and LCOE for onshore wind, 2010–2018



The global weighted-average total installed cost of onshore wind farms declined by 6% in 2018, year-on-year, falling from USD 1600/kW in 2017 to USD 1500/kW in 2018, as wind turbine prices continued to decline.

Total installed cost reductions continue to be underpinned by reductions in wind turbine prices, which fell around 10% to 20% between 2017 and 2018 (Figure 1.2), as well as by reductions in the balance of project costs.

Improvements in technology and manufacturing processes, regional manufacturing facilities and competitive supply chains are all contributing to maintain pressure on turbine prices.

In 2018, with the exception of China and India, average turbine prices were between USD 790 and USD 900/kW depending on their size, down from a range of between USD 910 and USD 1050/kW in 2017.

For onshore wind farms installed in 2018, the country-specific average total installed costs were around USD 1170/kW in China, USD 1200/kW in India, USD 1660/kW in the United States, USD 1820/kW in Brazil, USD 1830/kW in Germany, USD 1870/kW in France and USD 2 030/kW in the United Kingdom (Figure 1.4).

In Australia, which almost broke the 1GW of new capacity mark (940 MW added), installed costs were a competitive USD 1640/kW.

The trend towards higher wind turbine hub heights, larger swept areas and higher capacities, harvesting more electricity from the same wind resource, saw the global weighted-average capacity factor of onshore wind farms commissioned in 2018 increase to 34% from the 32% seen in 2017.

Although the final data is not available for 2018, between 2010 and 2017, there was significant growth in both turbine rotor diameter and turbine size, with this likely to have continued into 2018. Higher hub heights allow access to higher wind speeds, while larger swept areas can increase output across the range of operating wind speeds. There is a trade-off involved in the slightly higher costs for longer blades and taller towers, but an overall reduction in LCOE can be achieved with the right optimisation.

In the ongoing trend towards larger turbines with greater swept areas, Ireland stands out, although it still lags behind market leader Denmark in absolute terms for both these metrics (Figure 1.1). Ireland increased average nameplate capacity by 95% between 2010 and 2017 and rotor diameter by 76%. For projects commissioned in 2017, Denmark had an average rotor diameter of 118 metres (m) and a turbine capacity of 3.5 MW.

Brazil, Canada, France and the United States are interesting examples of markets that have increased the rotor diameter faster than the nameplate capacity. Between 2010 and 2017, the rotor diameter of newly commissioned projects increased by 42% in Brazil, 64% in Canada, 25% in France and 34% in the United States, while the growth in nameplate capacity was 31%, 41%, 16% and 29%, respectively.

In 2017, Canada, Germany, Sweden and Turkey were close to crossing the threshold of 3 MW turbines, on average, while Denmark with its smaller market was a clear leader with average nameplate capacity of 3.5 MW. In 2017, Brazil, Denmark, Germany, India, Sweden, Turkey and the United States all had average rotor diameters that exceeded 110 m, compared to 2010, when the range for these countries was between 77 m (India) and 96 m (Denmark).

In 2018, the weighted average capacity factor of onshore wind farms commissioned was 46% in Brazil, 44% in the United States, 40% in the United Kingdom, 37% in Australia; while it was 29% in China, France and Germany (Figure 1.7). Year-on-year in 2018, the country-specific weighted-average capacity factor declined slightly in India and went from 48% to 46% in Brazil. In 2018, most other major markets saw an increase.

1.3 SOLAR PHOTOVOLTAICS

The sustained, dramatic decline in the cost of electricity from utility-scale solar PV continued in 2018, with a fall in the global weighted-average LCOE of solar PV to USD 0.085/kWh – 13% lower than for projects commissioned in 2017. This takes the decline between 2010 and 2018 in the global weighted-average LCOE of solar PV to 77%.

In 2018, 94 GW of new solar PV capacity was added, accounting for 55% of total new renewable power generation capacity additions. The largest markets for new capacity additions in 2018 were China (44 GW), India (9 GW), the United States (8 GW), Japan (6 GW), Australia and Germany (4 GW), and the Republic of Korea, Mexico and Turkey (around 2 GW each) (IRENA, 2019a).

The global weighted-average LCOE of utility-scale solar PV in 2010 was USD 0.371/kWh, while by 2018 this had fallen to USD 0.085/kWh, 77% lower than in 2010. The year-on-year decline in 2018 was 13% (Figure S.5).

Cost reductions in 2018 were supported by crystalline silicon module price declines of between 26% and 32%, between December 2017 and December 2018, after modest declines of between 1% and 7% for the 12 months from December 2016 to December 2017 (Figure 2.1). In December 2018, benchmark prices for modules in Europe ranged from USD 216/kW for low-cost manufacturers, to USD 306/kW for mainstream manufacturers products, USD 400/kW for high-efficiency modules and to USD 420/kW for 'all black' panels. At the same time, the continued growth in new solar PV markets with excellent solar resources saw the global weighted average capacity factor increase slightly, but it remains at around 18%.

Lower solar PV module prices and ongoing reductions in balance of system costs remain the main driver of reductions in the cost of electricity from solar PV.

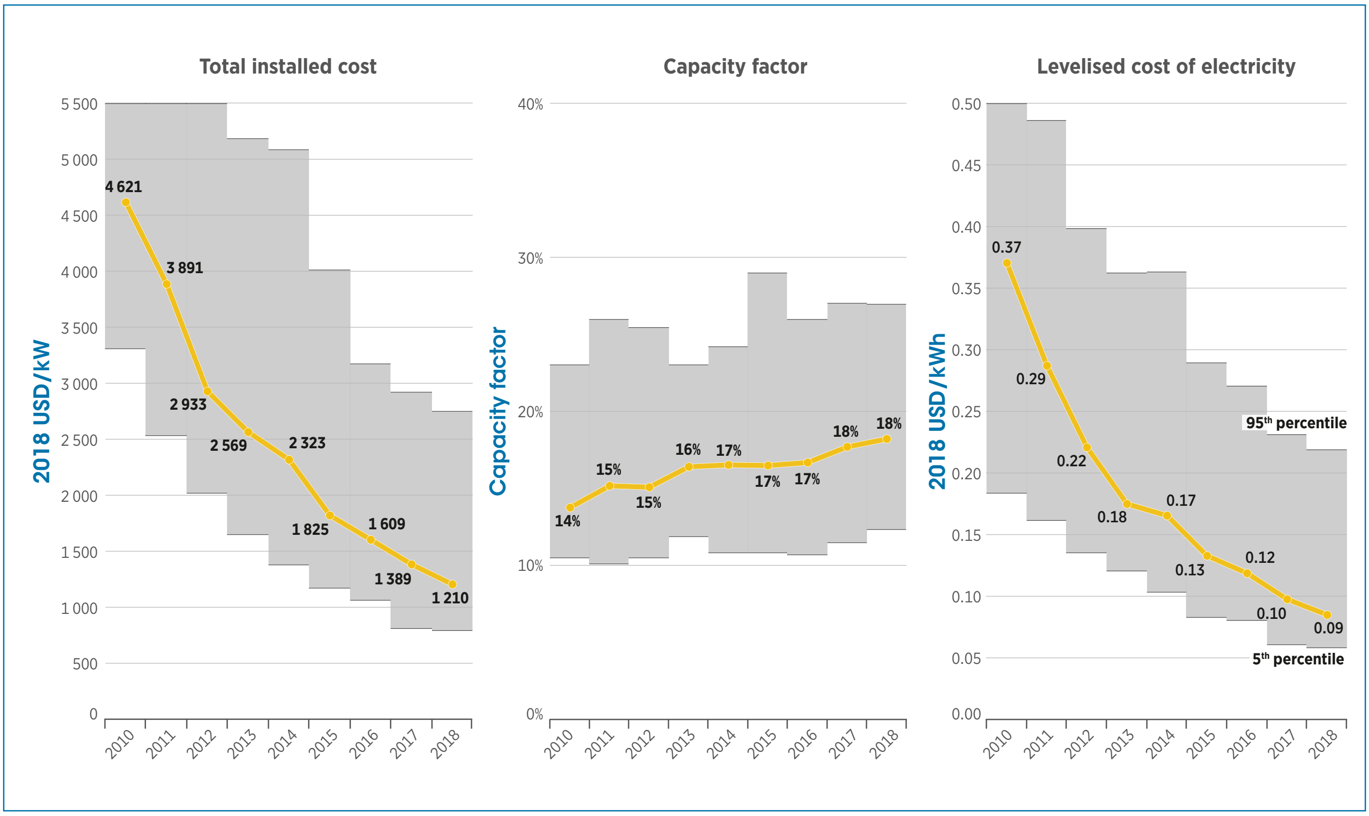
The global weighted-average total installed cost of utility-scale solar PV projects commissioned in 2018 was USD 1 210/kW, down from USD 1 389/kW in 2017, a 13% decline (Figure S.5 and 2.2). Although there has been a convergence in total installed costs towards the most competitive benchmark countries, which have historically been China and Germany, there still remains a wide spread in total installed costs.

India was estimated to have the lowest total installed costs for new utility-scale solar PV projects that were comissioned in 2018 at USD 793/kW, 27% lower than for projects commissioned in 2017 (Figure 2.3 and 2.4). Both China and Italy also saw very competitive installed costs for 2018 of USD 879/kW (23% lower than in 2017) and USD 870/kW (9% lower than in 2017) respectively. Of the major markets for utility-scale solar PV in 2018, Japan had the highest installed costs at USD 2 101/kW, which was 3% lower than for projects commissioned in 2017. Total installed costs in the United States and Australia declined by 16% and 20% respectively between 2017 and 2018, but remain relatively high at around USD 1 500/kW in 2018.

The country-specific LCOE of utility-scale solar PV declined by between 62% (in Japan) and 80% (in Italy) between 2010 and 2018. The year-on-year reduction in the LCOE in 2018 ranged from 21% in India to a low of 1% in Japan, although there was a slight uptick in costs in Germany and the United Kingdom.

In China, the weighted-average LCOE of new utility-scale solar PV plants commissioned in 2018 declined, year-on-year, by 20%, to USD 0.067/kWh (Figure 2.7). The decline in India was 21%, to USD 0.063/kWh, in the United States, 18%, to USD 0.082/kWh, and in Japan the decline was 1%, to USD 0.153/kWh. The average LCOE of new utility-scale solar PV projects in Germany increased by an estimated 2% year-on-year in 2018, driven by a slight uptick in total installed costs.

Figure S.5 Global weighted average total installed costs, capacity factors and LCOE for solar PV, 2010–2018



Note: Solar PV, unlike all other technologies in this report have their costs expressed per kilowatt direct current (DC) and their capacity factors are expressed as an AC-to-DC value.

The estimated learning rate for the LCOE of utility-scale solar PV for the period 2010 to 2020 has increased from the 35% estimated by IRENA in January 2019 to 37% based on the data presented here.

Solar PV has the highest learning rate[12] of all the renewable power generation technologies (IRENA, 2018). Indeed, updated data available for 2018 and 2020 suggests that the learning rate is higher than IRENA calculated back in January 2018 (IRENA, 2018).

Current PPA and auction price data suggests that by 2020, the price of electricity from solar PV could fall to USD 0.048/kWh. Assuming, conservatively, the deployment of 100 GW in 2019 and 105 GW in 2020, this would imply that between 2010 and 2020, the learning curve will rise from the 35% estimated in 2018, to 37%. This would cover a period in which 94% of global cumulative installed solar PV capacity is added.

12 The “learning rate” is the percentage reduction in cost or price for every doubling in cumulative deployment or production, depending on what data is used.

1.4 OFFSHORE WIND POWER

In 2018, global offshore wind power installations totalled 4.5 GW – almost exclusively in Europe and China. The global weighted average LCOE for offshore wind in 2018 was USD 0.127/kWh – 1% lower than in 2017 and 20% lower than in 2010.

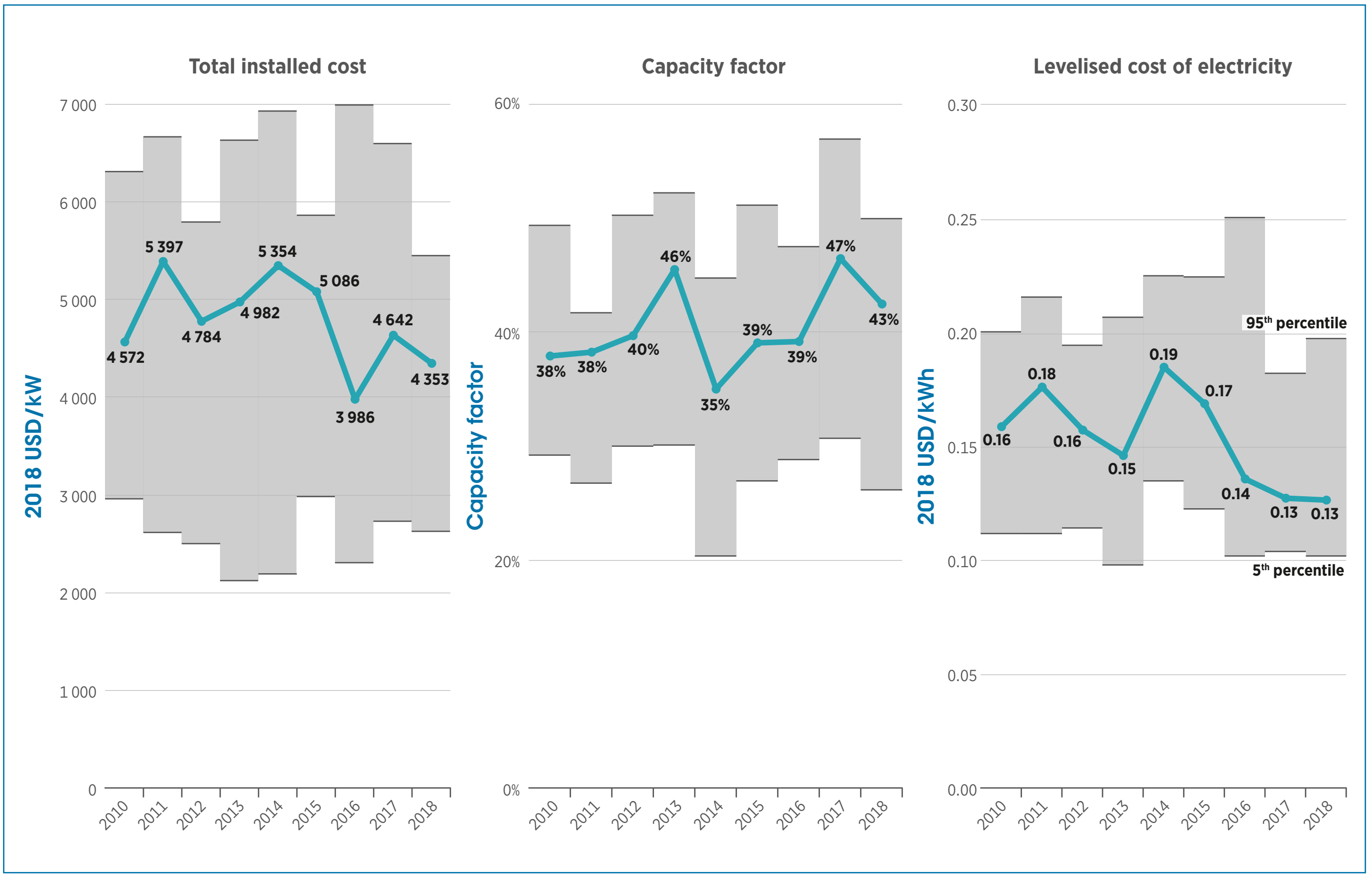
The 4.5 GW of new offshore wind capacity added in 2018 was concentrated in China (40% of the total), with a significant share of the growth in capacity in the United Kingdom (29%) and Germany (22%). The market therefore remains confined to a small number of major players. Deployment is set to broaden to North America and Oceania with projects that will be developed in the coming years.

In 2018, there was a slight decline (-1%) in the global weighted-average LCOE of offshore wind projects commissioned compared to 2017 (Figure S.6 and 3.5). This takes the decline in the LCOE of offshore wind between 2010 and 2018 to 20%, as the LCOE fell from USD 0.159/kWh to USD 0.127/kWh. The total installed costs of offshore wind projects commissioned in 2018 were 5% lower than those commissioned in 2010.

The major drivers of this reduction in the cost of electricity from offshore wind have been: innovations in wind turbine technology, installation and logistics; economies of scale in O&M (from larger turbine and offshore wind farm clustering); and improved capacity factors from higher hub heights, better wind resources (despite increasing cost in deeper waters offshore), and larger rotor diameters (Figure 3.1 and 3.2).

The trend towards larger turbines, which expands the capacity of a wind farm and/or reduces the number of turbines required for a given capacity, has helped reduce installation costs and project development costs below what they would otherwise have been. This reduction has been offset, to a greater or lesser extent, however, by the shift to offshore wind farms being located in deeper waters further from ports (Figure 3.1) – but often with better, more stable wind regimes. These factors have helped to increase the yields of offshore wind farms and seen the global weighted-average capacity factor for offshore wind increase from 38% in 2010 to 43% in 2018. At the same time, O&M costs have been reduced by the optimisation of O&M strategies; preventative maintenance programmes based on predictive analysis of failure rates; and economies-of-scale in servicing offshore wind zones, rather than individual wind farms.

Figure S.6 Global weighted average total installed costs, capacity factors and LCOE for offshore wind, 2010–2018



The market for offshore wind is still relatively thin and there is wide variation in country-specific declines in LCOE since 2010.

In Europe, which has the largest deployment of offshore wind, between projects commissioned in 2010 and 2018, there was a 14% drop in LCOE, from USD 0.156/kWh to USD 0.134/kWh. The largest drop occurred in Belgium, by 28% between 2010 and 2018, with the LCOE dropping from USD 0.195/kWh to USD 0.141/kWh. In Germany and the UK, which were the biggest markets for commissioned projects in Europe in 2018, there were 24% and 14% drops between 2010 and 2018, with the LCOEs in Germany and the UK falling to USD 0.125/kWh and USD 0.139/kWh for projects commissioned in 2018, respectively. In Asia, the LCOE reduction between 2010 and 2018 stands at 40% (from USD 0.178/kWh to US 0.106/kWh). This was driven by China, which has over 95% of offshore wind installations in Asia. The LCOE in Japan is high in comparison to China, at an estimated USD 0.20/kWh given that projects to date are small in scale and are perhaps better categorised as demonstration projects.

Total installed costs of offshore wind farms have declined modestly since 2010. There is, however, a significant degree of year-on-year volatility in the total installed costs of newly commissioned offshore wind farms given the relatively low annual capacity additions in some years.

The global weighted-average installed costs for offshore wind declined by 5% between 2010 and 2018, from USD 4 572/kW to USD 4 353/kW (Figure S.6 and 3.3). There are a complicated array of factors behind this overall evolution in installed costs, with some factors pushing costs down and others pushing them up. In Europe, initial challenges with small scale and capacity in the supply chain and logistics, as well as the shift to deployment farther offshore and in deeper waters, in some cases added upward pressure on installed costs by increasing installation, foundation and grid connection costs. The industry has scaled in recent years, however, and some of these pressures have eased. At the same time, innovation in turbine technology, larger turbine ratings, greater experience with project development and economies of scale have, on balance, helped to push down costs.

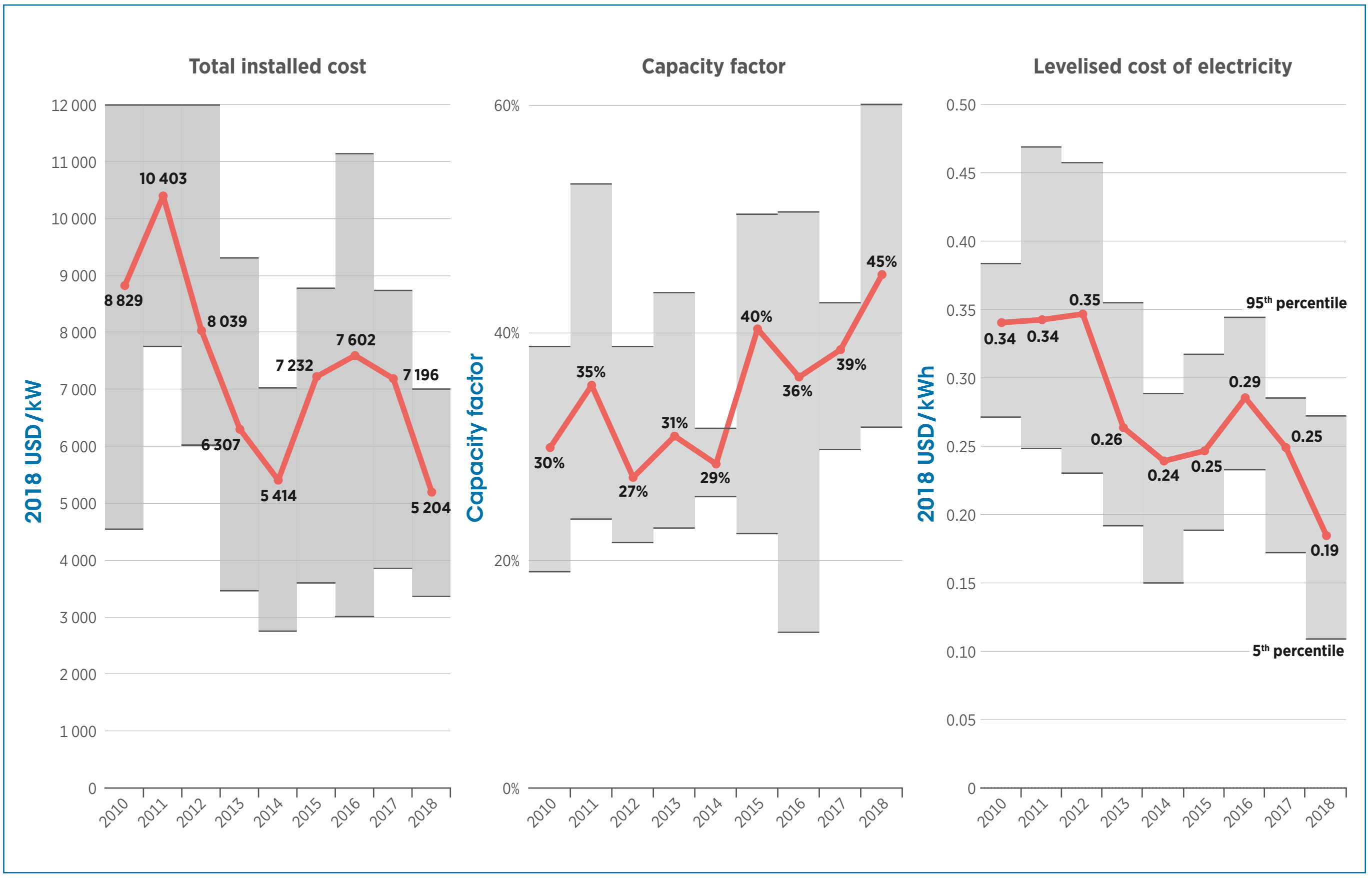
1.5 CONCENTRATING SOLAR POWER

In 2018, around 0.5 GW of new concentrating solar power was commissioned – predominantly in China, Morocco and South Africa. The global weighted average LCOE concentrating solar power in 2018 was USD 0.185/kWh – 26% lower than in 2017 and 46% lower than in 2010.

The total installed capacity of CSP globally at the end of 2018 was around 5.5 GW, 4.3 times what it was in 2010. Despite this growth, CSP is the technology (of all those discussed in this report) with the lowest total installed capacity. To put this in context, today's 5.5 GW of installed CSP was achieved by solar PV in 2005. Given the small scale of the market and suppply chains, it is therefore not surprising that the global weighted-average LCOE of the 0.5 GW of capacity added in 2018 was USD 0.185/kWh (Figure S.7), just outside the fossil fuel-fired cost range.

However, the growing developer experience and broadening of supply chains from the steady, if low, commissioning of new projects in recent years is bearing fruit. The 26% decline in the global weighted-average LCOE in 2018 compared to that of 2017 has been driven by the emergence of China as an important player in supply chains and project development. With a number of projects in the process of commissioning in China, the global weighted-average LCOE for 2019 is likely to be lower than 2018. As already mentioned, the results from recent auction and PPA programmes suggest that a step-change in CSP competitiveness will occur in the next four years as the cost of electricity from CSP will potentially fall into the range of USD 0.06 to USD 0.10/kWh. With its ability to provide dispatchable renewable power, CSP could play an increasingly important role in allowing high shares of solar PV and wind in areas with good direct solar resources.

Figure S.7 Global weighted average total installed costs, capacity factors and LCOE for CSP, 2010–2018



Lower total installed costs and higher capacity factors are driving the decline in the cost of electricity from CSP. The global weighted-average total installed cost of CSP declined by 28% in 2018, year-on-year, falling from around USD 7 200/kW in 2017 to USD 5 200/kW in 2018. At the same time the global weighted-average capacity factor increased from 39% in 2017 to 45% in 2018.

Although year-on-year variability in average installed costs is relatively high due to the small number of projects commissioned in any one year, the decline in 2018 to around USD 5 200/kW is likely to be sustained given that a number of Chinese CSP plants will be comissioned in 2019 that have lower installed costs than other markets. The 5th and 95th percentile range for individual projects comissioned in 2018 starts at around USD 3 400/kW and ends at around USD 7 000/kW, depending on project location and storage duration (Figure S.7 and 4.1). CSP projects can achieve the lowest LCOE by including storage to improve the overall utilisation of the projects power block and associated investments. This has been reflected to some extent in trends in deployment, as the average storage of projects commissioned in 2018 (8.3 hours) was more than twice the level observed in 2010 (3.6 hours). The optimal level of storage, however, varies depending on the solar resource and the storage and collector costs, but is typically in the range of 7–10 hours.

The trend towards higher levels of storage and capacity factors for commissioned CSP plants is visible in Figure 4.2. This has been supported by the shift in the market away from Spain, where the direct normal irradiance (DNI) is typically in the range 2 000 to 2 250 kWh/m^2/year to markets with higher levels of DNI (Figure 4.3) from 2014 onwards.

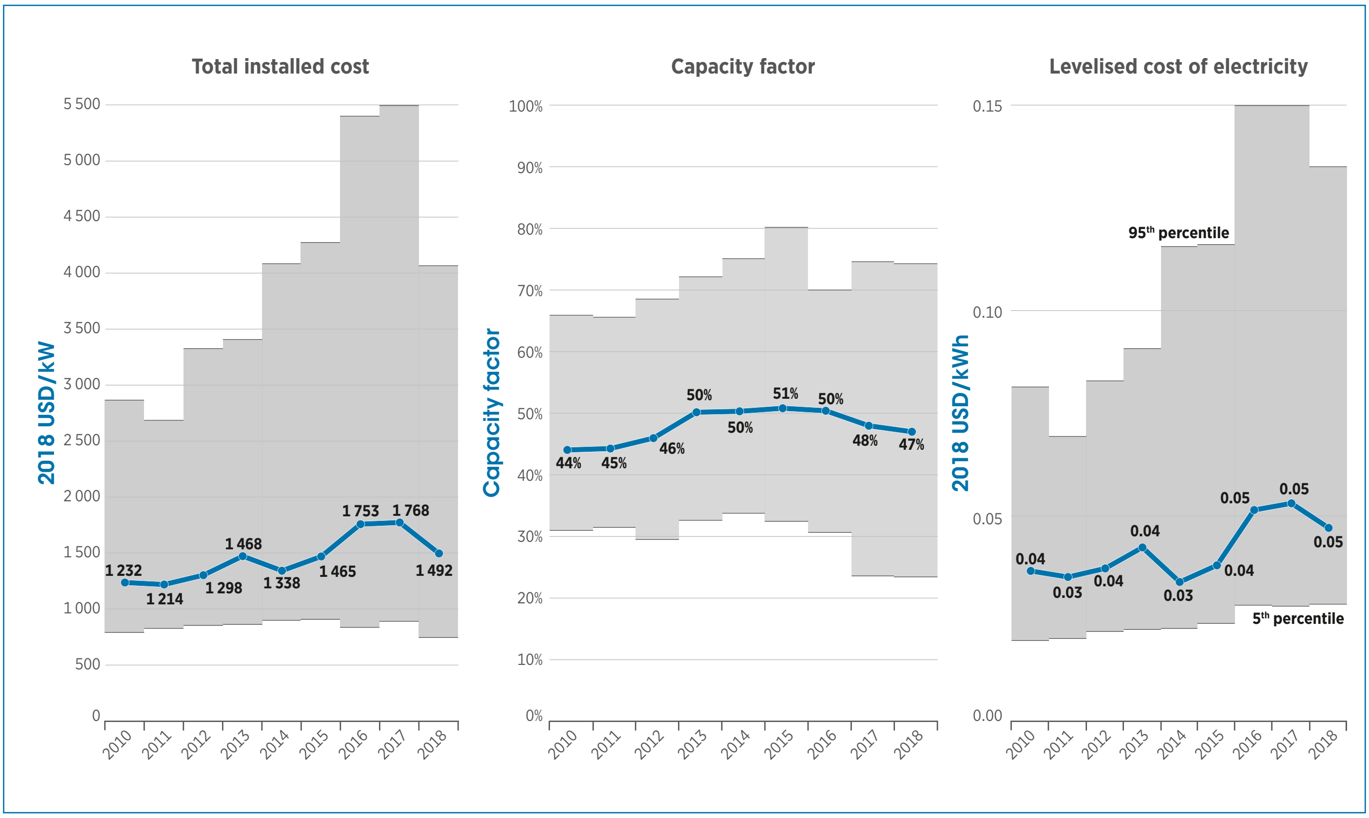
1.6 HYDROPOWER

Hydropower is an extremely attractive renewable technology, due to the low-cost of the electricity it produces and the flexibility it can provide to the grid. In 2018, the global weighted-average LCOE of hydropower was USD 0.047/kWh – 11% lower than in 2017, but 29% higher than in 2010.

Between 2010 and 2013, the global weighted-average LCOE of hydropower was relatively stable, before starting to rise from 2014 onwards to a new, slightly higher level (Figure S.8). The reason for this was the increased total installed cost in 'Other Asia' (Asia, excluding China, India and Japan). Given that hydropower is a highly site-specific technology, with each project designed for a particular location within a given river basin, the exact reasons for this cost increase are difficult to identify. While further analysis is necessary, the rise in costs in Other Asia was likely due to the increased number of projects with more expensive development conditions compared to earlier projects when the best sites were developed. Current sites may be in more remote locations, further from existing grid infrastructure, necessitating higher grid connection, access and logistical costs. They may also be in areas with more challenging geological conditions, increasing the cost of construction. A combination of these factors could be driving the recent cost trends.

In 2018, the global weighted-average total installed cost of hydropower projects declined to USD 1 492/kW (Figure S.8 and 5.1), 16% lower than the value for 2017 (which was similar to the 2016 value). It remains to be seen whether this represents a fluctuation around a new higher average cost level, or whether the average costs will continue to decline. Much will depend on the location of where future hydropower projects will be commissioned, as part of the reason for the 2018 fall in the global weighted-average installed cost for hydropower was the high share of projects taken by China (8.5 GW) in the total new capacity commissioned in 2018 (21 GW). This is because China has installed costs that are typically 10%–20% lower than the average.

Figure S.8 Global weighted average total installed costs, capacity factors and LCOE for hydropower, 2010–2018



Small-scale hydropower projects up to 50 MW can achieve competitive installed costs of on average USD 1 500/kW, although total installed costs for these projects span a much wider range than for large projects. There is, however, some evidence that projects above around 700 MW exhibit material economies of scale.

The full dataset of hydropower projects in the IRENA Renewable Cost Database for the years 2000 to 2018 (Figure 5.2) suggests that the total installed costs of smaller projects span a wider range than larger projects, but in terms of deployment, the weighted-average installed cost is not materially lower for large projects, except for sizes beyond around 700 MW. Although the data is thinner, projects in the range 250 MW–700 MW appear to have slightly higher installed costs than smaller or larger projects.

The global weighted-average capacity factors for hydropower projects commissioned between 2010 and 2018 varied between 44% in 2010 and a high of 51% in 2015, before settling at 47% for projects commissioned in 2018.

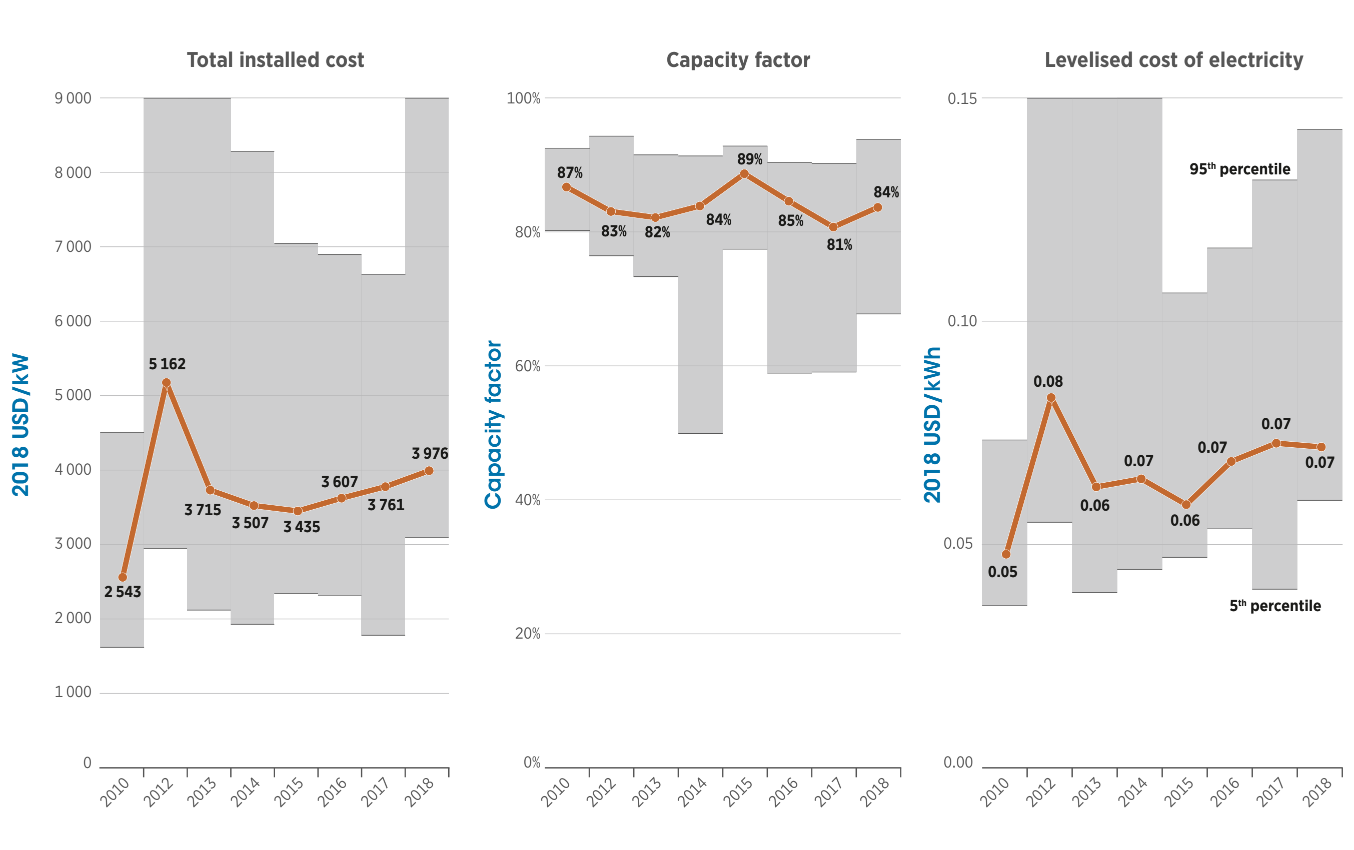
There is often a significant variation in the weighted average capacity factor by region in the IRENA database. For large hydropower projects the regional or country average capacity factor varied from a low of 21% in North America in the period 2010 to 2013 inclusive, to a high of 65% in Brazil (Figure 5.5). For the period 2014 to 2018 inclusive, the range was between 34% in Europe and 62% in South America excluding Brazil ('Other South America'). Small hydropower projects (less than 10 MW) showed a smaller range of country-level average variation (Figure 5.6). For these, there was a country-level average low of 46% in China in the period 2010 to 2013, with a high of 67% in Other South America for the period 2014 to 2018.

1.7 GEOTHERMAL POWER GENERATION

In 2018, just over 500 MW of new geothermal power generation capacity was added. Where good high-temperature resources exist, geothermal can be a very economical source of round-the-clock power. In 2018, the global weighted-average LCOE of new geothermal plants commissioned was USD 0.072/kWh, 1% lower than in 2017.

The market for geothermal remains modest, with between a minimum of 90 MW (in 2011) and a maximum of 650 MW (in 2015) of annual new capacity comissioned between 2010 and 2018. Given the small number of projects commissioned each year, the global weighted-average LCOE in any given year is heavily influenced by the site-specific characteristics of the project, as well as the country. The global weighted-average LCOE of newly commissioned geothermal plants was USD 0.05/kWh in 2010, with this rising to USD 0.08/kWh in 2012, while between 2013 and 2018, the average was between USD 0.06/kWh and USD 0.07/kWh (Figure S.9 and 6.3).

Figure S.9 Global weighted average total installed costs, capacity factors and LCOE for geothermal power, 2010–2018



1.8 BIOENERGY

Bioenergy, where low-cost feedstocks are available as by-products from agricultural or forestry processes, can provide competitive electricity. In 2018, when around 5.7 GW of new bioenergy electricity generation capacity was added worldwide, the global weighted-average LCOE of new bioenergy power plants commissioned was USD 0.062/kWh – 14% lower than in 2017.

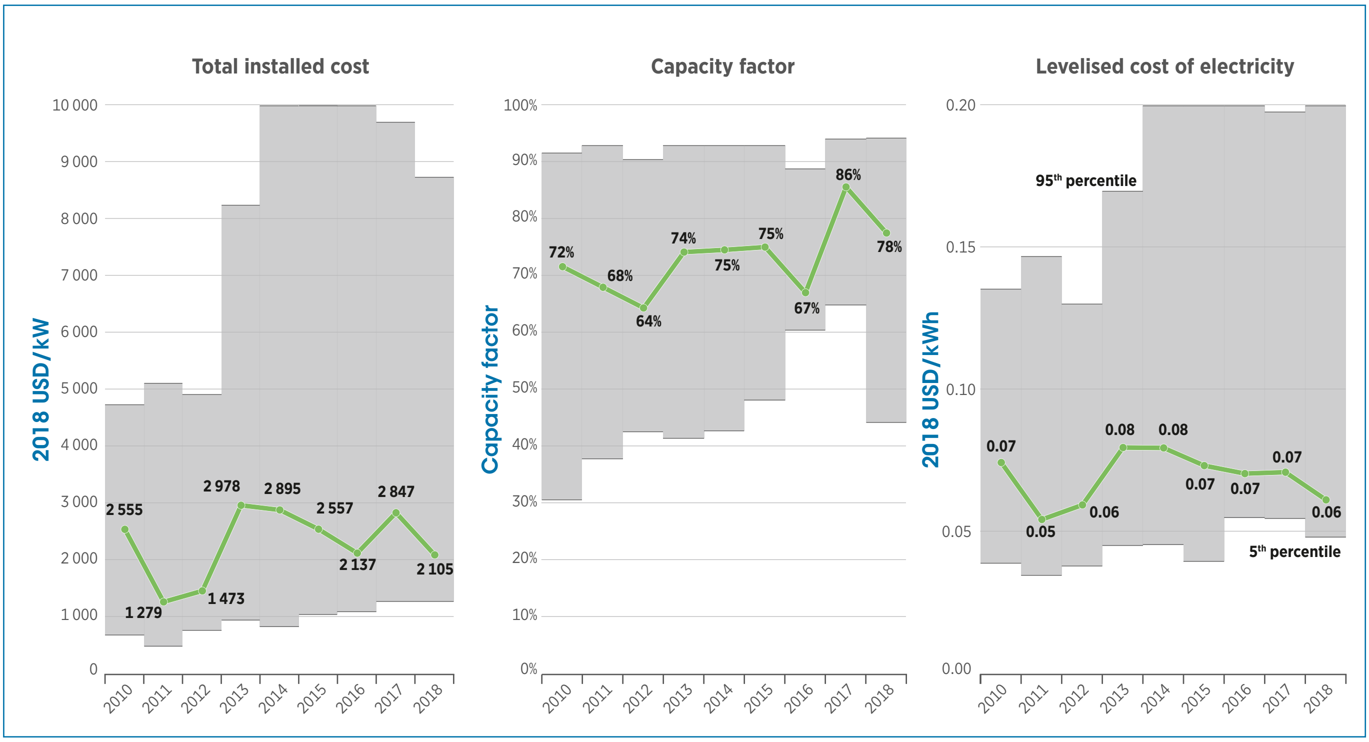
Bioenergy electricity generation options span a wide range of feedstocks and technologies. These range from mature, low-cost options, like the combustion of agricultural and forestry residues, to less mature and/or expensive options, like biomass gasification or municipal solid waste generators with stringent emissions controls.

The global weighted-average total installed costs of bioenergy projects fell to around USD 2 100/kW in 2018, down form around USD 2 850/kW in 2017 (Figure S.10). Outside of the Organisation of Economic Co-operation and Development (OECD) countries, the combustion of sugar cane bagasse, wood waste and other vegetal or agricultural wastes uses proven, low-cost technologies. By country or region, these have weighted-average total installed costs that range between USD 950/kW and USD 1 650/kW (Figure 7.1). The costs for these technologies is typically higher in Europe and North America.

Economies of scale are evident in China and India, where large numbers of plants have been deployed (Figure 7.2). Bioenergy electricity generation plants are small compared to fossil fuel plants, though, as the logistical costs of transporting feedstock from far afield often make plants much larger than 50 MW economically unattractive.

For the data available in the IRENA Renewable Cost Database (Figure 7.4), the country/region specific weighted-average capacity factor for these dispachable resources ranges from a low of 64% in China to a high of 83% in North America. Capacity factors for many bioenergy plants depend on whether the availability of feedstocks is seasonal or year-round (Figure 7.5), so the weighted average in any given year for a country is heavily influenced by the type of feedstock that is being used by the plants that have been newly commissioned in that year.

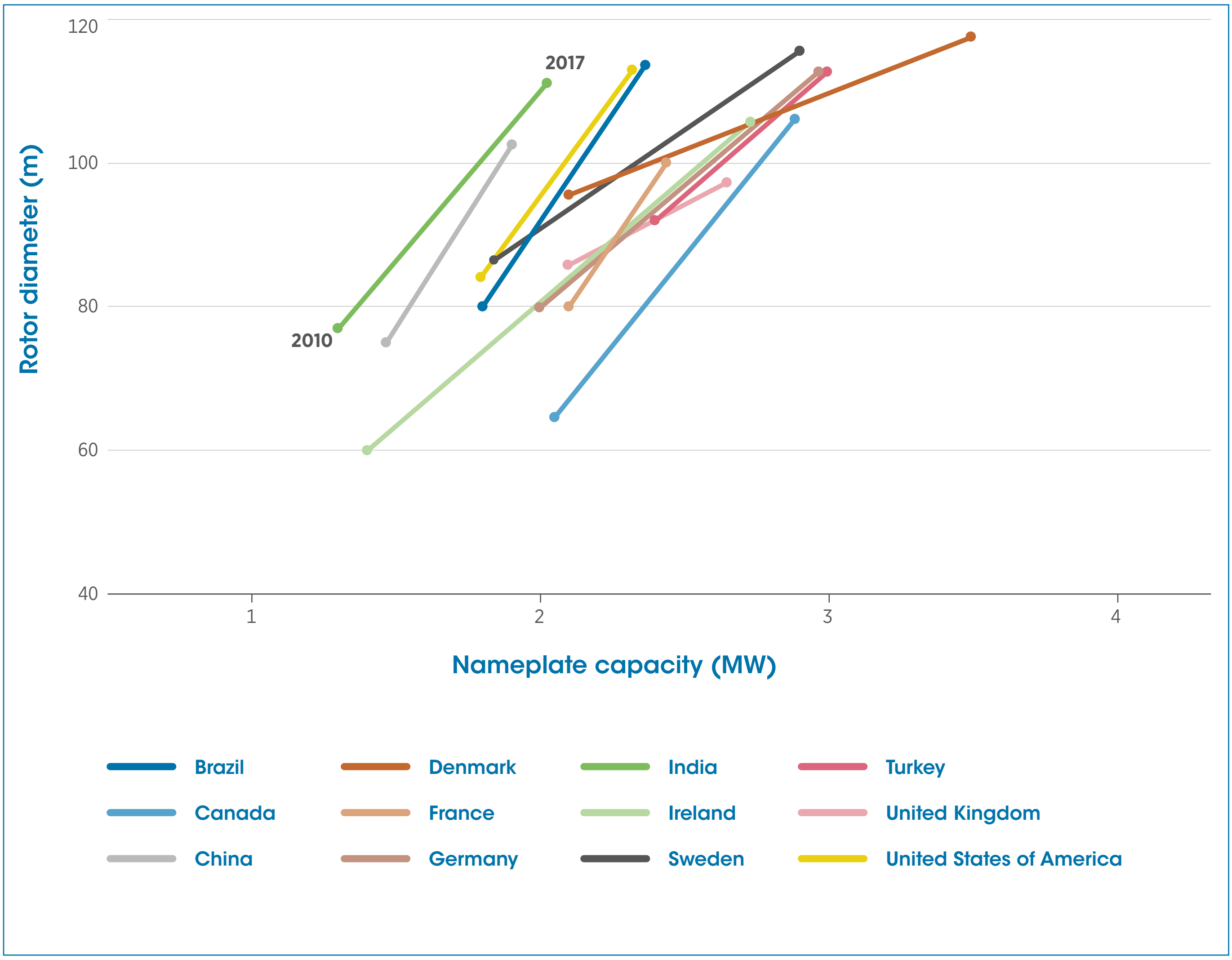
Figure S.10 Global weighted average total installed costs, capacity factors and LCOE for bioenergy, 2010–2018



The sections that follow contain technology-specific figures that describe the evolution of technology characteristics, total installed costs, capacity factors and the LCOE. These sections are followed by Annex I which descsribes the details behind the IRENA cost metrics and how the LCOE is calculated. Annex II provides an overview of the IRENA Renewable Cost Database and the IRENA Auction and PPA database.

1 ONSHORE WIND POWER

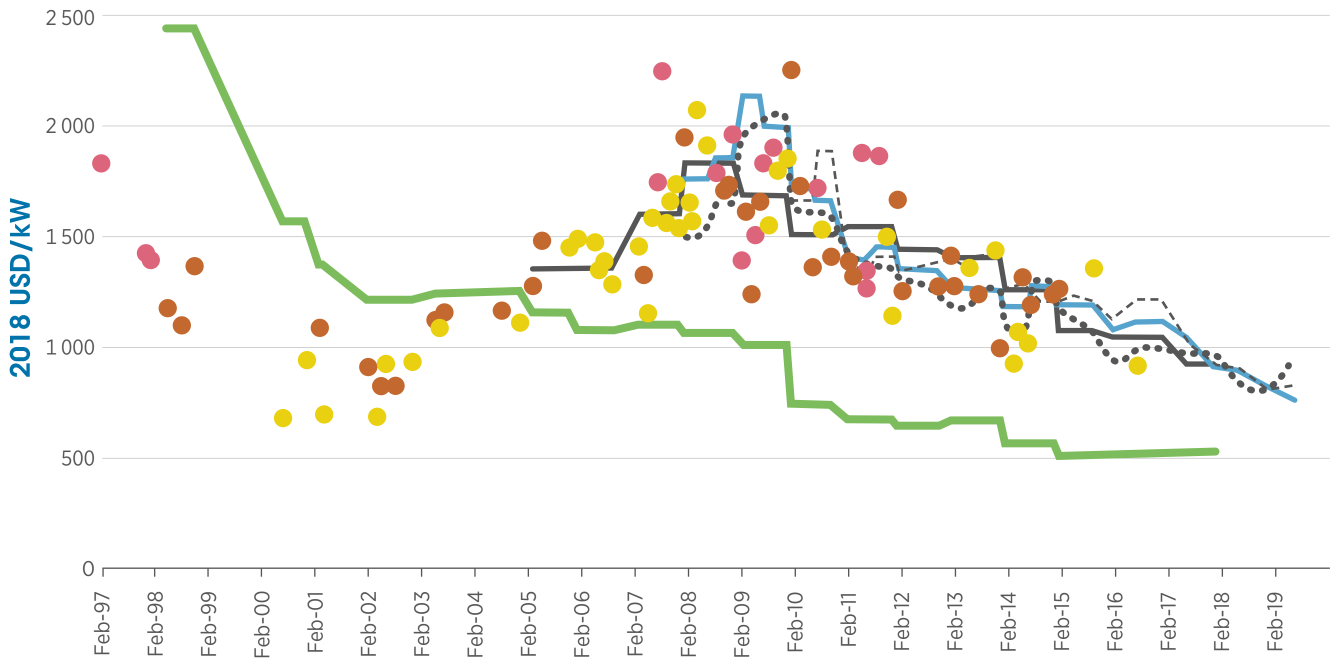
Figure 1.1 Weighted average rotor diameter and nameplate capacity evolution, 2010–2018



Sources: Based on CanWEA, 2016; IEA Wind, 2019; Wiser and Bollinger, 2018; Danish Energy Agency, 2019; and Wood MacKenzie, 2019.

All major onshore wind markets have seen rapid growth in both rotor diameter and the capacity of turbines since 2010. Denmark had the largest turbines and rotor diameters on average in 2017. Average turbine capacity ranged from 1.9 MW to 3.5 MW, and rotor diameter from 97 to 118 m, by country.

Figure 1.2 Wind turbine price indices and price trends, 1997–2018

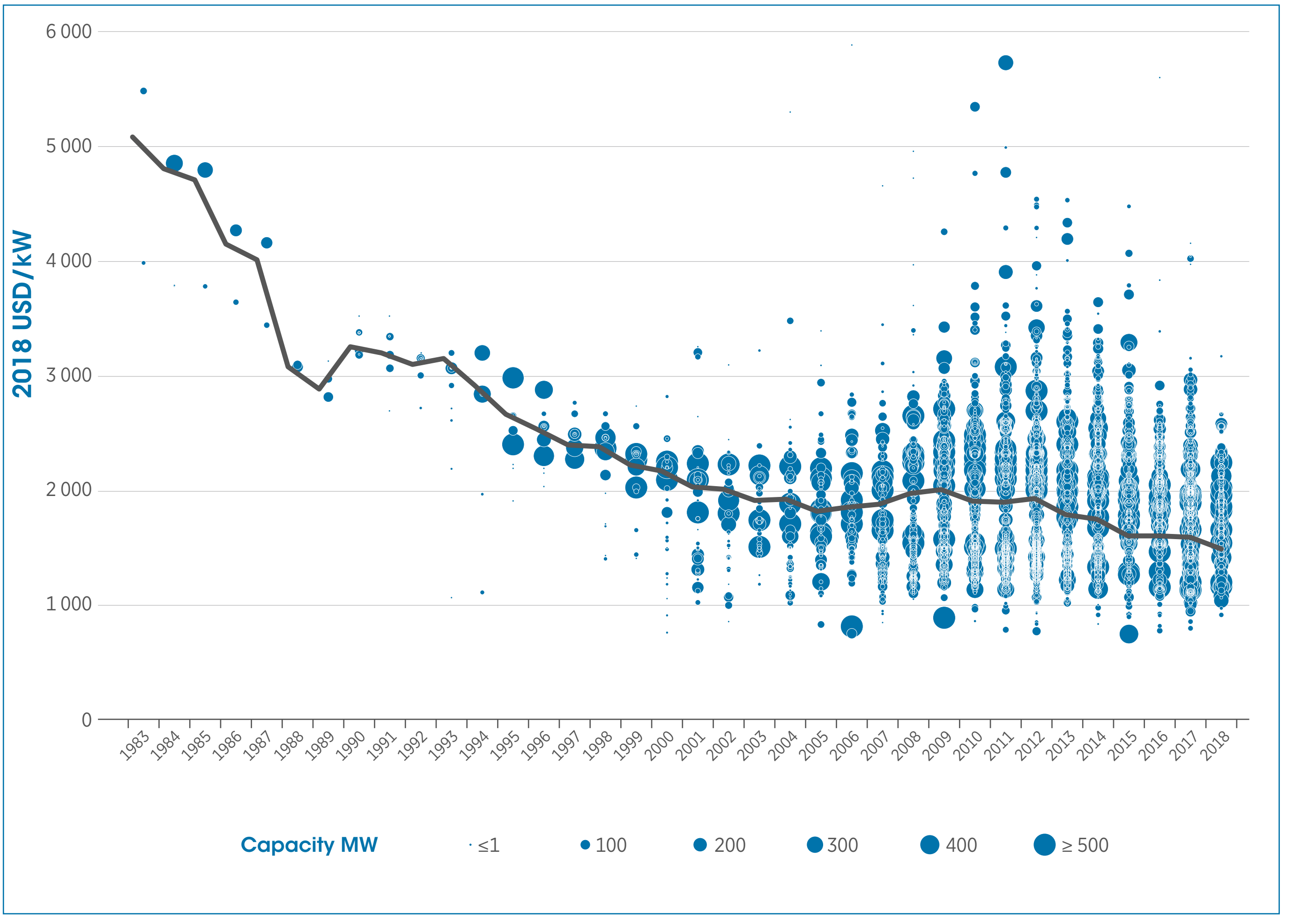


	Period	% Decrease
United States of America <5 MW	2007–2011	17%
United States of America 5–100 MW	2010–2015	44%
United States of America >100 MW	2008–2016	56%
BNEF WTPI	2009–2019	64%
BNEF WTPI <100 m ø	2009–2019	53%
BNEF WTPI >=100 m ø	2010–2019	56%
Chinese turbine prices	1998–2017	78%
Vestas average selling price	2008–2017	50%

Source: Based on Wiser and Bollinger, 2018; BNEF, 2018a; IEA Wind, 2019; Vestas Wind Systems, 2005–2017; Global Data, 2018a; and the IRENA Renewable Cost Database.

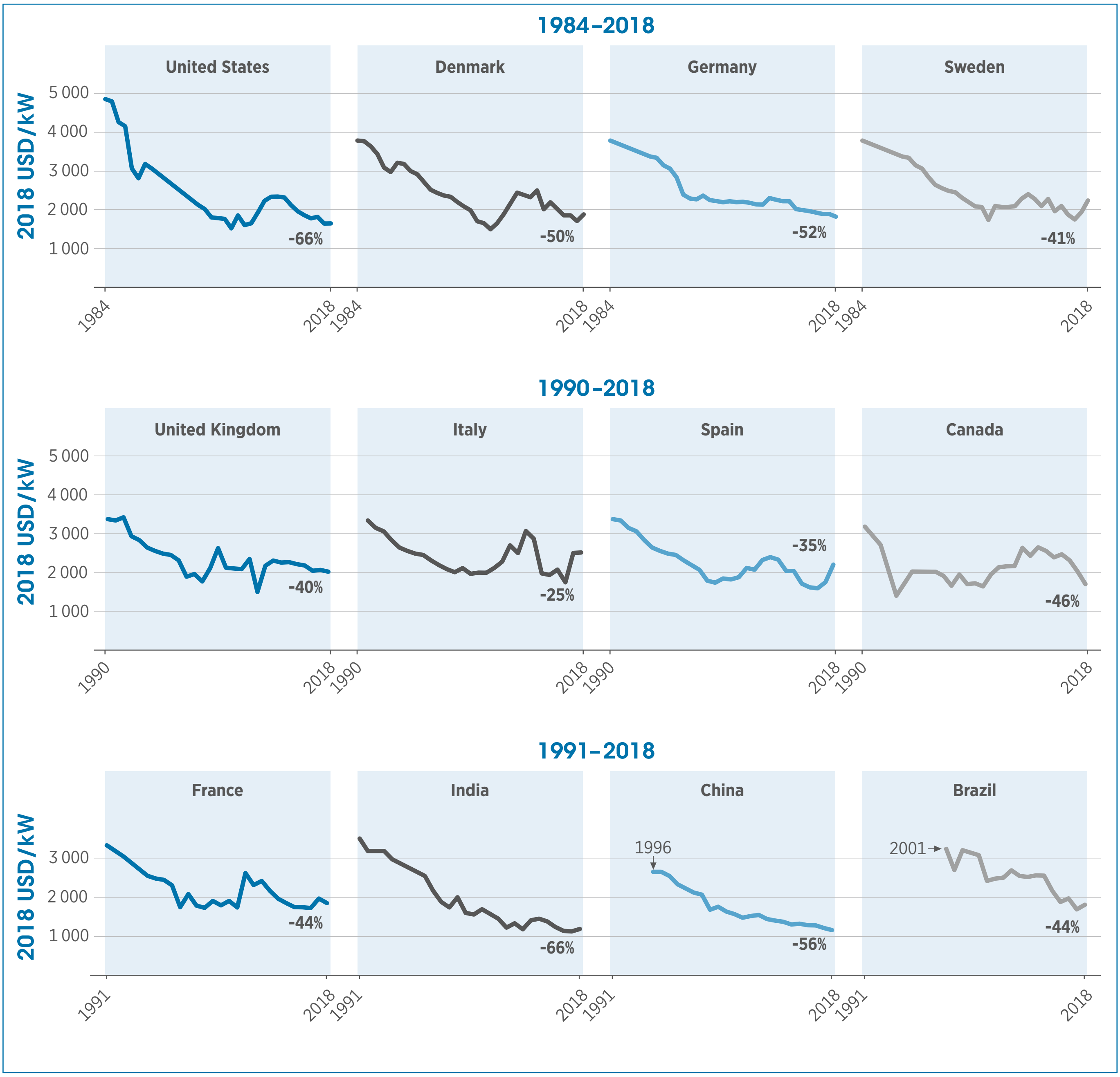
Wind turbine prices have fallen by between 44% and 64% since their peak in 2007–2010, depending on the market. Chinese wind turbine prices have fallen in a step-wise fashion by 78% since 1998, but have been broadly flat since 2015. The most recent data shows average turbine prices around USD 500/kW in China and USD 855/kW elsewhere.

Figure 1.3 Total installed costs of onshore wind projects and global weighted average by year of commissioning, 1983–2018



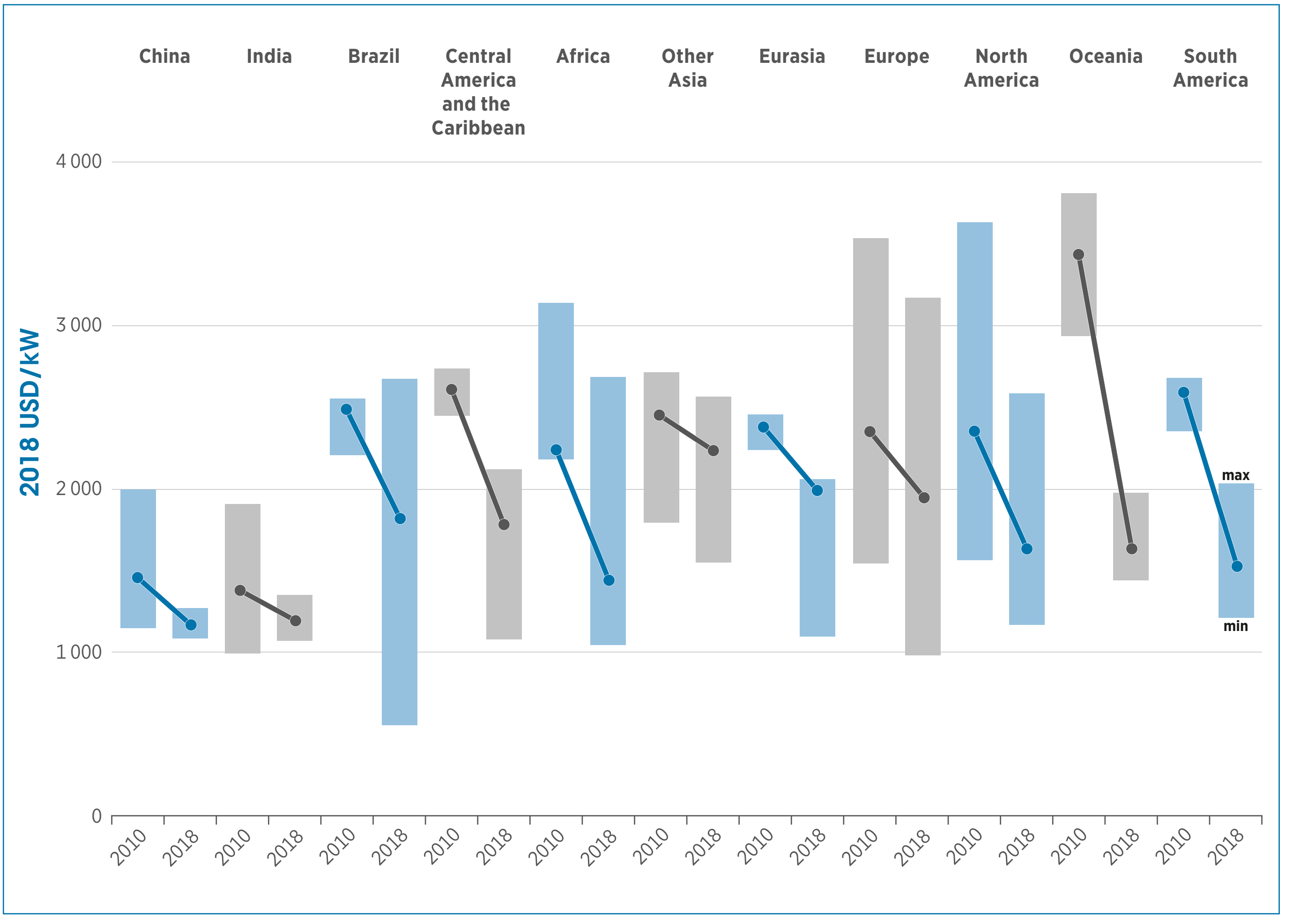
The global weighted-average installed costs of onshore wind have declined by 71% in 35 years, from around USD 5 000/kW in 1983 to USD 1 500/kW in 2018. This was driven by declines in wind turbine prices and balance of project costs.

Figure 1.4 Onshore wind weighted average installed costs in 12 countries, 1984–2018



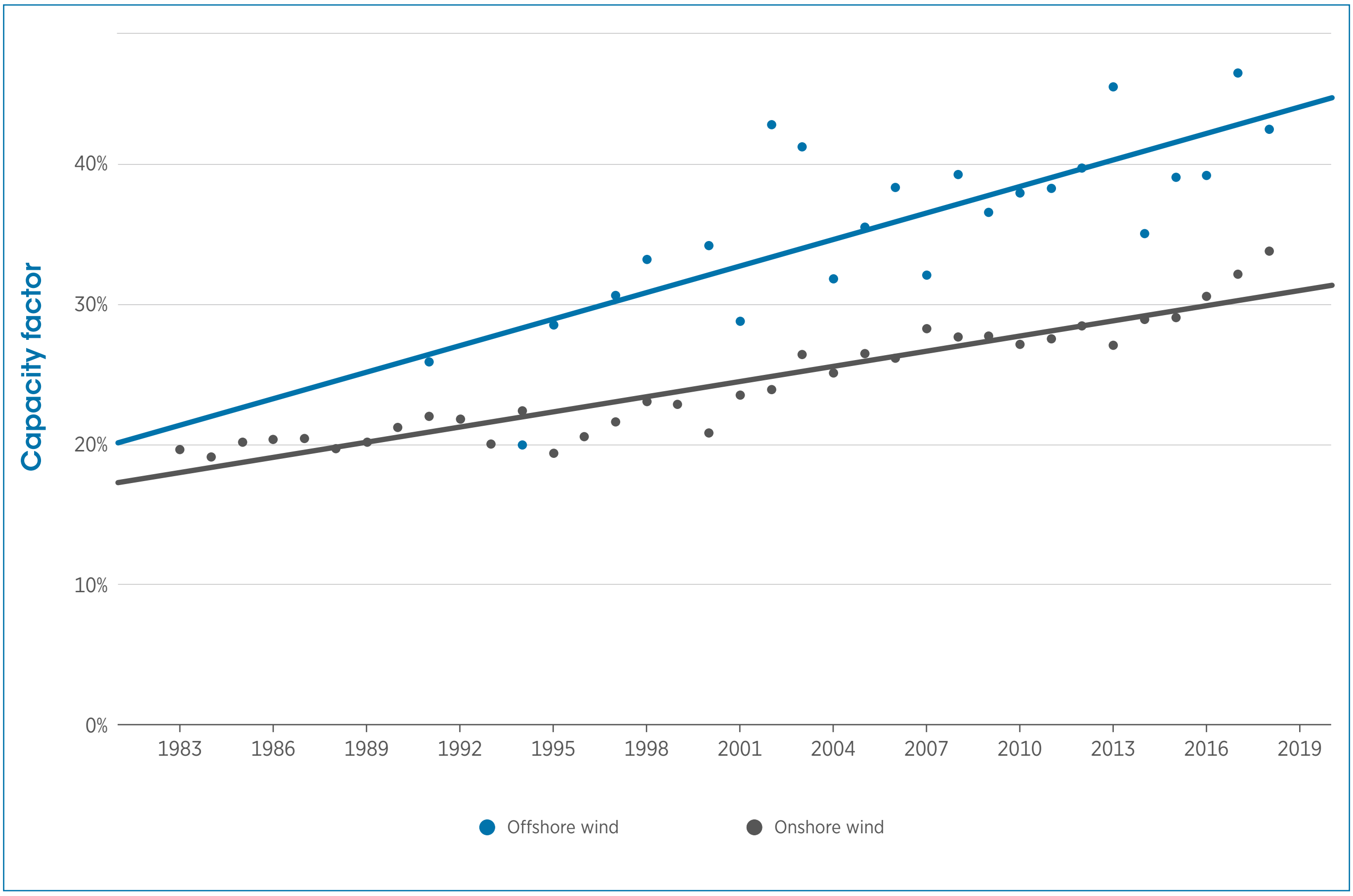
Reductions in total installed costs vary by country and when large-scale commercial deployment starts. China, India and the United States have experienced the largest declines in total installed costs. In 2018, typical country-average total installed costs were around USD 1 200/kW in China and India, and between USD 1 660 and USD 2 250/kW elsewhere.

Figure 1.5 Total Installed cost ranges and weighted averages for onshore wind projects by country/ region, 2010–2018



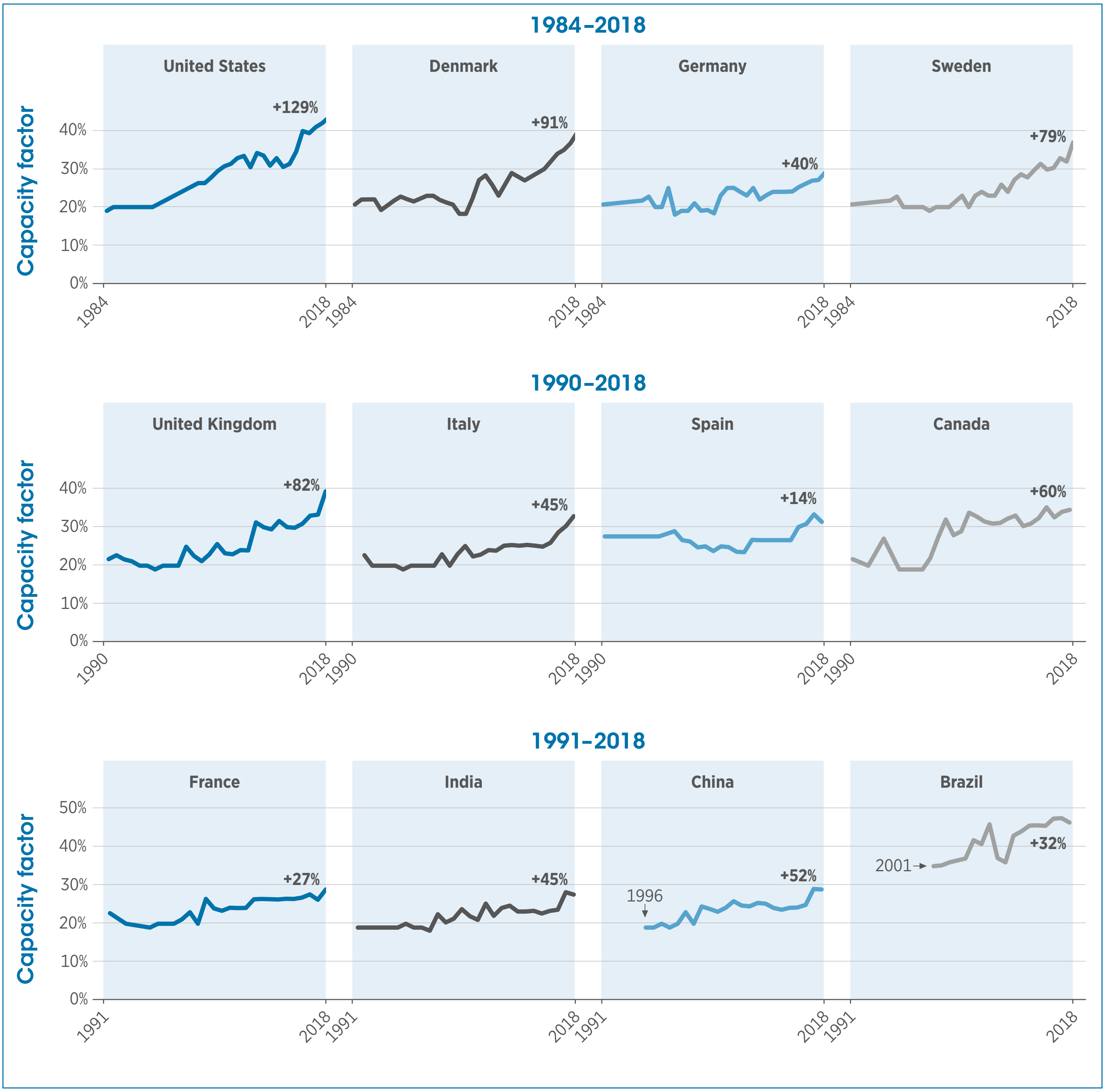
The total installed costs for onshore wind projects are very site- and market-specific. For projects commissioned in 2018, the range between the lowest and the highest installed cost was significant for onshore wind in most regions, except for China and India. The average installed costs range from USD 1170/kW in China to USD 2237/kW in Other Asia.

Figure 1.6 Global weighted-average capacity factors for new onshore and offshore wind capacity additions by year of commissioning, 1983–2018



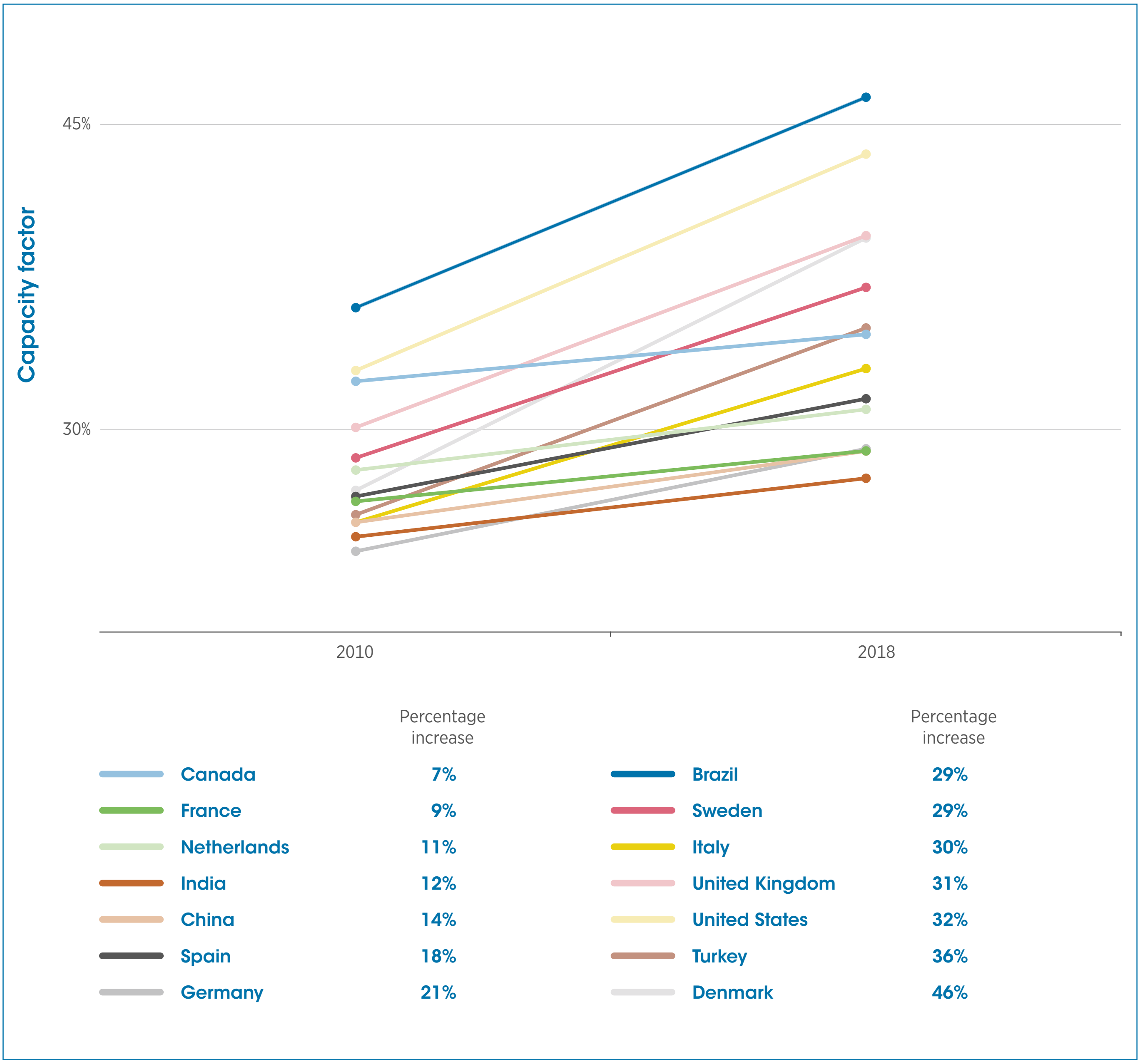
Driven by technology improvements, global weighted-average capacity factors have improved substantially for onshore and offshore wind between 1983 and 2018. The capacity factor of new onshore wind projects increased from 20% in 1983 to 34% in 2018, and from 26% in 1991 to between 43% and 47% in 2018 and 2017 respectively for offshore wind. The gap between onshore and offshore wind capacity factors has narrowed since 2015 as onshore wind capacity factors have surged.

Figure 1.7 Historical onshore wind weighted average capacity factors in a sample of 12 countries by year of commissioning, 1984–2018



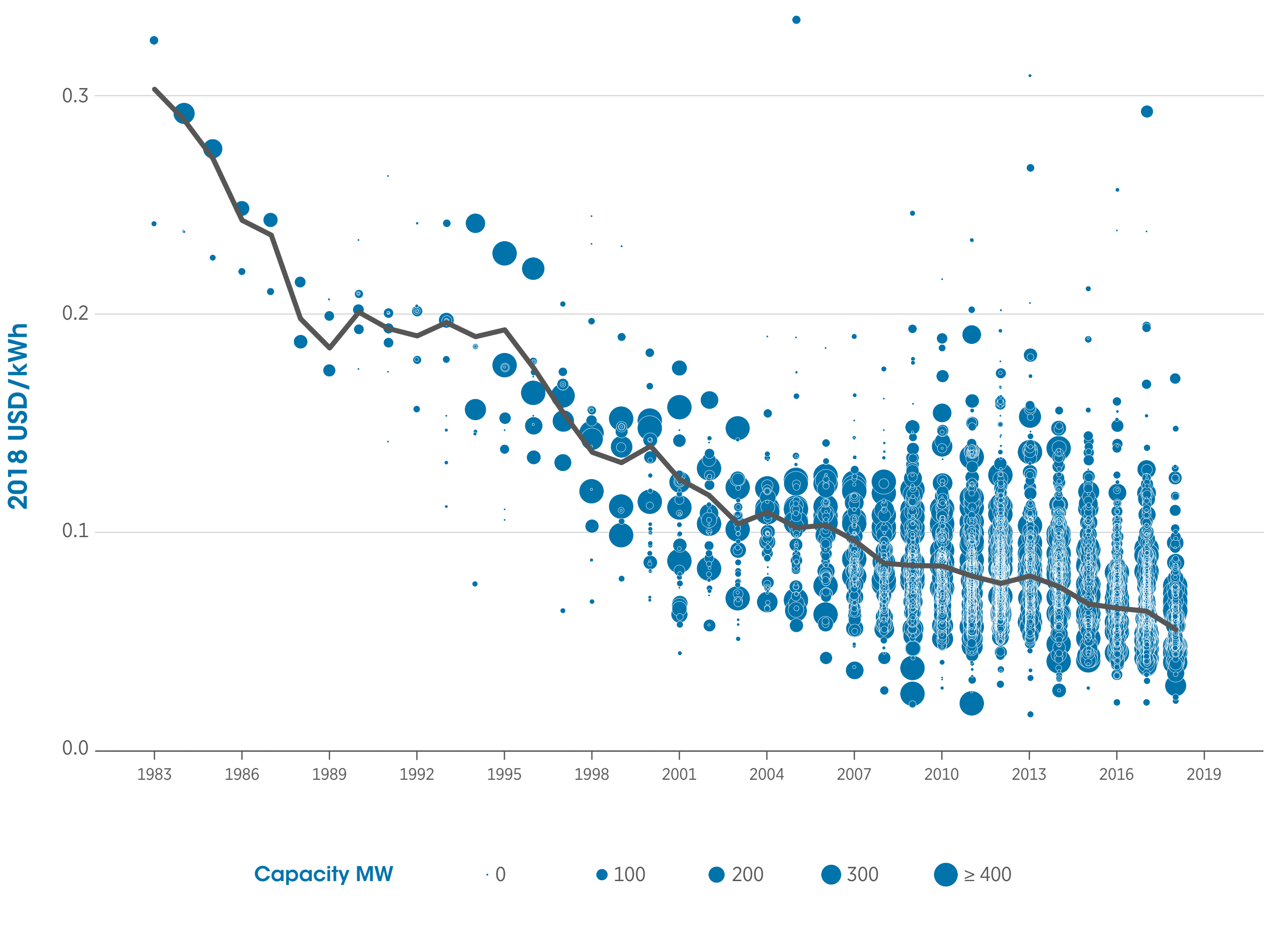
The United States is leading the improvement of global onshore wind capacity factors. The average capacity factors for newly commissioned onshore wind farms in 2018 in Denmark, Germany, Sweden and the United States were 40% to 129% higher than onshore wind farms commissioned in 1984.

Figure 1.8 Country-specific average capacity factors for new onshore wind projects, 2010 and 2018



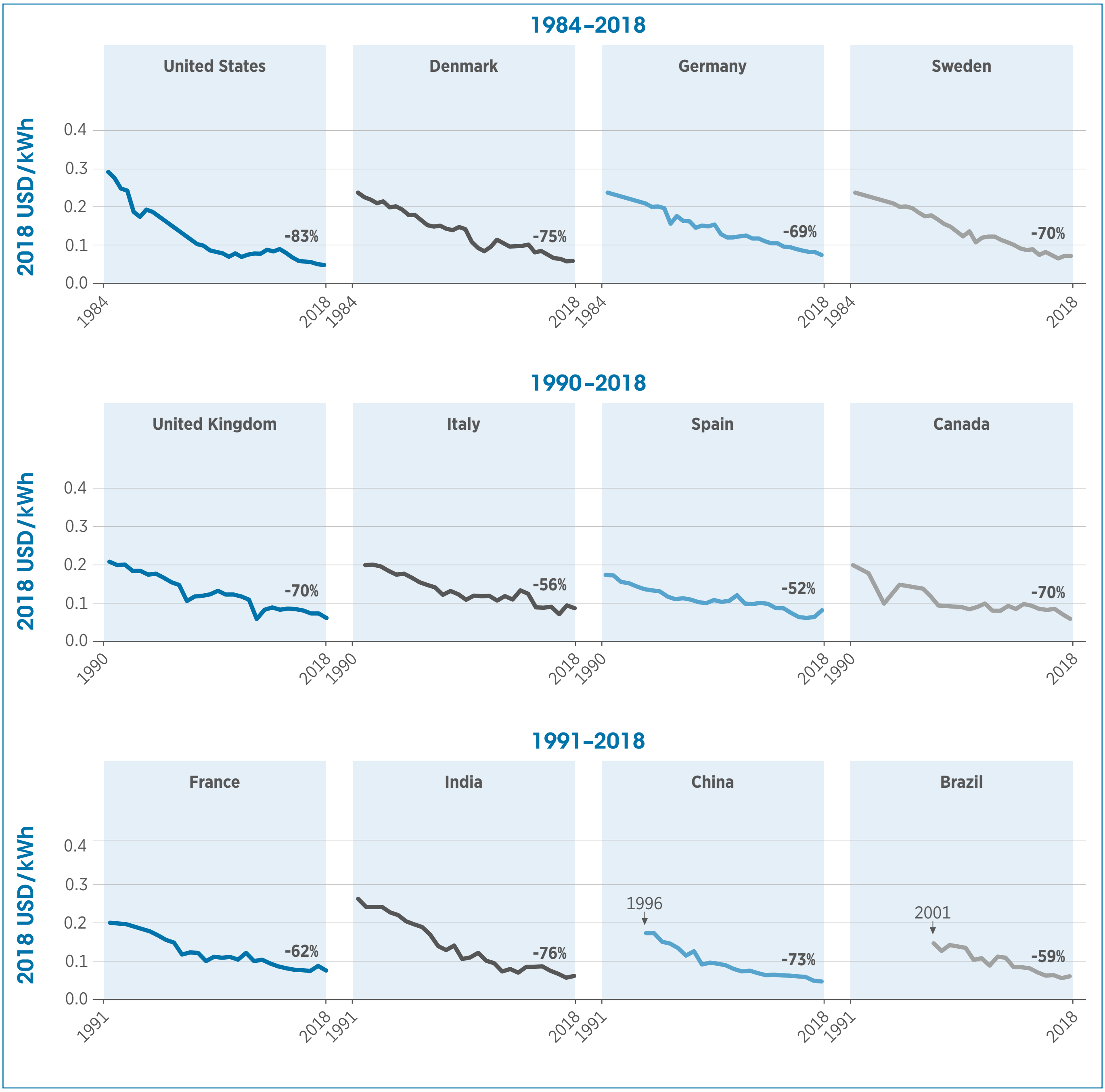
Virtually all major wind markets have seen a significant increase in the average capacity factor of newly commissioned onshore wind farms between 2010 and 2018. In Denmark, their average capacity factor grew by almost half, from 27% in 2010 to 39% in 2018. For projects commissioned in 2018, Brazil, Denmark, the United Kingdom and the United States had the highest capacity factor.

Figure 1.9 LCOE of onshore wind projects and global weighted average by year of commissioning, 1983–2018



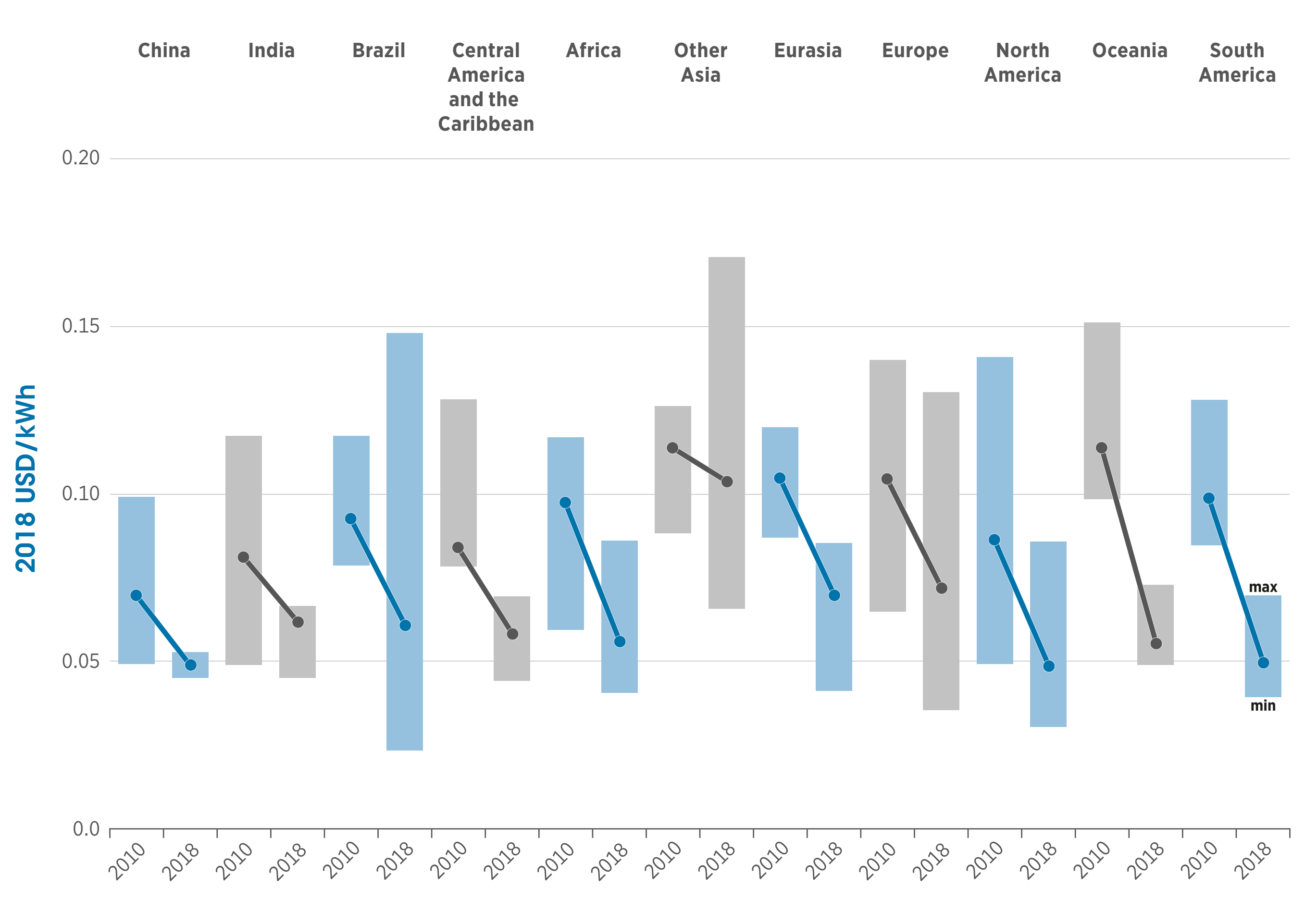
The global weighted-average LCOE for onshore wind fell by 82% between 1983 and 2018, over which time cumulative installed capacity grew to 540 GW.

Figure 1.10 The weighted average LCOE of commissioned onshore wind projects in 12 countries, 1984–2018



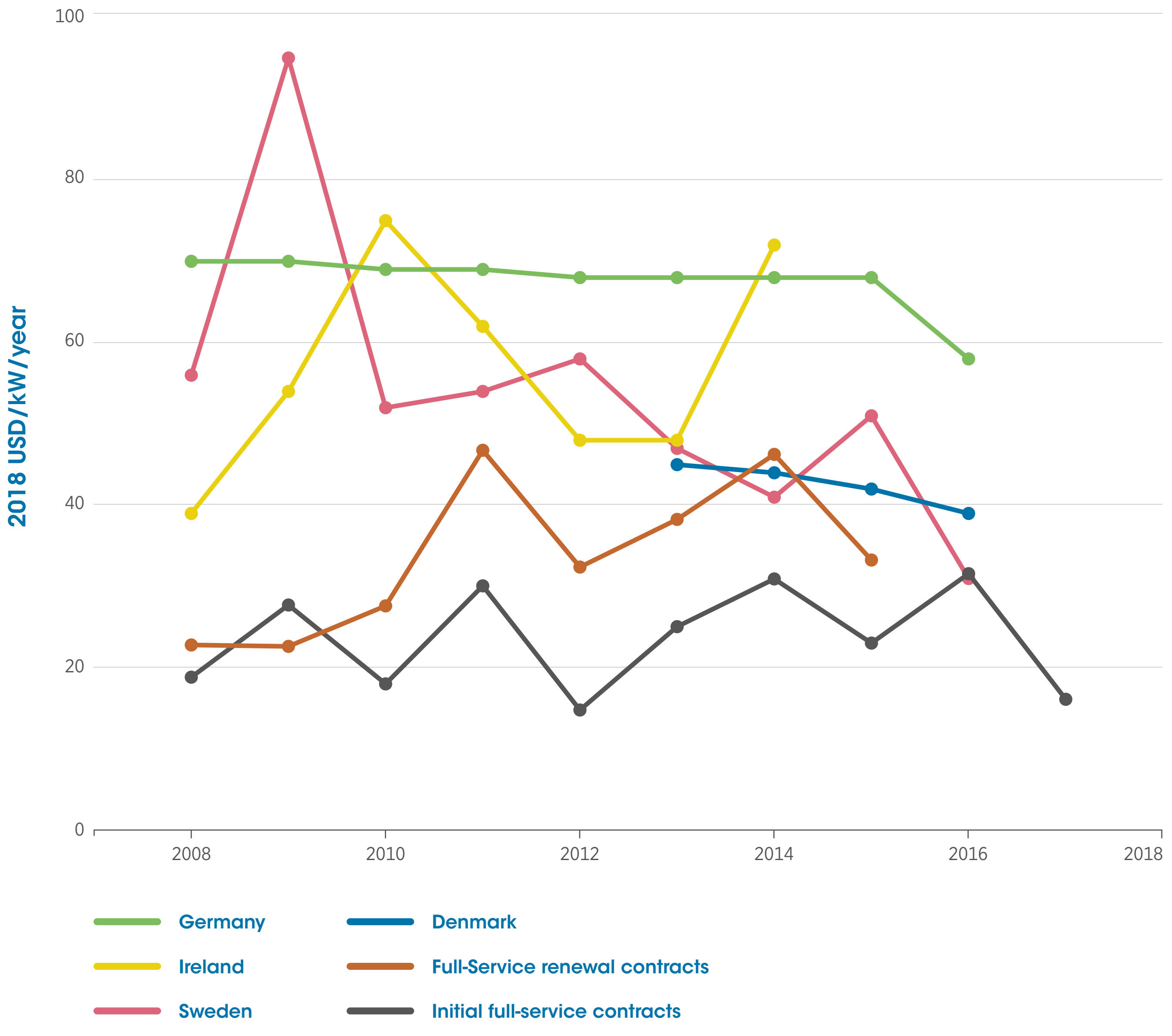
The average LCOE of newly commissioned onshore wind farms in Denmark, Germany, Sweden and the United States were 69% to 83% lower in 2018 than for those commissioned in 1983. The United States and China both had country-average LCOEs of USD 0.05/kWh, while Brazil, Canada, Denmark, India and the United Kingdom all averaged USD 0.06/kWh in 2018.

Figure 1.11 Regional weighted average LCOE and ranges for onshore wind in 2010 and 2018



The country or regional weighted-average LCOE was between USD 0.05 and USD 0.07/kWh in 2018, except in Other Asia. The weighted-average LCOE of new projects in 2018 in China, North America and South America (excluding Brazil) was USD 0.05/kWh.

Figure 1.12 Full-service (initial and renewal) O&M pricing indexes, weighted average O&M revenues of two manufacturers, and O&M costs in Denmark, Ireland and Sweden, 2008–2017

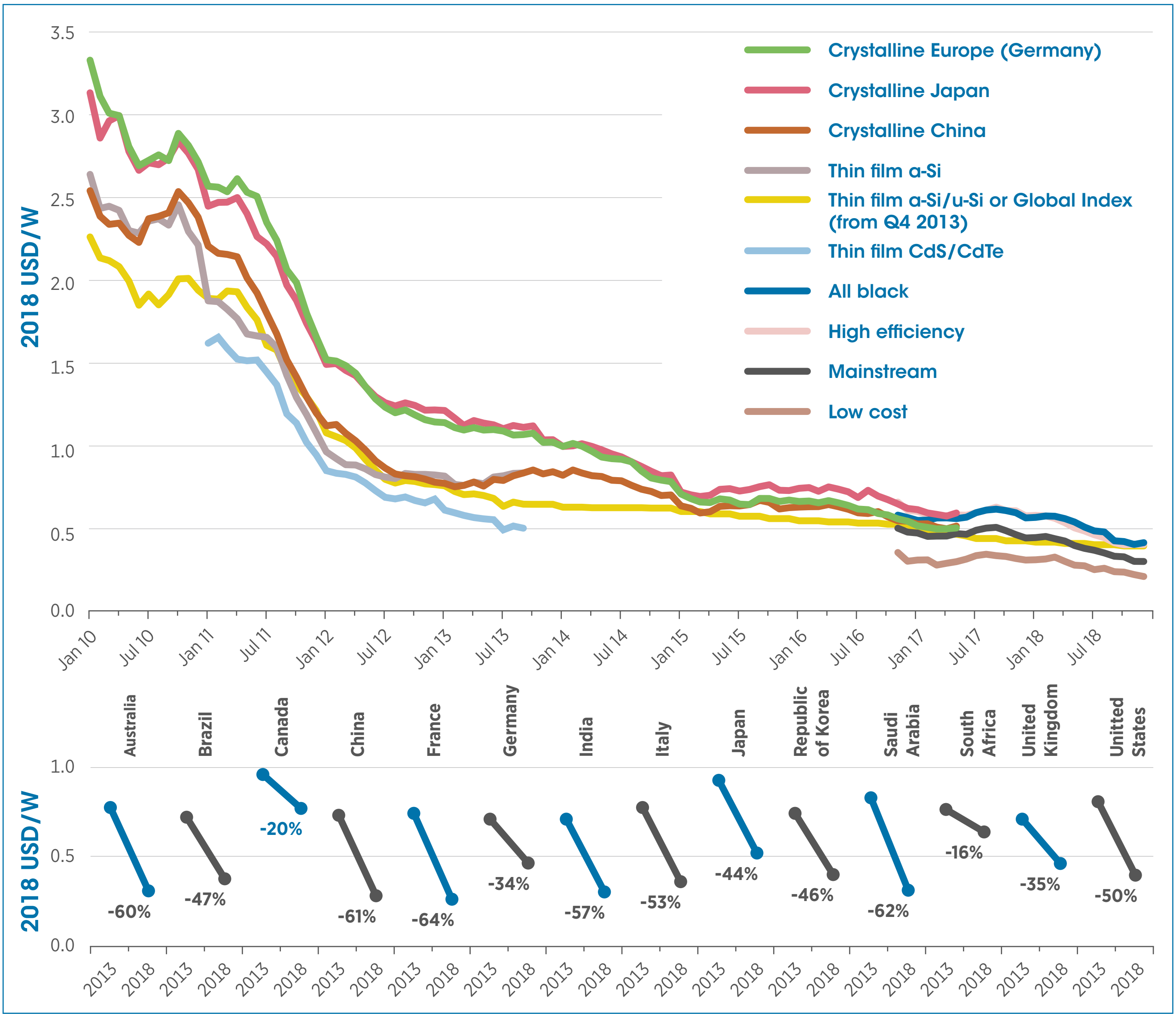


Sources: Based on BNEF, 2018b; GlobalData, 2018a; and IEA Wind, 2019.

Current O&M costs for onshore wind have ranged from USD 20 to USD 60 USD/kW/year on average, depending on the market. Germany is notable for having higher onshore wind O&M costs. Annual costs per kilowatt have been flat or have fallen slightly in recent years. With rising capacity factors, however, this translates into declining O&M costs per kilowatt-hour.

2 SOLAR PHOTOVOLTAICS

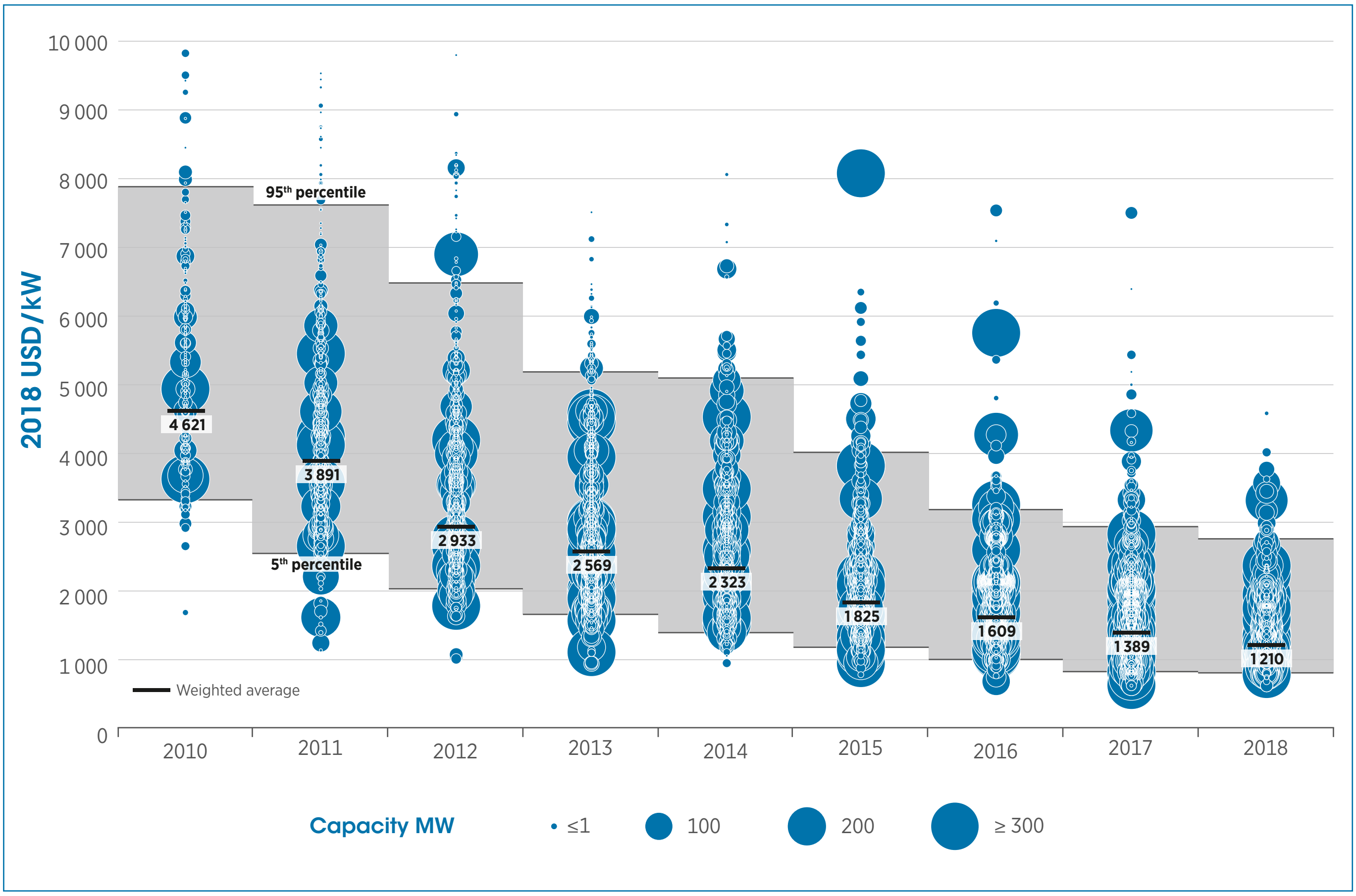
Figure 2.1 Average monthly European solar PV module prices by module technology and manufacturer, Jan 2010–Jul 2018 (top) and average yearly module prices by market in 2013 and 2018 (bottom)



Sources: Based on GlobalData, 2018; IRENA Renewable Cost Database, 2019; Photon Consulting, 2018; and pvXchange, 2019.

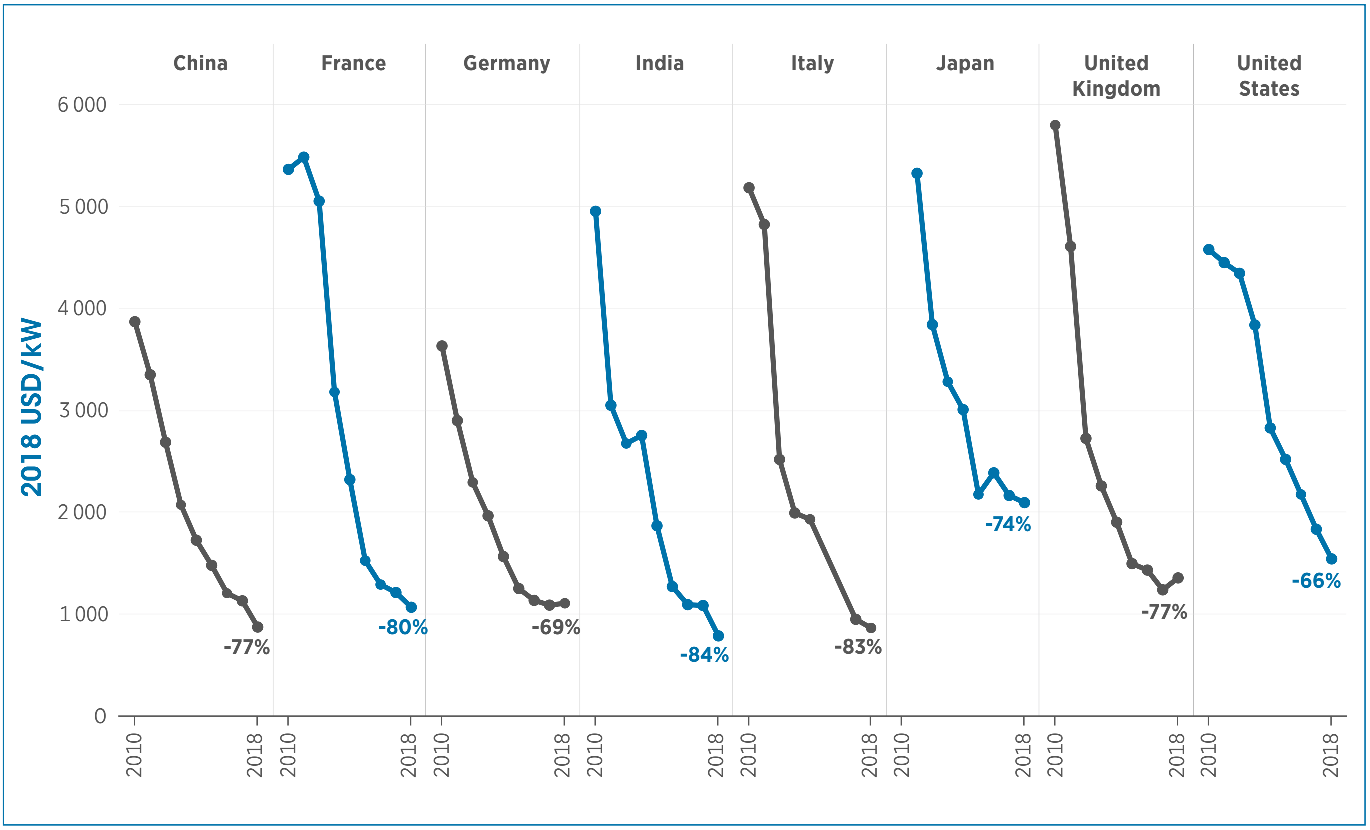
Solar PV module prices have fallen by around 90% since the end of 2009. At the end of 2018, module prices in Europe ranged from USD 0.22/W for "low cost" modules to USD 0.42/W for "all black" modules. Benchmark solar PV module prices fell rapidly between 2010 and 2013, but average module prices by country continued falling between 2013 and 2018, with declines between 34% and 61% for gigawatt-scale markets.

Figure 2.2 Total installed cost for utility-scale solar PV projects and the global weighted average, 2010–2018



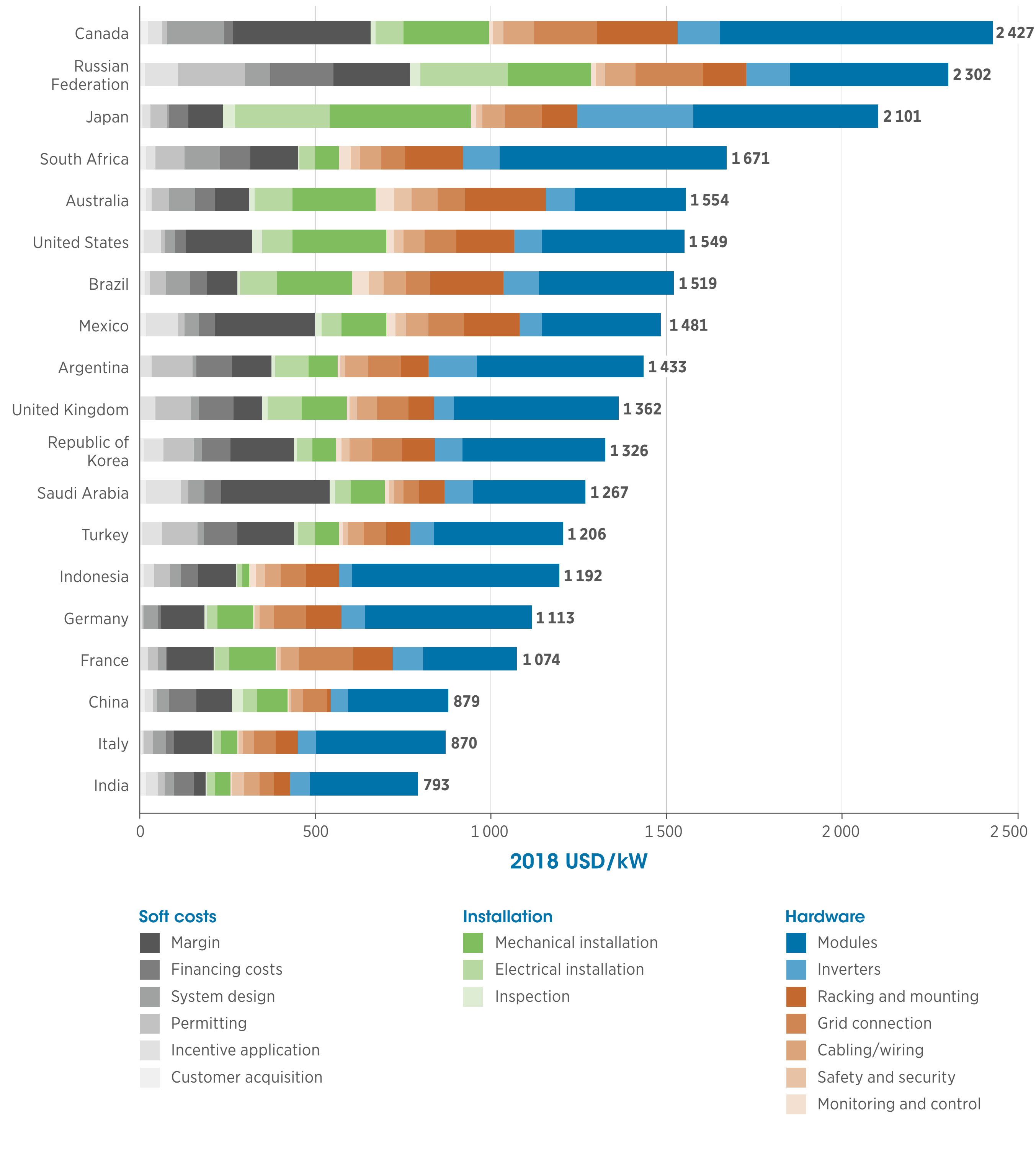
The global weighted-average total installed cost of utility-scale solar PV has fallen by 74% between 2010 and 2018. Installed costs have also converged closer to the average, with the 5th and 95th percentile range dropping from the USD 3 300–7 900/kW range in 2010 to USD 800–2 700/kW in 2018. Utility-scale solar PV project investment costs have fallen from USD 4 621/kW in 2010 to USD 1 210/kW in 2018.

Figure 2.3 Utility-scale solar PV total installed cost trends in selected countries, 2010–2018



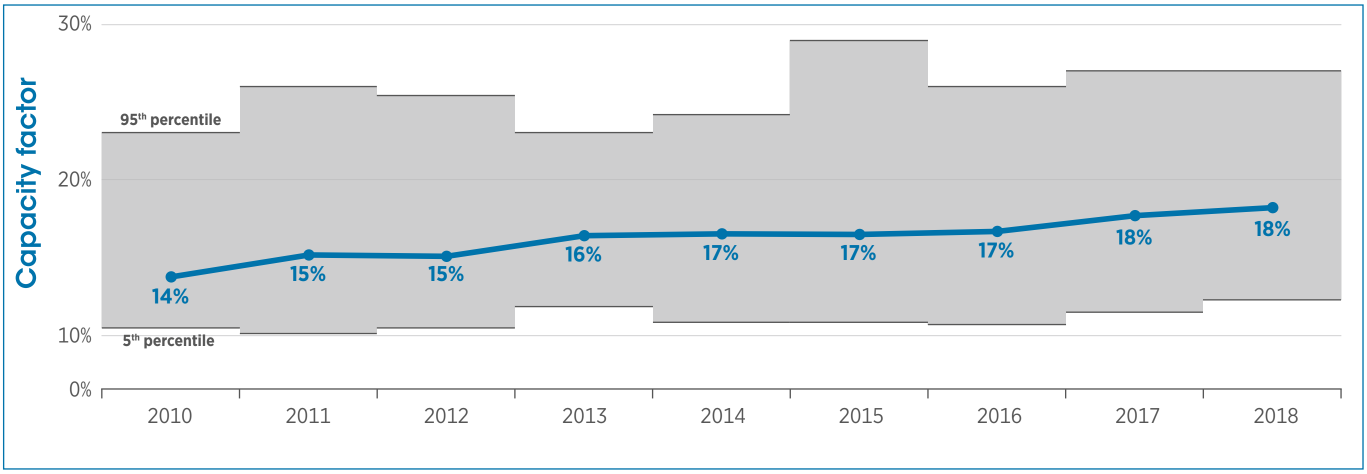
The average total installed costs of utility-scale solar PV projects in major markets have declined by between 66% and 84% in 2010–2018.

Figure 2.4 Detailed breakdown of utility-scale solar PV total installed costs in G20 countries, 2018



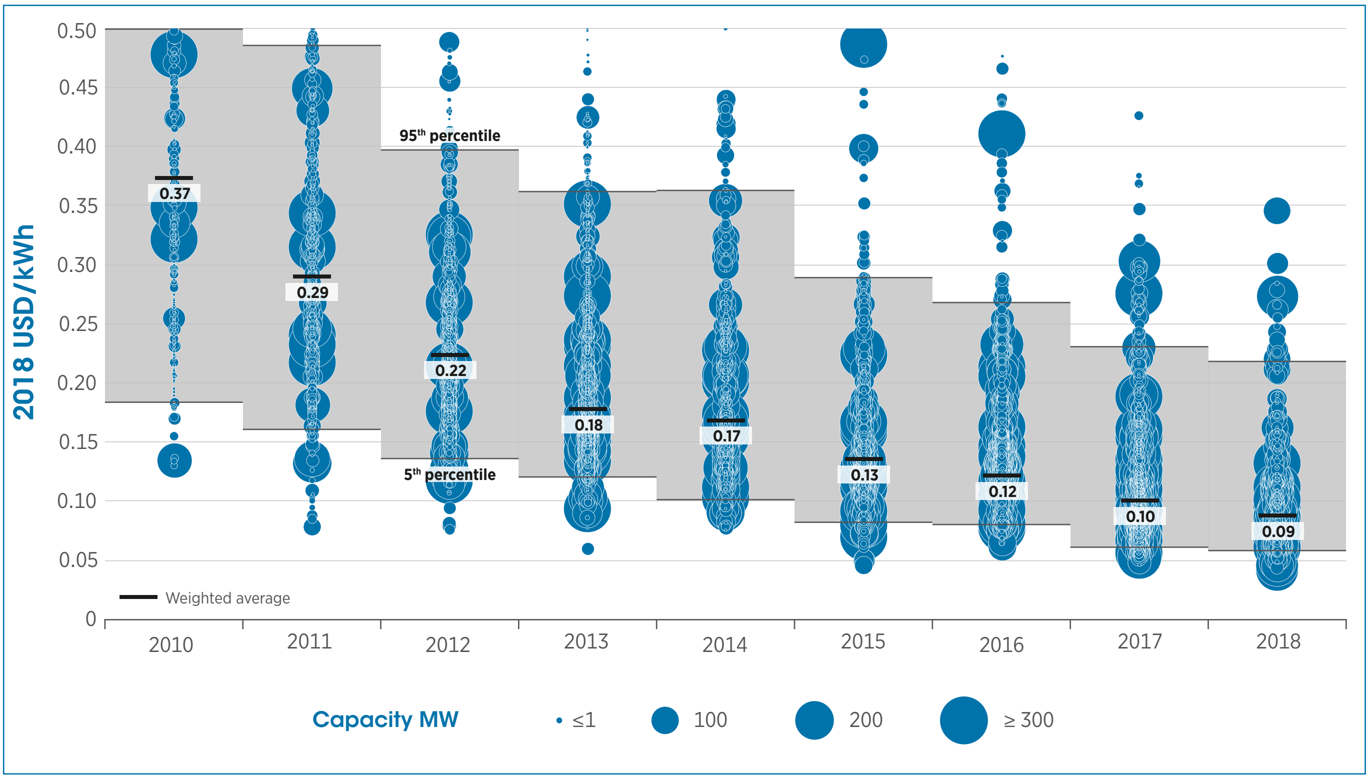
The country average for the total installed costs of utility scale solar PV in G20 countries ranged from a low of USD 793/kW in India to a high of USD 2 427/kW in Canada in 2018. The lowest cost average was three times less than the highest, despite the convergence of installed costs in major markets in the last three years.

Figure 2.5 Global weighted average capacity factors for utility-scale PV systems by year of commissioning, 2010–2018



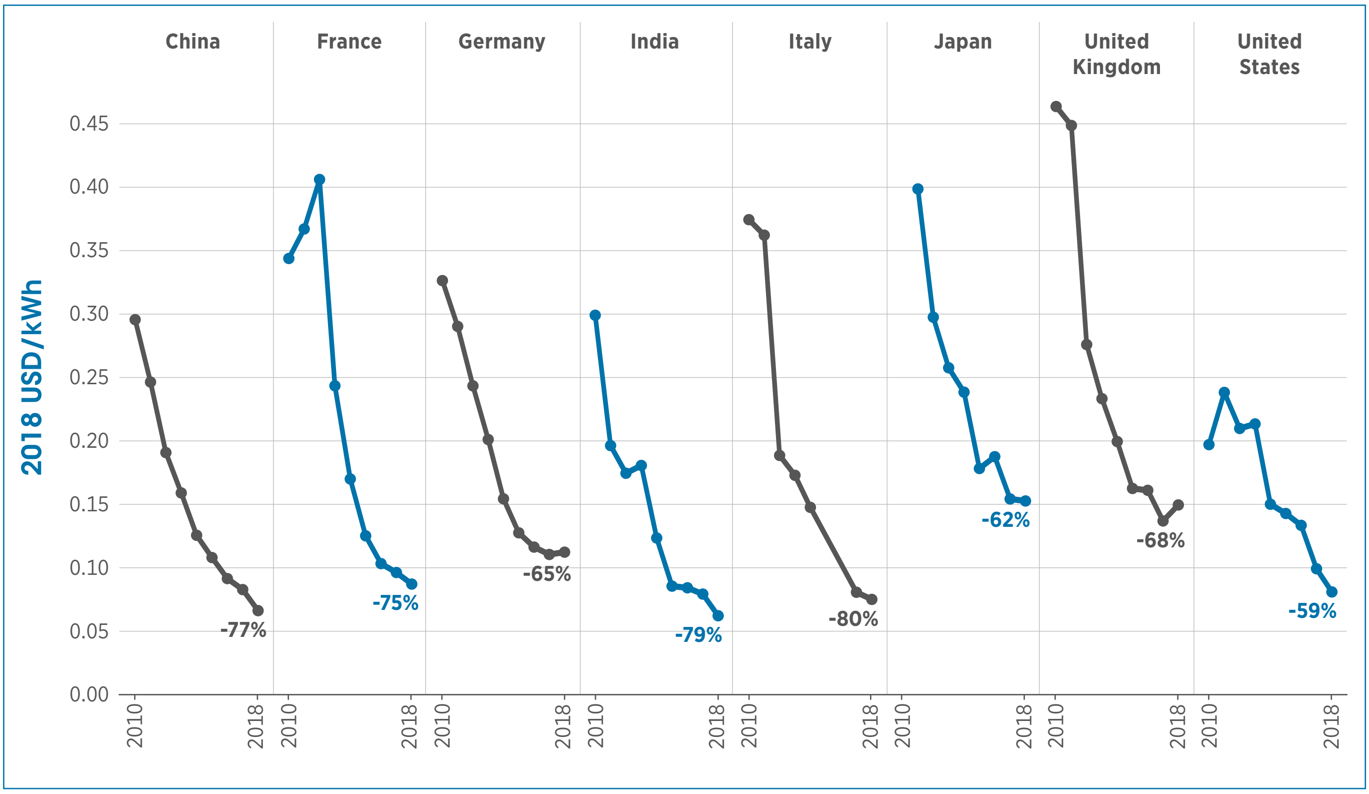
The global weighted-average capacity factor for new utility-scale solar PV, by year commissioned, has increased from 14% in 2010 to 18% in 2018 as the share of deployment in sunnier locations has risen.

Figure 2.6 LCOE from utility-scale solar PV projects, global weighted average and range, 2010–2018



The global weighted-average LCOE of utility-scale solar PV declined by 77% between 2010 and 2018, from USD 0.371 to USD 0.085/kWh. Globally, although the range has narrowed, the 5th and 95th percentile for projects in 2018 ranged from USD 0.058 to USD 0.219/kWh.

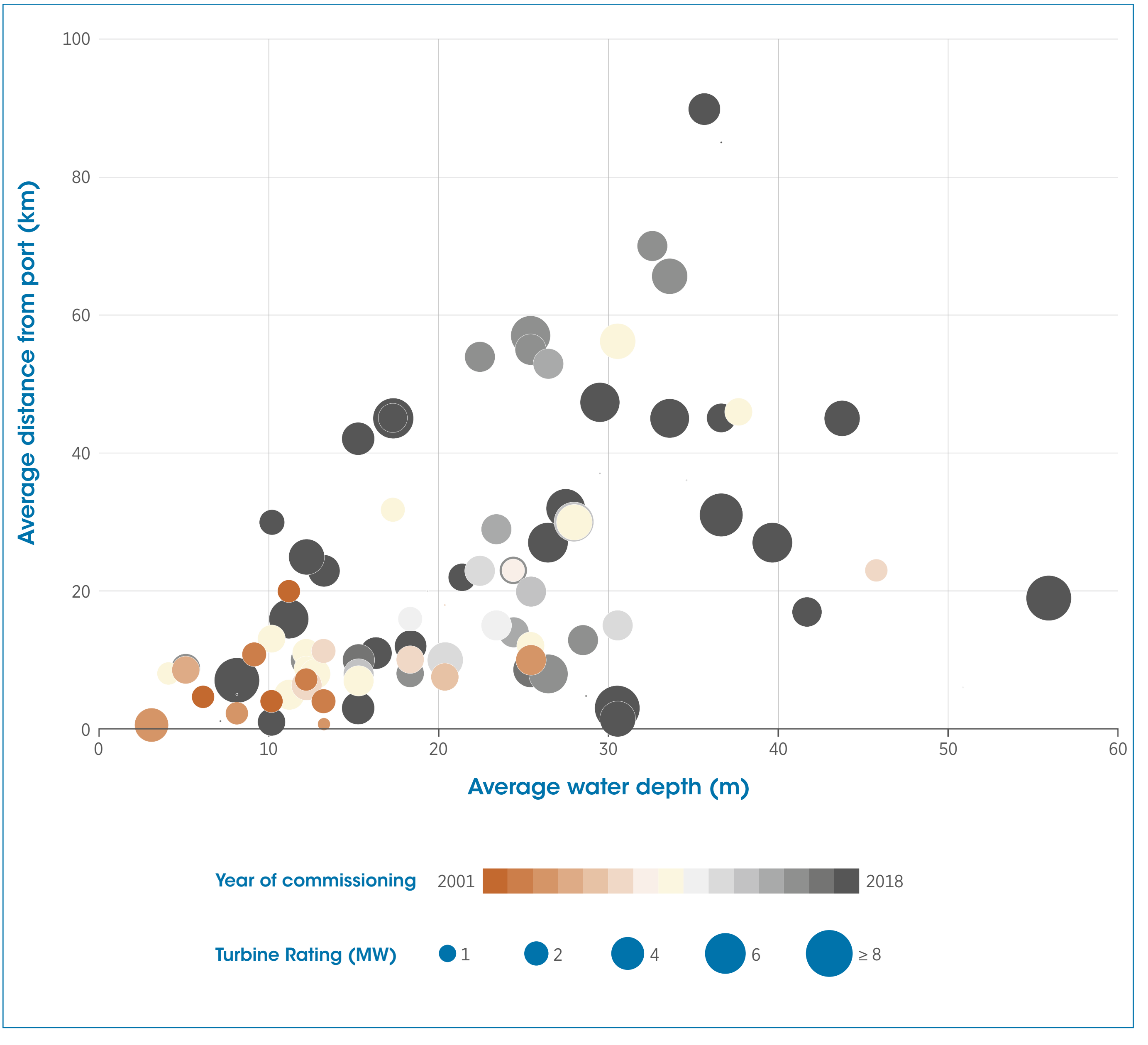
Figure 2.7 Utility-scale solar PV weighted-average LCOE trends in selected countries, 2010–2018



The country-average LCOE of utility-scale solar PV projects has declined rapidly between 2010 and 2018, by 62% to as much as 80% depending on the country. Country-average LCOE ranged from USD 0.06/kWh in India to USD 0.11/kWh in Germany. LCOEs were higher for Japan and the United Kingdom, both at around USD 0.15/kWh in 2018.

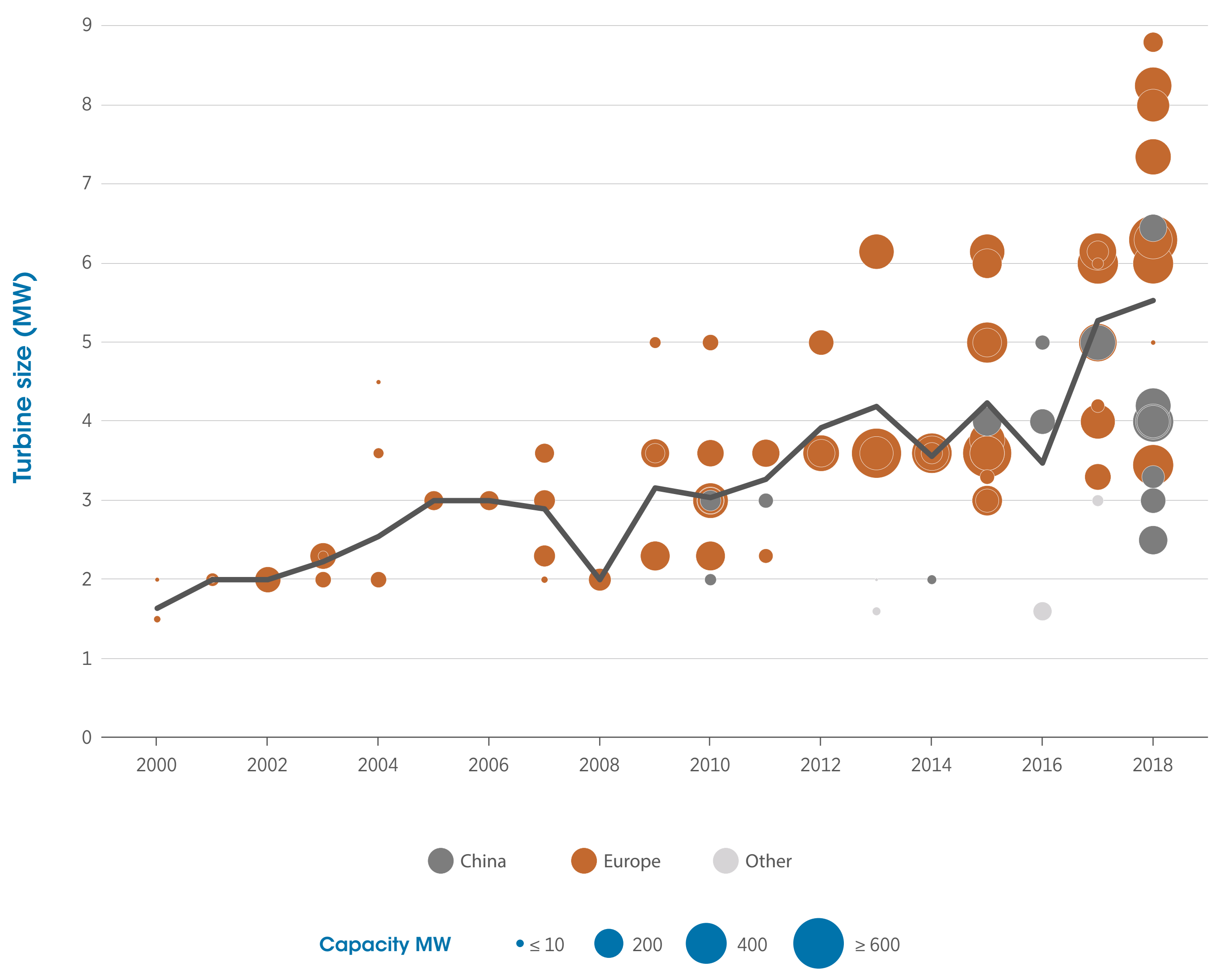
3 OFFSHORE WIND POWER

Figure 3.1 Average distance from port and water depth for commissioned offshore wind projects, 2001–2018



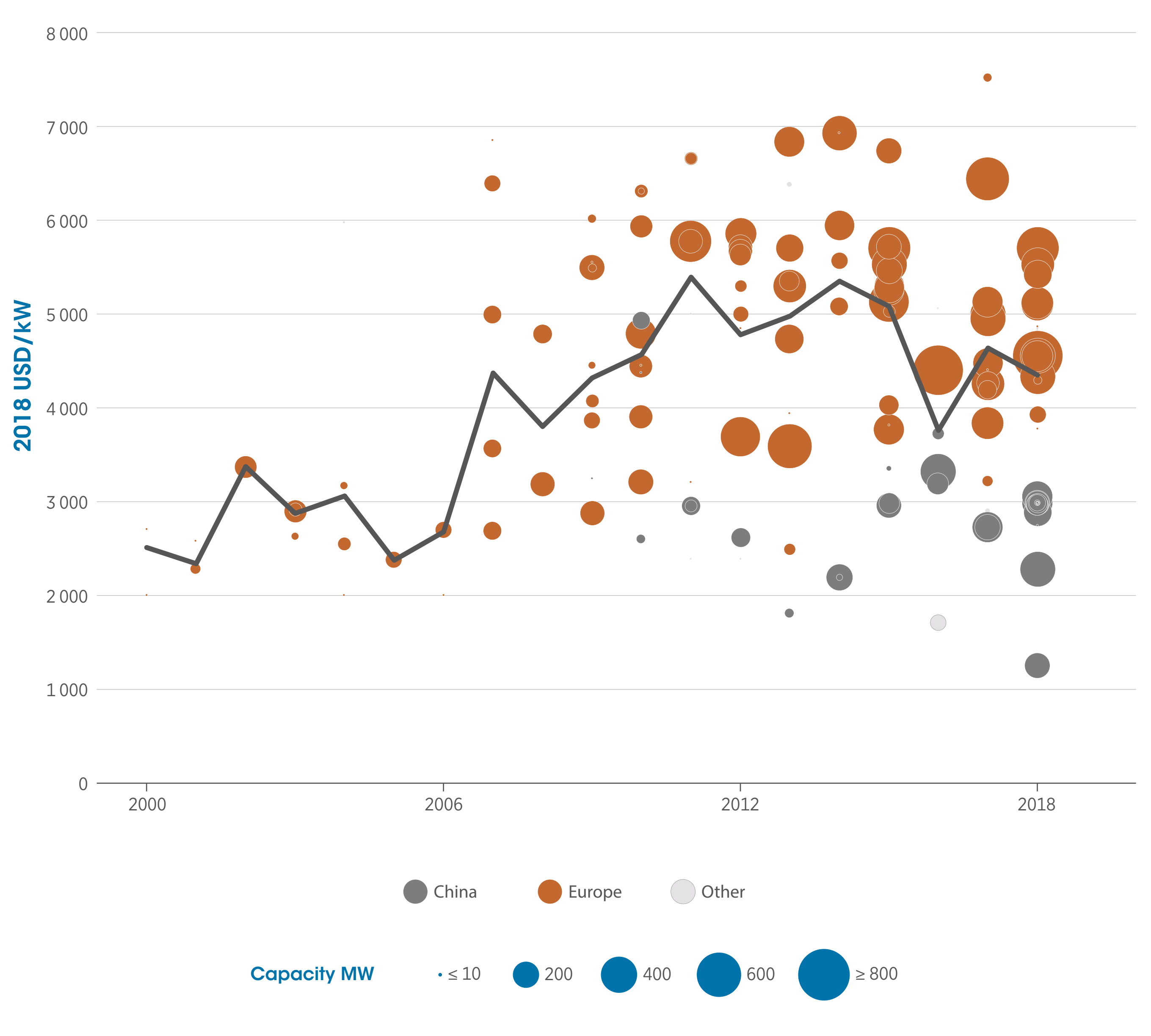
New offshore wind projects have moved to deeper waters and further offshore. Projects in recent years have typically been built at water depths between 10 m and 55 m and up to 90 km offshore, compared to around 10 m water-depth in 2001–2006, when distances to port rarely exceeded 20 km.

Figure 3.2 Turbine sizes for commissioned offshore wind projects and global weighted average, 2000–2018



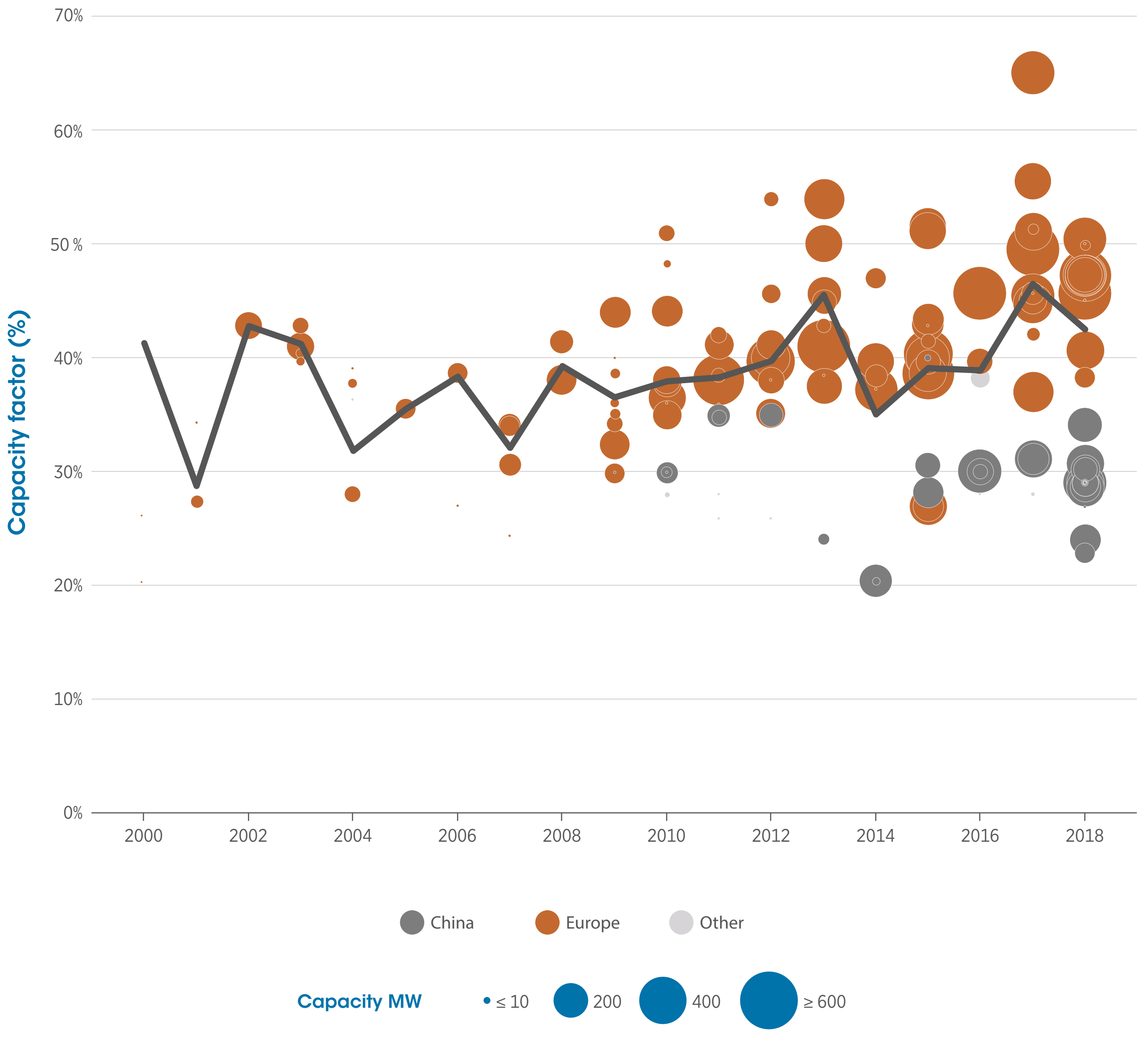
The average size of offshore wind turbines grew by a factor of 3.4 in less than two decades, from 1.6 MW in 2000 to 5.5 MW in 2018. Offshore wind farms commissioned in Europe in 2018 used turbines between 3.5 MW and 8.8 MW capacity.

Figure 3.3 Total installed costs for commissioned offshore wind projects and global weighted average, 2000–2018



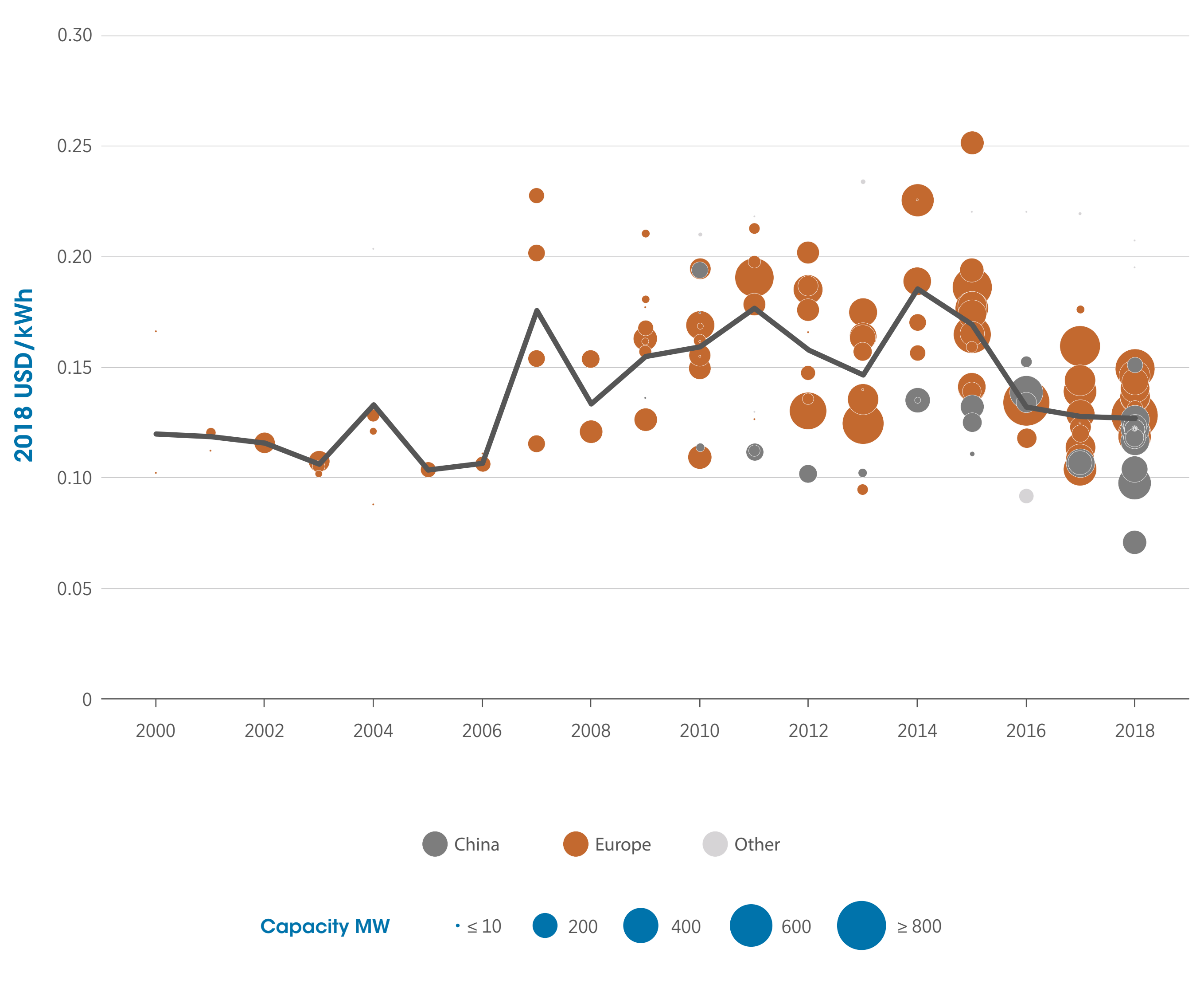
With the shift to deeper water and sites further from ports, the total installed costs of offshore wind farms rose, from an average of around USD 2 500/kW in 2000 to around USD 5 400/kW by 2011–2014, before falling to around USD 4 350/kW in 2018. Total costs are higher in Europe than in China, reflecting the fact that Chinese deployment to date remains in shallow waters, close to ports.

Figure 3.4 Capacity factors for commissioned offshore wind projects and global weighted average, 2000–2018



Capacity factors are higher in Europe (38% to 50% in 2018) than in China (23 to 34%), reflecting the relatively poorer wind resource and smaller turbines for near-shore Chinese projects. A clear trend to higher capacity factors for new offshore European wind farms can be seen since 2008, with average capacity factors rising from an average of around 35% to around 50% in 2017 and 2018.

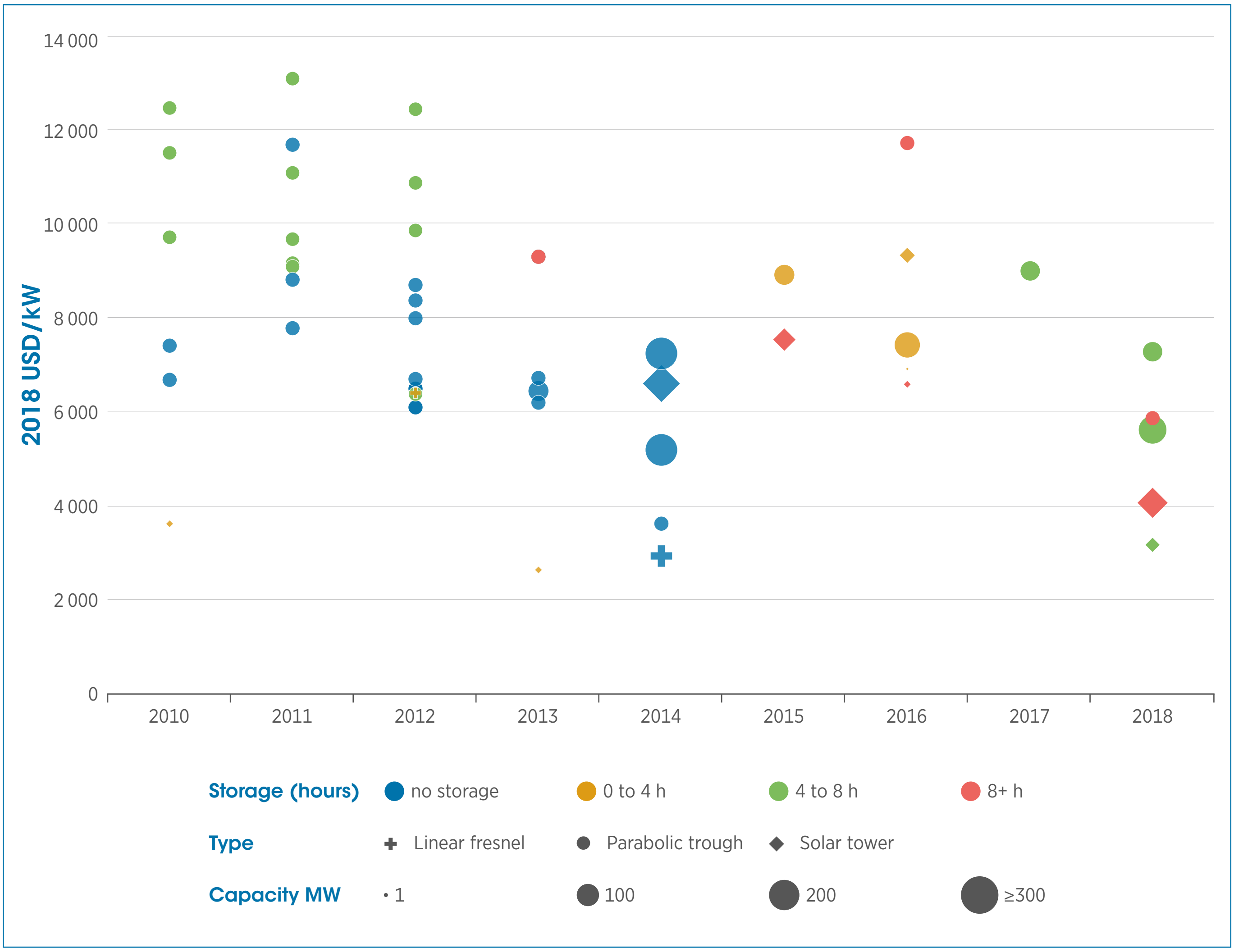
Figure 3.5 LCOE for commissioned offshore wind projects and global weighted average, 2000–2018



The global weighted-average LCOE of offshore wind projects commissioned in 2018 was USD 0.127/kWh. Like total installed costs, the average LCOE increased up to around 2011, before declining noticeably between 2016 and 2018. The weighted average LCOE was around USD 0.134/kWh in Europe in 2018. This was 28% higher than in China, where the value was around USD 0.105/kWh.

4 CONCENTRATING SOLAR POWER

Figure 4.1 Total installed costs of CSP plants by technology and storage duration, 2010–2018



CSP investment costs have declined from the USD 6 100–13 100/kW range for up to eight hours storage between in 2010–2012, to USD 3 200–7 300/kW in 2018 for projects with higher storage capacities (4–8 hours or more). No Linear Fresnel designs have been installed since 2014.

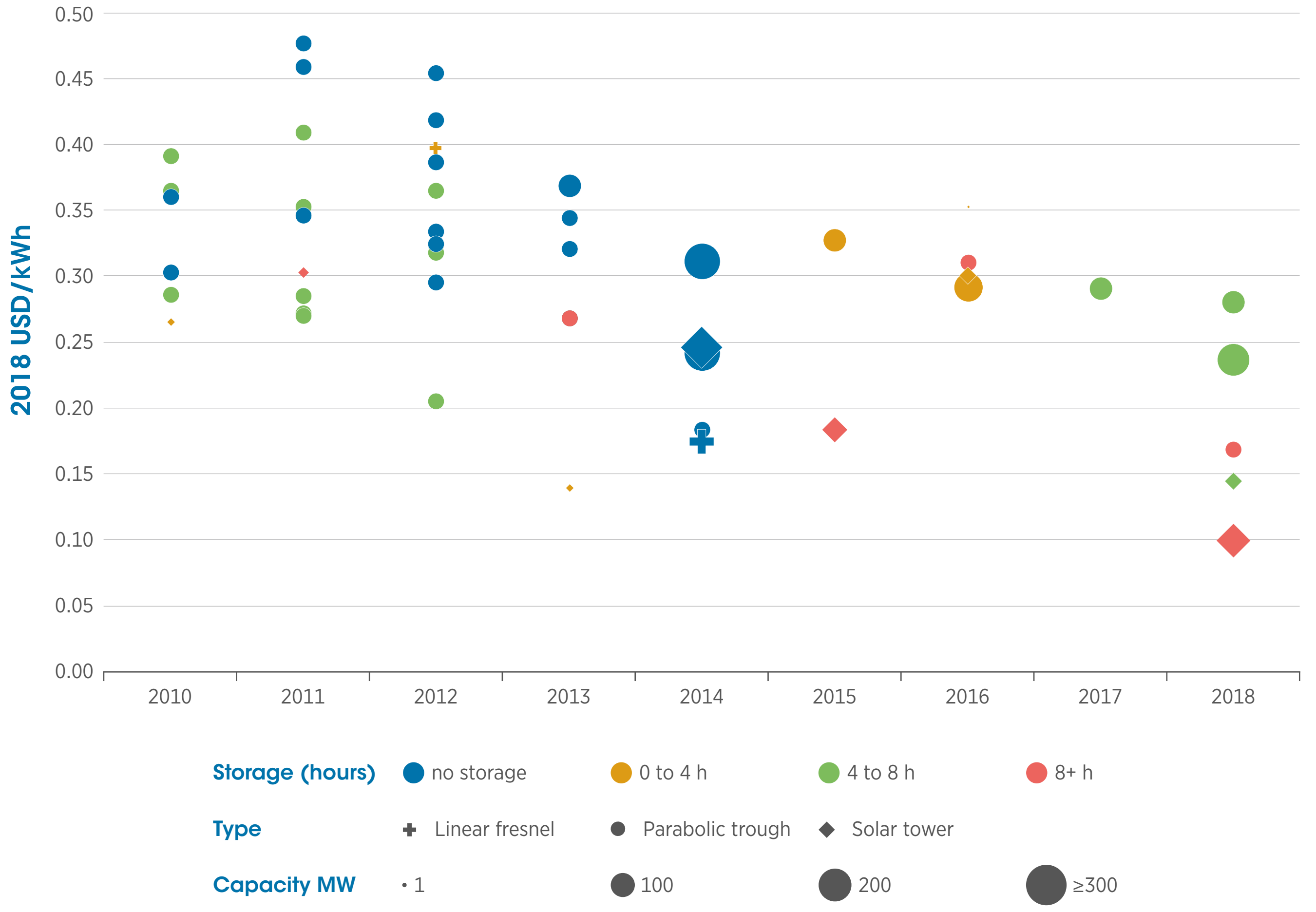
Figure 4.2 Capacity factor trends for CSP plants by technology and storage duration, 2010–2018

Capacity factors for new CSP plants increased between 2012 and 2018, with storage capacities growing and projects increasingly being developed in areas with better solar resources. New CSP projects commissioned in 2018 have estimated capacity factors ranging from 31% to 64%.

Figure 4.3 Direct normal irradiation levels for CSP projects by year of commissioning and technology, 2010–2018

One driver of higher capacity factors in recent years is deployment in areas with higher direct normal irradiance (DNI). CSP projects commissioned in Spain in 2010–2013 were typically sited in areas with DNI in the 2 000–2 200 kWh/m2/year range, while sites with DNI of 2 500–3 000 kWh/m2/year became the norm in 2014–2018.

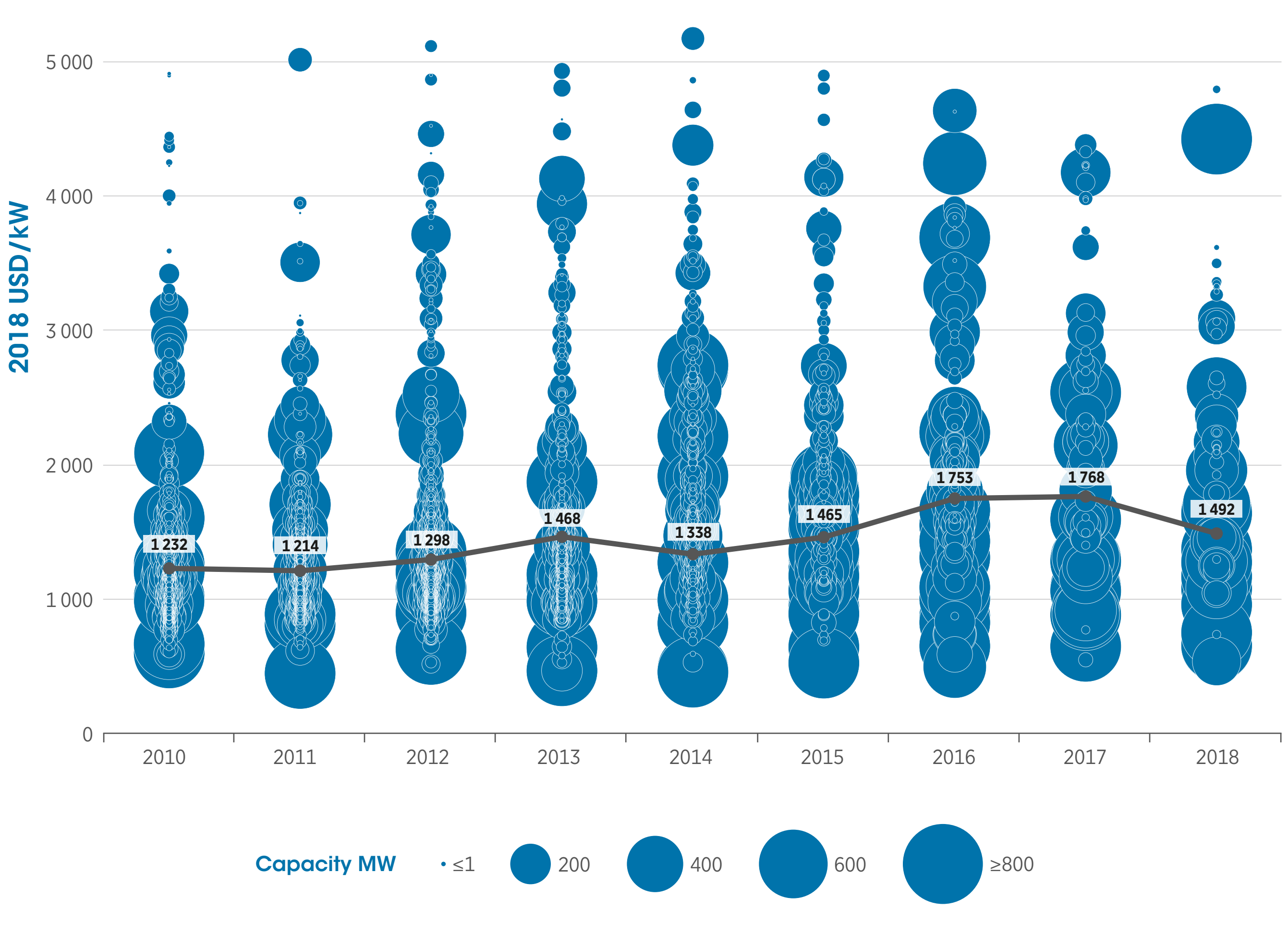
Figure 4.4 LCOE for CSP projects by year of commissioning, 2010–2018



The combination of increasing capacity factors and falling installed costs has seen the LCOE of new CSP projects fall from between USD 0.27–0.48/kWh in 2010 and 2011 to USD 0.10–0.28/kWh in 2018. No projects have been built without storage since 2014, given that including storage minimises LCOE.

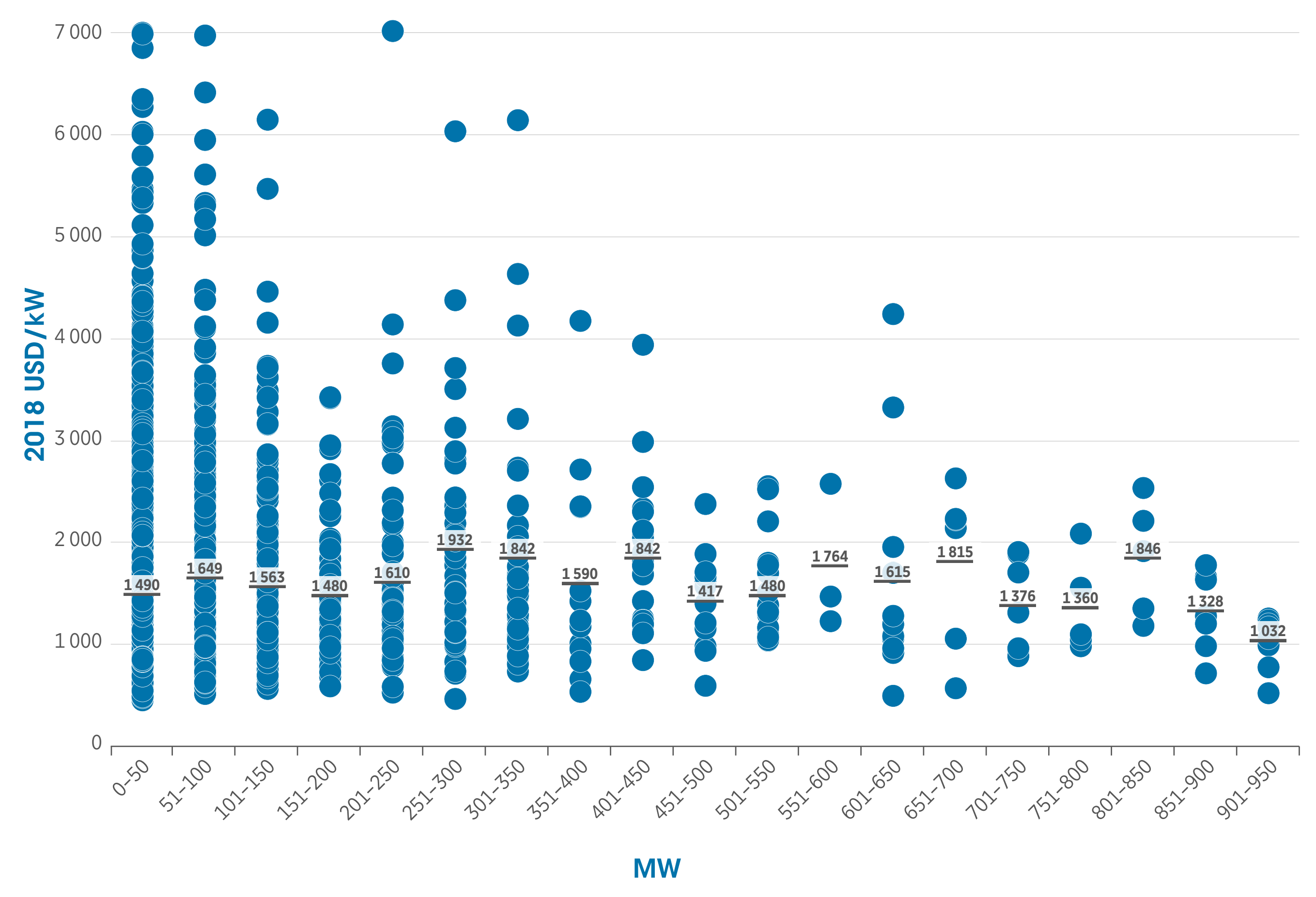
5 HYDROPOWER

Figure 5.1 Total installed costs by hydropower project and global weighted average, 2010–2018



Installed costs for hydropower have increased from USD 1 232/kW in 2010 to USD 1 492/kW in 2018. Total installed costs span a wide range, reflecting the very site-specific nature of hydropower projects, but generally fall within the USD 1 000–2 500/kW range. In 2018, total installed costs fell from their recent highs in 2016 and 2017.

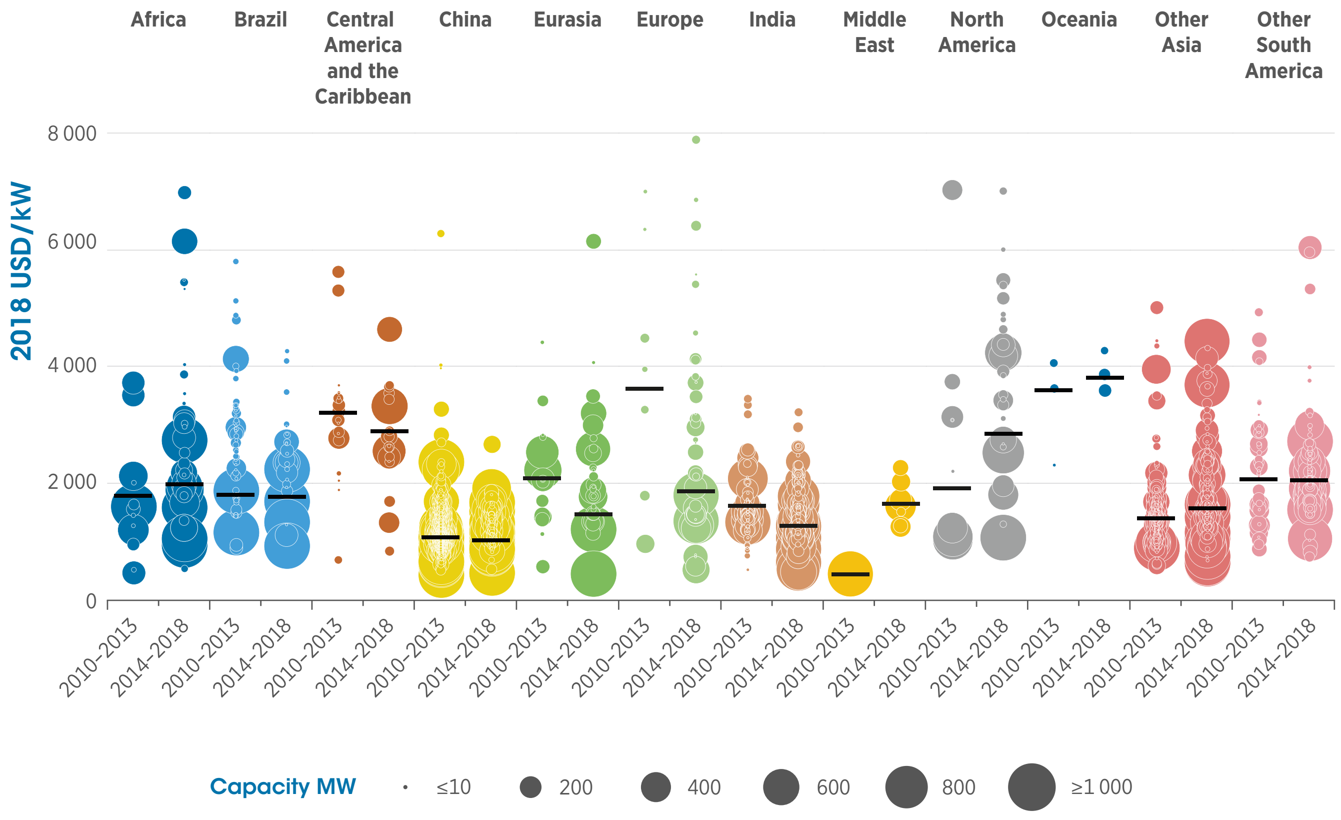
Figure 5.2 Total installed costs for hydropower by project and weighted average by capacity range, 2000–2018



Note: For each capacity range presented the horizontal line represents the weighted average total installed cost for projects in that capacity range.

Total installed costs depend on project size, with smaller projects typically having higher costs. Larger projects tend to have much more homogeneous costs than smaller-scale projects, which span much wider ranges.

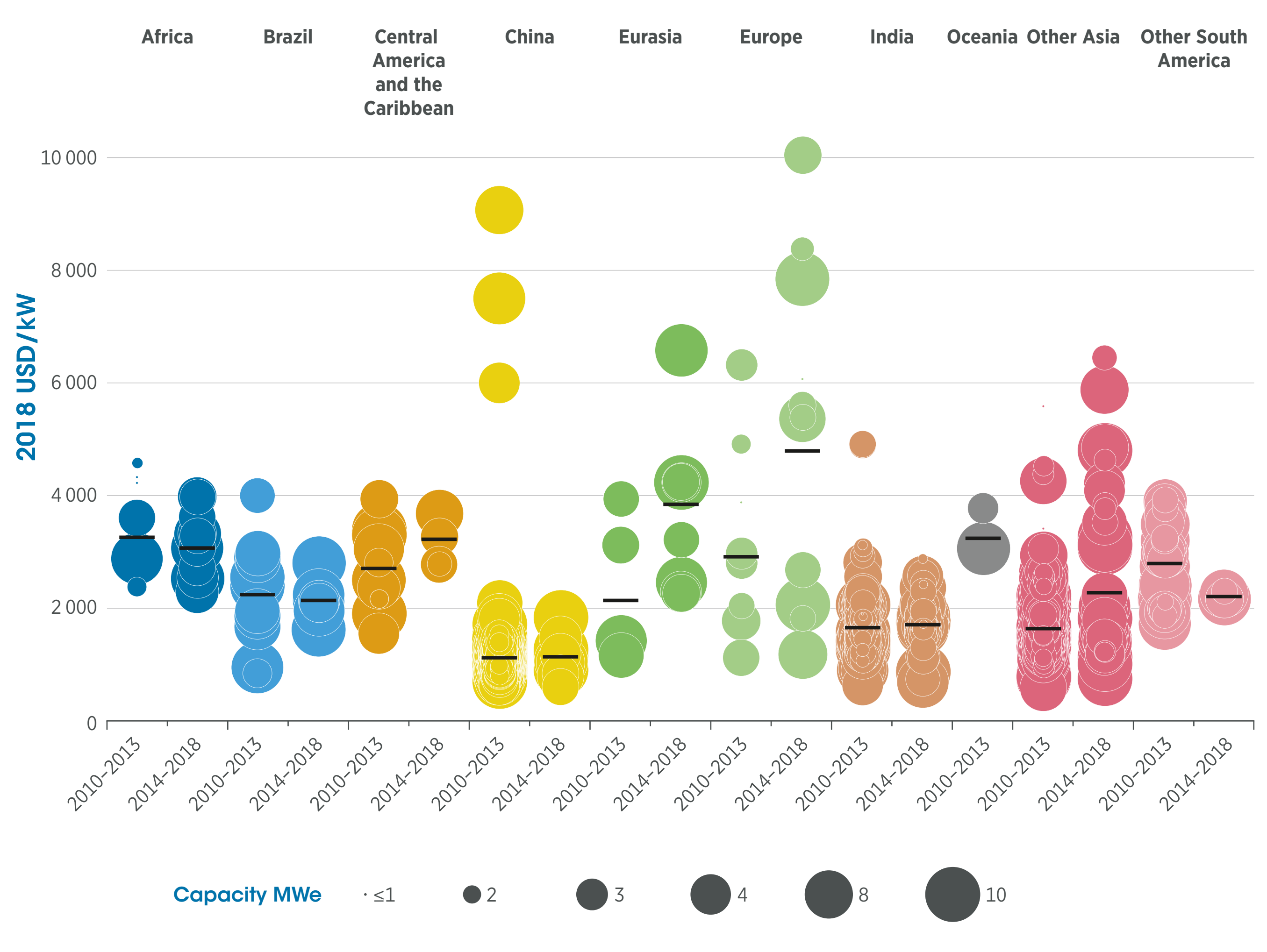
Figure 5.3 Total installed cost ranges and capacity weighted averages for large hydropower projects by country/region, 2010–2018



Note: Large hydropower projects in this figure are all those with capacity greater than 10 MW.

Installed costs by country or region have developed differently in 2014–2018, compared to the 2010–2013 period, in many regions, although costs were relatively stable in South America and China. For regions with significant deployment, the weighted average for the 2014–2018 period ranges from a low of USD 1030/kW in China to a high of USD 2920/kW in Central America and the Caribbean.

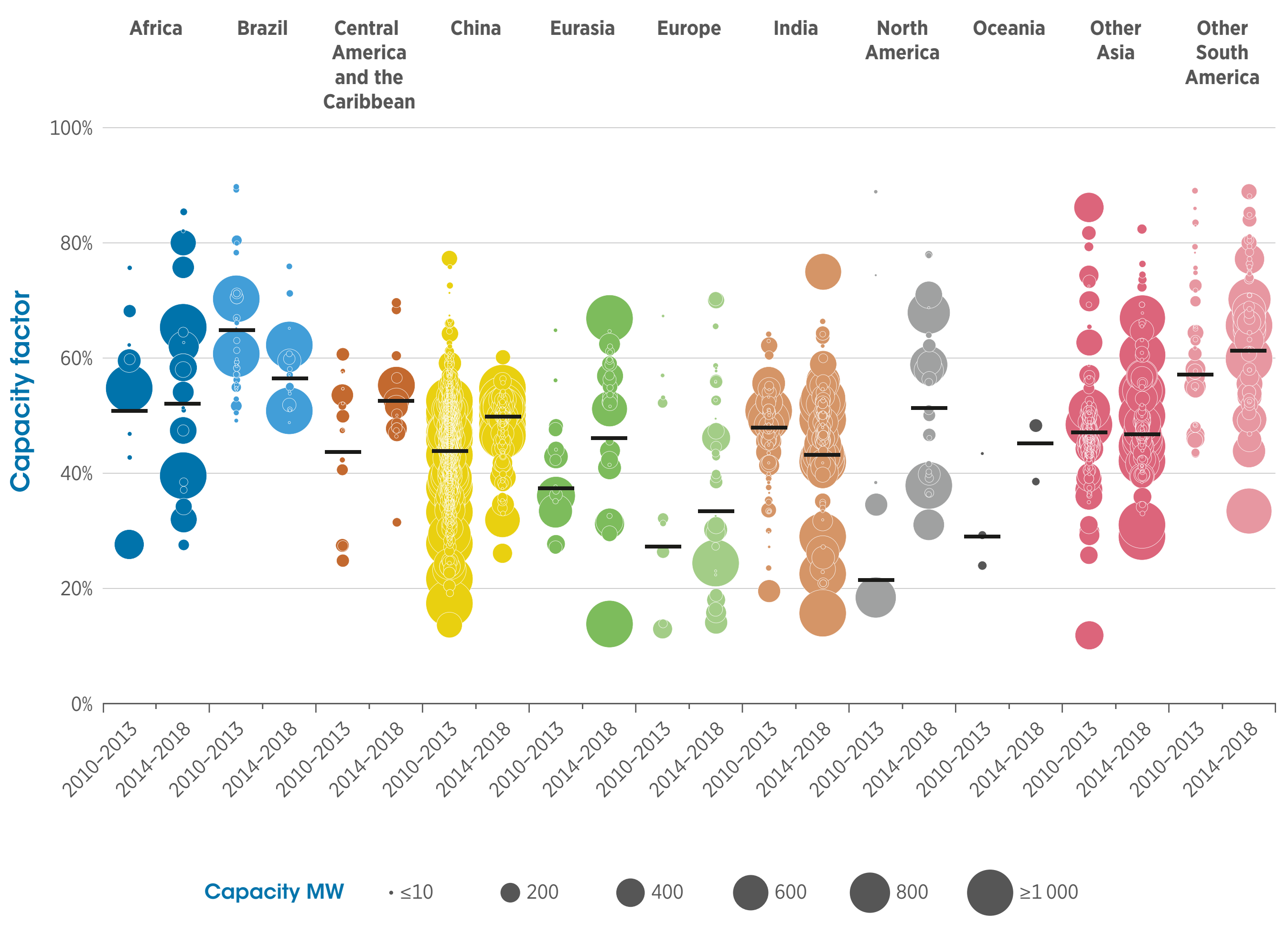
Figure 5.4 Total installed cost ranges and capacity weighted averages for small hydropower projects by country/region, 2010–2018



Note: Small hydropower projects in this figure are all those with capacity less than or equal to 10 MW.

Installed costs for small-scale hydropower projects have also varied depending on project trends. The weighted average for 2014–2018 ranged from a low of USD 1 150/kW in China to a high of USD 4 800/kW in Europe, with higher costs on average than for large-scale projects.

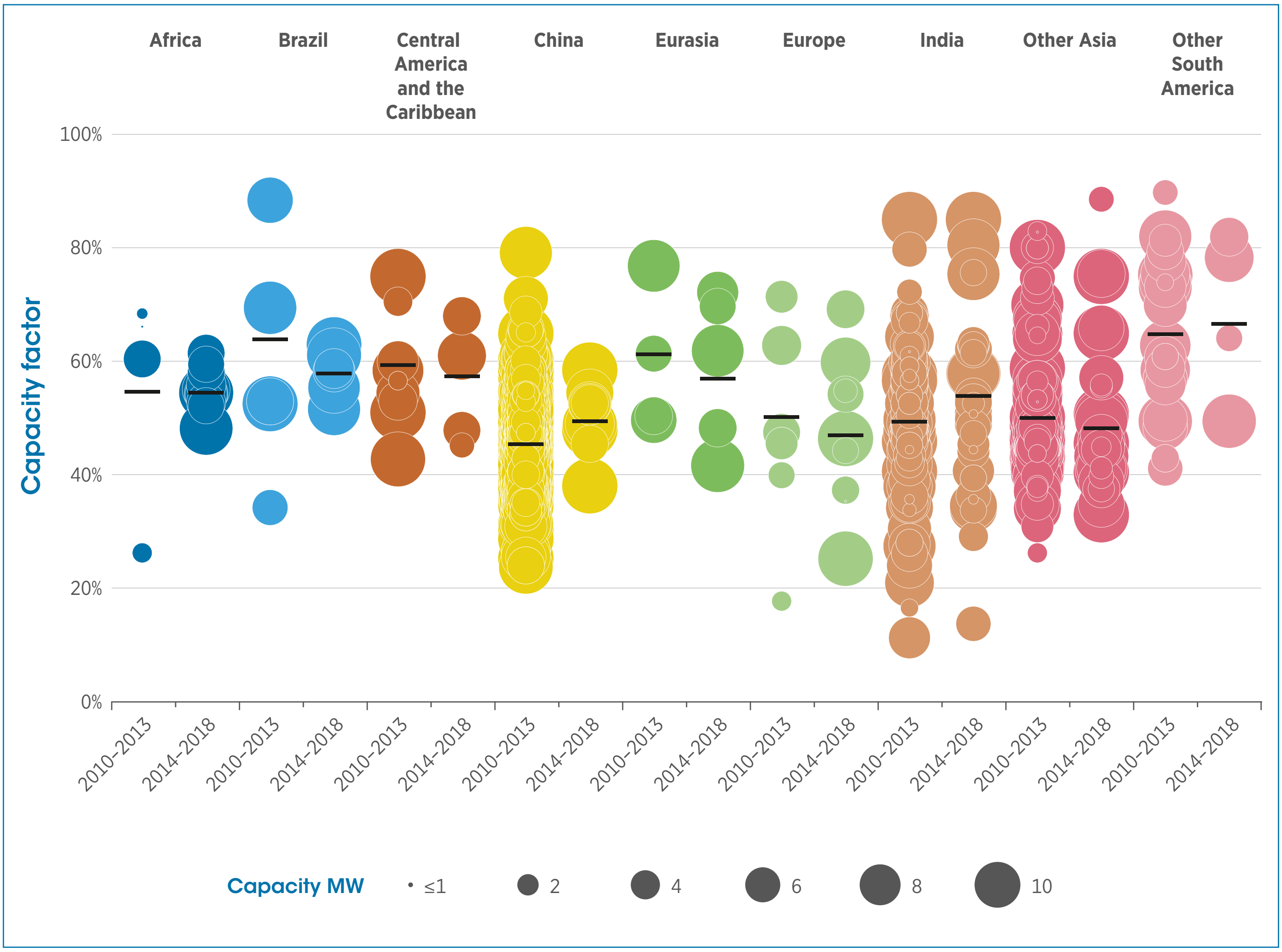
Figure 5.5 Hydropower project capacity factors and capacity weighted averages for large hydropower projects by country/region, 2010–2018



Note: Large hydropower projects in this figure are all those with capacity greater than 10 MW.

Average capacity factors for new projects commissioned between 2014 and 2018 by country and region have varied from a low of 34% in Europe to a high of 62% in South America, excluding Brazil. Average capacity factors increased in all regions in 2010–2013 and 2014–2018, except for Brazil and Other Asia.

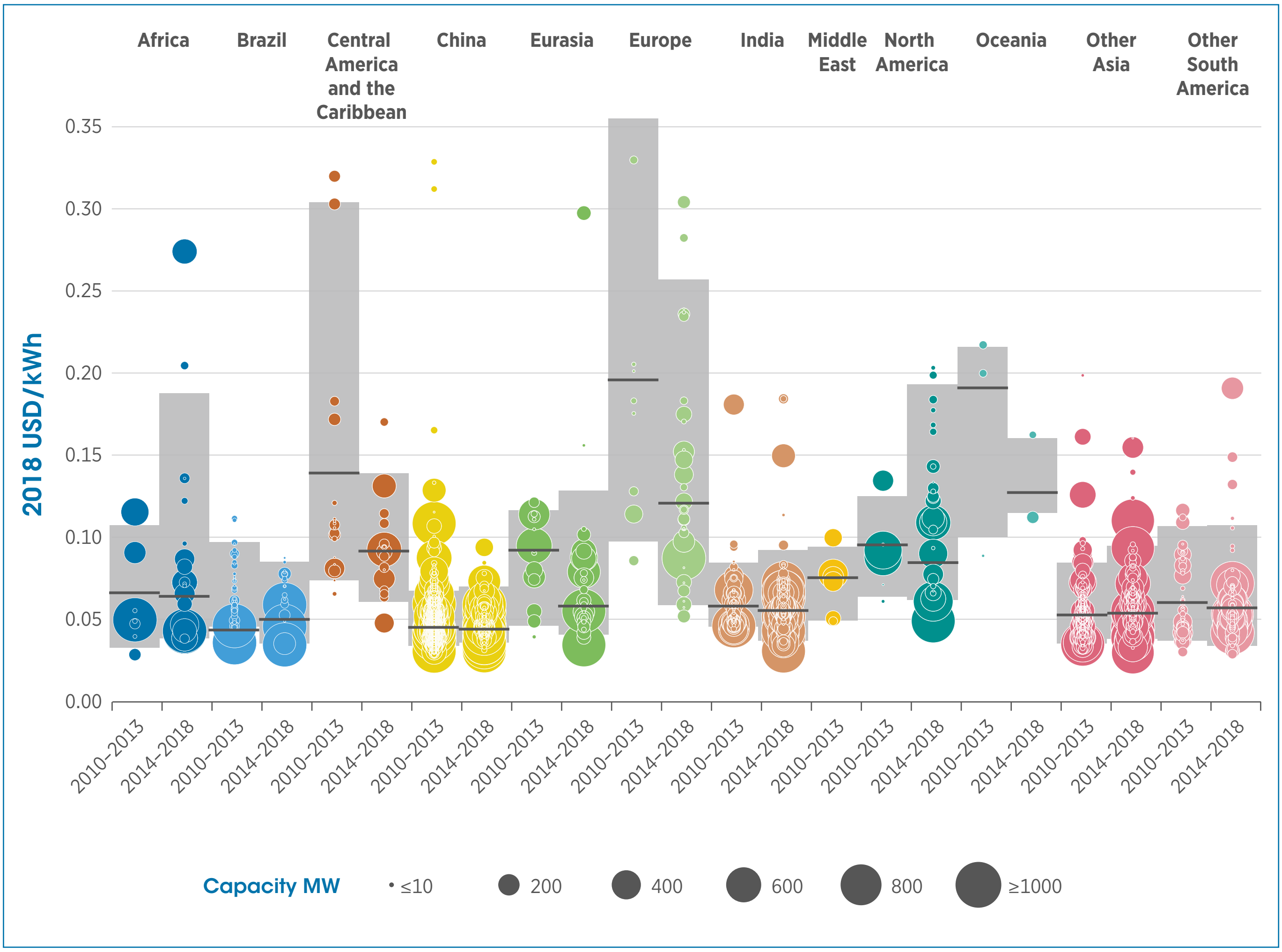
Figure 5.6 Hydropower project capacity factors and capacity weighted averages for small hydropower projects by country/region, 2010–2018



Note: Small hydropower projects in this figure are all those with capacity less than or equal to 10 MW.

The country or regional average capacity factor for small hydropower changed little for projects commissioned in 2014–2018, compared to those from 2010–2013. The lowest average occurred for projects in China from 2010–2013 (46%) and the highest for South America, excluding Brazil, in 2014–2018 (67%).

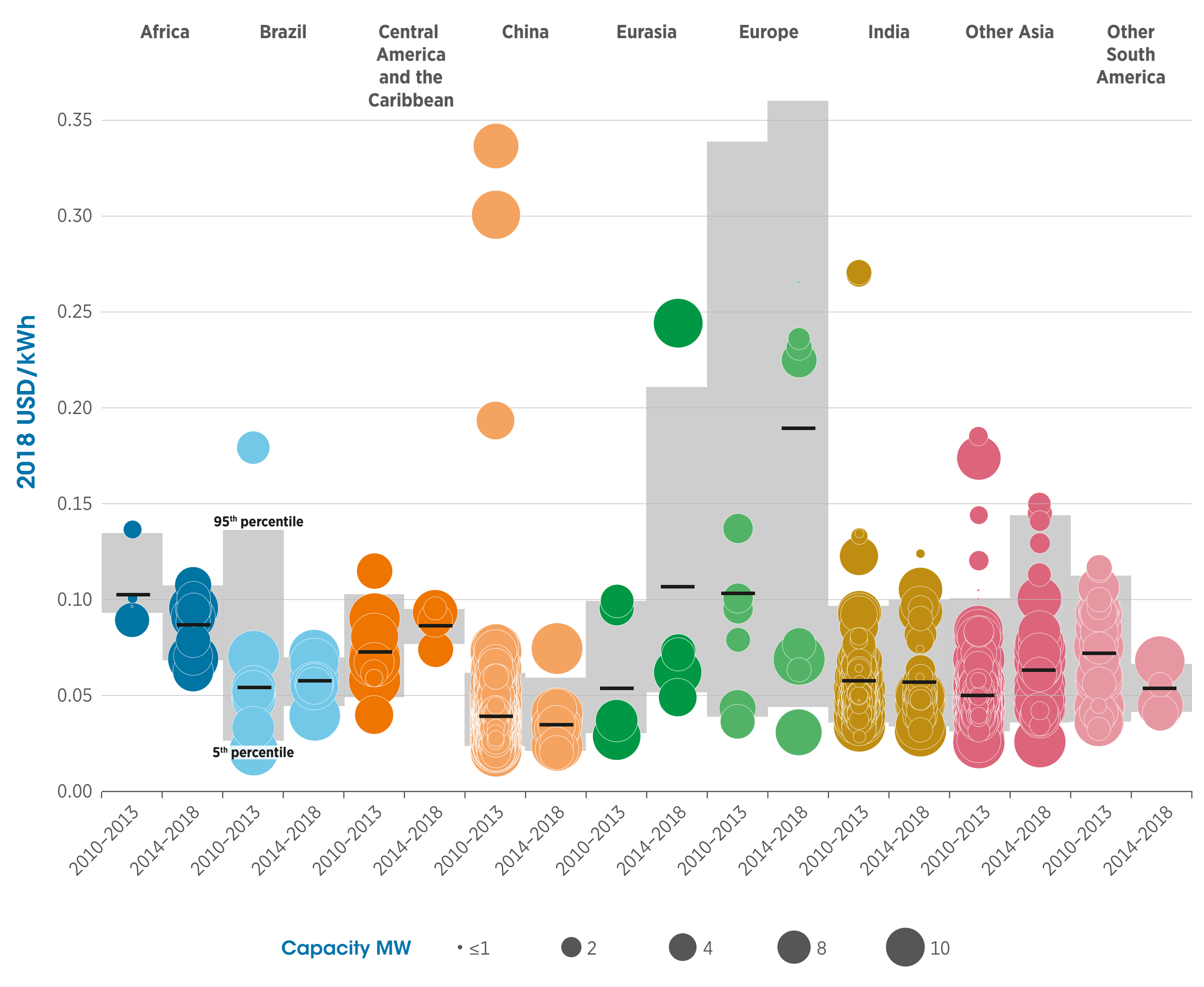
Figure 5.7 Large hydropower project LCOE and capacity weighted averages by country/region, 2010–2018



Note: Large hydropower projects in this figure are all those with capacity greater than 10 MW.

The country or regional weighted-average LCOE of newly commissioned large hydropower projects are in the USD 0.04–0.09/kWh range in most instances, although it is higher in Europe and Oceania. Average LCOE's were broadly flat, or slightly down, in major markets (Africa, Brazil, China, India, North America, Other Asia and Other South America) between 2010–2013 and 2014–2018.

Figure 5.8 Small hydropower project LCOE and capacity weighted averages by country/region, 2010–2018

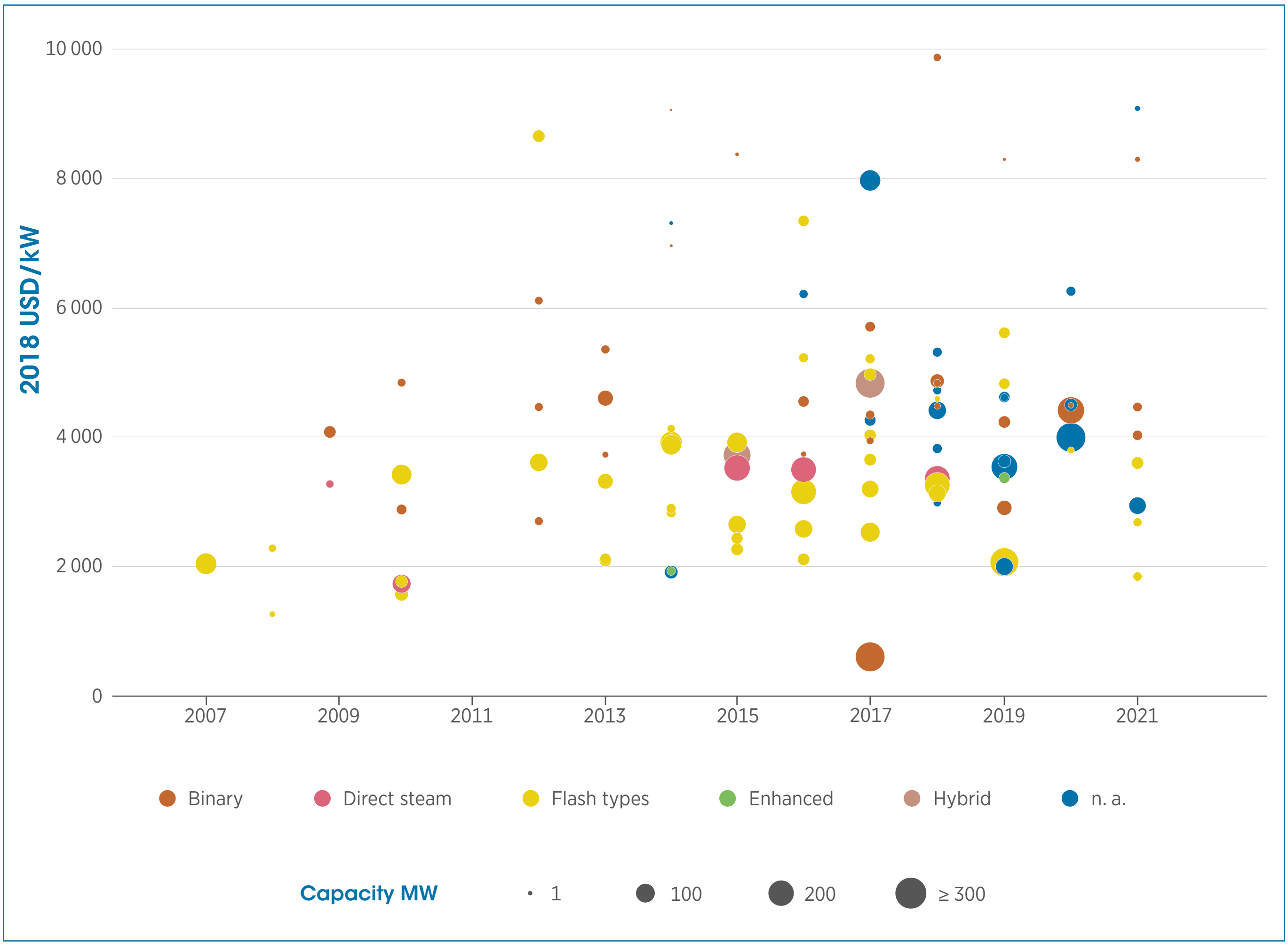


Note: Small hydropower projects in this figure are all those with capacity less than or equal to 10 MW.

The country or regional weighted-average LCOE of newly commissioned small hydropower projects was in the range of USD 0.04–0.09/kWh in the 2014–2018 period, but were higher in Eurasia (USD 0.11/kWh) and Europe (USD 0.19/kWh).

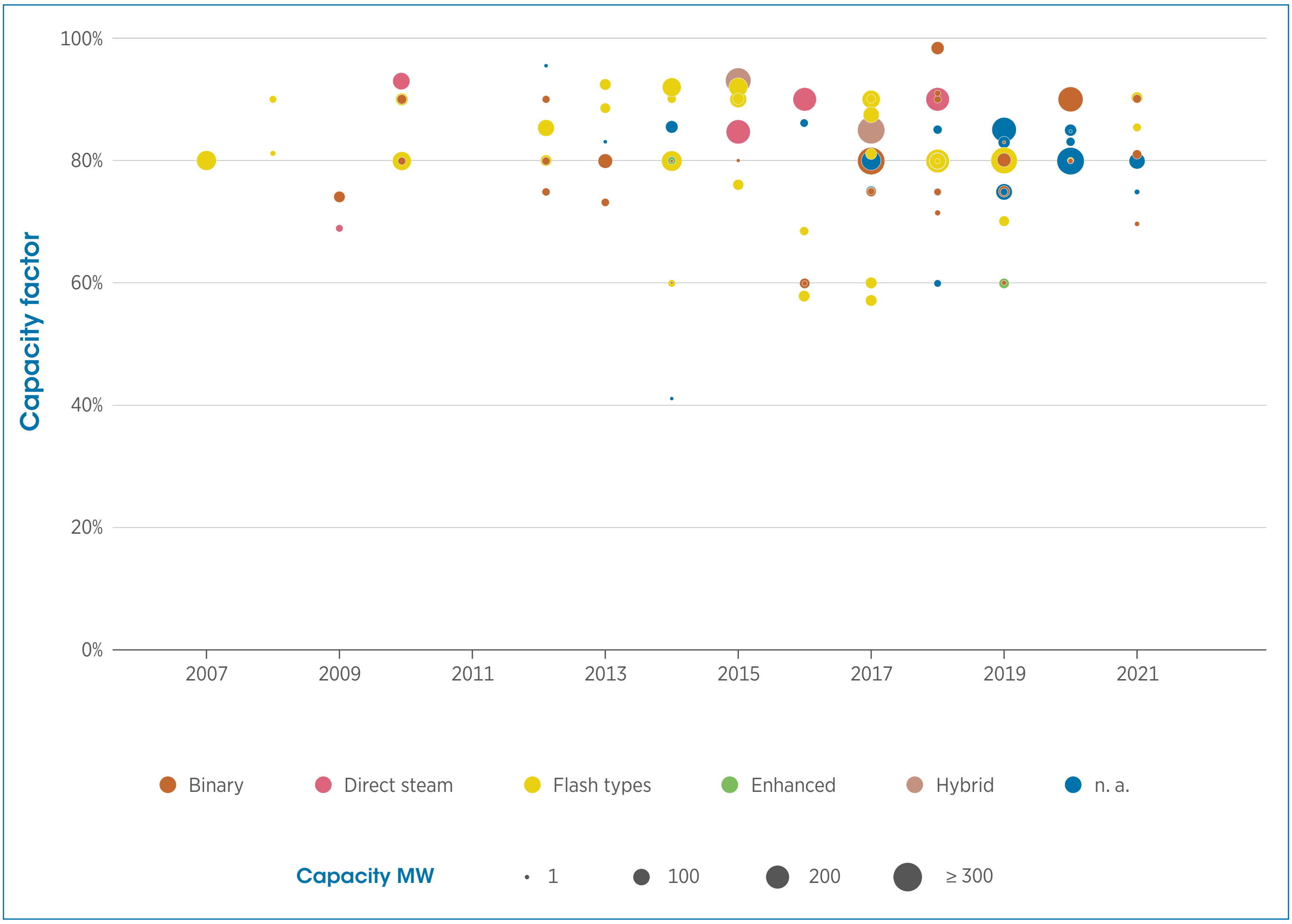
6 GEOTHERMAL POWER

Figure 6.1 Geothermal power total installed costs by project, technology and capacity, 2007–2021



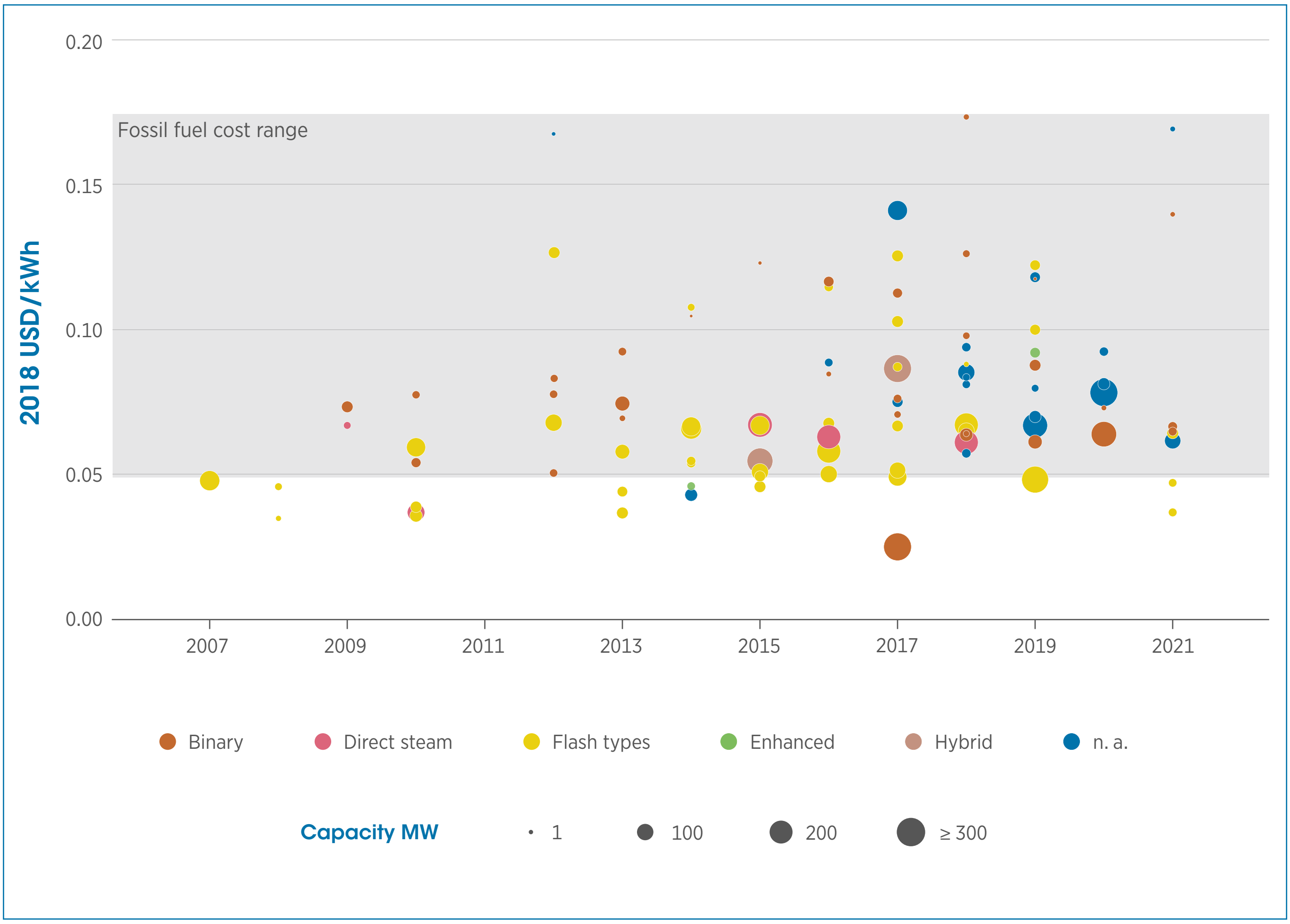
The market for geothermal power is relatively thin, leading to significant year-on-year variations in installed costs. Total installed costs for geothermal plants are typically between USD 2000 and USD 5000/kW. On average, the costs for "binary" geothermal plants are higher than those for "flash" types that exploit higher-temperature resources.

Figure 6.2 Capacity factors of geothermal power plants by technology and project size, 2007–2021



Capacity factors for geothermal plants are typically expected to be in the range of 80–90%, but lifetime capacity factors will depend heavily on well performance and ongoing investment to maintain production wells.

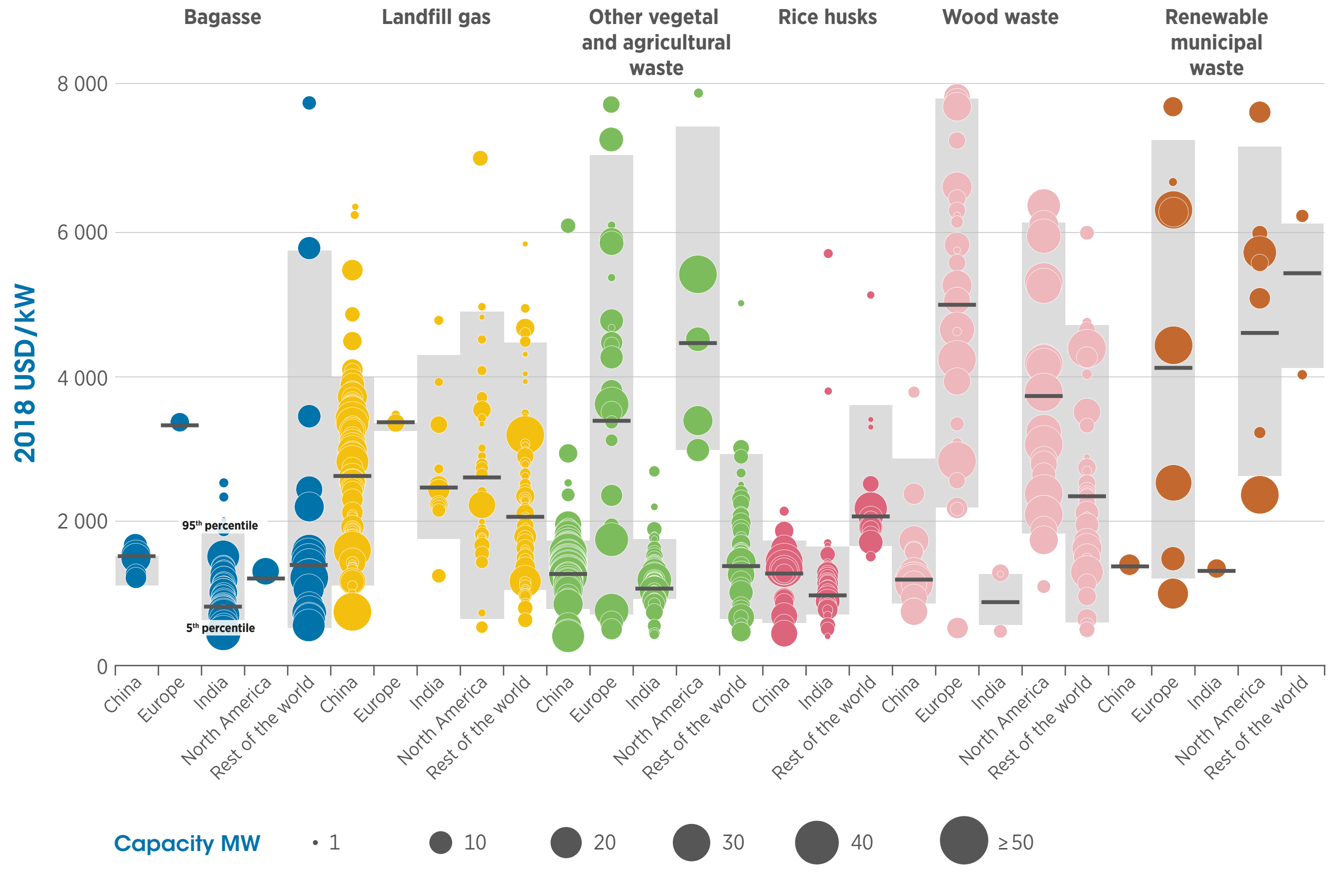
Figure 6.3 LCOE of geothermal power projects by technology and size, 2007–2021



Most geothermal power projects have LCOEs between USD 0.05 and USD 0.08/kWh, which is at the lower end of the fossil-fuel cost range. Between 2013 and 2015, the weighted-average LCOE was around USD 0.06/kWh, rising to around USD 0.07/kWh during 2016–2018.

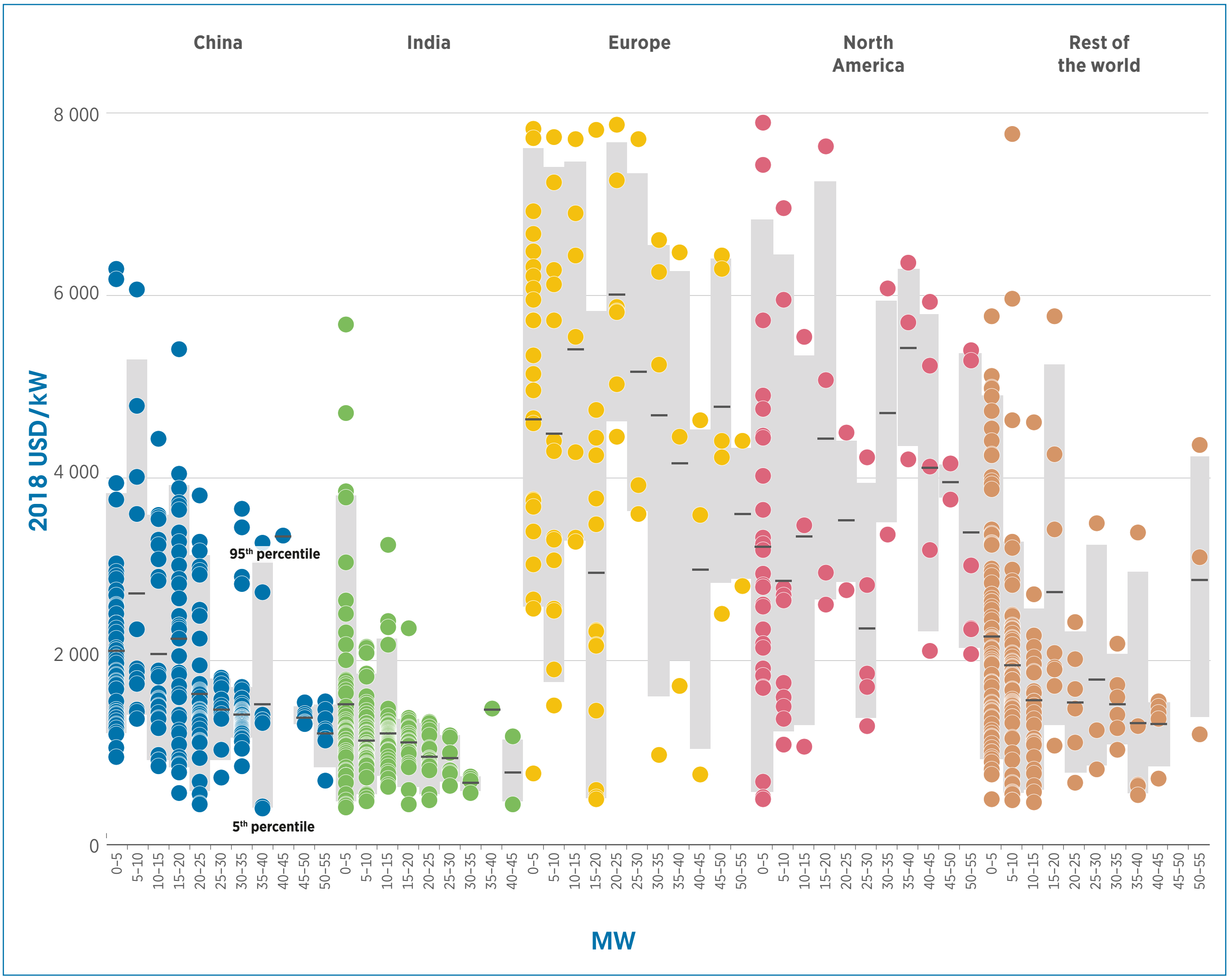
7 BIOENERGY FOR POWER

Figure 7.1 Total installed cost of bioenergy-fired power generation projects by selected feedstocks and country/region, 2000–2018



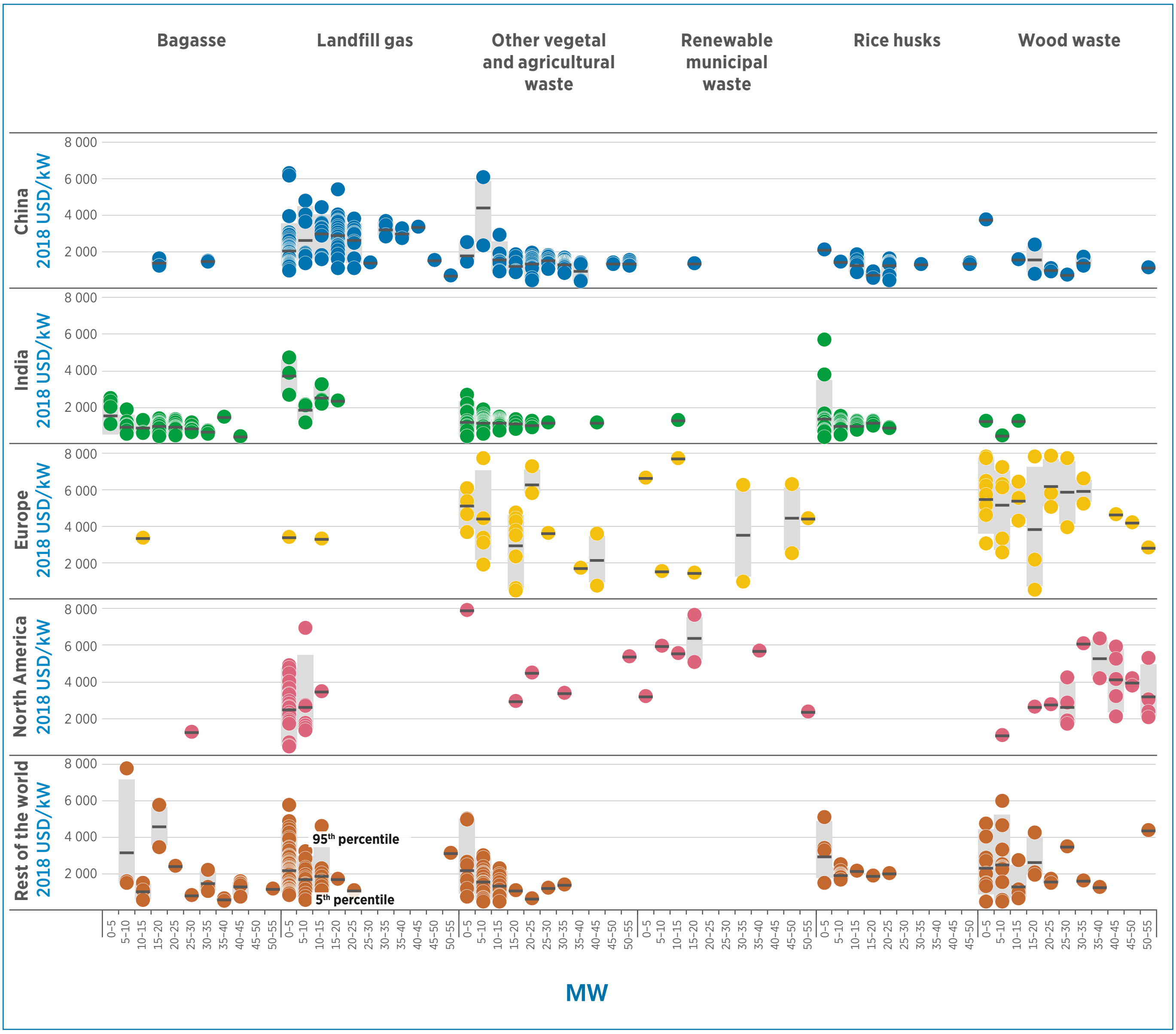
Differences in total installed costs for bioenergy are more significant between countries than feedstock types. Total installed costs vary significantly within countries or regions depending on the technology employed. Bioenergy projects using bagasse and rice husks as feedstocks tend to have lower installed costs than those using landfill gas, wood waste, other vegetal and agricultural waste and renewable municipal waste.

Figure 7.2 Total installed cost of bioenergy-fired power generation projects for different capacity ranges by country/region, 2000–2018



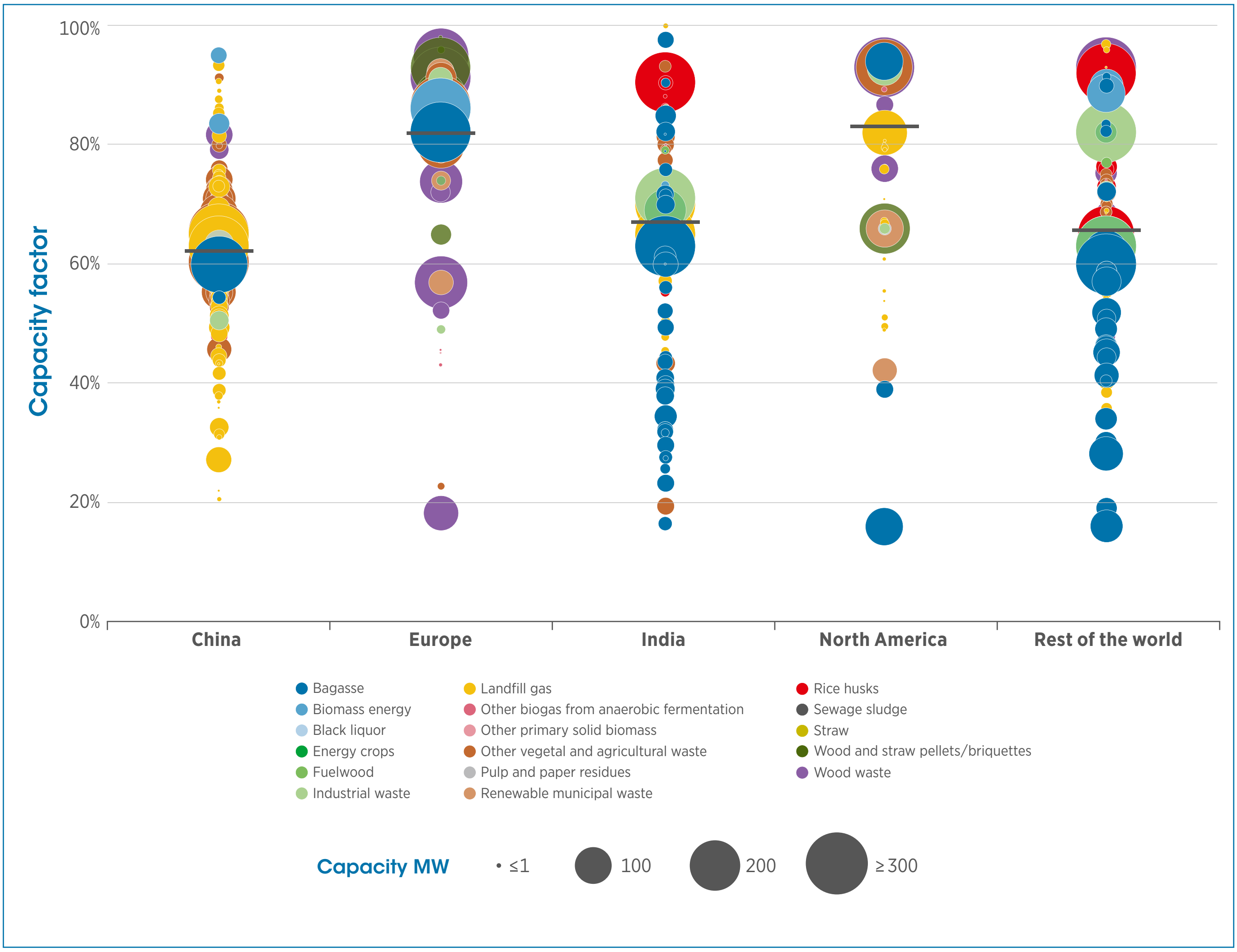
Economies of scale are visible for total installed costs in China, India and the rest of the world, but less evident in Europe and North America.

Figure 7.3 Total installed cost of bioenergy-fired power generation projects for different capacity ranges by selected feedstock and country/region, 2000–2018



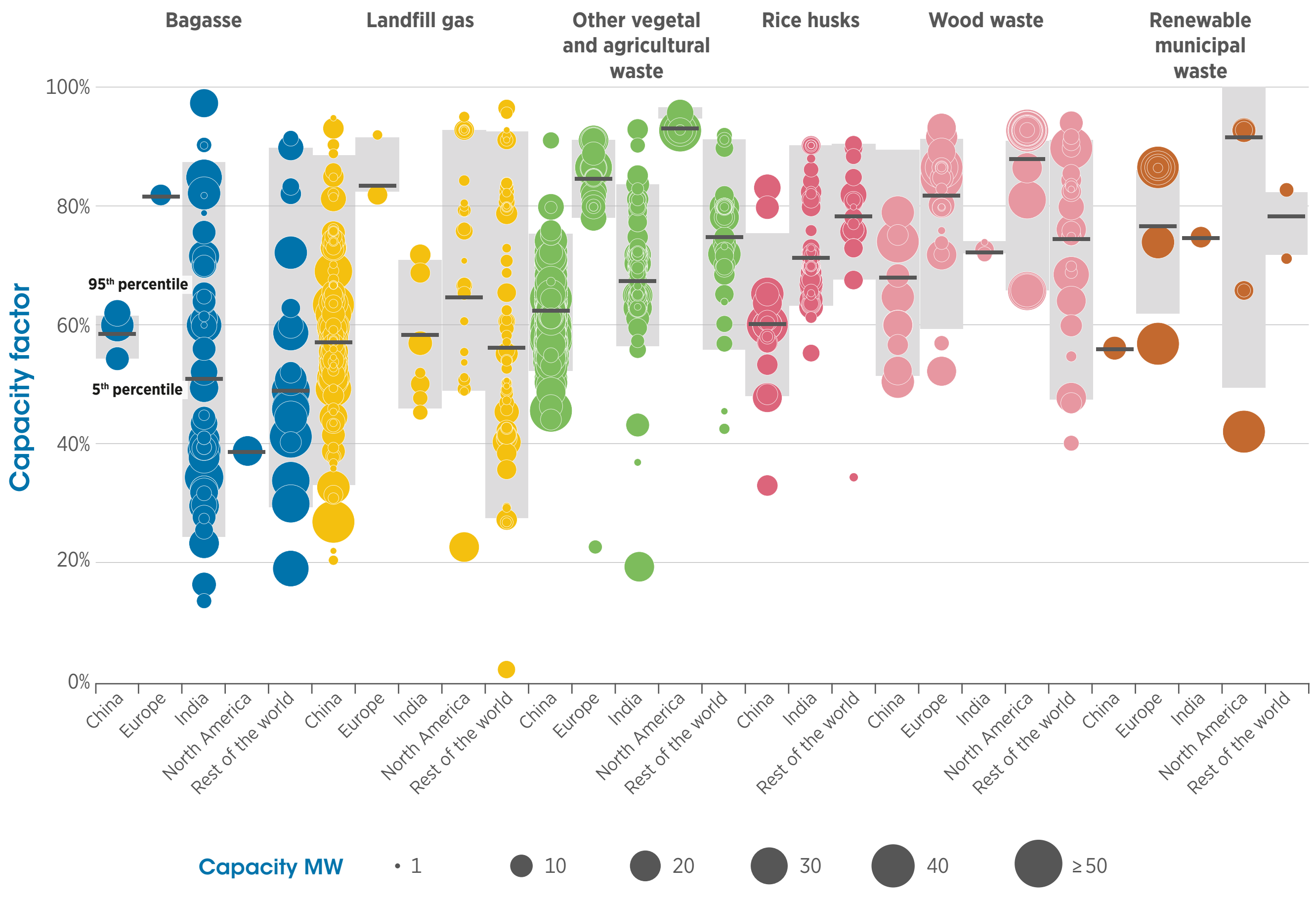
Economies of scale are evident across feedstocks for bioenergy power projects in China and India, but less evident elsewhere, given the smaller data samples available.

Figure 7.4 Project capacity factors and weighted averages of bioenergy-fired power generation projects by feedstock and country/region, 2000–2018



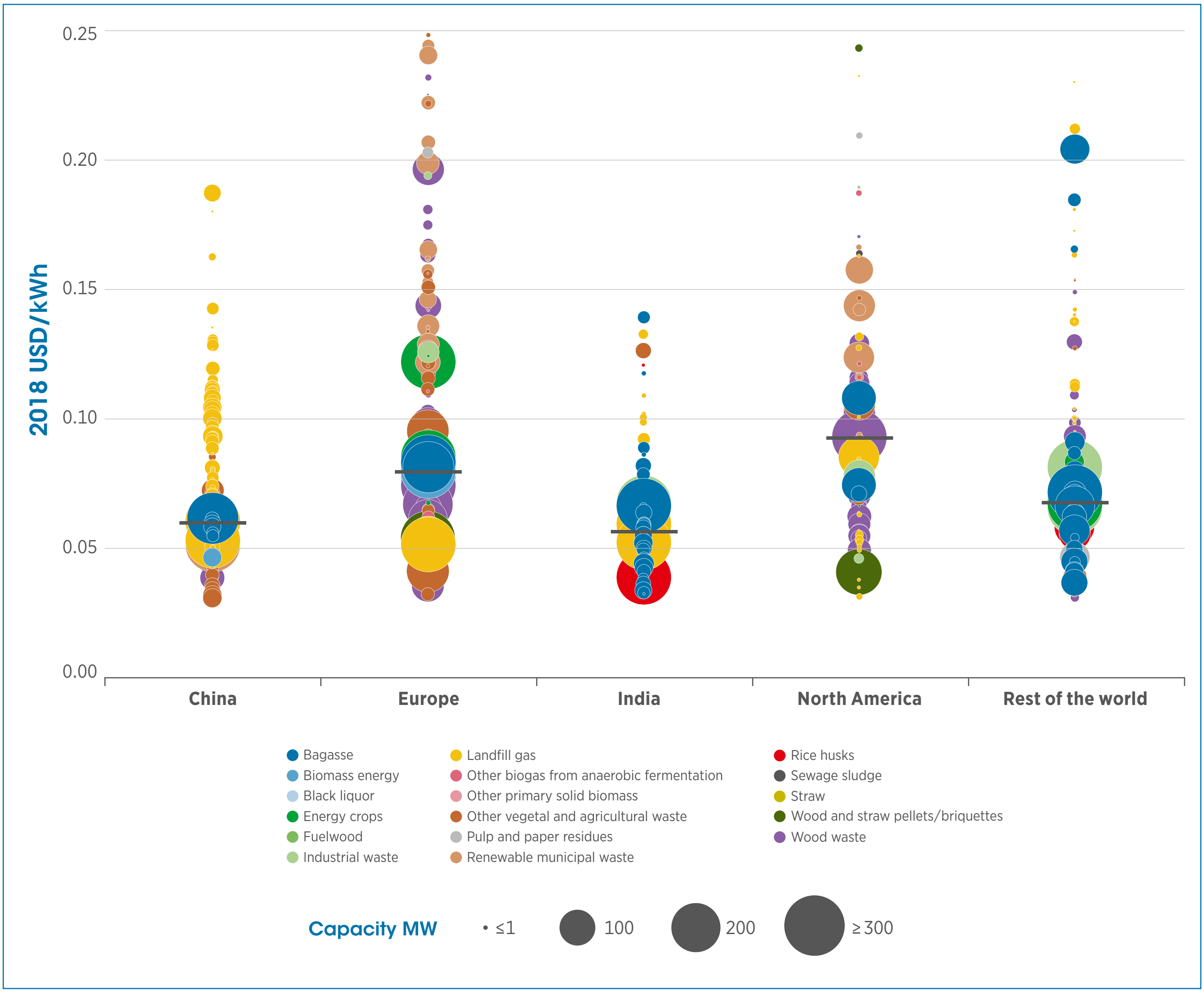
Country and regional weighted-average capacity factors range from 63% in China to 83% in North America. Capacity factors tend to be higher for larger projects.

Figure 7.5 Project capacity factors and weighted averages of selected feedstocks for bioenergy-fired power generation projects by country and region, 2000–2018



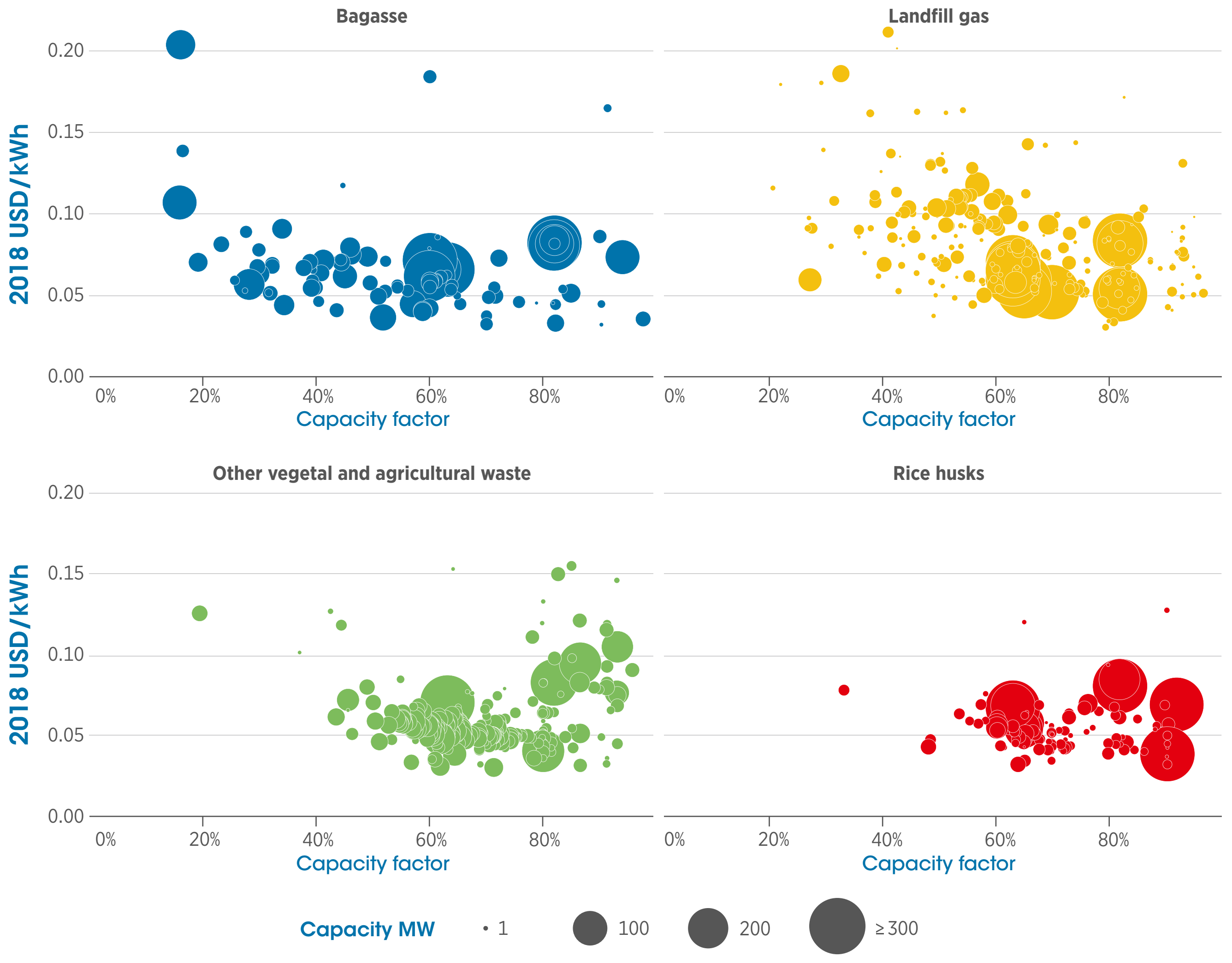
Capacity factors for individual projects typically span the 25–90% range, with weighted averages by technology and region ranging from 39% to 93%. Capacity factors for bagasse are lower than for other feedstocks, reflecting the seasonal availability of feedstock supplies.

Figure 7.6 LCOE by project and weighted averages of bioenergy-fired power generation projects by feedstock and country/region, 2000–2018



China and India have the lowest average LCOEs at around USD 0.06/kWh. LCOEs are higher in Europe and North America, at around USD 0.08/kWh and USD 0.09/kWh, respectively, due to higher shares of plants combusting renewable municipal waste. Ranges are wide across all regions, reflecting the diversity of installed costs, feedstock availability and technologies employed.

Figure 7.7 LCOE and capacity factor by project and weighted averages of selected feedstock for bioenergy-fired power generation projects by country/region, 2000–2018



Bagasse plant LCOEs typically fall between USD 0.03/kWh and USD 0.08/kWh, with capacity factors ranging from 40% to 90%. LCOEs for landfill gas projects have lower LCOEs at higher capacity factors, while some larger projects utilising "other vegetal and agricultural waste" (with higher feedstock costs) tend to have higher LCOEs. Bioenergy projects using rice husks as feedstocks tend to have LCOEs between USD 0.03 and USD 0.07/kWh, for capacity factors between 50% and 90%.

REFERENCES

BNEF, (2018a), 2H 2018 Wind Turbine Price Index, Bloomberg New Energy Finance, London.

BNEF, (2018b), 2H 2018 Wind O&M Price Index, Bloomberg New Energy Finance, London.

BNEF, (2018c), *China's new offshore wind market: State of the market and auction forecast*, Bloomberg New Energy Finance, London.

Bolinger, M., S. Weaver, and J. Zuboy (2015), "Is $50/MWh solar for real? Falling project prices and rising capacity factors drive utility-scale PV toward economic competitiveness," *Progress in Photovoltaics: Research and Applications*, Vol. 23, No. 12, pp. 1847–1856, http://dx.doi.org/10.1002/pip.2630.

CanWEA (2016), Canadian Wind Farm Database, Canadian Wind Energy Association.

Carbon Tracker (2018), *Powering down coal: Navigating the economic and financial risks in the last years of coal power*, Carbon Tracker, London.

Danish Energy Agency (2019), Data on operating and decommissioned wind turbines, Danish Energy Agency, Copenhagen.

deea (2016), *Report on Solar PV Balance of System Cost Reduction Potential to 2025*, deea Solutions, Frankfurt am Main.

Department for Business, Energy & Industrial Strategy (BEIS) (2019), *Energy Trends March 2019*, BEIS, London.

Fu, R. et al. (2015), Economic Competitiveness of US Utility-Scale Photovoltaics Systems in 2015: Regional Cost Modeling of Installed Cost ($/W) and LCOE. ($/kWh), Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd, New Orleans.

GlobalData (2018a), "Wind Power Sector", Generation and Markets Database, GlobalData, London.

GlobalData (2018b), "Solar Power Sector", Generation and Markets Database, GlobalData, London.

IEA Wind (2011), *Task 26: Multinational case study of financial cost of wind energy, work package 1, final report*, IEA Wind Energy Systems.

IEA Wind (2015), *Task 26: Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the United States: 2007–2012*, IEA Wind Energy Systems.

IEA Wind (2019), Onshore Wind Data Viewer, IEA Wind Energy Systems, https://community.ieawind.org/task26/dataviewer.

IRENA (2016a), *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2016b), *Solar PV in Africa: Costs and Markets*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2017), *Renewable Energy Auctions: Analysing 2016*, IRENA, Abu Dhabi.

IRENA (2018), *Renewable Power Generation Costs in 2017*, IRENA, Abu Dhabi.

IRENA (2019a), *Renewable Capacity Statistics 2019*, IRENA, Abu Dhabi.

IRENA (2019b), *Global Energy Transformation: A Roadmap to 2050*, IRENA, Abu Dhabi.

IRENA (2019c), *Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables*, IRENA, Abu Dhabi.

Make Consulting, (2016), *European Offshore Wind Power O&M*, Make Consulting, Aarhus.

STA (2014), *Cost Reduction Potential of Large Scale Solar PV*, Solar Trade Association, London.

Photon Consulting (2018), Data from Photon Consulting's Demand subscription, Photon Consulting.

pvXchange (2018), PV module price index (PV marketplace), https://www.pvxchange.com/en/news/price-index.

Stehly, Tyler J. et al. (2018), *2017 Cost of Wind Energy Review*, National Renewable Energy Lab., United States.

Vestas Wind Systems A/S (2005–2017), Annual Financial Reports, Copenhagen.

Wiser, R.H. and M. Bollinger (2018), *2017 Wind Technologies Market Report*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Wood Mackenzie, Global wind power project installation database: Q1 2019, Wood Mackenzie.

ANNEX I: COST METRIC METHODOLOGY

Cost can be measured in different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (*e.g.*, photovoltaic [PV] modules or wind turbines), financing costs, total installed costs, fixed and variable operating and maintenance costs (O&M), fuel costs (if any) and the levelised cost of electricity (LCOE).

The analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used here is a simplified one that focusses on the core cost metrics for which good data is readily available. This allows greater scrutiny of the underlying data and assumptions, improves transparency and confidence in the analysis, and facilitates the comparison of costs by country or region for the same technologies, in order to identify the key drivers in any cost differences.

The five key indicators that have been selected are:

- equipment cost (factory gate, free onboard [FOB], or delivered at site)
- total installed project cost, including fixed financing costs
- capacity factor by project
- the LCOE.

The analysis in this paper focuses on estimating the costs of renewables from the perspective of private investors, whether they are a state-owned electricity generation utility, an independent power producer or a community looking to invest in renewables. The analysis excludes the impact of government incentives or subsidies, system balancing costs associated with variable renewables and any system-wide cost-savings from the merit order effect. Furthermore, the analysis does not take into account any CO_2 pricing, nor the benefits of renewables in reducing other externalities (*e.g.*, reduced local air pollution or contamination of the natural environment). Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. These issues are important, but are covered by other programmes of work at IRENA.

Clear definitions of the technology categories are provided, where this is relevant, to ensure that cost comparisons are robust and provide useful insights (*e.g.*, small hydropower *vs.* large hydropower). Similarly, functionality has to be distinguished from other qualities of the renewable power generation technologies being investigated (*e.g.*, concentrating solar power [CSP] with and without thermal energy storage). This is important to ensure that system boundaries for costs are clearly set and that the available data are directly comparable. Other issues can also be important, such as cost allocation rules for combined heat and power plants, and grid connection costs.

The data used for the comparisons in this paper comes from a variety of sources, such as IRENA Renewable Costing Alliance members, business journals, industry associations, consultancies, governments, auctions and tenders. Every effort has been made to ensure that this data is directly comparable and is for the same system boundaries. Where this is not the case, the data has been corrected to a common basis using the best available data or assumptions. This data has been compiled into a single repository – The IRENA Renewable Cost Database – that includes a mix of confidential and public domain data.

An important point is that, although this report examines costs, strictly speaking, the data points available are actually prices, and are sometimes not even true market average prices, but price indicators (*e.g.*, surveyed estimates of average module selling prices in different markets). The difference between costs and prices is determined by the amount above, or below, the normal profit that would be seen in a competitive market.

The rapid growth of renewables markets from a small base means that the market for renewable power generation technologies is sometimes not well-balanced. As a result, prices can rise above costs in the short term if supply is not expanding as fast as demand, while in times of excess supply, losses can occur and prices may be below production costs. This can make analysing the cost of renewable power generation technologies challenging for some technologies in given markets at certain times. Care should therefore be taken in interpreting the data in this report.

Although every effort is made to identify the reasons why costs differ between markets for individual technologies, the absence of the detailed data required for this type of analysis often precludes a definitive answer. IRENA conducted a number of analyses focusing on individual technologies and markets in an effort to fill this gap (IRENA, 2016a & b).

The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology.

The approach used in the analysis presented here is based on a discounted cash flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. Given the capital-intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC) used to evaluate the project – often also referred to as the discount rate – has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. This has the additional advantage, however, that the analysis is transparent and easy to understand. In addition, more detailed LCOE analyses result in a significantly higher overhead in terms of the granularity of assumptions required. This can give the impression of greater accuracy, but when the model cannot be robustly populated with assumptions, and if assumptions are not differentiated based on real-world data, then the supposed accuracy of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation
I_t = investment expenditures in the year ***t***
M_t = operations and maintenance expenditures in the year ***t***
F_t = fuel expenditures in the year ***t***
E_t = electricity generation in the year ***t***
r = discount rate
n = economic life of the system.

All costs presented in this report are real, 2018 USD; that is to say, after inflation has been taken into account, unless otherwise stated. The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yield a lower return on capital, or even a loss.

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used first order measure by which power generation technologies can be compared. More detailed DCF approaches – taking into account taxation, subsidies and other incentives – are used by renewable energy project developers to assess the profitability of real world projects, but are beyond the scope of this report.

The calculation of LCOE values in this report is based on project-specific total installed costs and capacity factors, as well as the O&M costs – as detailed in the subsequent section. The standardised assumptions used for calculating the LCOE include the WACC, economic life and cost of bioenergy feedstocks.

The analysis in this report assumes a WACC for a project of 7.5% (real) in Organisation for Economic Co-operation and Development (OECD) countries and China, where borrowing costs are relatively low and stable regulatory and economic policies tend to reduce the perceived risk of renewable energy projects. A WACC of 10% is assumed for the rest of the world. These assumptions are average values, but the reality is that the cost of debt and the required return on equity, as well as the ratio of debt-to-equity, varies between individual projects and countries, depending on a wide range of factors. This can have a significant impact on the average cost of capital and the LCOE of renewable power projects. It also highlights an important policy issue: in an era of low equipment costs for renewables, ensuring that policy and regulatory settings minimise perceived risks for renewable power generation projects can be a very efficient way to reduce the LCOE, by lowering the WACC.

Table 2 Standardised assumptions for LCOE calculations

TECHNOLOGY	ECONOMIC LIFE (YEARS)	WEIGHTED AVERAGE COST OF CAPITAL (REAL)	
		OECD AND CHINA	REST OF THE WORLD
WIND POWER	25	7.5%	10%
SOLAR PV	25		
CSP	25		
HYDROPOWER	30		
BIOMASS FOR POWER	20		
GEOTHERMAL	25		

O&M COSTS

Solar PV

O&M costs for utility-scale plants in the United States have been reported to be between USD 10/kW per year to USD 19/kW per year (Bollinger, Weaver and Zuboy, 2015; and Fu, et al. 2015). O&M costs in OECD markets account for 20–25% of the LCOE (STA, 2014 and deea, 2016).

CSP

The IRENA CSP cost analysis assumes an insurance-included average O&M cost range of USD 0.02/kWh to USD 0.03/kWh for parabolic trough collector plants (PTC) and USD 0.03/kWh to USD 0.04/kWh for solar towers (ST) (IRENA, 2016a).

Onshore wind

Based on the annual range of O&M onshore wind costs in China, India and the rest of the world for the 448-project subset with O&M data in the IRENA Renewable Cost Database, the largest share of O&M costs is represented by maintenance operations, which have a weighted average of 67%, followed by salaries at 14% and materials at 7% (IRENA, 2018). In China, costs range from USD 0.008/kWh to USD 0.029/kWh. In India, weighted average O&M costs range from USD 0.005/kWh to USD 0.028/kWh. The weighted average O&M cost in the database for Central and South America is USD 0.015/kWh.

Table 3 presents data for O&M costs reported for a range of OECD countries. In these, O&M data is not consistently reported, making comparisons difficult. Averages of USD 0.02/kWh to USD 0.03/kWh appear to be the norm, with certain exceptions (IRENA, 2018).

Table 3 O&M costs of onshore wind in selected OECD countries

COUNTRY	VARIABLE (2018 USD/KWH)	FIXED (2018 USD/KW/YEAR)
Germany	0.03	69
Denmark	0.02	
Ireland	0.00	77
Norway	0.03	
United States		55
Austria	0.04	
Finland		43
Italy		52
Japan		79
The Netherlands	0.01	
Spain	0.03	
Sweden	0.03	
Switzerland	0.05	

Source: Based on IEA Wind, 2011 and IEA Wind, 2015

Offshore wind

O&M costs for offshore wind farms are higher than those for onshore wind. This is mainly due to the higher costs of access to the site and to the need to perform maintenance on towers and cabling. The marine environment is harder than dry land to operate within, adding to the overall O&M costs. These are estimated to be between USD 0.02/kWh to USD 0.05/kWh. The lower range is seen with projects in China and established European markets with sites closer to shore, while the latter, higher-cost range is seen for less established offshore wind markets or markets with harsher metocean conditions, like Japan (Stehly, et al., 2018; BNEF, 2018c; Make Consulting, 2016).

Hydropower

IRENA collected cost breakdown data for 25 projects which confirmed the average O&M cost was slightly less than 2% of total installed costs per year, with a variation of between 1% and 3% of total installed costs per year (IRENA, 2018). Larger projects have O&M costs below the 2% average, while smaller projects approach 3%, or are higher than the average O&M costs.

Bioenergy

Fixed operations and maintenance (O&M) costs for bioenergy power plants typically range from 2% to 6% of total installed costs per year, while variable O&M costs are typically relatively low, at around USD 0.005/KWh. Fixed O&M costs include labour, scheduled maintenance, routine component/equipment replacement (for boilers, gasifiers, feedstock handling equipment, etc.), insurance, etc. The fixed O&M costs of larger plants are lower per kW due to economies of scale, especially for labour.

Variable O&M costs are determined by the output of the system and are usually expressed as USD/kWh. Non-biomass fuel costs, such as ash disposal, unplanned maintenance, equipment replacement and incremental serving costs are the main components of variable O&M costs. Unfortunately, the available data often merges fixed and variable O&M costs into one number, thus rendering impossible a breakdown between fixed and variable O&M costs.

Table 4 provides data for the fixed and variable O&M costs for selected bioenergy for power technologies.

Table 4 Fixed and variable O&M costs for bioenergy power

COUNTRY	FIXED O&M (% OF CAPEX/YEAR)	VARIABLE O&M (2018 USD/MWH)
STOKER/BFB/CFB BOILERS	3.2	4.25–5.24
GASIFIER	3–6	4.25
ANAEROBIC DIGESTER	2.1–3.2	4.68
	2.3–7	
LANDFILL GAS	11–20	n.a

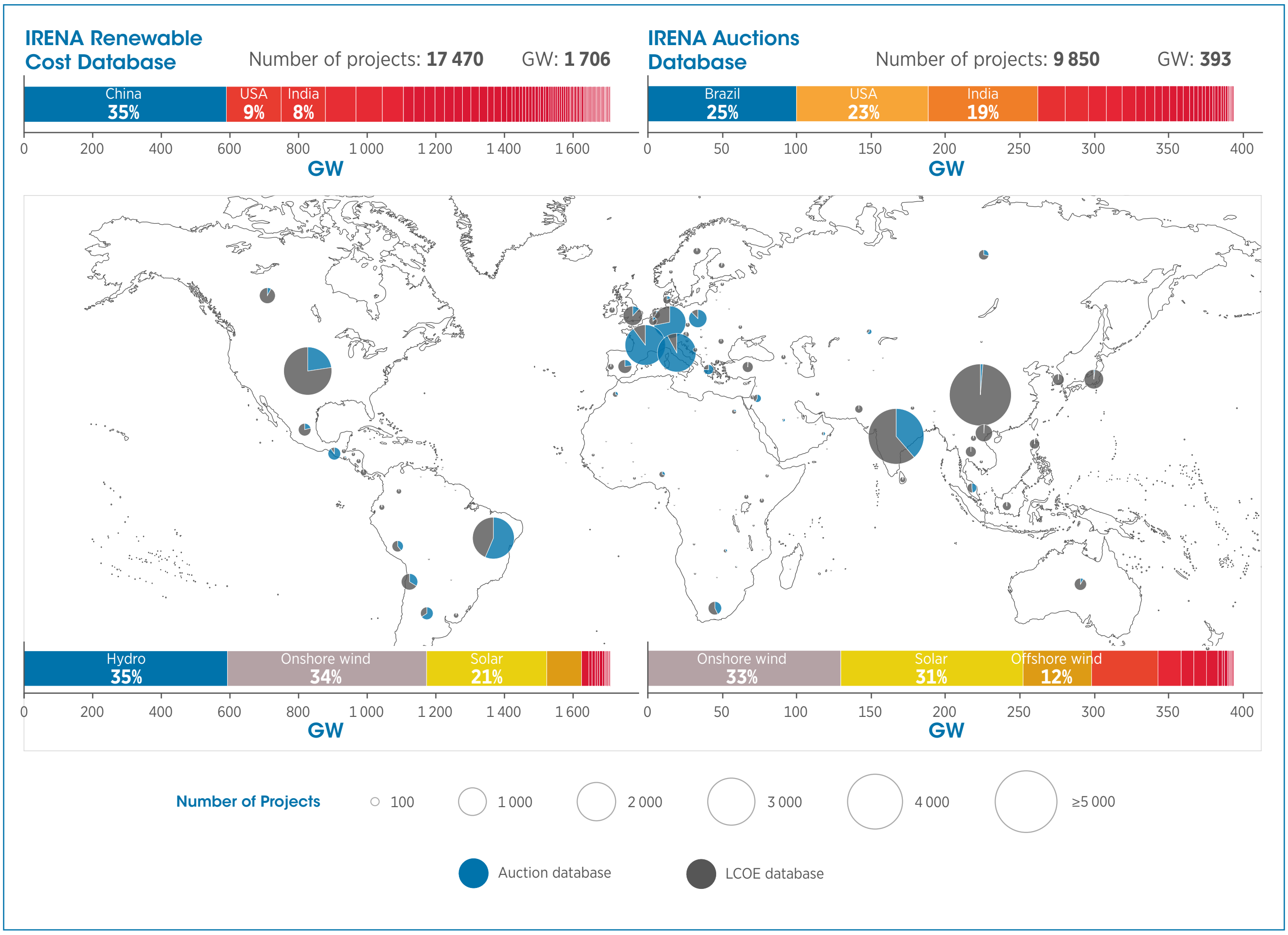
Geothermal

An O&M cost of USD 115/kW/year is assumed for geothermal power generation projects, based on project data. O&M costs are high for geothermal projects, because of the need to work over production wells on a periodic basis to maintain fluid flow and hence production.

ANNEX II: THE IRENA RENEWABLE COST DATABASE

The composition of the IRENA Renewable Cost Database largely reflects the deployment of renewable energy technologies over the last ten to fifteen years. Most projects in the database are in China (590 GW), the United States (159 GW), India (132 GW), and Germany (88 GW). Collecting cost data from OECD countries, however, is significantly more difficult due to greater sensitivities around confidentiality issues. The exception is the United States, where the nature of support policies leads to greater quantities of project data being available.

Figure A.1 Distribution of projects by technology and country in the IRENA Renewable Cost Database and Auctions Database



Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

After these four major countries, Brazil is represented by 77 GW of projects, the United Kingdom by 61 GW, Canada by 32 GW, Japan and Italy are represented by 31 GW of projects, Spain by 28 GW, Viet nam by 27 GW and Australia by 25 GW of projects.

With data for a small number of very large hydropower projects and the more extensive time series available, hydropower is the largest single technology represented in the IRENA Renewable Cost Database. The database has cost data for 593 GW of projects since 1961, with around 90% of those projects commissioned in the year 2000 or later. The next largest technology represented in the database is onshore wind, with cost data for 579 GW of projects, worldwide. Cost data is available for 352 GW of solar PV projects, 101 GW of commissioned and proposed offshore wind projects, 64 GW of biomass for power projects, 8.7 GW of geothermal projects and 7.6 GW of CSP projects.

The coverage of the IRENA Renewable Cost Database is more or less complete for offshore wind and CSP, where the relatively small number of projects can be more easily tracked. The database for onshore wind and hydropower is representative from around 2007, with comprehensive data from around 2009 onwards. Gaps in technology-specific data in some years, for some countries that are in the top ten for deployment in a given year require recourse to secondary sources, in order to develop statistically representative averages. Data for solar PV at the utility-scale has only become available more recently and the database is representative from around 2011 onwards, and comprehensive from around 2013 onwards.

ANNEX III: REGIONAL GROUPINGS

Asia: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, People's Republic of China, Democratic People's Republic of Korea, India, Indonesia, Japan, Kazakhstan, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Republic of Korea, Singapore, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Turkmenistan, Uzbekistan, Viet Nam.

Africa: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Eswatini, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe.

Central America and the Caribbean: Antigua and Barbuda, Bahamas, Barbados, Belize, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago.

Eurasia: Armenia, Azerbaijan, Georgia, Russian Federation, Turkey.

Europe: Albania, Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Kingdom of the Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland.

Middle East: Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Kingdom of Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen.

North America: Canada, Mexico, United States of America.

Oceania: Australia, Fiji, Kiribati, Marshall Islands, Micronesia (Federated States of), Nauru, New Zealand, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu.

South America: Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of).

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