IRENA

International Renewable Energy Agency

Renewable Technology Innovation Indicators: Mapping progress in costs, patents and standards

Acknowledments

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For further information or to provide feedback: info@irena.org

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The report was developed by IRENA's Innovation and Technology Centre (IITC), directed by Dolf Gielen.

The report was authored by Michael Taylor, Francisco Boshell, Paul Durrant, Martina Lyons, Pablo Ralon, Francesco Pasimeni, Alessandra Salgado, Sonia Al-Zoghoul, Elisa Asmelash, Remi Cerdan, Karan Kochhar, Mustafa Abunofal, Ufuk Sezer, Peter Chawah.

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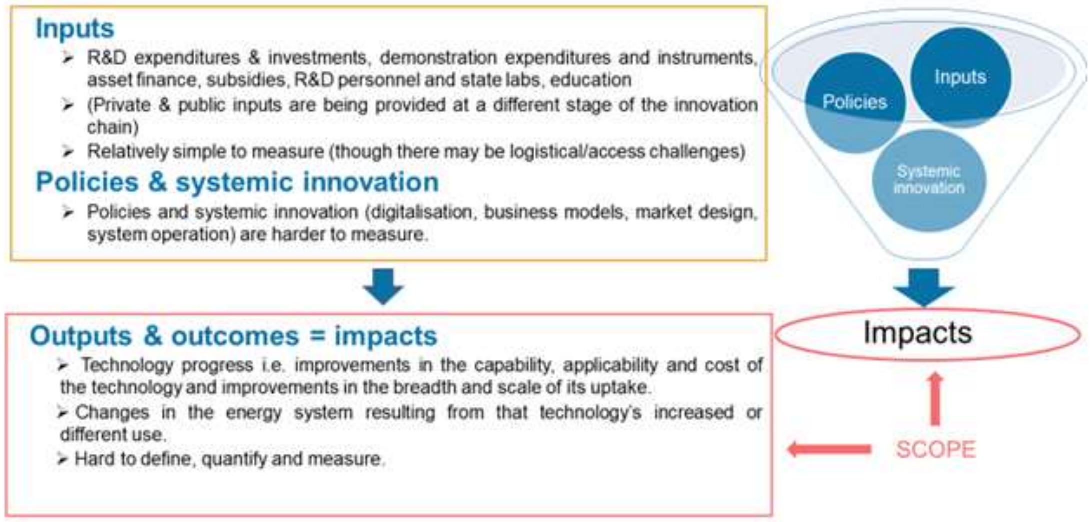
Introduction

Clean energy technology innovation – particularly research, development and demonstration (RD&D) – plays a critical role in accelerating the global energy transition. As this transition progresses and ambitions grow, the need for strong support for innovation therefore grows with it.

That innovation support comes from a combination of measures, including RD&D funding, public and private sector investments, market instruments and policies. Together, these guide and encourage innovation activities. In the Tracking Energy Innovation Impacts Framework (TEIIF) project, funded by the European Commission's Horizon 2020 programme, those support mechanisms are described as 'inputs' in the innovation process. The purpose of these inputs is to lead to outputs (*i.e.* new or improved technologies, processes and systems) and ultimately outcomes (*i.e.* positive changes in energy systems, such as reductions in CO_2 emissions). Given the sometimes complex interconnections between outputs and outcomes, TEIIF project groups them as 'impacts'.

To date, the principal focus has been on gathering data on inputs into the innovation process. There has been substantially less activity trying to define meaningful metrics to track the outputs and outcomes from clean energy technology innovation. Such metrics would allow for a more rigorous comparative analysis of the relative performance of innovation support for different technologies.



Innovation involves uncertainty and a time lag between generating and codifying knowledge and reducing costs and increasing deployment. Linking the impact of innovation inputs to the progress of clean energy technology innovation and understanding that impact can therefore be a challenging process. Yet, understanding those impacts is important in assessing past support mechanisms and informing decision making on future funding and support.

This TEIIF project approach does not address RD&D policies or inputs (*e.g.* RD&D funding), nor does it attempt to prove a causal link between progress made and RD&D inputs (*e.g.* RD&D funding) or policies.

IRENA Innovation & Technology Centre

PART I
Datasets and analysis on costs and performance of energy technologies

Key insights

- The dramatic decline of solar photovoltaics (PV) costs in the last decade have been driven down significantly by technology innovation, which has also helped to enhance the performance of products. After a decline of 85% in the levelised cost of electricity between 2010 and 2020, the technology continues to adapt into new markets with components and material usage push on towards optimisation route.

- Despite its modest deployment amongst commercial renewable energy technologies, the competitiveness of concentrating solar power (CSP) has improved consistently over the last decade. The LCOE of newly commissioned CSP plants fell by 68% between 2010 and 2020, as installed costs fell – in part due to increasing economies of scale at the plant level – O&M costs declined, and capacity factors increased. Targeting output in high costs periods irrespective of whether the sun in shining gives CSP with low-cost thermal energy storage the ability to integrate higher shares of variable renewables. This means CSP could play an increasingly important role in the future.

- Policy support for distributed, behind-the-meter (BTM) battery storage has played an important role in increasing the scale of main markets, though significant potential for growth remains. Lithium-ion (Li-ion) technologies have benefitted from significant investment in recent years due to their versatility.

- The increased research activity and a growing manufacturing landscape have meant that energy, power and safety characteristics of Li-ion BES have improved with time. They have become the dominant technology for behind-the-meter residential applications. Residential time series data for small-scale residential battery systems in the German market suggests that prices fell by 71%, between 2014 and 2020 to USD 776/kWh.

- With higher hub heights and larger swept areas there was an almost one-third increase in the global weighted-average capacity factor of onshore wind, from just over 27% in 2010 to 36% in 2020. Driven by the cost reductions from wind turbines and balance of plant costs, and the technology improvements that have seen capacity factors increase, the global weighted-average LCOE of onshore wind fell 56% between 2010 and 2020, from USD 0.089/kWh in 2010 to USD 0.039/kWh in 2020.

Key insights

- Offshore wind has experienced a decade of rapid growth and the arrival of competitive offshore wind projects. Average project sizes increased, as turbine sizes grew, and projects moved into deeper waters further from shore. With higher hub-heights and swept blade areas, offshore wind capacity factors have increased over time due to technology improvements in the turbine, wind farm layout and connections, and due to improved O&M practices that have reduced downtime in the windiest periods. Between 2010 and 2020, the global weighted-average LCOE of offshore wind fell 48%, from USD 0.162/kWh to USD 0.084/kWh.

- Electrolysers have been commercially deployed since the beginning of last century and several different types exist. However, the main commercial technologies are alkaline (AEL) and proton exchange membrane (PEM) electrolysers. The cost of AEL electrolysers declined from USD 1 210 to 1 970/kW between 2003 and 2005, to between USD 260 to USD 1 200/kW in 2020. The cost decline trend was 60% between 2005 and 2020. PEM electrolysers cost between USD 2 920 and 7 450/kW between 2003 and 2005, falling to between USD 400 to USD 2 494/kW in 2020.

- There is significant ongoing R&D activity, while a still relatively small number of companies exist that manufacture, perform system integration, and provide turnkey solutions for customers. This R&D effort and learning by doing, despite very low levels of deployment, have likely seen efficiency of AEL systems improve by at least 10%, with consumption dropping 50-78 kWh/kg H2 to 45-75 kWh/kg H2 between 2021 and 2020. The efficiency of PEM systems has likely not improved to the same extent but appears to have fallen to the 49-58 kWh/kg H2 range from 50-84 kWh/kg H2 in 2012.

- Europe has supported the development of solar heat for industrial process (SHIP) projects over the last decade, albeit in small numbers. The total installed cost of new European SHIP projects fell from a weighted average of USD 1 670/kW in 2010 to USD 541/kW in 2019. This more than two-thirds decline in installed costs, in the back of modest deployment, highlights not only the benefits of policy support, but the importance of also achieving plant-level economies of scale to help drive down costs in the early years of commercial deployment.

Solar photovoltaic

Key insights

- Solar photovoltaics (PV) offer one of the clearest pictures of how technology innovation can drive costs lower and improve the performance of a technology. The impact of economies of scale, learning-by-doing and process improvements in manufacturing, as well as at the project-level, do, however, obscure the overall picture.

- Solar module prices fell by up to 93% between 2010 and 2020, as the cumulative installed capacity of solar PV grew from 40 gigawatts (GW) to 710 GW.

- The typical, commercially deployed cell technology in 2020 consisted of mono-PERC 166 millimeter (mm) half-cut 'pseudo-square' cells placed in 72 cell modules with power ratings of 400 watts (W) to 550 W. This was up from 156 mm 'full square' multi-C-Si aluminium back surface field (Al-BSF) cells in 2010 in 72 cell modules, with module power ratings of 250 W to 300 W.

- Losses during the cutting of cell wafers using diamond wire sawing techniques have fallen 58% compared to 2010, while wafer thickness has also fallen. The end result, with the help of other manufacturing improvements, is that polysilicon usage per area of cell has fallen over the last decade.

- The use of relatively expensive silver in modules declined by over two-thirds between 2010 and 2020, as technology and manufacturing improvements designed to reduce costs were able to reduce silver needs for metallisation.

- Average module efficiencies grew from around 15% in 2010, when Al-BSF multicrystalline cell modules dominated, to around 20% in 2020, when mono-PERC cell architectures have dominated.

- Higher module efficiencies directly reduce module prices, as the same wattage can be achieved with a reduced area. They also project costs directly related to surface area, such as racking and mounting, cabling and installation. Higher efficiencies also reduce the land area required, which has fallen from an estimated 2.7 hectares/megawatt (MW) in 2010 to 1.9 hectares/MW in 2020.

- The global weighted-average total installed costs for newly commissioned utility-scale projects fell 81% between 2010 and 2020, from USD 4 731/kilowatt (kW) to USD 883/kW.

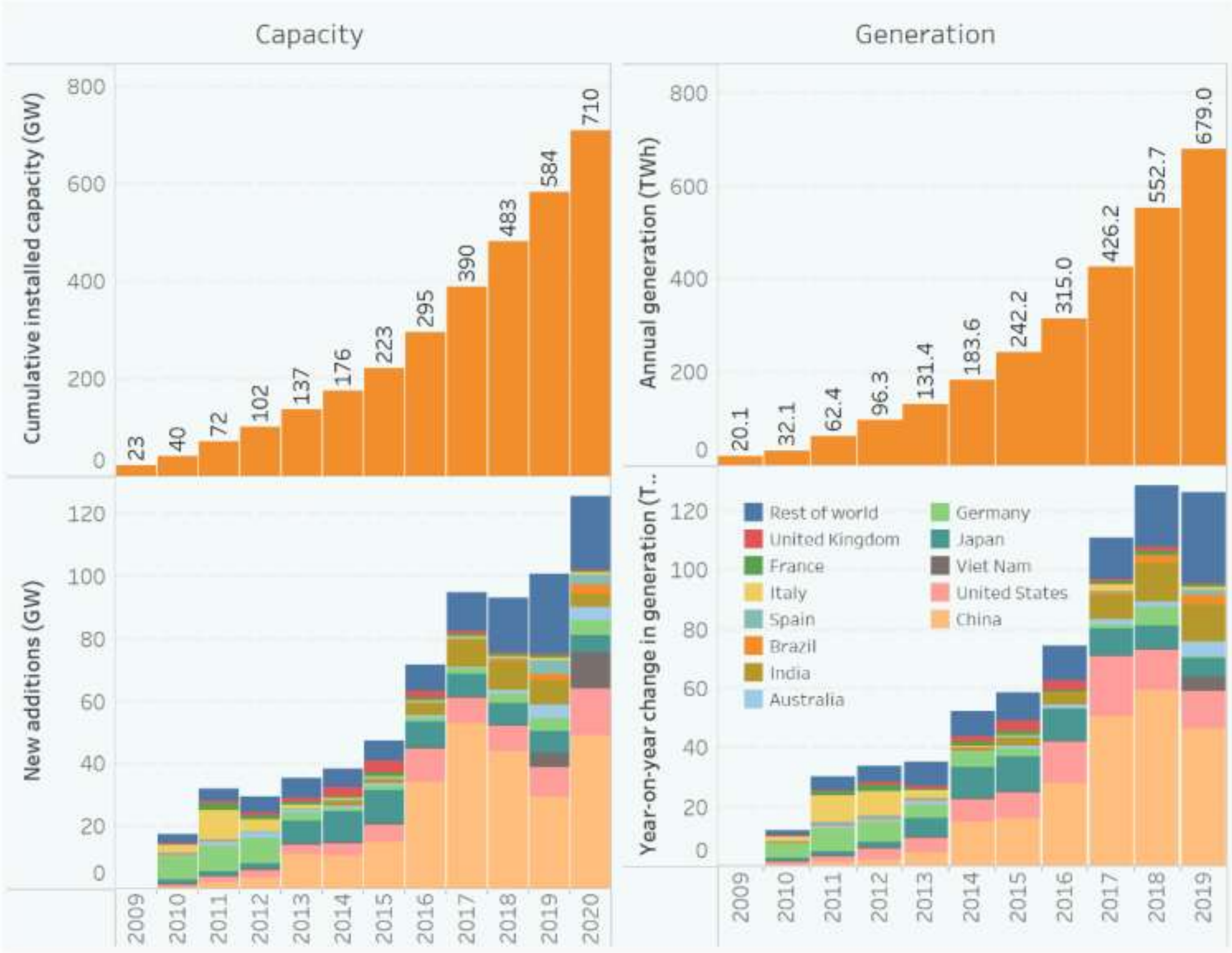
- With capacity factors changing, primarily based on location, the global weighted-average LCOE for utility-scale projects fell by 85% between 2010 and 2020.

Market development

New capacity additions in 2020, including off-grid systems, reached 126 GW in 2020. This was an increase of one-quarter over 2019, which was also a record year for such additions.

In 2020, new capacity additions in China rebounded, but remained below the record year of 2017. Strong additions occurred in the United States, and Viet Nam emerged as a new powerhouse in Asia and the world during 2018-2020. Japan added 5.5 GW, while Germany, Australia and India all added more than 4 GW each. Brazil added 3.3 GW, while Spain continued its recent resurgence, adding 2.8 GW.

Electricity generation statistics lag capacity data availability by a year, but generation in 2019 reached a record contribution of 679 terawatt hours (TWh) globally, a thirty-four-fold increase over the decade. In both 2018 and 2019 solar PV generation grew by just over 120 TWh per year.



Utility-scale solar PV from 2010 to 2020

-93% PV module prices

-81% Total installed costs

-85% Levelised cost of electricity

COSTS

PERFORMANCE

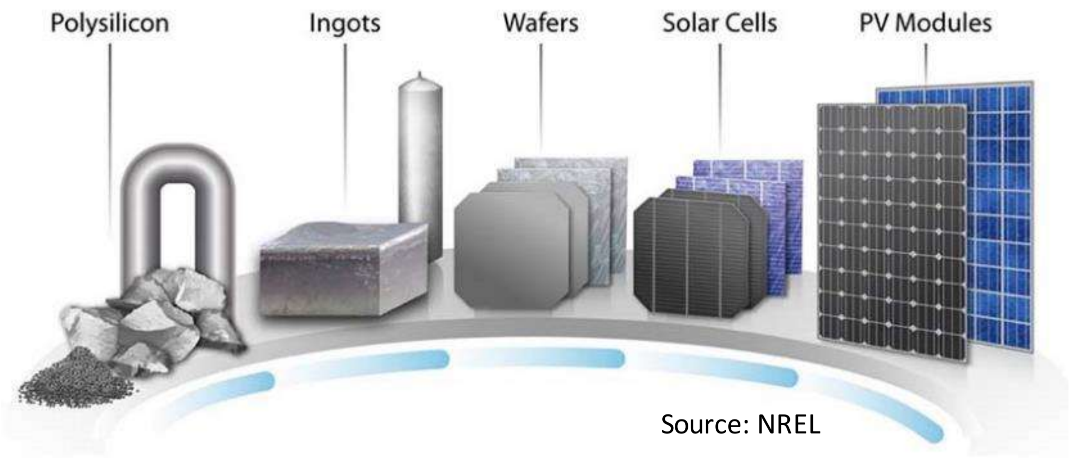
Module efficiency **+24%**

Module power (watts) **+55%**

Capacity factor **+17%**

Solar PV module cost reduction potential

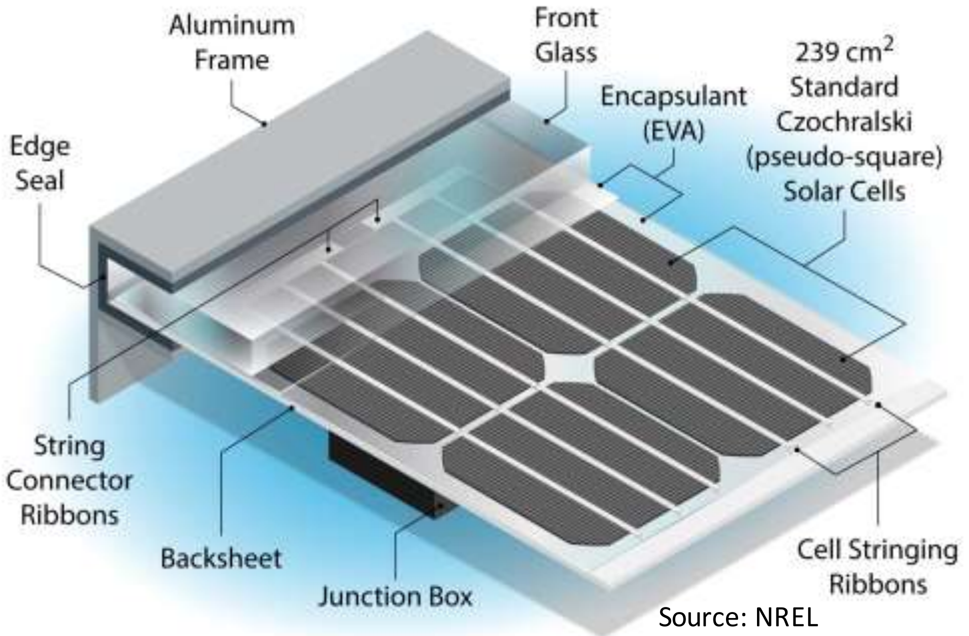
The solar photovoltaic value chain



Source: NREL

Solar photovoltaics (PV) are electronic devices that directly convert sunlight into electricity. A PV system consists of many PV cells grouped together in a weatherproof package to form a PV module. To deliver the electricity it produces, a PV system also needs auxiliary components (*i.e.* balance of system or 'BoS'), including the inverter, controls, etc. A wide range of PV cell technologies exists using different types of materials. During the 2010-2020 period, the market was dominated by wafer-based crystalline silicon (c-Si) technology, which accounted for 95% of production in 2020. C-Si modules can be either mono-crystalline or multi-crystalline, depending on the process used to manufacture the ingots, which result in materials that are different, but perform the same function.

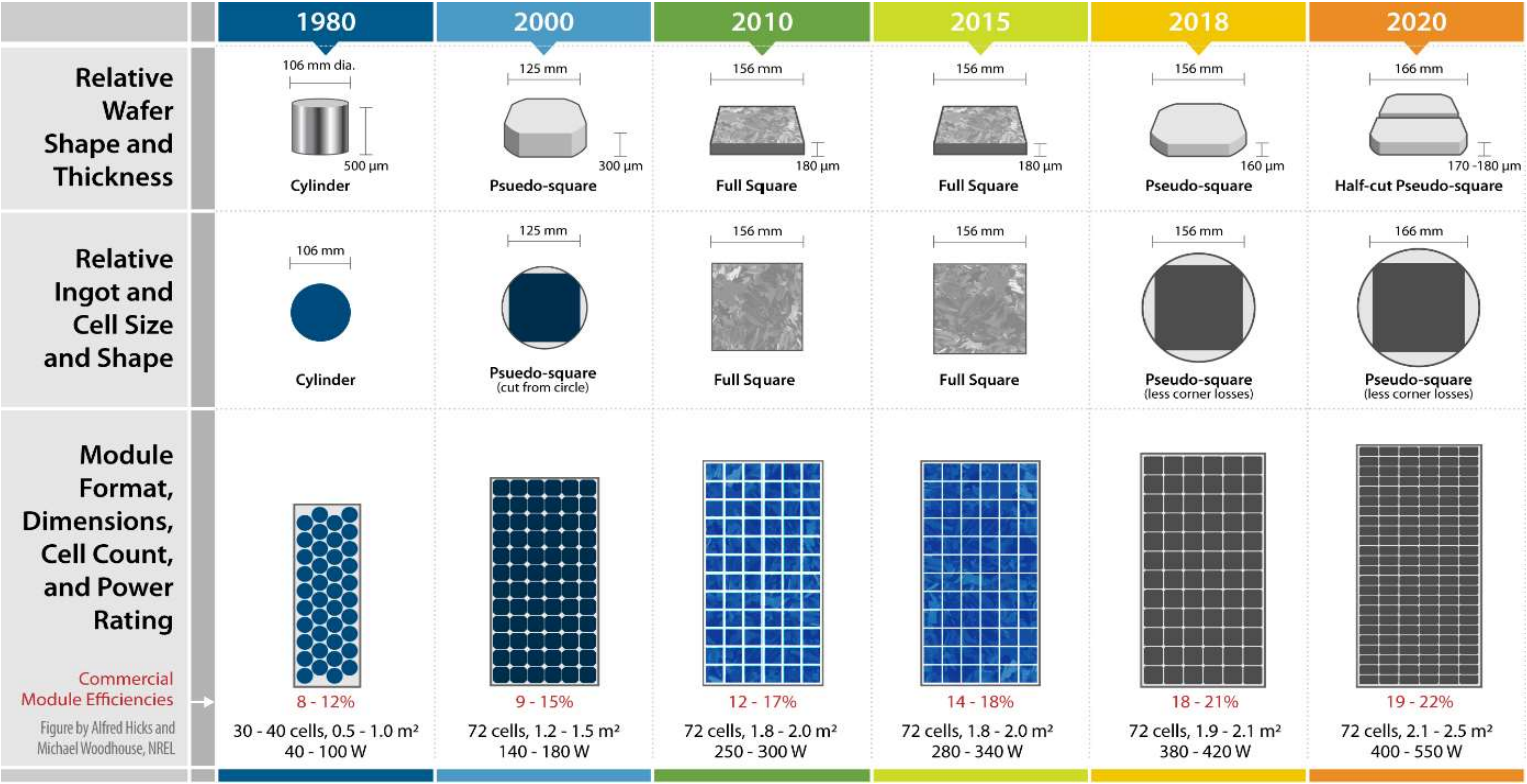
Silicon ingots are then sliced into wafers, that are used in the cell production step. Crystalline PV modules also typically contain the components shown in the diagram to encapsulate the cells.



Source: NREL

Apart from crystalline modules, PV systems based on thin-film PV technologies (and other materials) also exist in the market. These generally include three main families: 1) amorphous (a-Si) and micromorph silicon (a-Si/µc-Si); 2) Cadmium-Telluride (CdTe); and 3) Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS). Currently, the more prevalent of these is CdTe.

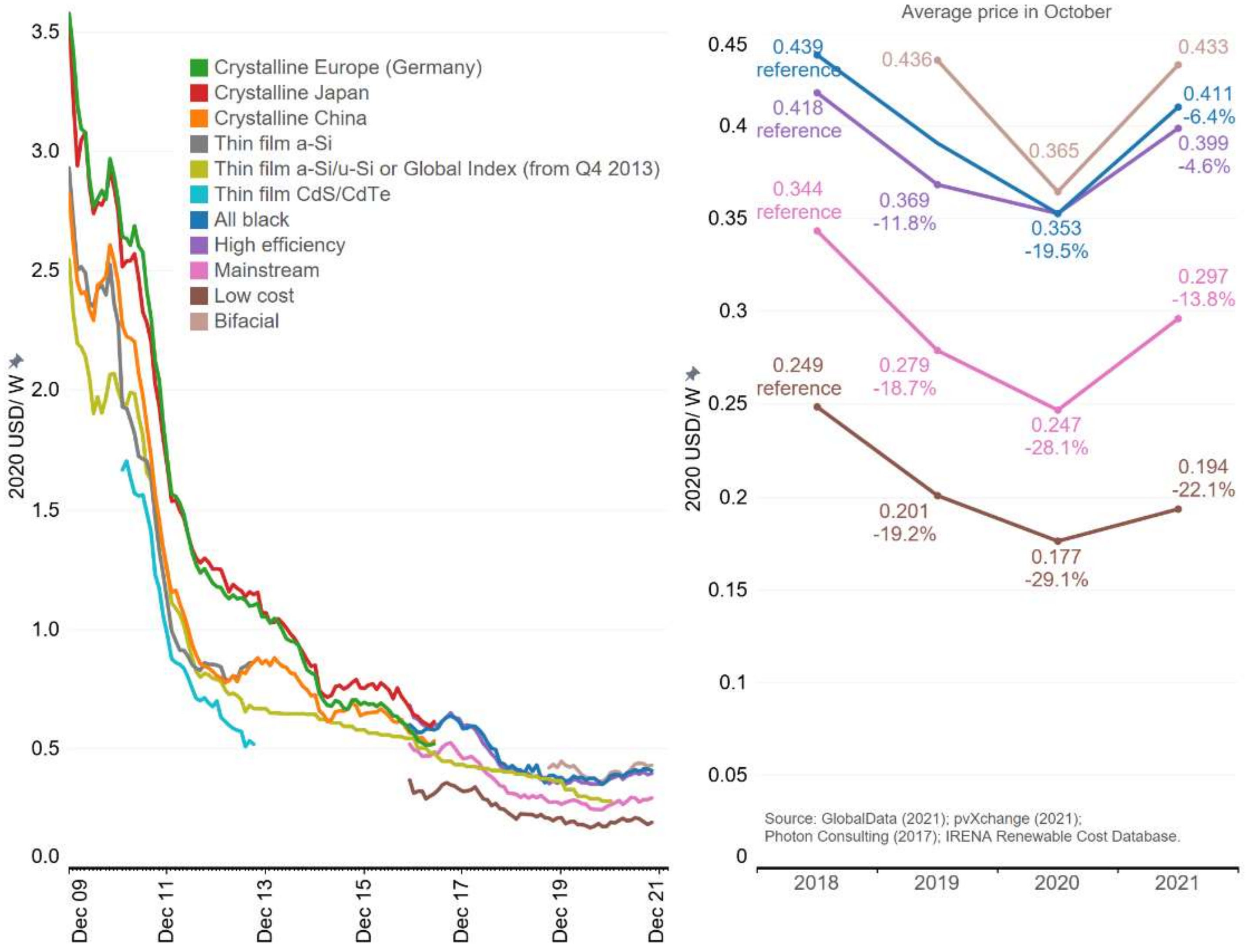
Changes to mainstream c-Si wafer, cell, and module technology over time



Source: Woodhouse, M, *et al.*, (2021) *Research and Development Priorities to Advance Solar Photovoltaic Lifecycle Costs and Performance*, NREL

Solar PV module price trends (2009 to 2021)

The decline of solar PV module costs has been an important driver of the technology's improved competitiveness. Between December 2009 and December 2020, crystalline silicon module spot prices declined between 89% and 95% for modules sold in Europe, depending on the type. Increased economies of scale in manufacturing, reduced labour costs, falling material prices and materials use efficiencies, as well as process optimisations, have unlocked module cost reductions. In addition to these manufacturing cost drivers, an important driver of lower module costs per Watt (and, indeed PV projects), has been the continuous increase in module efficiencies as a result of a shift to more efficient cell architectures – such as passivated emitter and rear cell (PERC) architectures becoming the state-of-the-art technology in modules. In 2021, the global solar PV module market has experienced supply chain disruptions, just like other sectors, leading to higher material costs or lower availability, pushing up prices.

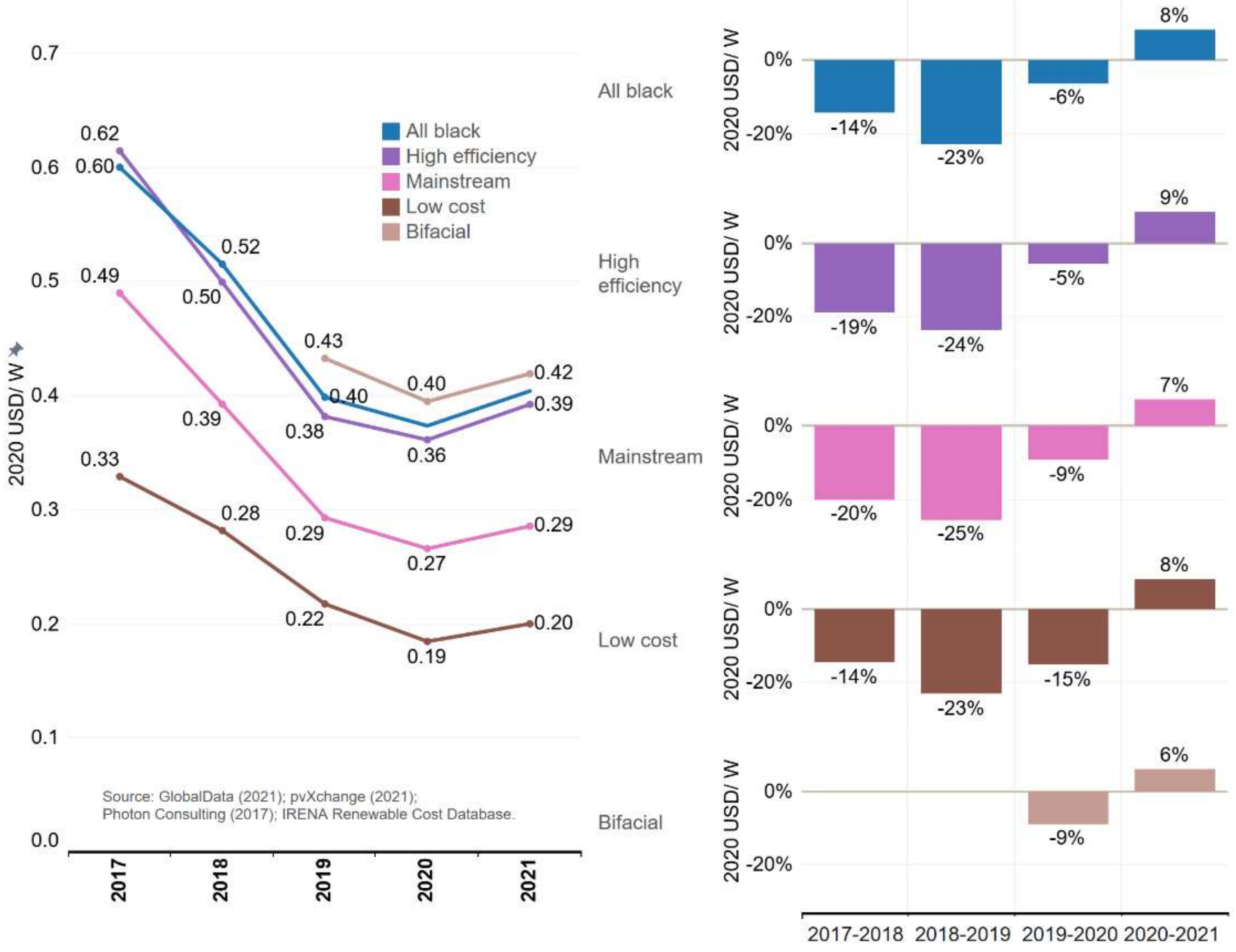


Solar PV module price trends (2017 to 2021)

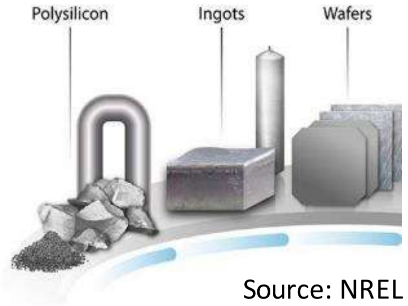
Considering yearly averages of the newer module technology categories, module costs declined from between USD 0.33/W and USD 0.62/W in 2017 to a narrower range of USD 0.19/W and USD 0.40/W in 2020 (a decline of between 35% and 42%).

The data shows that the year-on-year reduction was highest between 2018 and 2019 for all categories (declining between 23% and 25%). Data for bifacial modules became available only in 2019 and the category declined 9% between 2019 and 2020. Comparing 2020 with data for January to October 2021, yields a year-on-year percentage change of between 6% (for the bifacial category) and 9% (for the high efficiency modules category).

In the longer term, however, increasing efficiencies and further manufacturing optimisation and design innovation can be expected to more than offset this temporary cost increase, resulting in costs declining again.



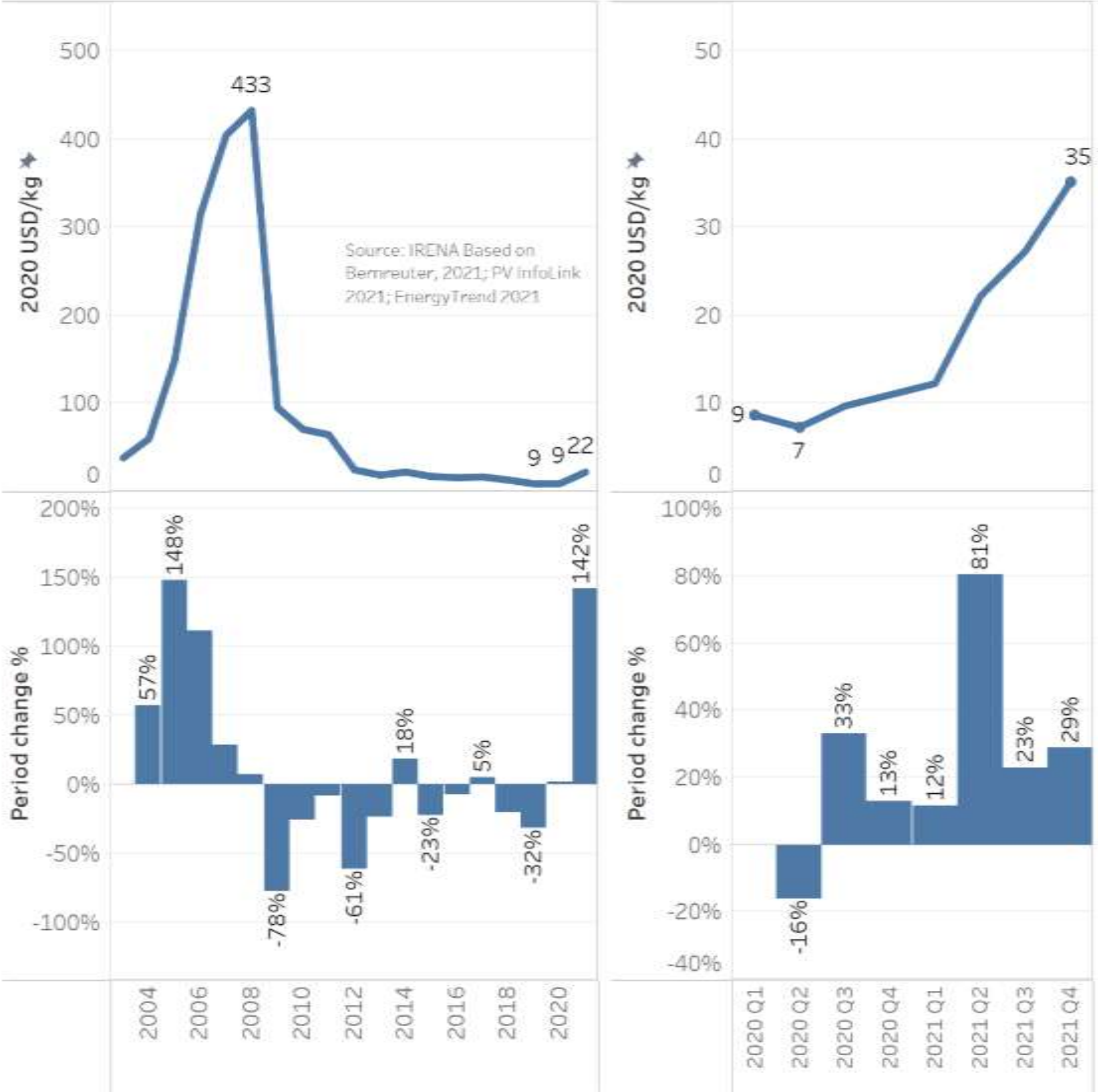
Polysilicon price trends (2003 to 2021)



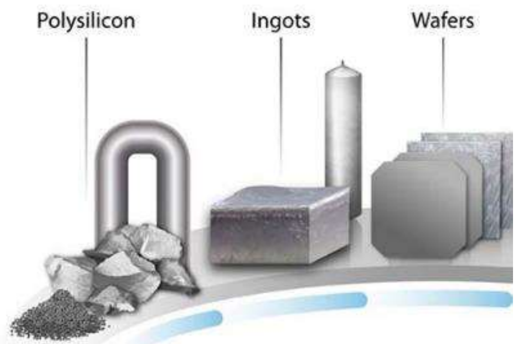
Source: NREL

Polysilicon prices today are dramatically lower than their peak in 2008. In percentage terms, the recent increase is on a par with the historic increase in 2005, but costs for 2021 are likely to average just 5% of their previous peak, after challenges in the supply chain this year that drove up polysilicon prices.

Theses challenges stem from recent factory shutdowns in China, which pushed polysilicon prices reach USD 35/kilogram (kg) in October 2021, as cell manufacturers raced to secure supplies, bidding up prices. Cost inputs, such as electricity and other energy prices have also played a role, with these factors, alongside pandemic-related logistic and shipping difficulties, driving the previously discussed uptick in module costs during the first part of 2021. Recent manufacturing capacity expansions and further technology improvements in manufacturing are, however, likely to drive polysilicon prices lower in 2022 – although exactly when prices will start to fall is still unclear.



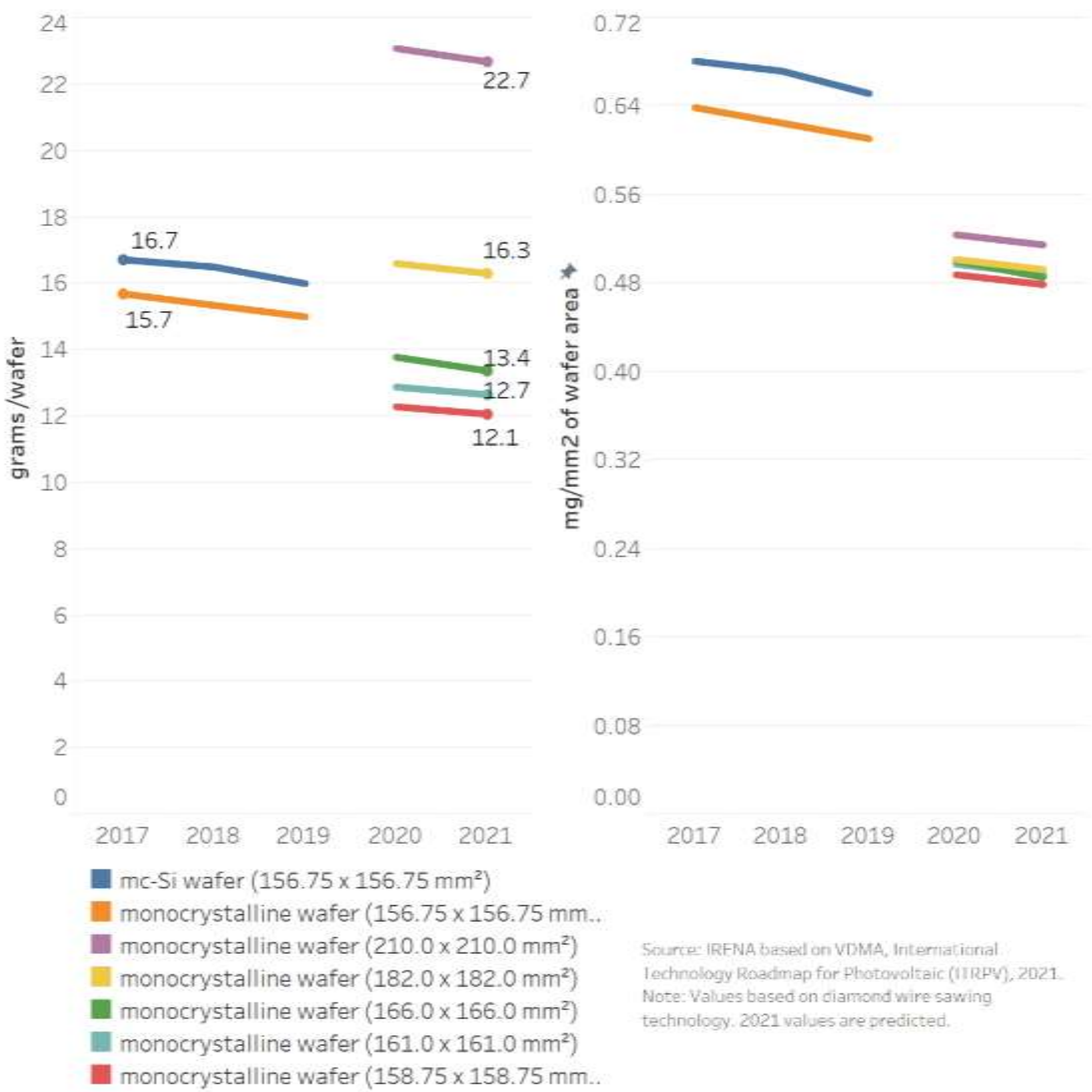
Polysilicon usage in wafers (2017 to 2021)



Source: NREL

Improved wafer sawing technologies, notably diamond wire sawing (DWS), have taken over from earlier slurry-based wafer sawing, contributing to reduced polysilicon use in the wafering step. The amount of polysilicon lost during cutting of the wafers (kerf loss) has also declined.

During 2020, kerf loss values of 65 micrograms (µg) were already typical (a decline of more than 58% from 2010). Wafer thickness is another important way to reduce polysilicon consumption. Reducing this at the speed the industry had hoped mid-decade has, however, proven challenging and polysilicon usage reduction has been predominantly linked to improved wafer slicing processes. In the past, the industry favoured cheaper thicker wafers over thinner wafers to reduce production line breakage and overall costs. Using thinner wafers to further decrease costs is becoming more important in the current market situation, however. After stagnating for a long time at 180 µm, recent progress has been made in the in the as-cut wafer thickness of crystalline silicon wafers. During 2020, for M6 (166 mm² x 166 mm²) wafers, as-cut thickness declined to 175 µm for p-type wafers (currently over 90% of the market) and 160 µm for n-type wafers. A thickness of 170 µm for p-type wafers is expected for 2021 (ITRPV, 2021).



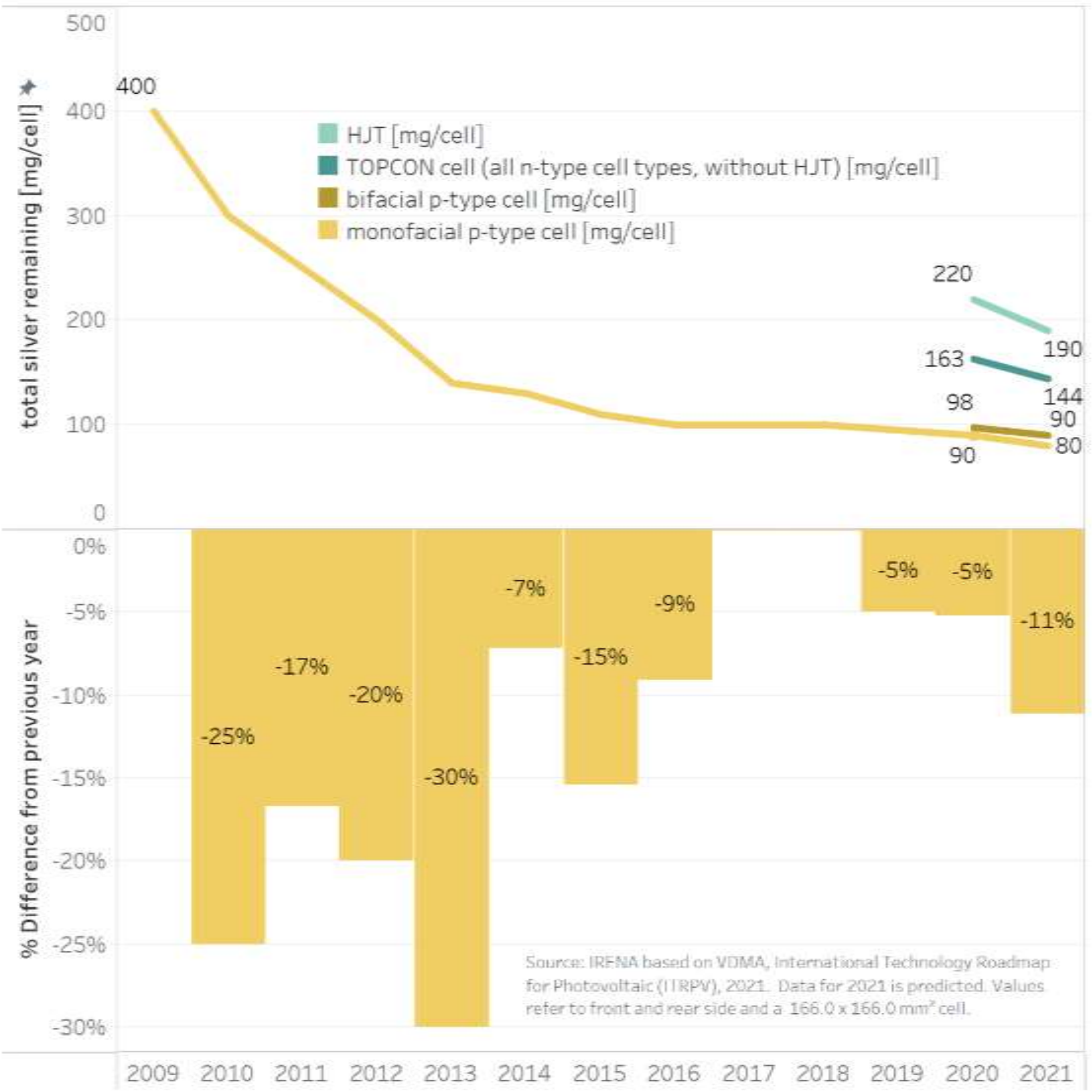
Source: IRENA based on VDMA, International Technology Roadmap for Photovoltaic (ITRPV), 2021.
Note: Values based on diamond wire sawing technology. 2021 values are predicted.

Silver usage per cell (2009 to 2021)

Source: NREL

Besides the wafer itself, metallisation pastes that contain silver have been an important cost component of the wafer-to-cell process. Given the relatively high cost of silver, the industry has placed significant focus on different ways to reduce metal consumption in cells.

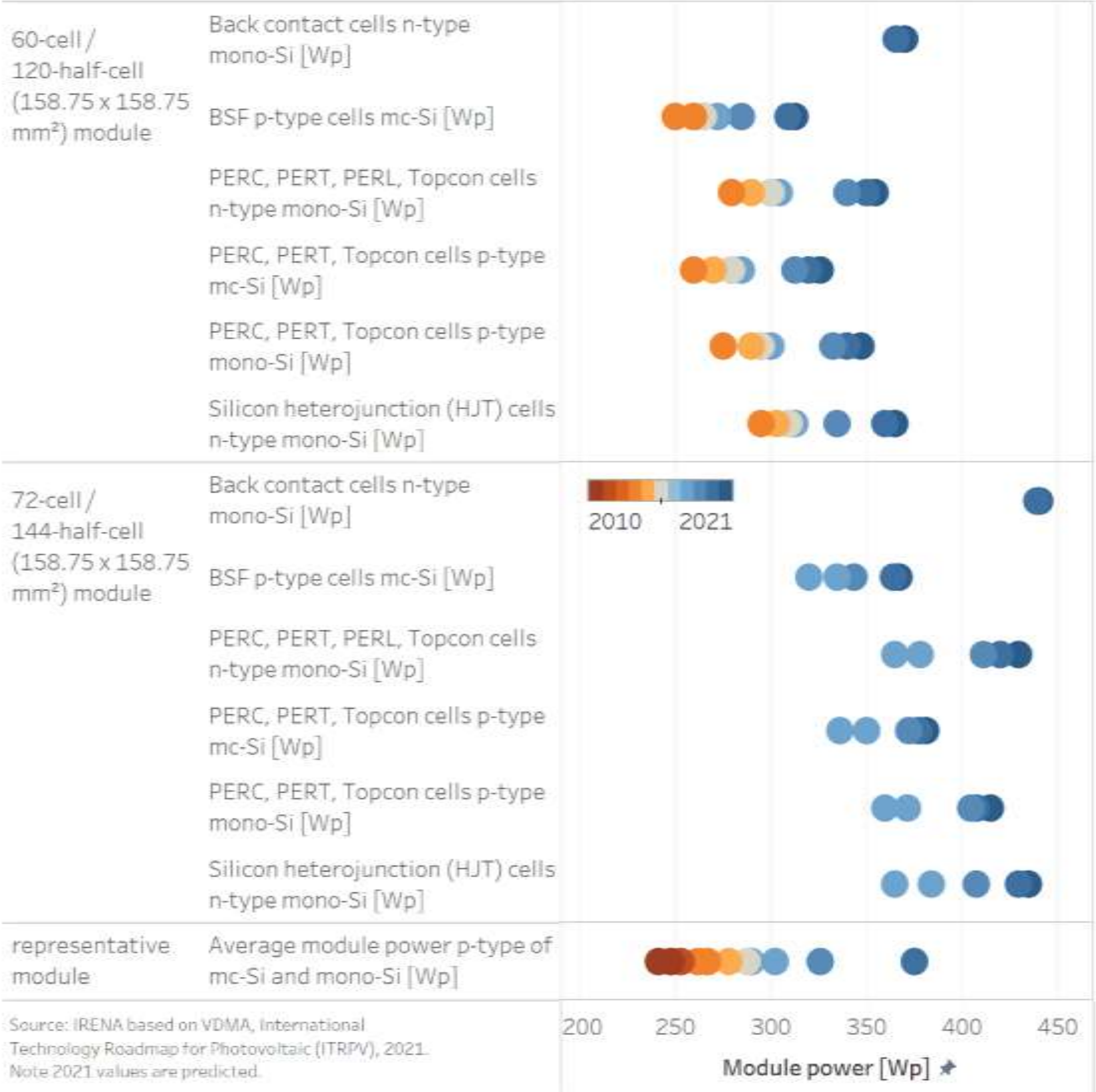
For mono-facial p-type cells, total silver remaining in the cells declined from 400 mg/cell in 2009 to 90 mg/cell in 2020 – a decline of 80%. The industry expects this to have declined another 10%, down to 80 mg/cell in 2021. In 2020, bifacial p-type cells had slightly higher consumption, at 98 mg/cell. In n-type cells (Heterojunction and TOPCON) , silver is used for front and full rear side metallisation, leading to significantly higher silver consumption than their p-type counterparts. In multi-busbar designs, cells go from having 3-5 busbars to having typically 12 much thinner busbars. In addition, the flat ribbon traditionally used for cell interconnection is replaced by round wire with a narrower diameter. This allows reduced finger width, potentially reducing silver usage. Copper is still envisioned as a substitute for silver, but technical challenges remain. These are related to adhesion, with rapid adoption not expected. In spite of this, new copper-based concepts keep developing (Zhan *et al.*, 2021).



Solar PV module power evolution (2010 to 2020)

Typical module design has changed in recent years, with variants such as half-cell modules, shingled cell modules and multi-busbar cells/modules (with as many as 12 thinner busbars) becoming increasingly popular.

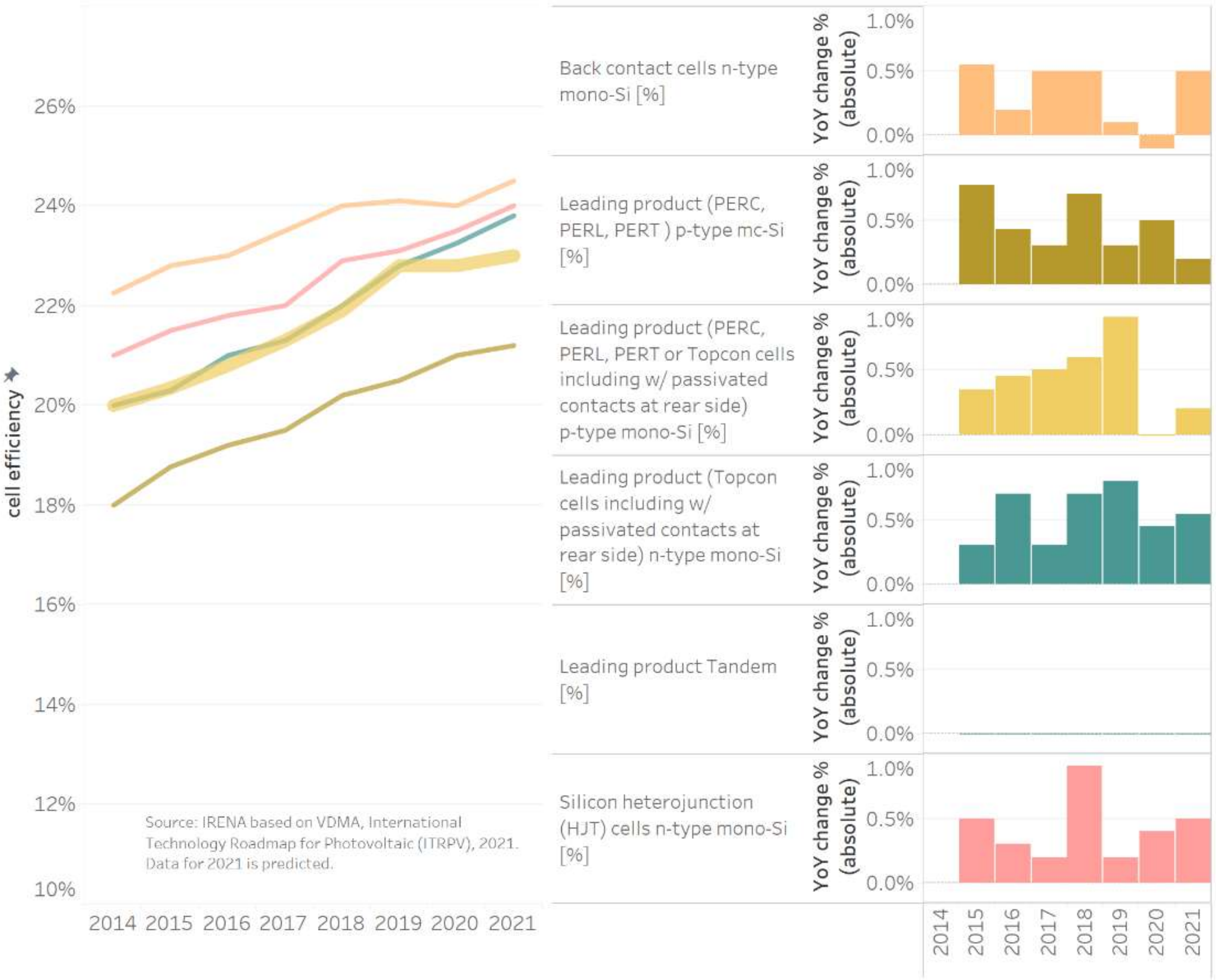
- Half-cell designs can reduce current flows in the string, compared to full-cells reducing resistive losses and improving performance. In 2020, 60-cell/120-half-cell modules made up about 40% of the global market, while larger 72-cell/144-half-cell modules accounted for 60%.
- Overall, half-cell modules made up about four-fifths of the market in 2020 (compared to 2% in 2015).
- These advances have resulted in a sustained, accelerating trend towards higher power ratings. The power rating of a representative p-type module rose from 326 W in 2019 to 375 W in 2020 (a value 55% higher than in 2010). All other factors being equal, increasing module power ratings result in LCOE benefits (*e.g.* due to reduced electrical balance of system and labour costs, lower installation costs, etc.).



Source: IRENA based on VDMA, International Technology Roadmap for Photovoltaic (ITRPV), 2021.
Note 2021 values are predicted.

Solar PV cell efficiency by cell type (2014 to 2021)

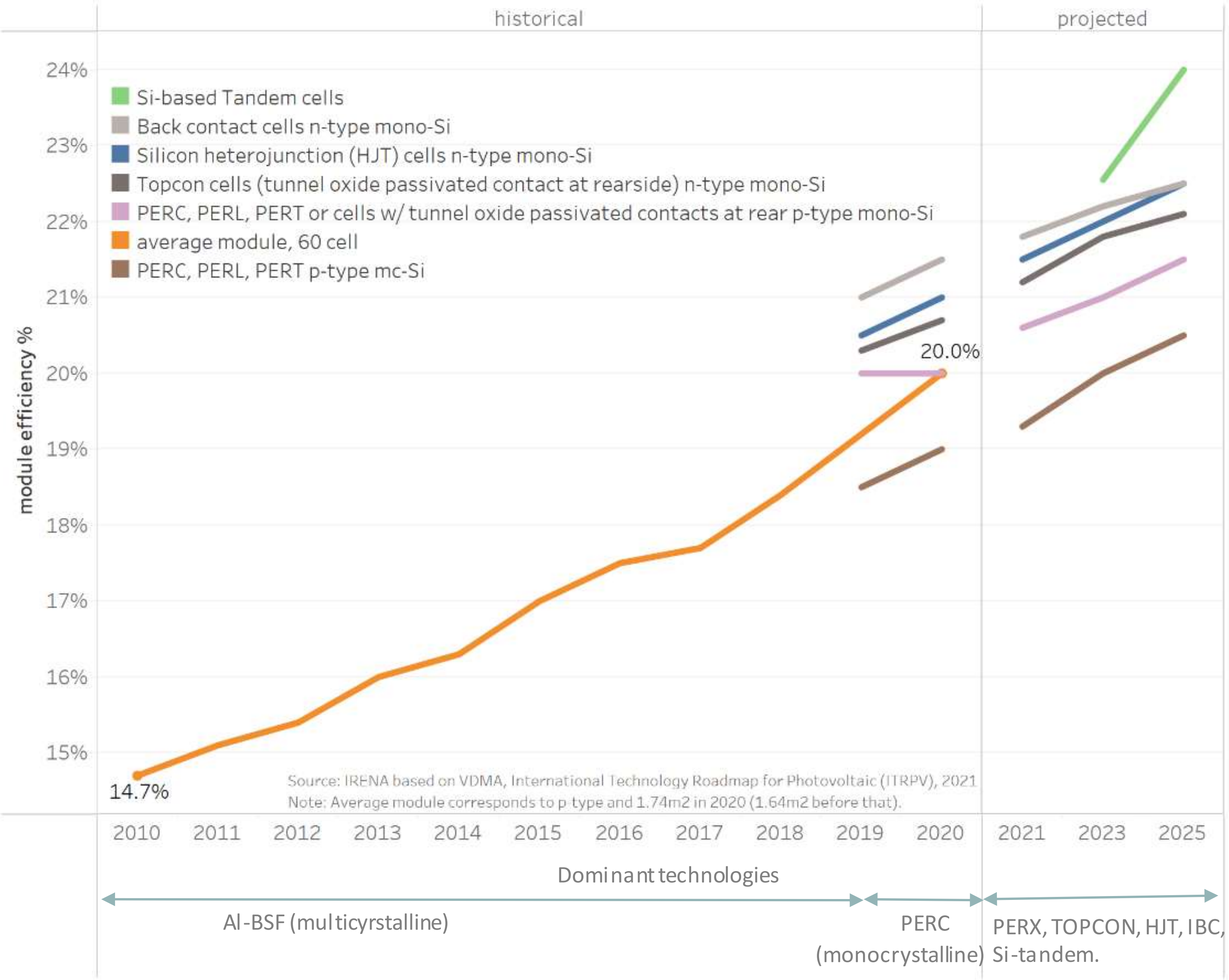
Higher module efficiencies in recent years can be largely attributed to a market shift from multi-crystalline to more efficient mono-crystalline cells. This has coincided with the rise, and now dominance, of PERC architectures. PERC cells based on p-type mono- silicon have now become the state-of the-art technology (thicker line). Cell architecture concepts aiming for higher efficiencies than PERC take two main approaches: first, by focusing on reducing losses at the contacts (*e.g.* heterojunction [HJT] and tunnel oxide passivated contact [TOPCon] technology); or second, by focusing on moving metallisation to the rear of the cell to reduce front-side shading (*e.g.* interdigitated back contact [IBC] cells). Early 2021 estimates put the commercial efficiency of both of these cell technologies close to 24%. Record laboratory cell efficiencies have been reported at 26.7% for mono-crystalline cells and at 24.4% for multi-crystalline technology (ITRPV, 2021; Fraunhofer ISE, 2021).



Solar PV module efficiency trends

Module efficiencies are lower than cell ones, due to the losses incurred in connecting the individual cells (typically 60 or 72 per module) in a self-contained module that can withstand a wide variety of weather conditions.
The average efficiency of crystalline modules increased, nonetheless, from 14.7% in 2010 to 20% in 2020 (ITRPV, 2021).

Multi-crystalline modules were the dominant technology up to about 2015, after which the market share of mono-crystalline modules started to grow. Mono-crystalline technologies have the advantage of reduced chemical impurities and material defects, which translate into higher efficiencies. The shift towards mono-crystalline products coincided with improved cell metallisation and interconnection concepts, particularly as the market shifted from early Al-BSF cell design to the emergence and uptake of PERC cell concepts.

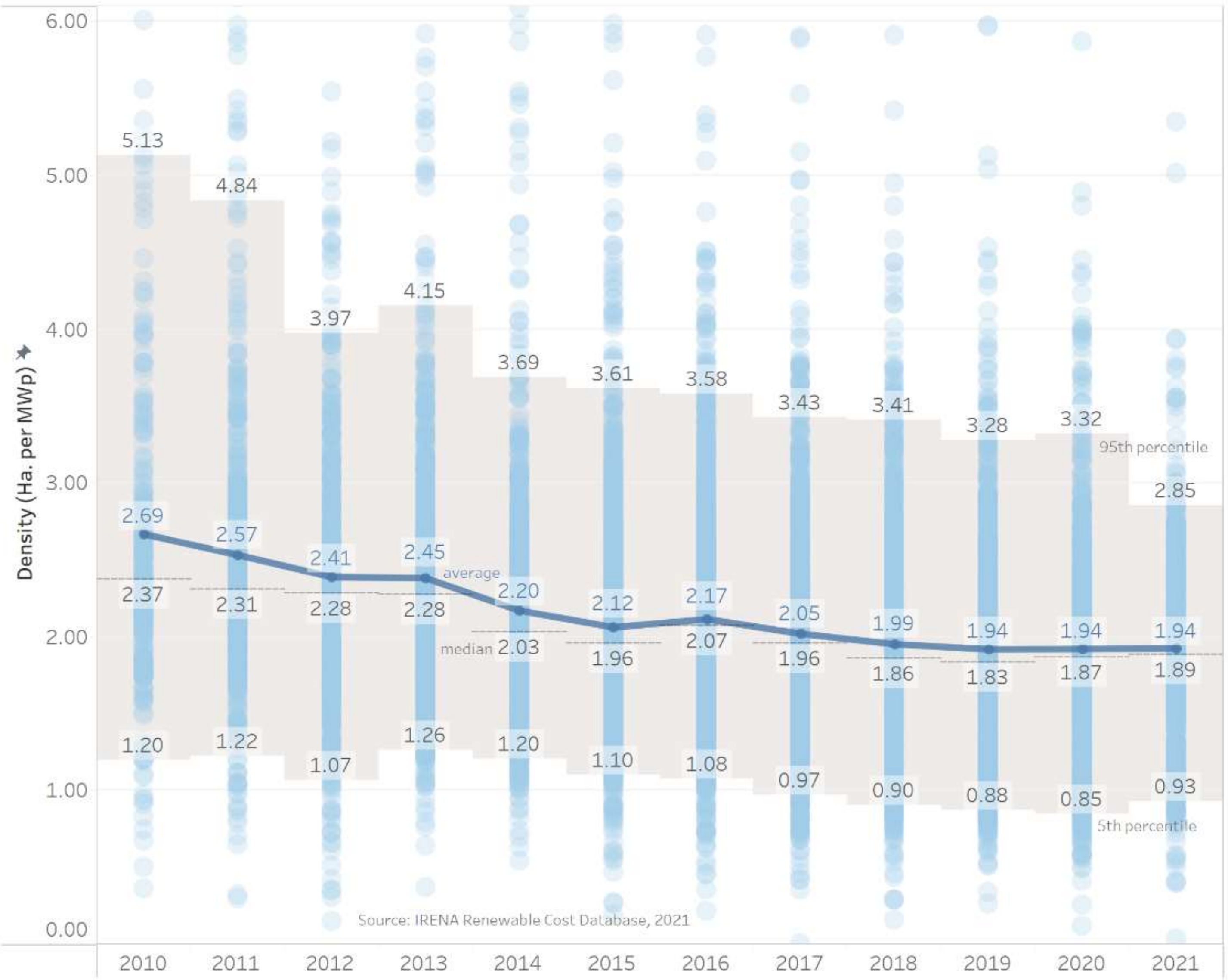


Land use of utility-scale solar PV: Hectares per MW

As the efficiency of solar PV modules increases, they require less surface area to generate a given power rating. This is obviously an important driver of materials cost reductions, but also has an impact on land use.

Solar field array placement is driven by land availability issues. The least land area is required where sufficient flexibility is available to create uniform arrays of square or rectangular shapes. As the shape of the land area becomes free-form, the land use efficiency declines somewhat, as some boundary curves or slope may result in less efficient placement, from a land-use perspective. There is also an economic driver; where land is relatively cheap there is less need to compromise on optimisation of panel location for energy capture.

The impact of this can be seen in the wide range of land use needs in hectares per MW on the right. The module efficiency trend is also visible.



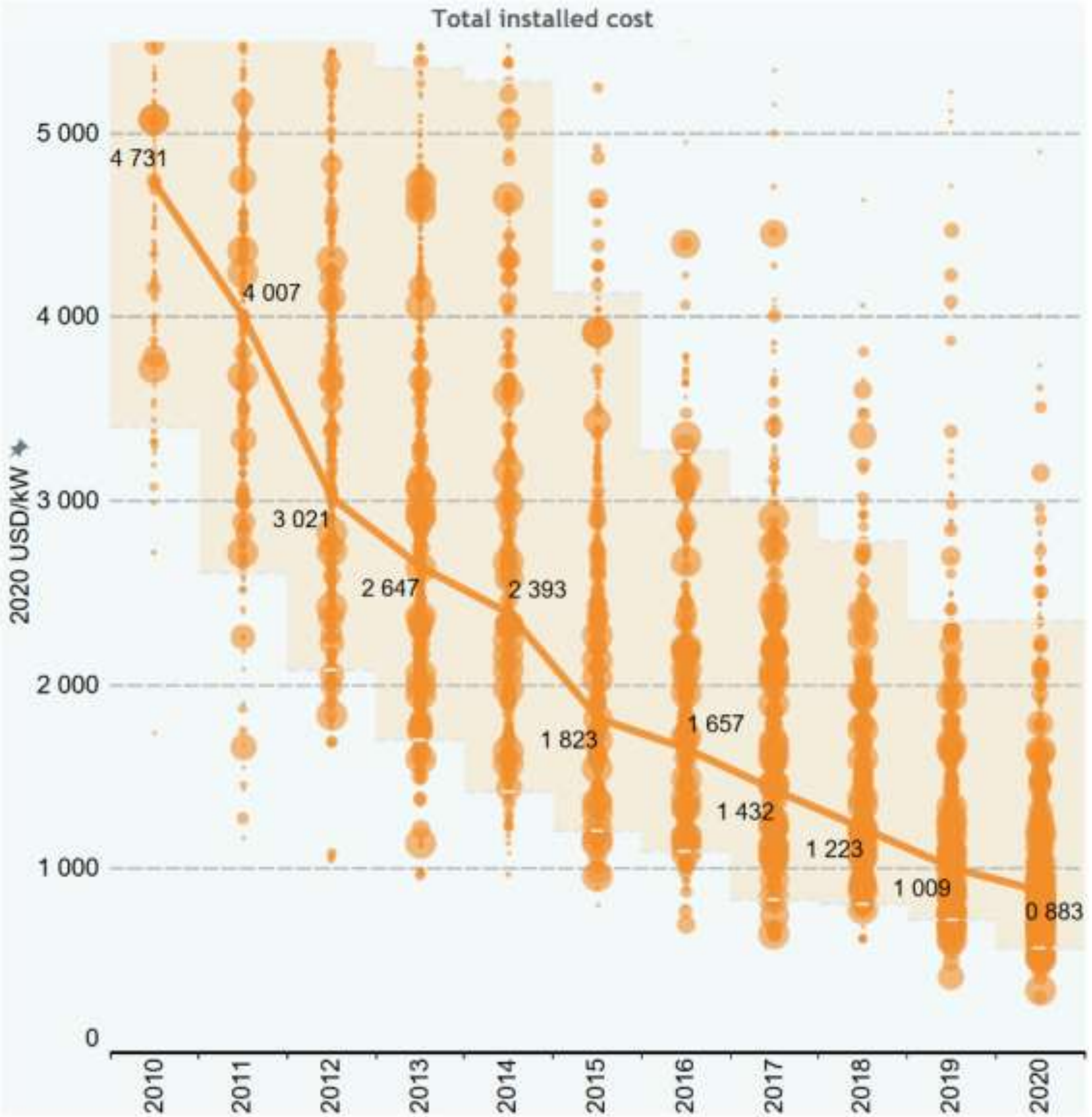
Utility scale solar PV

Utility-scale: Total installed costs (2010 to 2020)

Total installed costs for utility-scale solar PV plants fell by 81% between 2010 and 2020, from USD 4 731/kW to USD 883/kW. The global weighted-average total installed cost trend has remained remarkably consistent since 2016, too. Since then, the annual reduction in the global-weighted average total installed costs was between 13% and 17% depending on the year, with the smallest reduction in 2020.

Since 2015, the variation in total installed costs across markets has narrowed. There has been a convergence, albeit not complete, towards best practice cost levels taking into account structural cost differences (*e.g.* due to labour or materials costs).

Module price declines have driven the reduction in global weighted-average total installed costs. Technology improvements have reduced materials intensity, efficiency improvements have reduced the area required for a given wattage, manufacturing processes have become increasingly automated and refined to reduce costs and economies of scale – particularly upstream in the module value chain – have borne fruit. At the same time, balance of system (BoS) costs have fallen thanks to the simplicity and modularity of utility-scale solar PV – from a development and installation perspective – increased developer experience, more competitive supply chains, larger project sizes (in some markets), and competitive procurement.

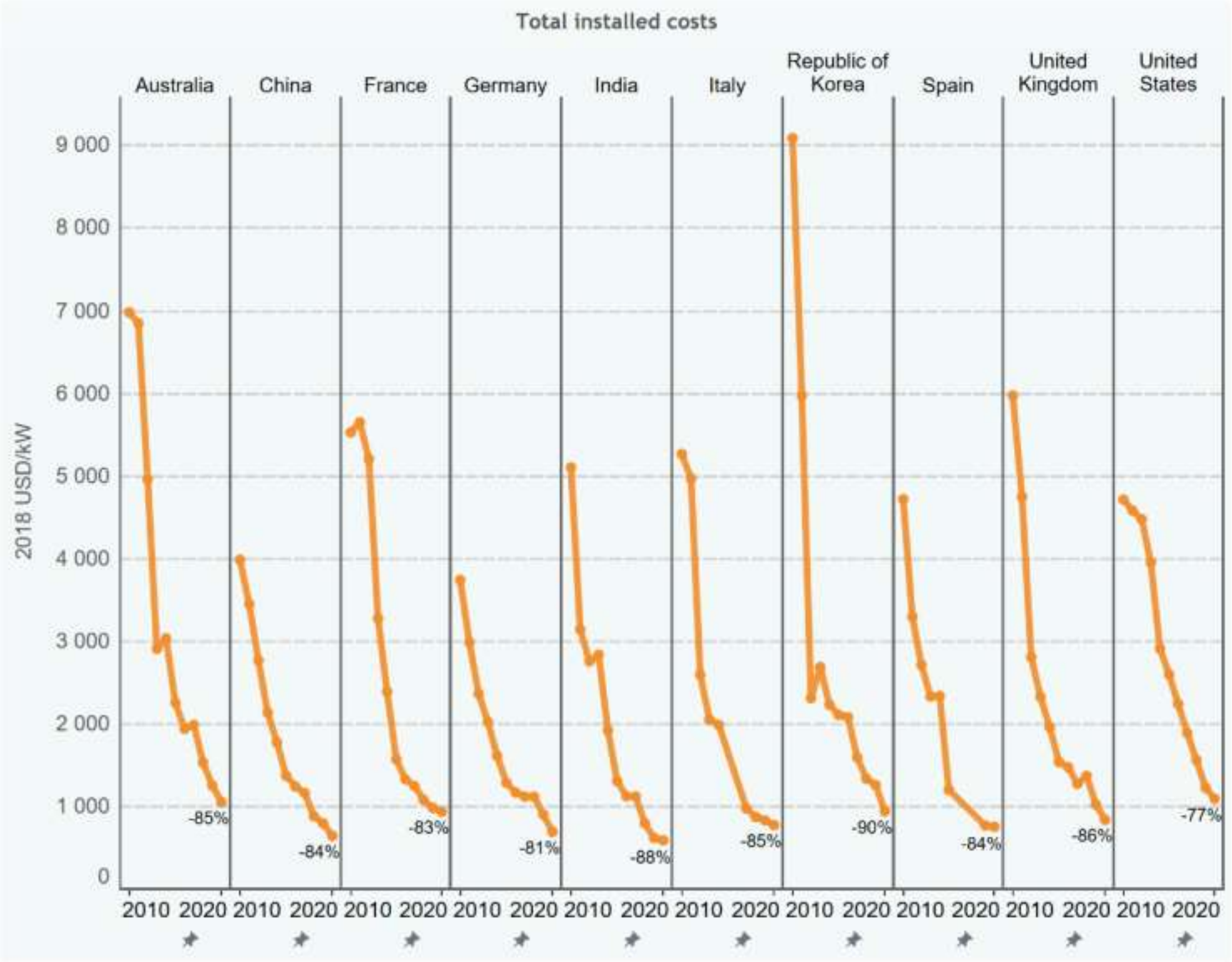


Utility-scale: Total installed costs (2010 to 2020)

Given the cost reductions of the last ten years, it is easy to forget that the utility-scale solar PV market is essentially only around a decade old. As a result, robust time series data for 2010 to 2020 is only available for ten countries, with another five countries with shorter time series.

For the 10 countries with a decade of data, total installed costs for utility-scale solar PV plants fell by between 77% and 90% between 2010 and 2020.

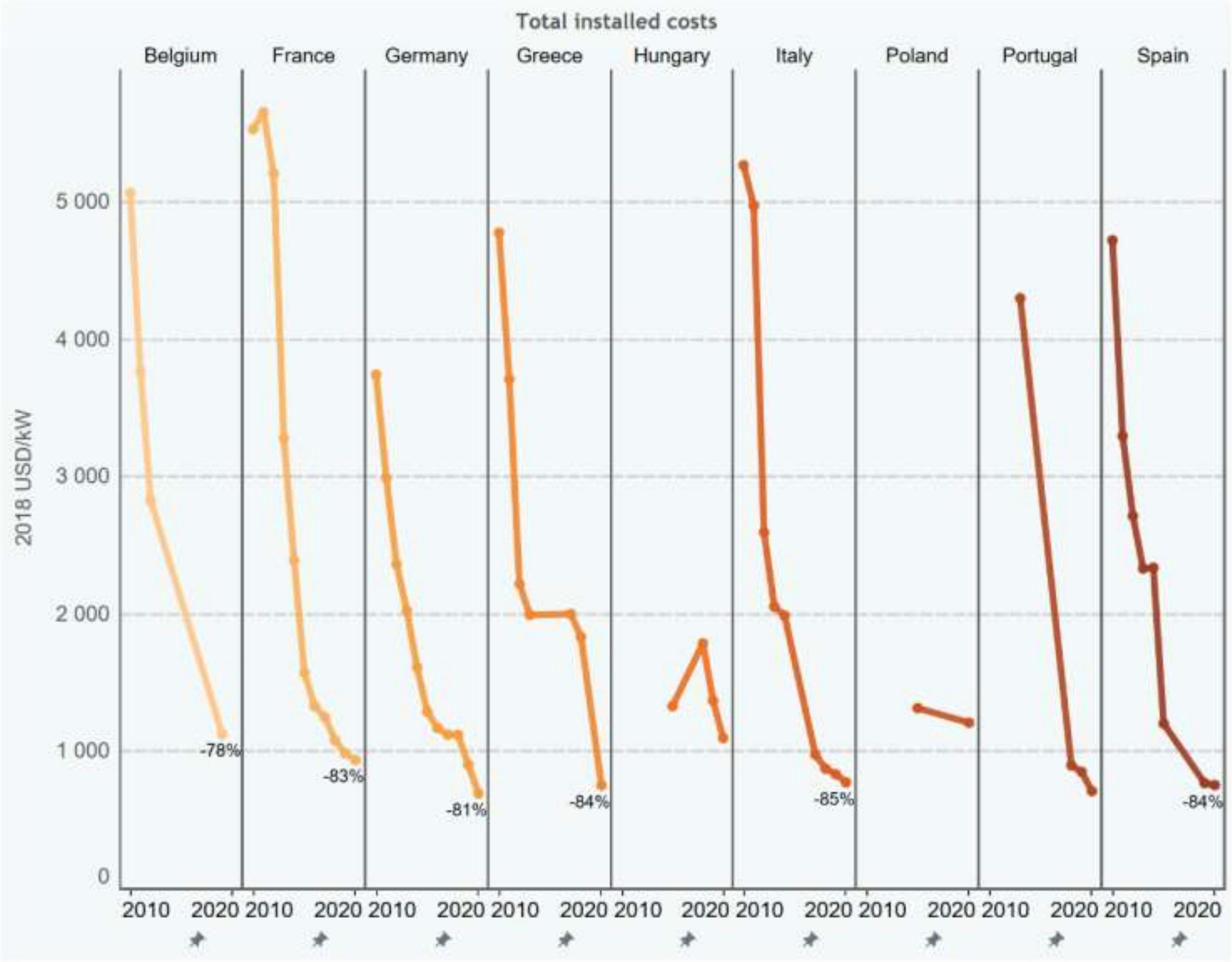
In 2010, the weighted-average total installed cost by country varied from USD 9 100/kW in the Republic of Korea to USD 3 994/kW in China. By 2020, the range had declined to between USD 596/kW in India and USD 1 101/kW in the United States. For this group of countries, the ratio between the most competitive and least competitive markets decreased from a factor of 2.3 in 2010 to a factor of 1.8 in 2020.



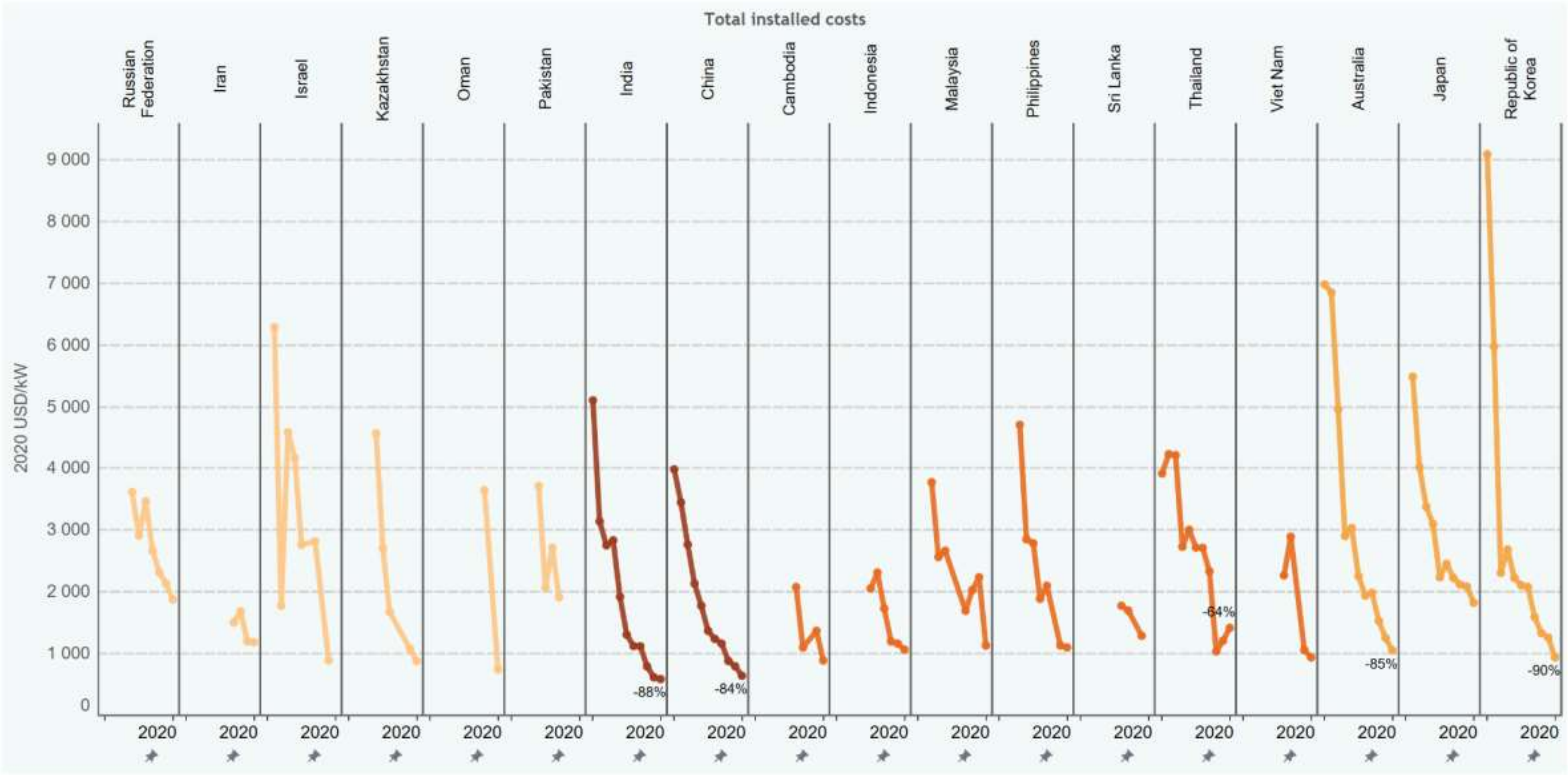
Utility-scale: Total installed costs in EU countries (2010 to 2020)

Focusing on the EU countries for which there is some time series data between 2010 and 2020, we can see that the decline was between 81% and 85% for countries with data for the entire decade. In 2020, there is little difference in total installed costs between Germany, Greece, Italy, Portugal and Spain. Cost structures are somewhat less competitive in Belgium, while the emerging markets of Hungary and Poland do not yet appear to have developed competitive local cost structures.

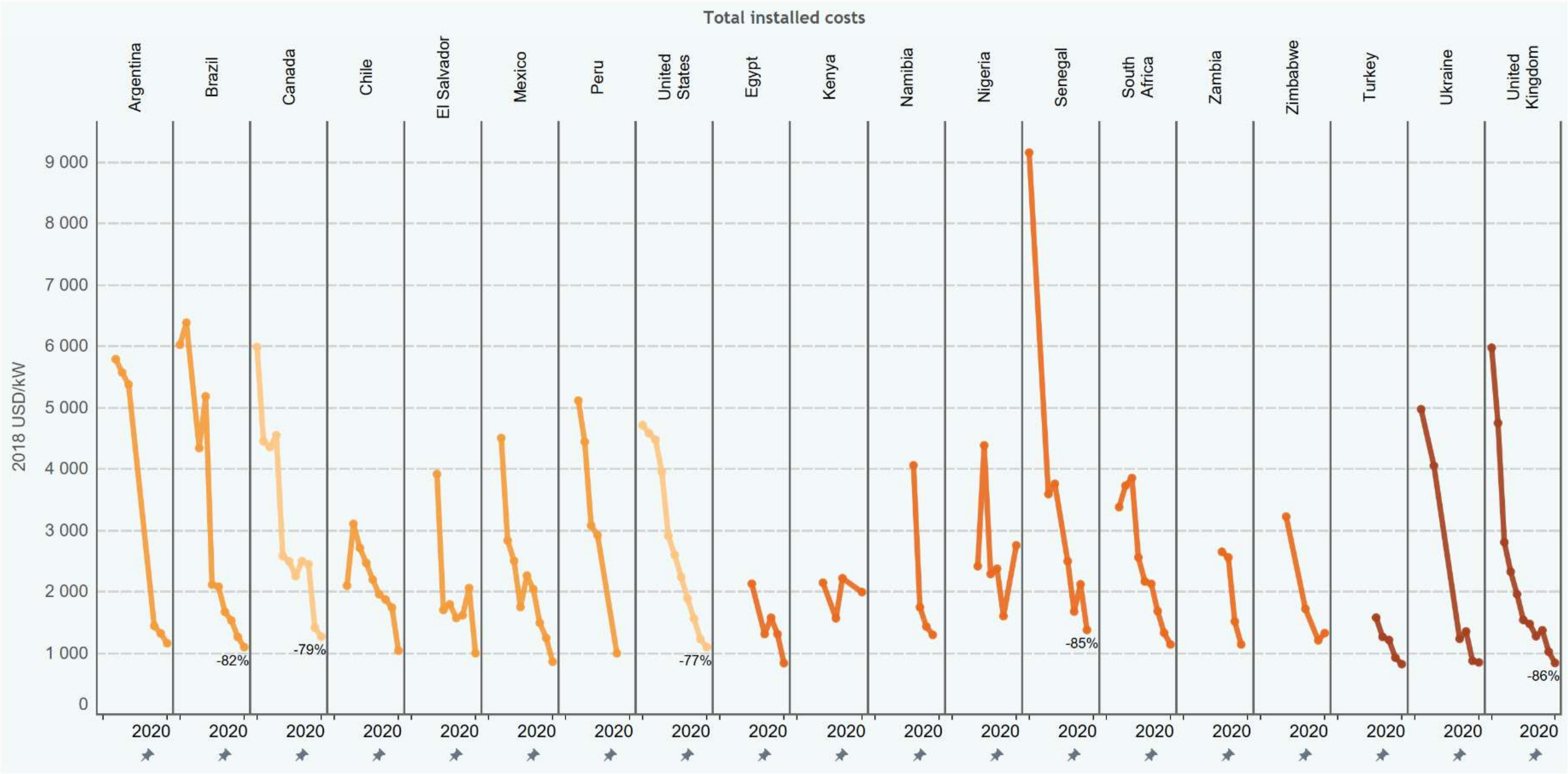
On the following to pages we see the data that is available for 37 other countries in the IRENA Renewable Cost Database. China and India standout as very low-cost markets, but where the policy and regulatory framework settings are right and there has been enough time and scale to ensure local supply chains and developer experience has grown, costs have converged at or below USD 1 000/kW in a remarkable number of markets, even those with relatively modest deployment.



Utility-scale: Total installed costs in Middle East and Asia-Pacific (2010 to 2020)



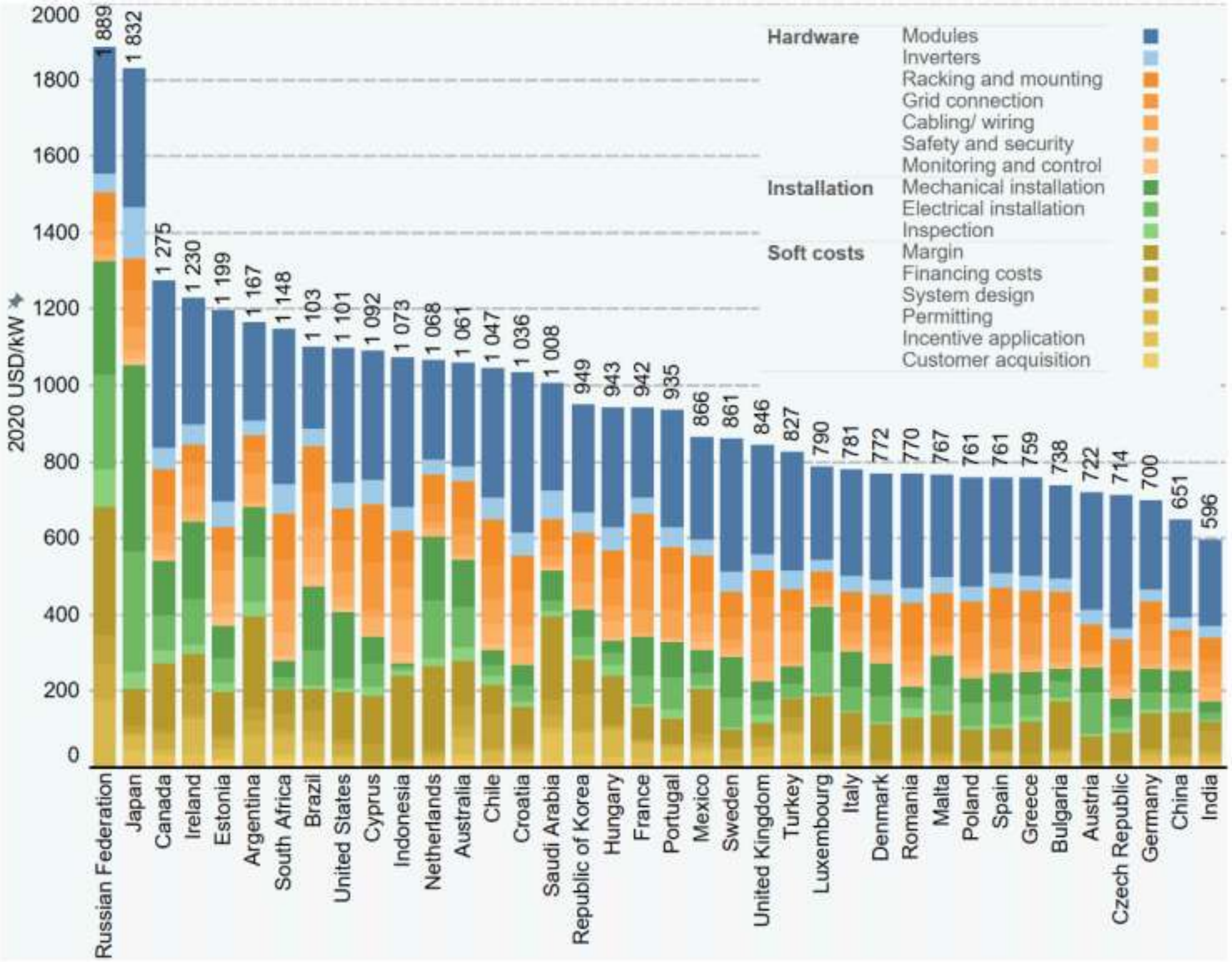
Utility-scale: Total installed costs in the Americas, Africa and other Europe (2010 to 2020)



Utility-scale: Total installed cost breakdown in 38 countries (2020)

There remains significant variation in total installed costs between markets. This is due to structural reasons, such as labour costs and commodity pricing, as well as by a range of other factors. The maturity and scale of local markets can affect the competitiveness of the local supply chains (*e.g.* for racking and mounting products, specialised installation contractors, etc.), while developers may not have as much experience. The policy and regulatory settings also play a role, impacting everything from grid connection costs to project development lead times, obtaining permits and environmental impact assessment costs.

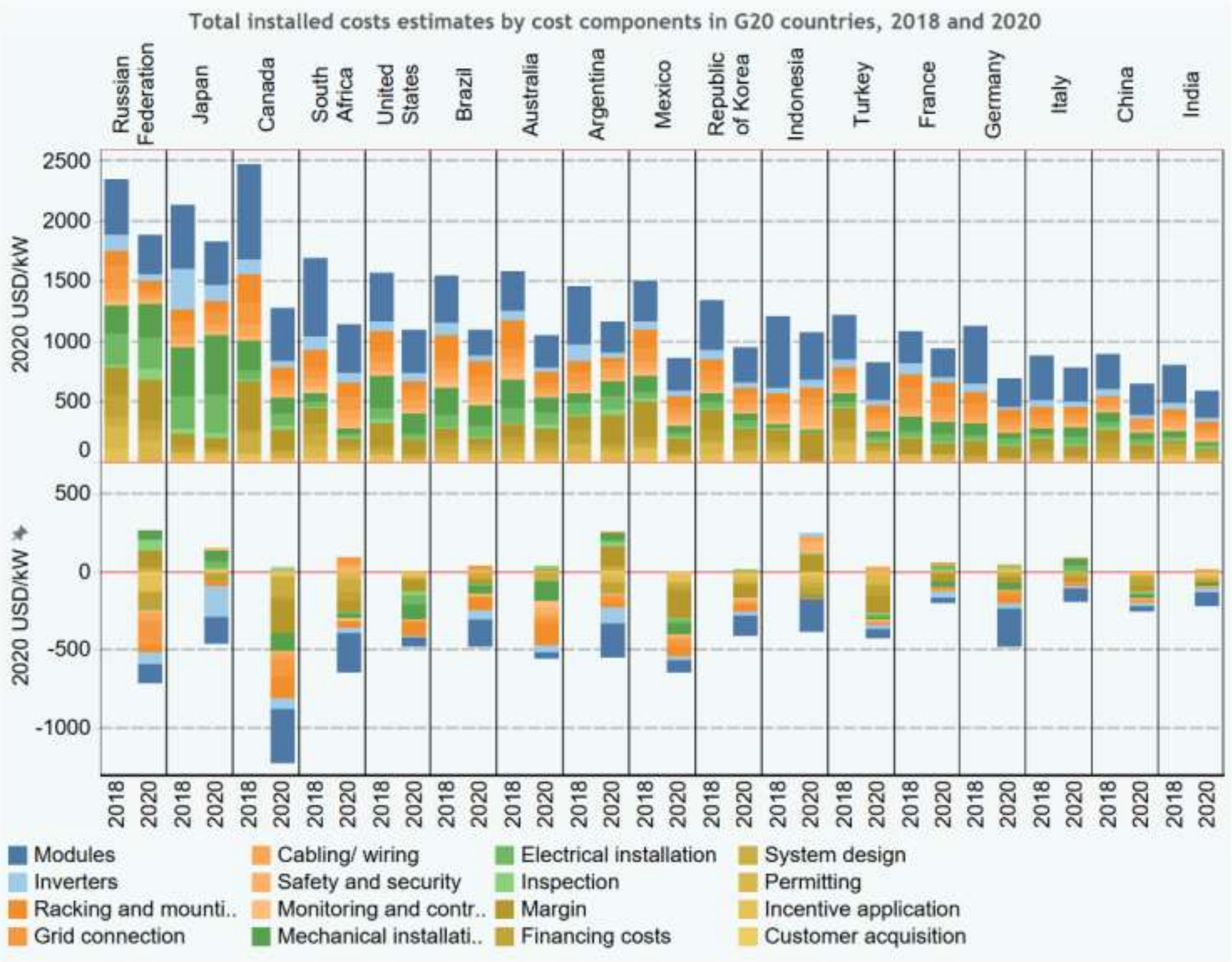
There has, however, been a trend towards cost convergence at more competitive levels. This is happening more rapidly than in the past, as experienced project developers seek opportunities in new markets, while competitive procurement processes have put pressure on developers to adhere to best practices, and supply chains have become more competitive.



Utility-scale: Total installed cost breakdown in the G20 (2018 and 2020)

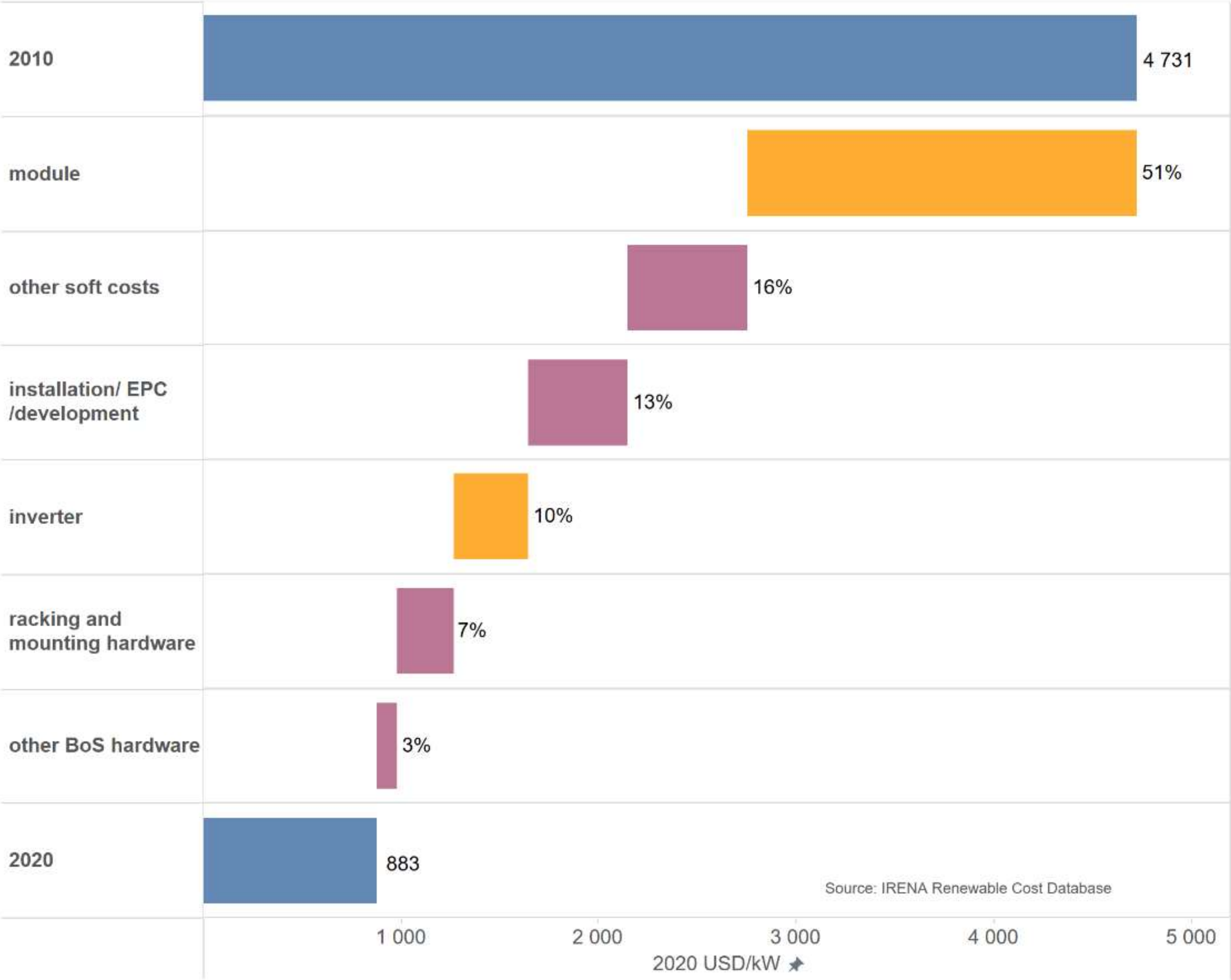
It is beyond the scope of this analysis to go into detail about cost reduction drivers. An analysis of the detailed cost components in G20 markets between 2018 and 2020 highlights some important commonalities and differences in recent cost reduction experiences, however.

Most G20 markets saw significant cost reductions across all categories. In some markets where the absolute reduction in costs has been relatively modest, however, there were increases in some costs over the two years. This was notably so in the less competitive markets of Russia and Japan, but also occurred in Argentina and Indonesia. In both the latter countries, significantly lower module costs were offset by higher soft costs and, in the case of Argentina, higher installation costs, while in the case of Indonesia, the offset was due to higher racking, mounting, connection and cable/wiring costs.



Utility-scale: Global total installed cost reduction by component (2010 to 2020)

The global capacity weighted-average total installed cost of utility-scale projects commissioned in 2020 was USD 883/kW (13% lower than in 2019 and 81% lower than in 2010). At a global level, cost reductions for modules and inverters accounted for 61% of the global weighted-average total installed cost decline between 2010 and 2020. The rest of the cost reductions came from BoS costs, which are an important contributor to declining global weighted-average total installed costs. Between 2010 and 2020, 13% of the global total installed cost reduction came from lower installation costs, 7% from racking, 3% from other BoS hardware (*e.g.* cables, junction boxes, etc.) and 16% from a range of smaller soft cost categories. The reasons for BoS cost reductions relate to competitive pressures and increased installer experience, improved installation processes and lower soft development costs. BoS costs that decline in proportion with the area of the plant have also declined as module efficiencies have increased.



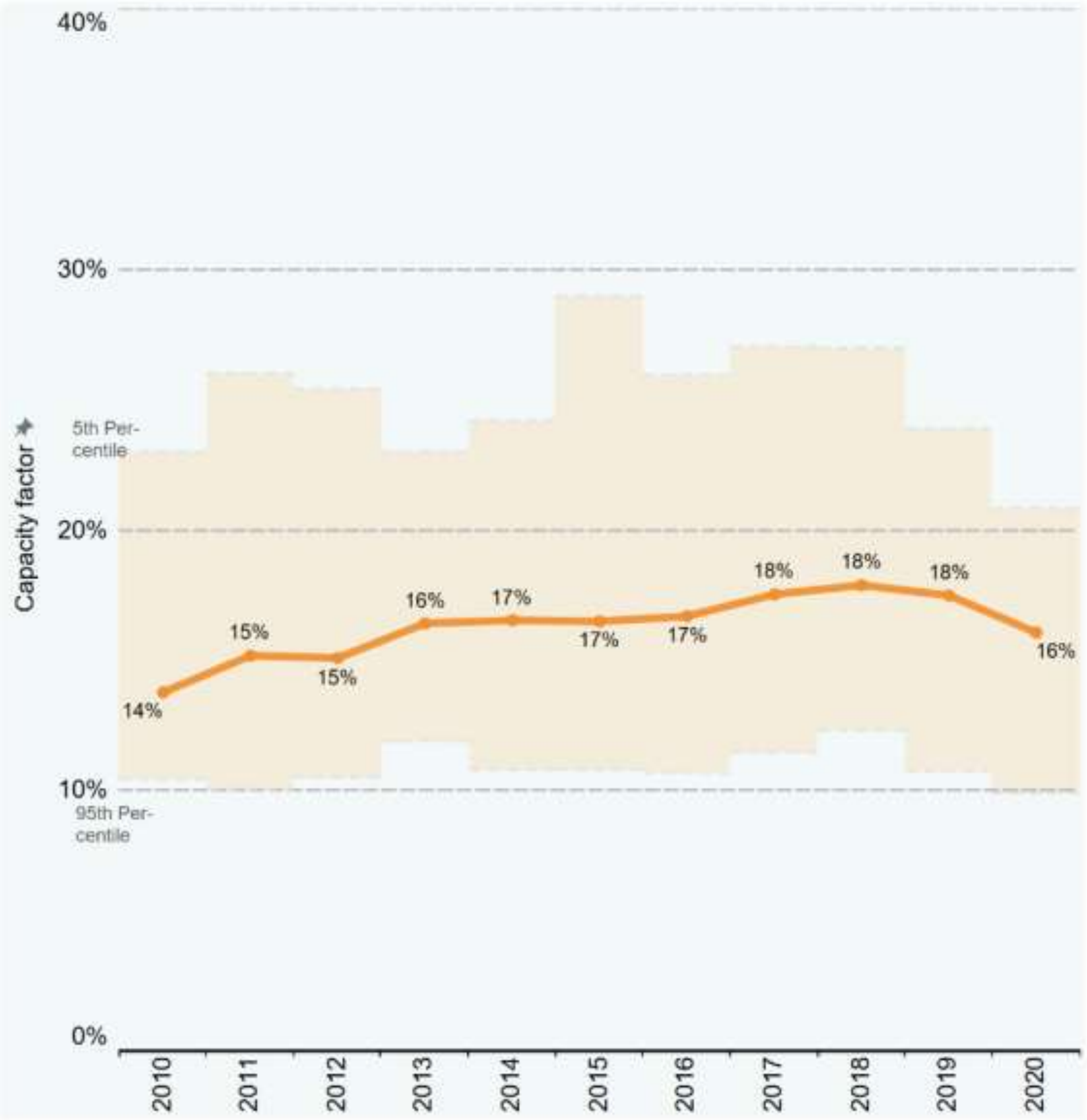
Utility-scale solar PV capacity factors (2010 to 2020)

The global weighted-average capacity factor of newly commissioned utility-scale solar PV plants increased from 13.8% in 2010 to 16.1% in 2020 as a result of a shift to deployment in areas with higher solar irradiation, the increased use of tracking systems (predominantly single-axis) and a number of smaller technical improvements that have reduced system losses.

The global weighted-average capacity factor has dipped from its peak as new deployment has shifted to a balance of slightly poorer resource locations in recent years, rather than any technical developments.

Data for the United States shows that tracking was used on 69% of the capacity installed there in 2018, up from 26% in 2010 (Bolinger *et al.*, 2019). Data for other markets, however, is limited and insufficient to enable an understanding of global capacity factor values at this time.

Another issue that has arisen as solar PV costs have fallen is an increase in inverter load ratios (ILRs). Higher ILR ratios (*e.g.* large direct current (DC) capacity compared to the alternating current (AC) inverter capacity) flatten the generation profile during peak sunshine hours. The small reduction in output may be economic, depending on the local electricity market context, with the benefit of reduced grid connection costs.

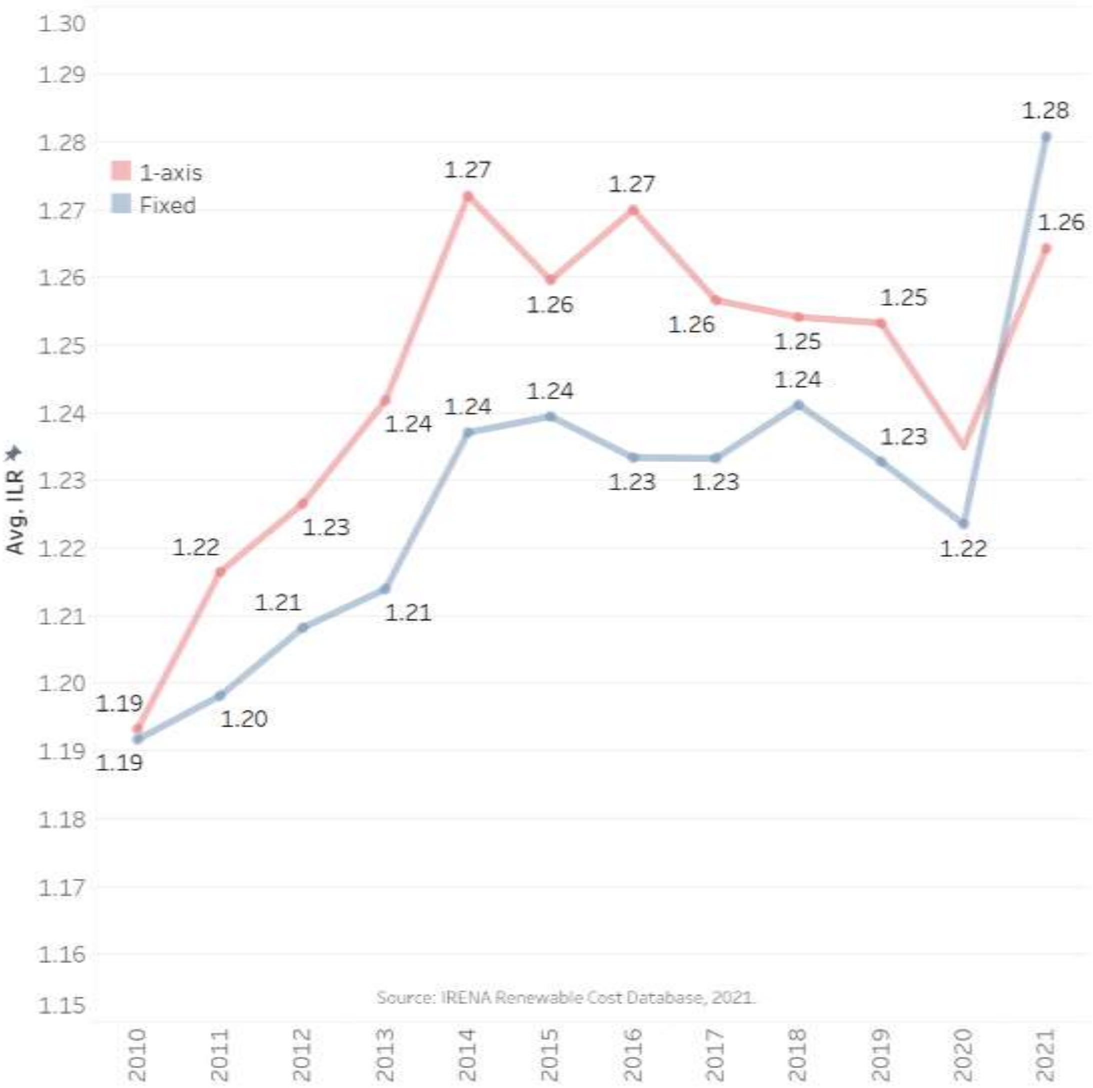


Inverter load ratio: global trend

Since 2010, the global PV market has experienced a trend towards higher ILRs, too. These growing ILR values have coincided with a decreasing trend in module cost per Watt. Depending on the context, increasing the DC array relative to the AC inverter capacity to achieve a higher ILR can be beneficial in reducing yield variability and enhancing revenue, depending on the context (Good and Johnson, 2016).

The choice of the ILR is a complex system design consideration and is influenced by a variety of factors. These include: the type of tracking used, project location, project cost and revenue structures, limits of the available grid connection and land availability in a given project.

Data from the IRENA Renewable Cost Database, shows the global ILR average increasing from 1.19 in 2010 to between 1.26 to 1.28 in 2020 depending on the tracking choice. Given the context dependency of the ILR choice, collecting data on this metric systematically is challenging. Better data is nonetheless needed on ILR ratios globally to better assess these trends.



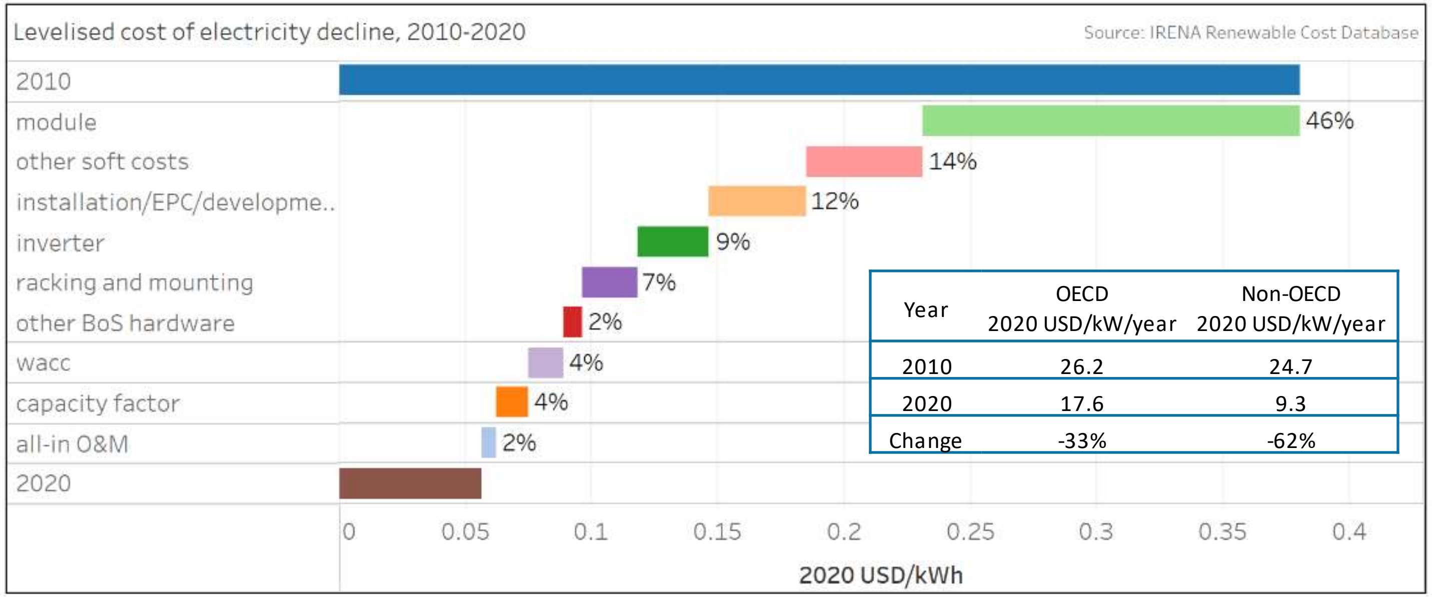
Operations and maintenance costs

The operation and maintenance (O&M) costs of utility-scale solar PV plants have declined in recent years, driven by module efficiency improvements, which have reduced the surface area required per MW of capacity.

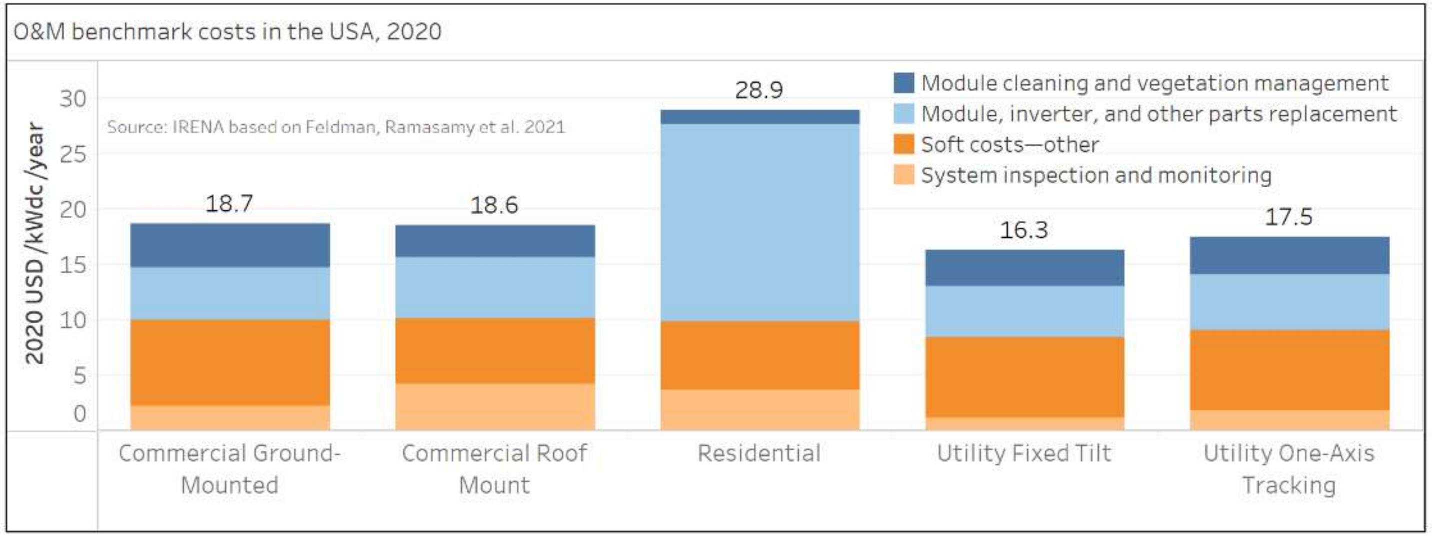
At the same time, competitive pressures and improvements in the reliability of the technology have resulted in system designs that are optimised to reduce O&M costs.

Innovations have also driven down O&M costs and reduced downtime. These innovations stretch from robotic cleaning to 'big data' analysis of performance to identify issues and enable preventative interventions ahead of failures.

For the period 2018 to 2020, utility-scale O&M cost estimates in the United States were reported at between USD 10/kW/year and USD 18/kW/year (Wiser *et al.*, 2020; Bolinger *et al.*, 2019; Bolinger *et al.*, 2020; EIA, 2020; NREL, 2018; Walker *et al.*, 2021). Although O&M contributed only 2% to the LCOE reduction between 2010 and 2020, this is poised to change as total installed costs decline further.

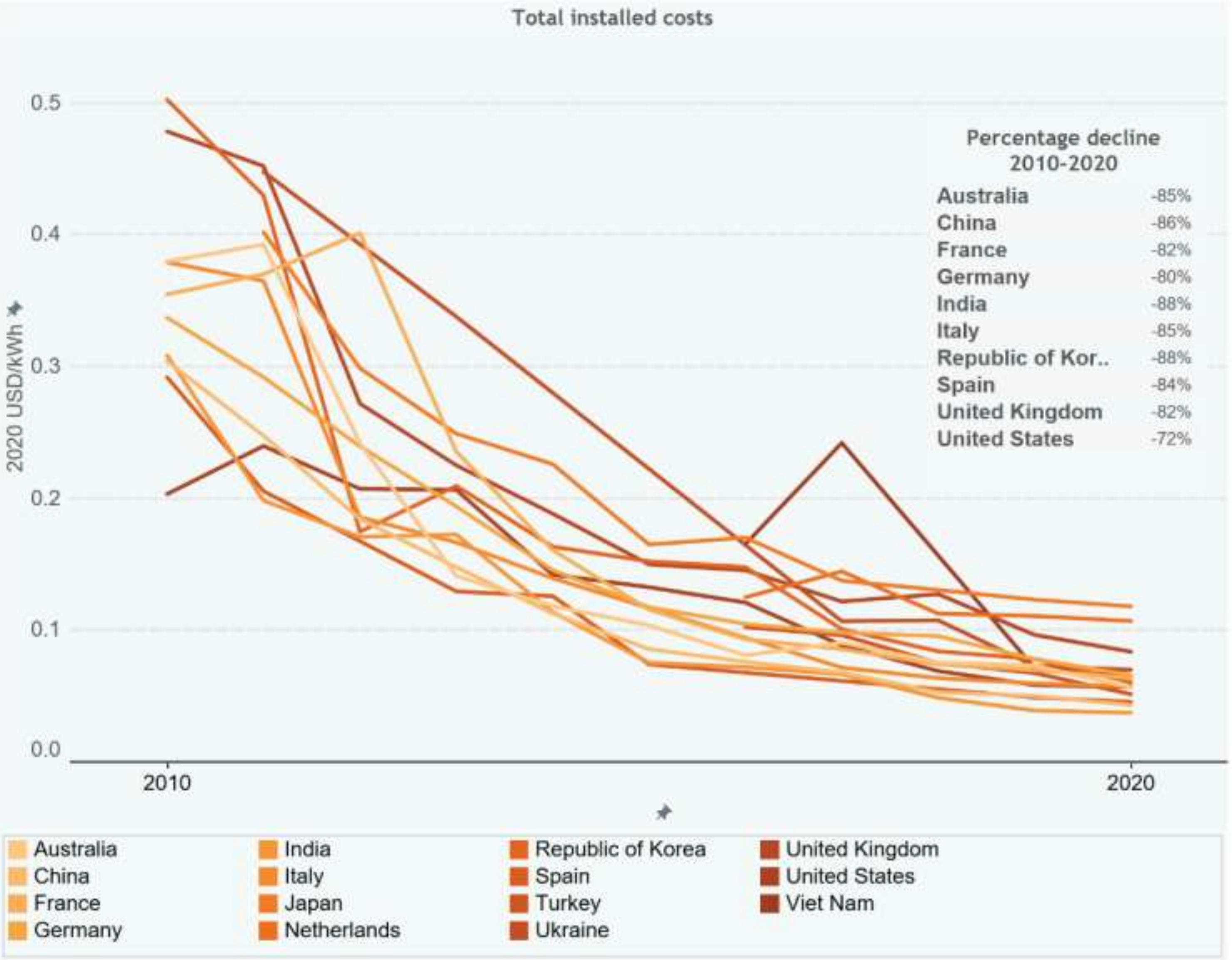


Year	OECD 2020 USD/kW/year	Non-OECD 2020 USD/kW/year
2010	26.2	24.7
2020	17.6	9.3
Change	-33%	-62%



Utility-scale: Levelised cost of electricity (2010 to 2020)

A rapid decline in total installed costs, increasing capacity factors and falling O&M costs have contributed to a remarkable reduction in the cost of electricity from solar PV and the improvement of its economic competitiveness. Going back to 2010, the downward trend in the LCOE of utility-scale solar PV by country shows that in markets where historical data is available, the weighted-average LCOE reduction of utility-scale solar PV between 2010 and 2020 was between 72% and 88%, depending on the country. The lowest weighted-average LCOE in the utility-scale sector could be observed in India, where between 2010 and 2020, costs declined by 88%, to reach USD 0.038/kWh – a value 33% lower than the global weighted average for that year. As solar PV technology has matured, the relevance of BoS costs has also increased, given the BoS share of total installed costs has tended to increase with time as module and inverter costs have historically decreased at a higher rate than non-module costs (IRENA, 2018).

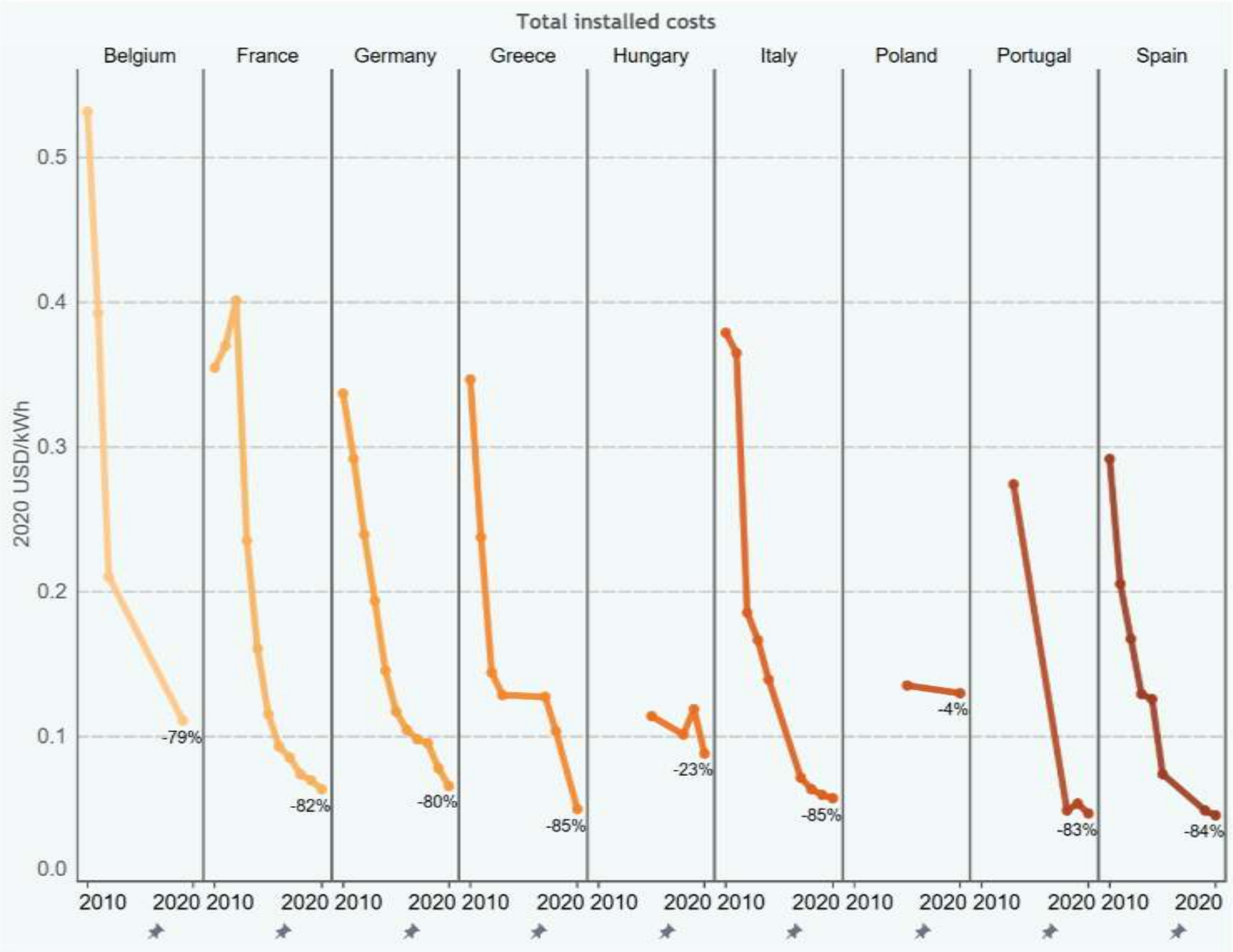


Utility-scale: LCOE in EU countries (2010 to 2020)

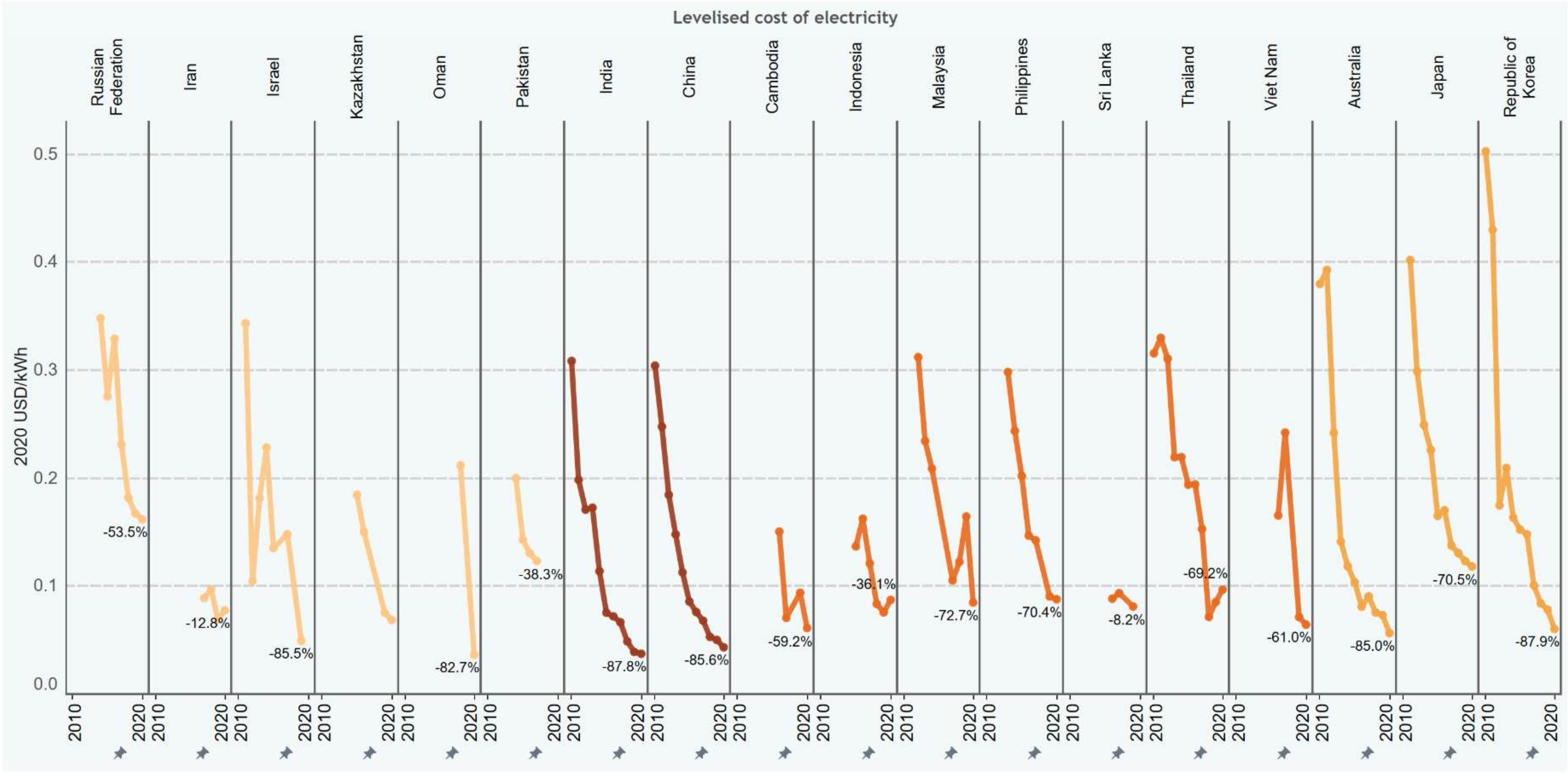
Focusing on the EU countries for which there is some time series data between 2010 and 2020, we can see that the decline was between 79% and 85% for countries with data for the entire decade. In 2020, there was little difference in total installed costs between Germany, Greece, Italy, Portugal and Spain. The very different solar resources in these countries result in more widely distributed weighted-average LCOE values for newly commissioned plants, however.

On the following pages we present the data available for 37 other countries in the IRENA Renewable Cost Database. China and India standout as very low-cost markets, driven by very low installed costs and, at least in the case of India, good to excellent solar resources.

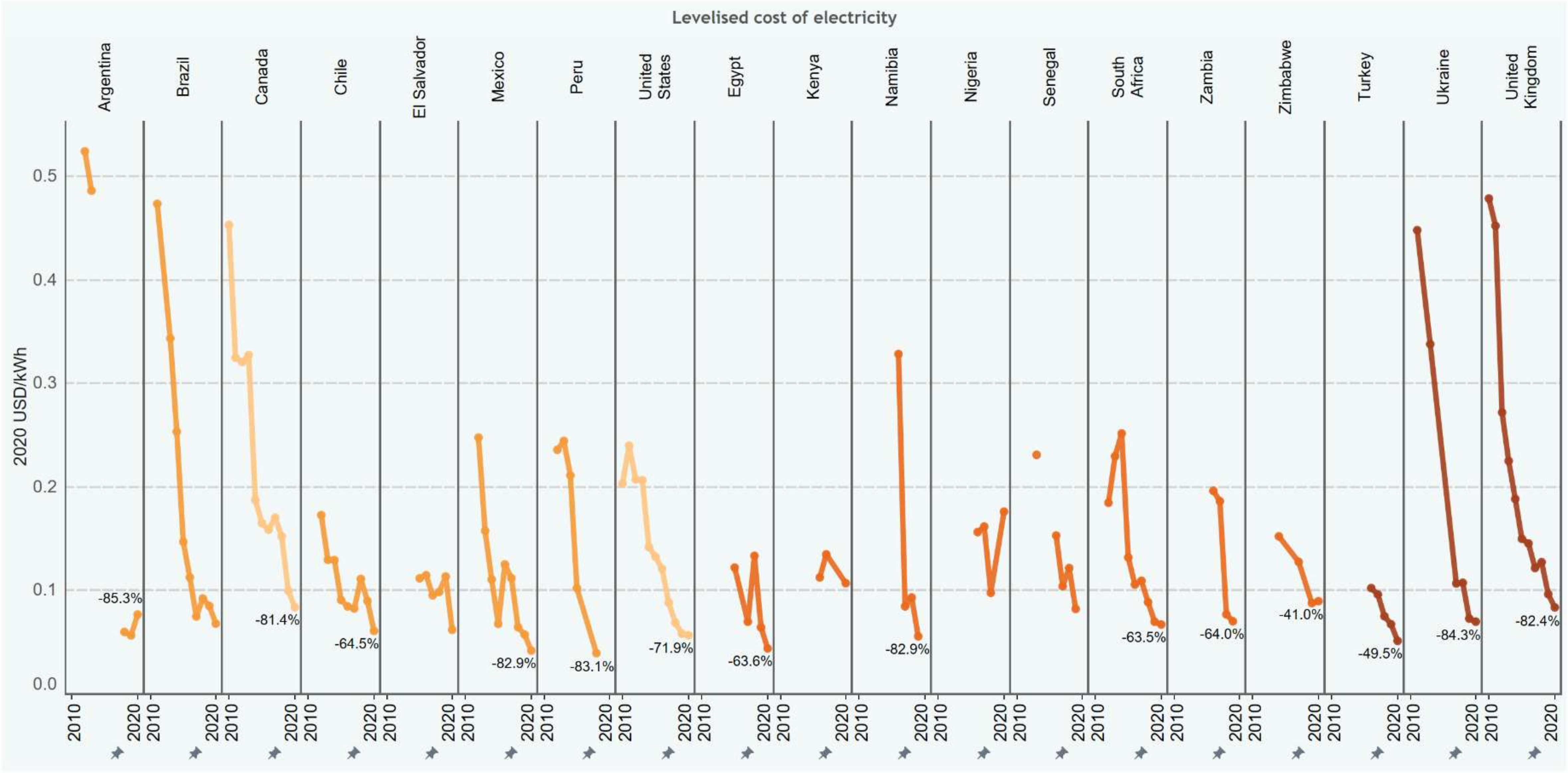
There are an increasing number of countries around the world, however, where utility-scale solar PV now has very competitive LCOEs. These range between USD 0.036/kWh and USD 0.055/kWh.



Utility-scale: LCOE trends in the Middle East and Asia-Pacific (2010 to 2020)



Utility-scale: LCOE trends in the Americas, Africa and other Europe (2010 to 2020)

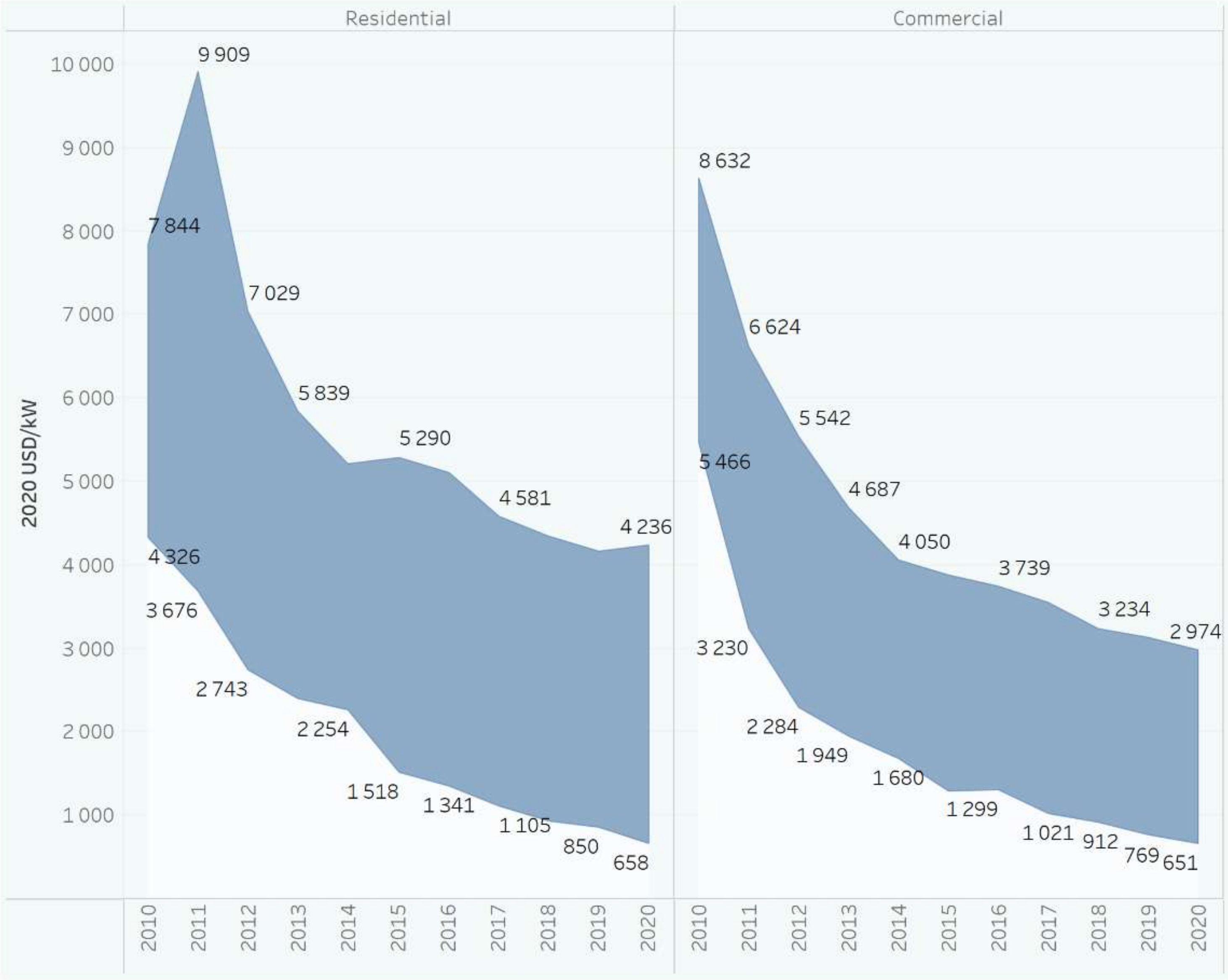


Residential and commercial solar PV

Residential and commercial sector PV installed costs (2010 to 2020)

Total installed costs in the residential rooftop PV market are higher than in the utility-scale market. Depending on the market, between 2010 and 2020, these costs decreased by between 46% and 85% following a declining cost trend in installed costs visible in a wide range of countries. Depending on the market, too, the total installed system costs decreased from between USD 4 326/kW and USD 7 844/kW in 2010, to between USD 658/kW and USD 4 236/kW in 2020. Since 2013, data for more markets beyond the early-adopter markets has also become available.

Between 2010 and 2020, total installed system costs in the commercial rooftop markets where data is available decreased between 69% and 88%. This corresponds to a change in the total installed cost range from between USD 5 466/kW and USD 8 632/kW in 2010 to between USD 651/kW and USD 2 974/kW in 2020. Since 2017, more data has become available, as new markets have emerged.

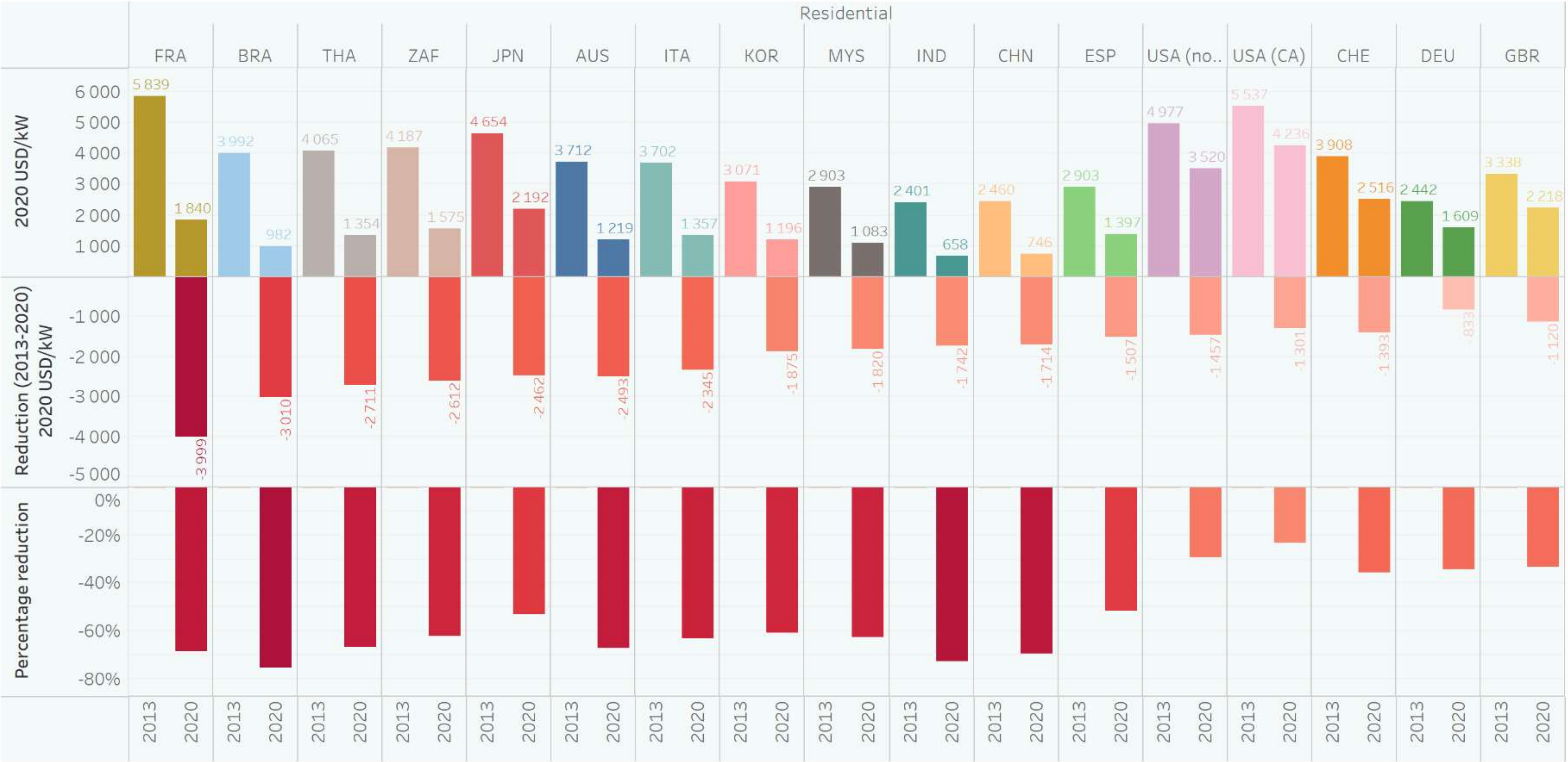


Residential and commercial sector PV installed costs by country (2010 to 2020)

Since 2010, in the residential and commercial PV sectors, a declining cost trend in installed costs can be seen in a wide range of countries. The residential, rooftop solar PV market has generally higher costs than the utility-scale market, due to the smaller scale of its systems. Commercial systems in a range of countries are now approaching utility-scale system costs, however.

France is notable for achieving a very rapid cost reduction between 2010 and 2015, while the United States has, in general, failed to take advantage of reductions in module and hardware costs, as soft costs remain stubbornly high there. Their systems, as a result, are significantly more expensive than in comparable developed country markets.

Residential sector trends



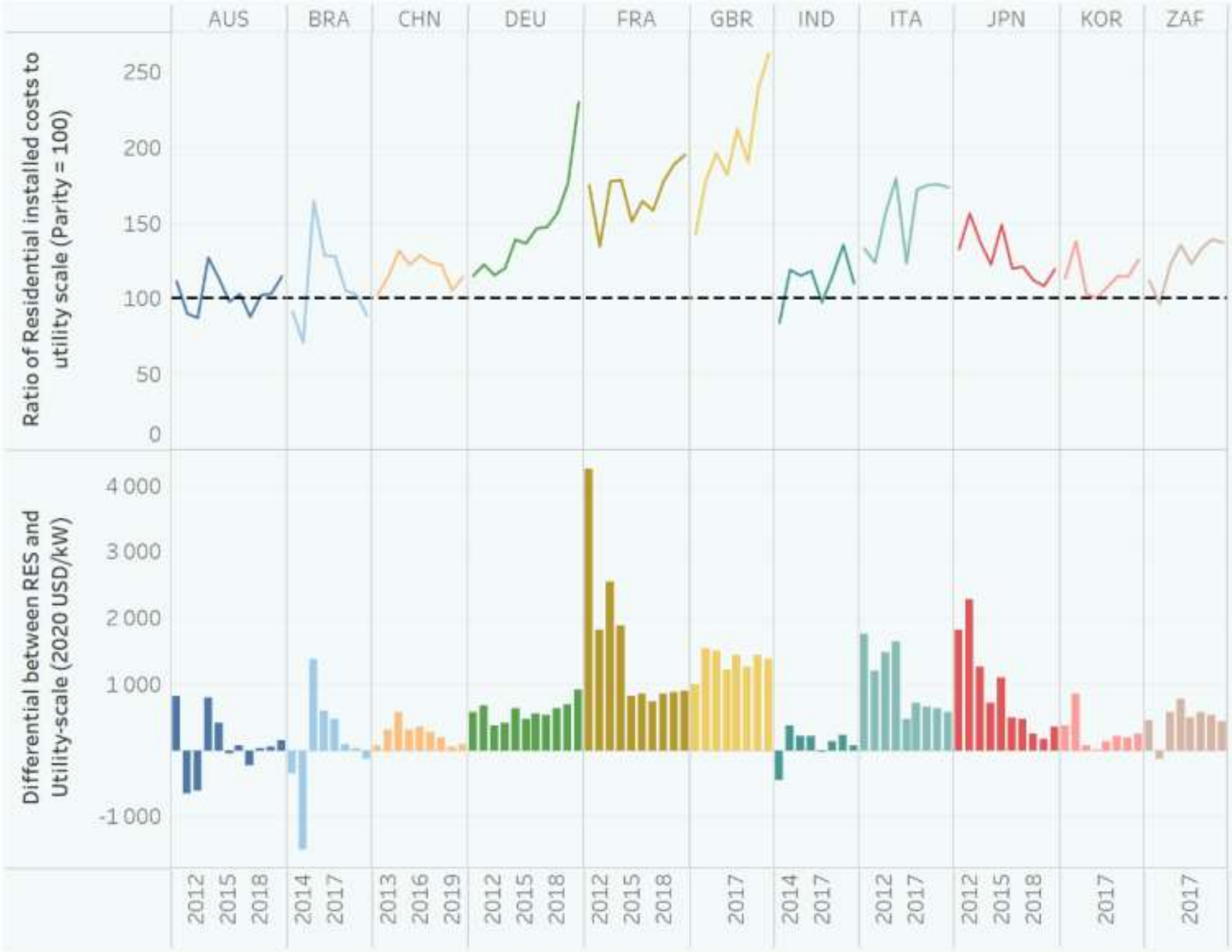
Comparing residential solar PV installed cost to utility-scale projects

The figure on the right shows the ratio of residential solar PV installed costs to the weighted-average utility scale value for that year, as well as the absolute difference between the two.

Australia and Brazil stand out as markets with, typically modest differentials between the two systems. This remains quite remarkable, although in both markets there is evidence that utility-scale systems are becoming more competitive.

France, Germany and the United Kingdom have all seen the relative cost premium of residential systems increase. This is because utility-scale costs have fallen faster than residential system costs, leading to a growing percentage difference.

Japan is the only market where residential system cost premiums declined strongly in both absolute and percentage terms.

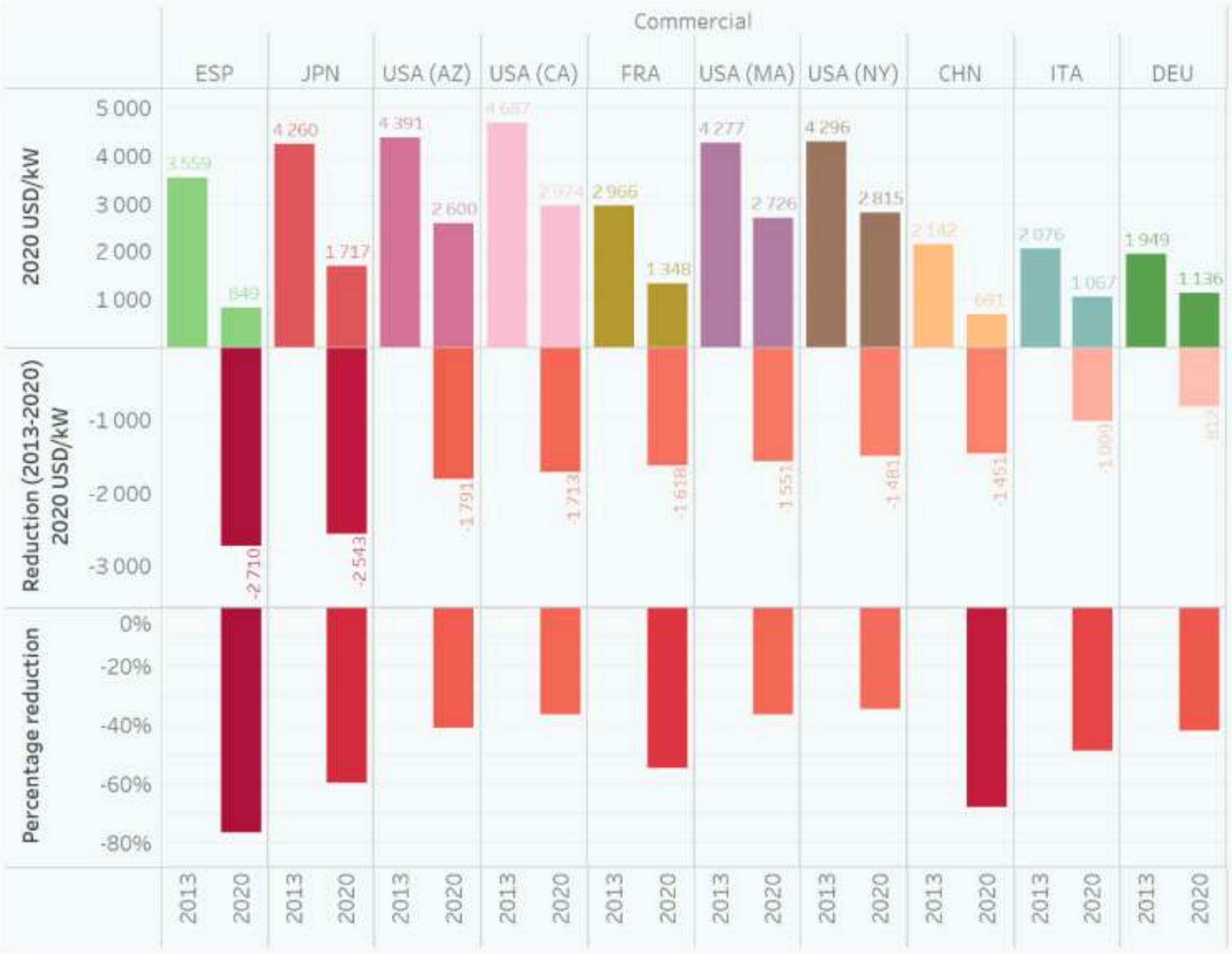


Commercial sector trends

Looking at the trend in installed costs between 2013 and 2020, Spain saw the largest absolute and percentage cost reduction for the larger commercial rooftop/ground mount segment, with a decline of USD 2 720/kW – a reduction around the same value as total installed costs for systems in Massachusetts in 2020.

Japan, also saw an impressive cost reduction over the period in view, making these systems potentially on a par with utility-scale systems, from a cost point of view, in that country.

China is also notable for seeing a very rapid reduction in costs to very competitive levels. Indeed, in China, commercial systems only cost slightly more than utility-scale systems. In 2020, Chinese commercial systems were also cheaper, on average, than utility-scale systems in almost all the other countries for which IRENA has robust data for.

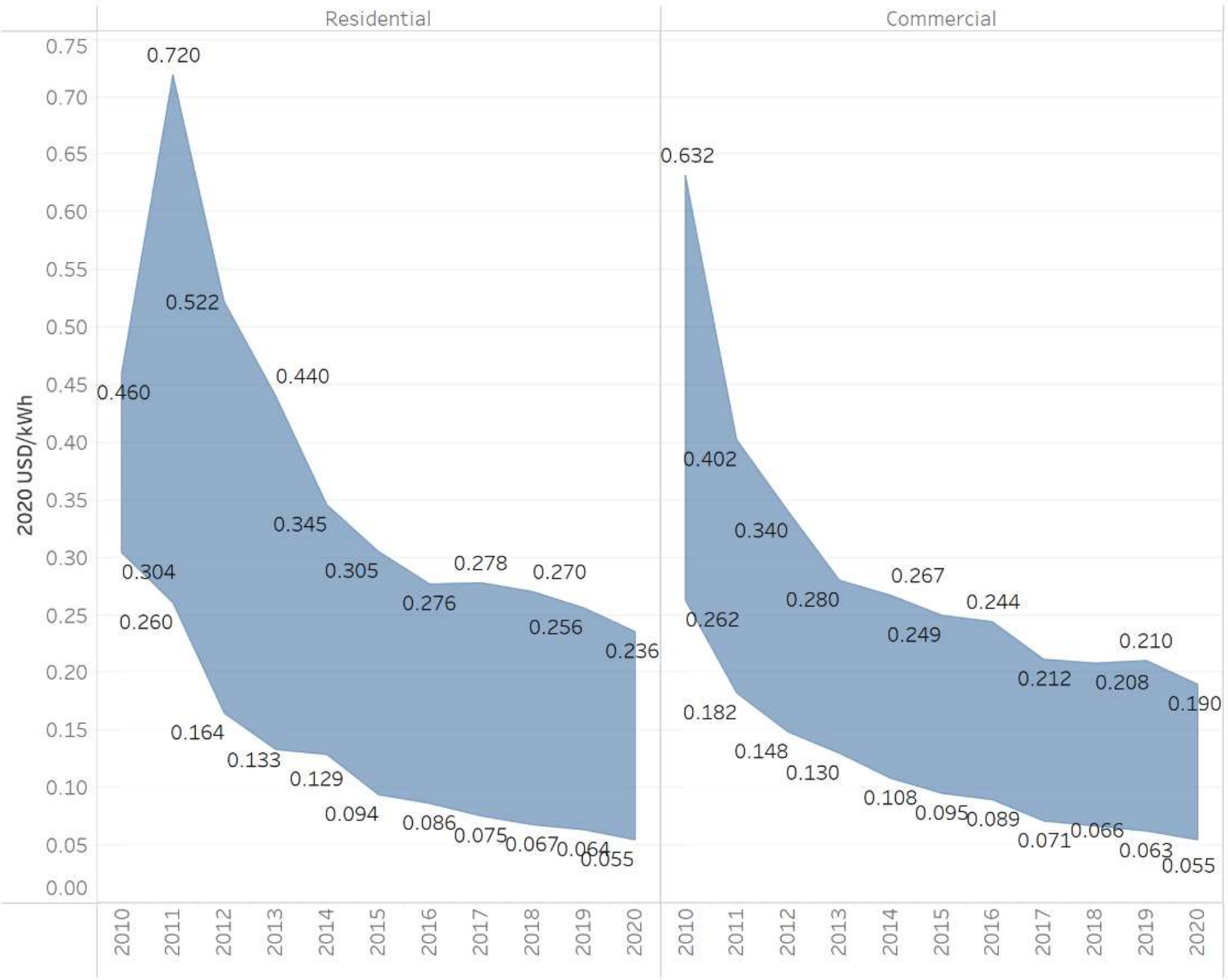


Residential and commercial sector levelised cost of electricity trends

The LCOE of residential PV systems also declined steeply over the period. Assuming a 5% weighted average cost of capital (WACC), the LCOE of residential PV systems in the markets tracked by IRENA declined from between USD 0.304/kWh and USD 0.460/kWh in 2010 to between USD 0.055/kW and USD 0.236/kWh in 2020 – a decline of between 49% and 82%. During 2020, the most competitive residential PV LCOE costs occurred in India, at USD 0.055/kWh, with Chinese costs 14% higher. The LCOE of residential systems in Australia was a quarter higher than in India.

Between 2010 and 2020, the LCOE for commercial PV up to 500 kW declined between 50% and 79% in those markets where data is available (Italy, France and the United States markets). During 2020, the LCOE in these markets ranged from USD 0.137 in France to USD 0.190/kWh in New York.

In 2020, the lowest average LCOEs for commercial PV up to 500 kW were in India and China, at USD 0.055/kWh and USD 0.060/kWh, respectively.



Concentrating solar power

Key insights

- Concentrating solar power (CSP) made remarkable progress over the 2010 to 2020 period, given that deployment has been modest, historically, and cumulative installed capacity is less than one-tenth of solar PV.

- Average project sizes increased from 54 MW in 2010 to 75 MW in 2020, with the emergence of commercial-scale solar towers (ST) to complement commercially-proven parabolic trough collector (PTC) plants.

- Total installed costs for CSP plants fell by 50% between 2010 and 2020, from USD 9 095/kW to USD 4 581/kW. Growing developer experience, more competitive supply chains, projects in markets with more competitive labour and civil engineering costs, larger project sizes, and competitive procurement of projects have all contributed to the reduction.

- The total installed costs of ST projects fell by two-thirds between 2011 and 2019, while those of PTC plants fell by 56% over the 2010 to 2020 period. Linear Fresnel development remains modest, but costs fell by 22% between 2012 and 2020.

- As costs for molten-salt thermal energy storage fell, the average project storage duration rose from 3.5 hours in 2010 to 11 hours of thermal storage capacity in 2020.

- Higher storage hours and other technology improvements have contributed to the global weighted-average capacity factor of new plants increasing from 30% in 2010 to 42% in 2020. Higher average operating temperatures, primarily due to the higher share of ST plants in 2020, saw average power block efficiencies increase.

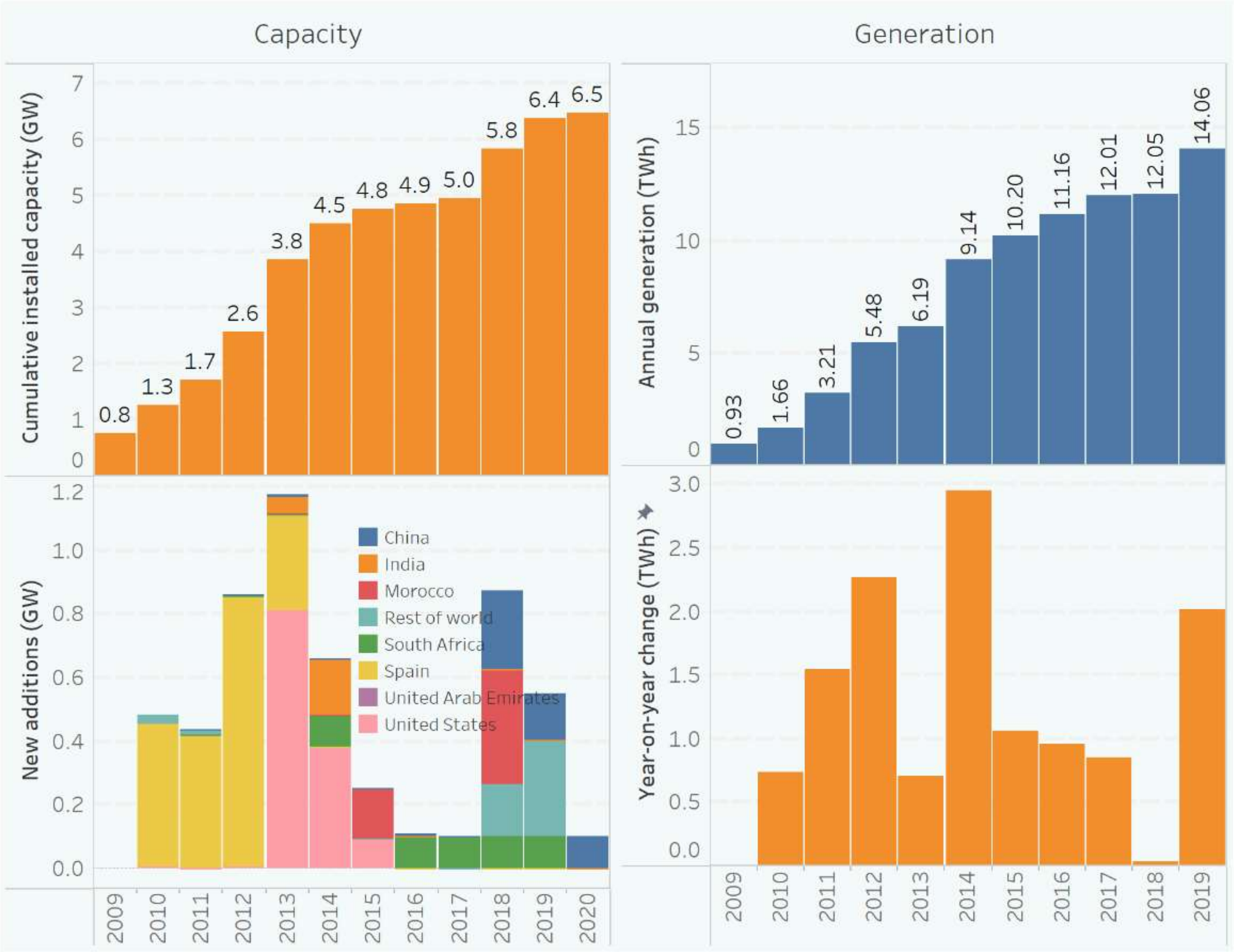
- The LCOE of newly commissioned CSP plants fell by 68% between 2010 and 2020, as installed costs fell (in part due to increasing economies of scale at the plant level) O&M costs declined, and capacity factors increased.

- The largest share (47%) of the more than two-thirds reduction in LCOE was due to the decline in the total installed cost of CSP plants, over the period. Improvements in technology and cost reductions in thermal energy storage – which led to projects with longer storage duration being commissioned in 2020 – led to an improvement in capacity factors. This, in turn, accounted for 28% of the reduction in LCOE over the 2010 to 2020 period. The assumed reduction in the WACC accounted for 20% of the total decline in LCOE during that time, while lower O&M costs accounted for the remainder (4%).

Market development

At the end of 2020, CSO's global cumulative installed capacity of CSP was less than 7 GW, a five-fold increase, globally, between 2010 and 2020.

The early years of last decade saw the re-emergence of CSP as a commercial technology, as a generous feed-in-tariff (FiT) in Spain kick-started a period of rapid development. Investment in the United States, funded under the US response to the 2007-2009 global financial crisis, sustained deployment until 2014. After modest activity in the period 2015 to 2017, which saw annual additions of between 100 MW and 200 MW per year – the global market for CSP grew during 2018 and 2019. In those years, an increasing number of projects came online in China, Morocco and South Africa. Some 150 MW was likely commissioned in 2020, although official statistics only capture 100 MW. Generation grew faster than deployment, given the increasing capacity factors of new plants.



CSP from 2010 to 2020

-70% Solar field costs

-50% Total installed costs

-68% Levelised cost of electricity

COSTS

PERFORMANCE

PTC aperture width **+24%**

Storage duration **+218%**

Capacity factor **+40%**

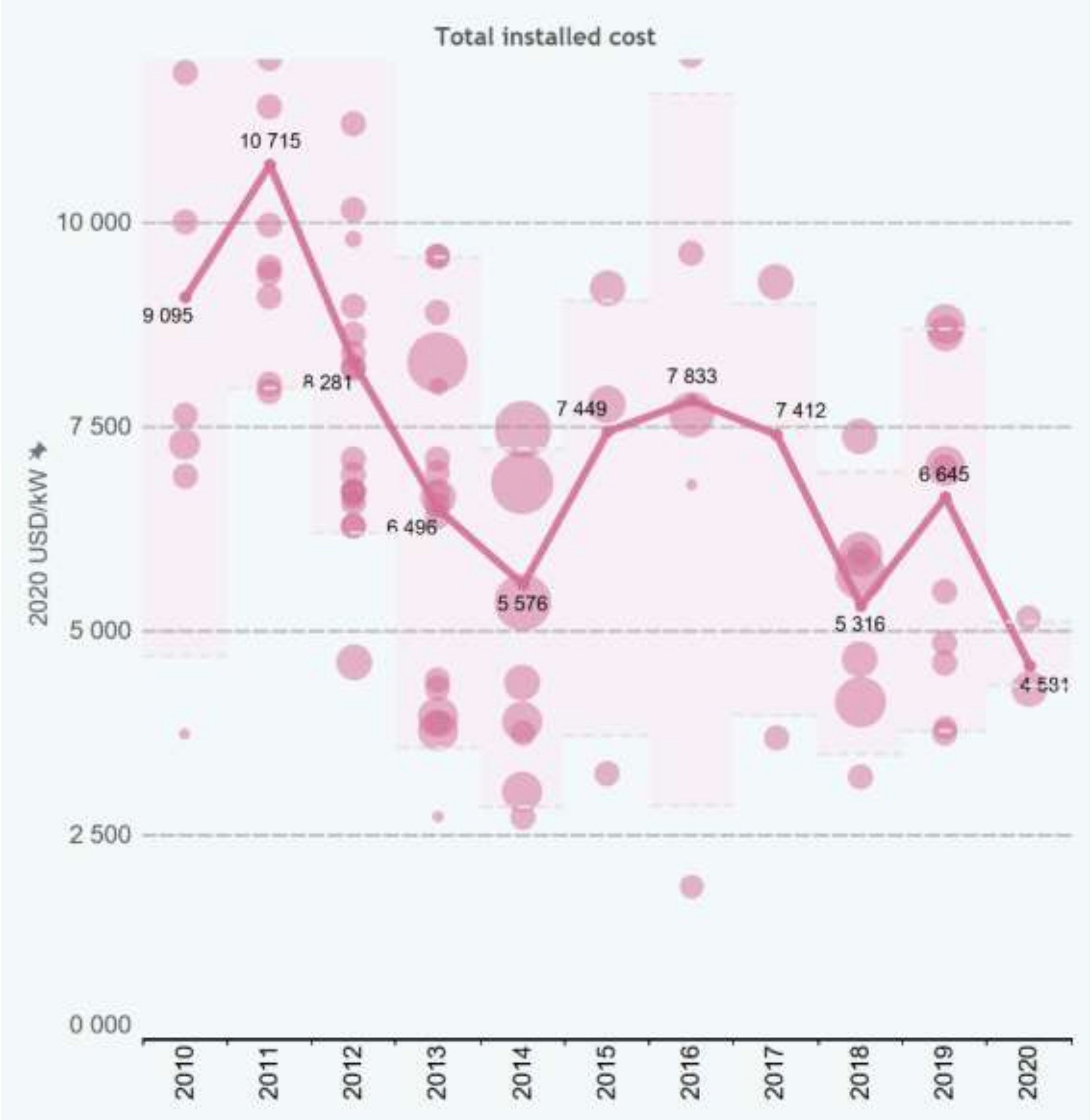
Total installed costs (2010-2020)

Total installed costs for CSP plants fell by 50% between 2010 and 2020, from USD 9 095/kW to USD 4 581/kW. Weighted-average total installed cost trends remained volatile, given the relatively thin market for CSP in any given year.

Despite this, there was a clear downward trend in costs, as the market grew from the early reboot of technology supported by Spain's FiT (which saw 2 022 MW commissioned between 2010 and 2013) to the more globally diversified market pf the period 2014 to 2020.

Growing developer experience, more competitive supply chains, projects in markets with more competitive labour and civil engineering costs, larger project sizes, and competitive procurement all contributed to reductions in installed costs over the period 2010 to 2020.

These cost reductions occurred despite projects increasingly incorporating larger thermal energy storage capacities over time, as will be seen in the following pages.

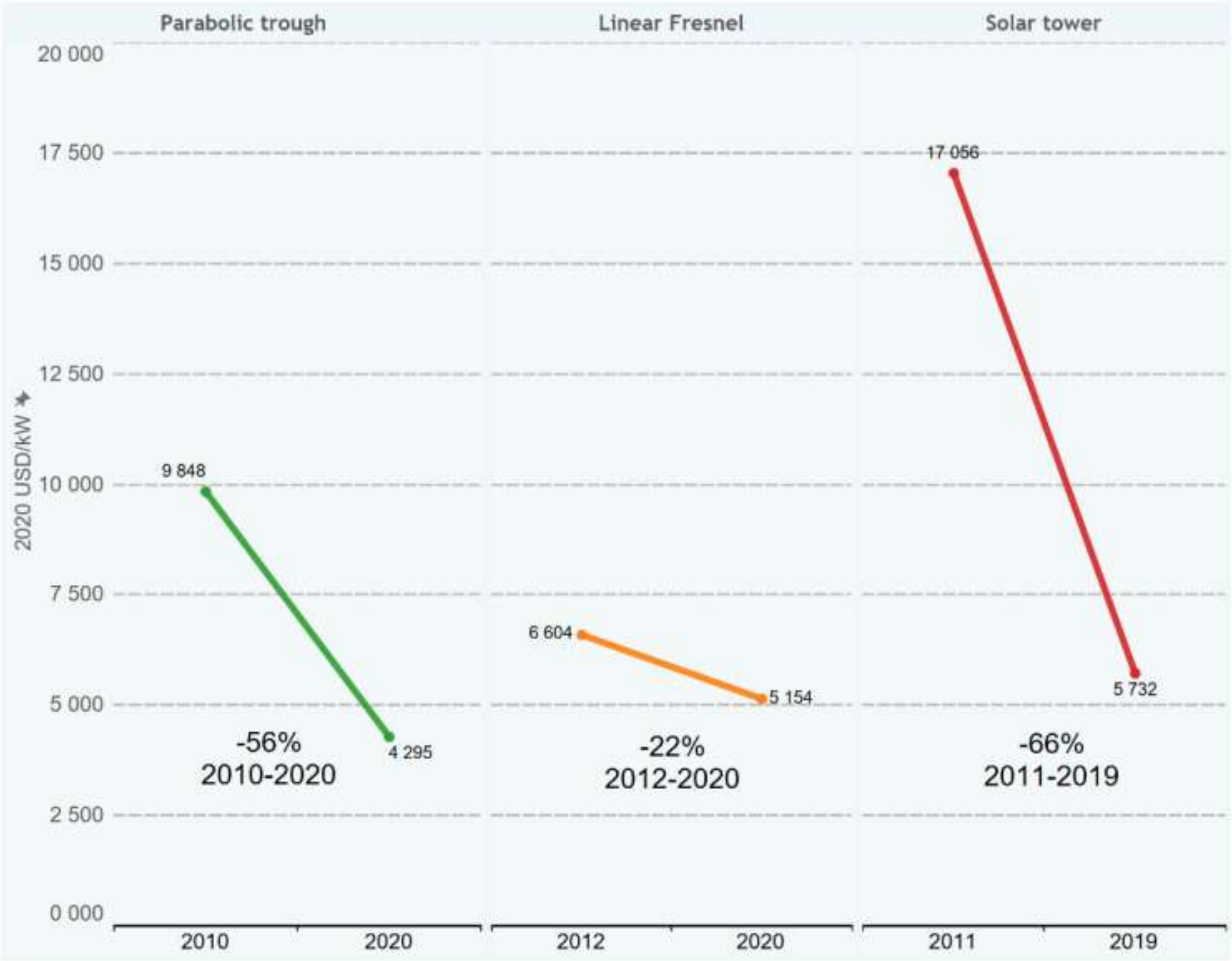


Total installed cost by technology (2010-2020)

PTC designs are commercially proven and represent the least technology risk, even as the technology continues to be improved. PTC has dominated deployment in the last decade and represents the bulk of the available data. The weighted-average total installed costs of new projects fell by 56% between 2010 and 2020, to an average of USD 4 295/kW in 2020.

Linear Fresnel plant deployment is much thinner, with the data available suggesting a cost decline of 22% for newly commissioned projects between 2012 and 2020.

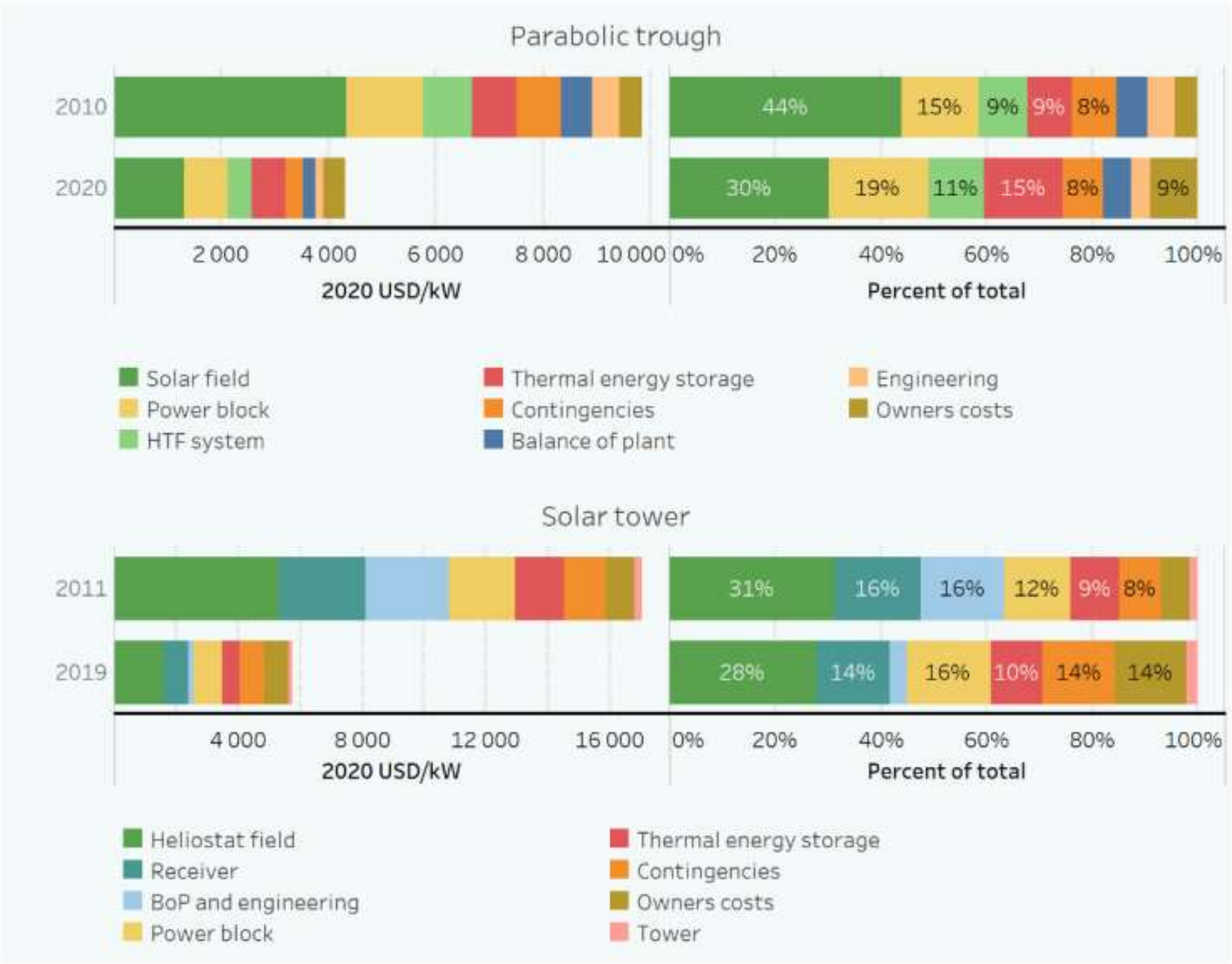
ST designs can achieve higher operating temperatures, which improves the power plant efficiency and reduces the volume of storage needed, given that a higher temperature differential is possible. While only a handful of such plants have been completed, the technology has grown from expensive small-scale commercial pilots to full-scale commercial projects in less than a decade.



Total installed cost breakdown by technology (2010 and 2020)

Although data on the total installed cost breakdown for 2010 relies on bottom-up techno-economic analyses (Hinkley, 2010; Fichtner, 2011), the data can be paired with IRENA's project level installed cost to get an understanding of the total installed cost breakdown in 2010/11 and 2019/20.

In 2010, the solar field cost an estimated USD 4 321/kW (44% of the total installed cost), but by 2020, this had fallen by 70% to USD 1 299/kW (30% of the total). With such a dramatic reduction in costs for the solar field, other cost areas with smaller declines saw their share of the total installed costs increase. The power block's share increased from 15% (USD 1 438/kW) in 2010 to 19% (USD 805/kW) in 2020, despite their costs falling by 44% over the period. This was also the case for the heat transfer fluid which increased its share from 9% (USD 909/kW) to 11% (USD 454/kW), despite these costs per kW falling by half over the period. This also occurred for thermal energy



storage which increased from 9% (USD 837/kW) to 15% (USD 637/kW) and owner's costs which rose from 5% (USD 446/kW) to 9% (USD 385/kW).

The costs of the balance of plant, engineering, and contingencies for PTC plants declined by 62%, 67% and 60% respectively over the 2010 to 2020 period. As a result, the share of balance of plant in total installed costs declined from USD 601/kW (6% of the total) to USD 228/kW (5%) between 2010 and 2020, while engineering costs fell from USD 486/kW (5% of the total) to USD 163/kW (4%).

A measure of how far the weighted-average total installed costs for PTC plants have fallen is the fact that the costs of the solar field alone in 2010 were 1% higher than the weighted-average total installed cost in 2020.

For ST plants, this comparison is very similar. The reduction in the cost of the heliostat field was significant, with costs falling 70% from USD 5 336/kW in 2011 to USD 1 595/kW in 2019, driving down the field's share of total installed costs from 31% to 28%. As a result, in 2019, the total installed cost of USD 5 732/kW, was only 7% higher than the cost of the heliostat field alone just eight years previous.

The cost of the receiver fell by 71% from USD 2 768/kW to USD 791/kW over the same period, with its share of total costs falling from 16% to 14%. Balance of plant and engineering saw the largest reduction, from USD 2 707/kW in 2011 to USD 198/kW in 2019, a decline of 93%, making its share of costs fall from 16% to just 3%.

Contingencies remain an important overall cost component, despite falling by 42% between 2011 and 2019 from USD 1 371/kW to USD 792/kW. At 14% of overall costs, in absolute terms, contingencies were still more than twice as high as those for PTC plants, per kilowatt. This is likely to reflect the fact that experience with STs remains relatively limited, with the replicability of their development and construction processes still holding greater uncertainty than for PTC plants. The latter have a longer commercial track record and a significantly larger number of installed projects. This may also be why owner's costs have fallen by only 12% over the period, with their share of overall costs increasing to 14% in 2019.

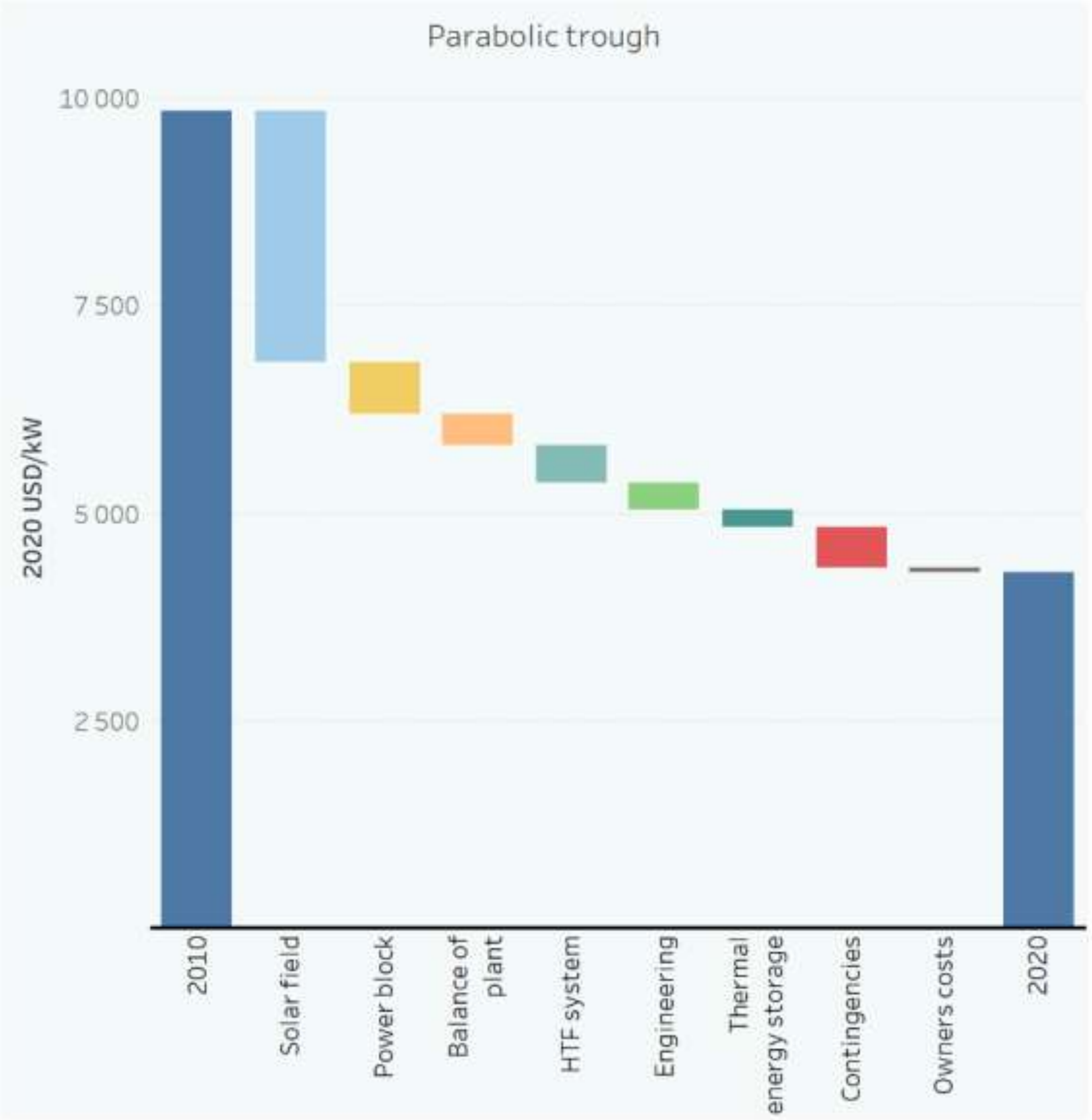
Total installed cost breakdown by technology (2010-2020)

Although data on the total installed cost breakdown for 2010 relies on bottom-up techno-economic analyses (Hinkley, 2010; Fichtner, 2011), it can be paired with IRENA's project level installed cost to get an understanding of where the greatest cost reductions have been achieved.

For PTC plants, the 56% reduction represents a fall of USD 5553/kW. Over half of this reduction occurred in the solar field (54%), driven by the fact that this was by far the largest cost component in 2010 (44% of the total), falling 70% from an estimated USD 4 321/kW in 2010 to USD 1 299/kW in 2020.

The next largest categories for cost reduction were the power block (11% of the total), contingencies (9%), the heat transfer fluid (HTF) system (8%), engineering (6%), thermal energy storage (4%) and owners costs (1%).

Aside from the solar field cost, the categories with the greatest percentage reduction per kW were engineering costs (down 67%), followed by balance of plant costs and contingencies, which fell by 62% and 60% respectively.

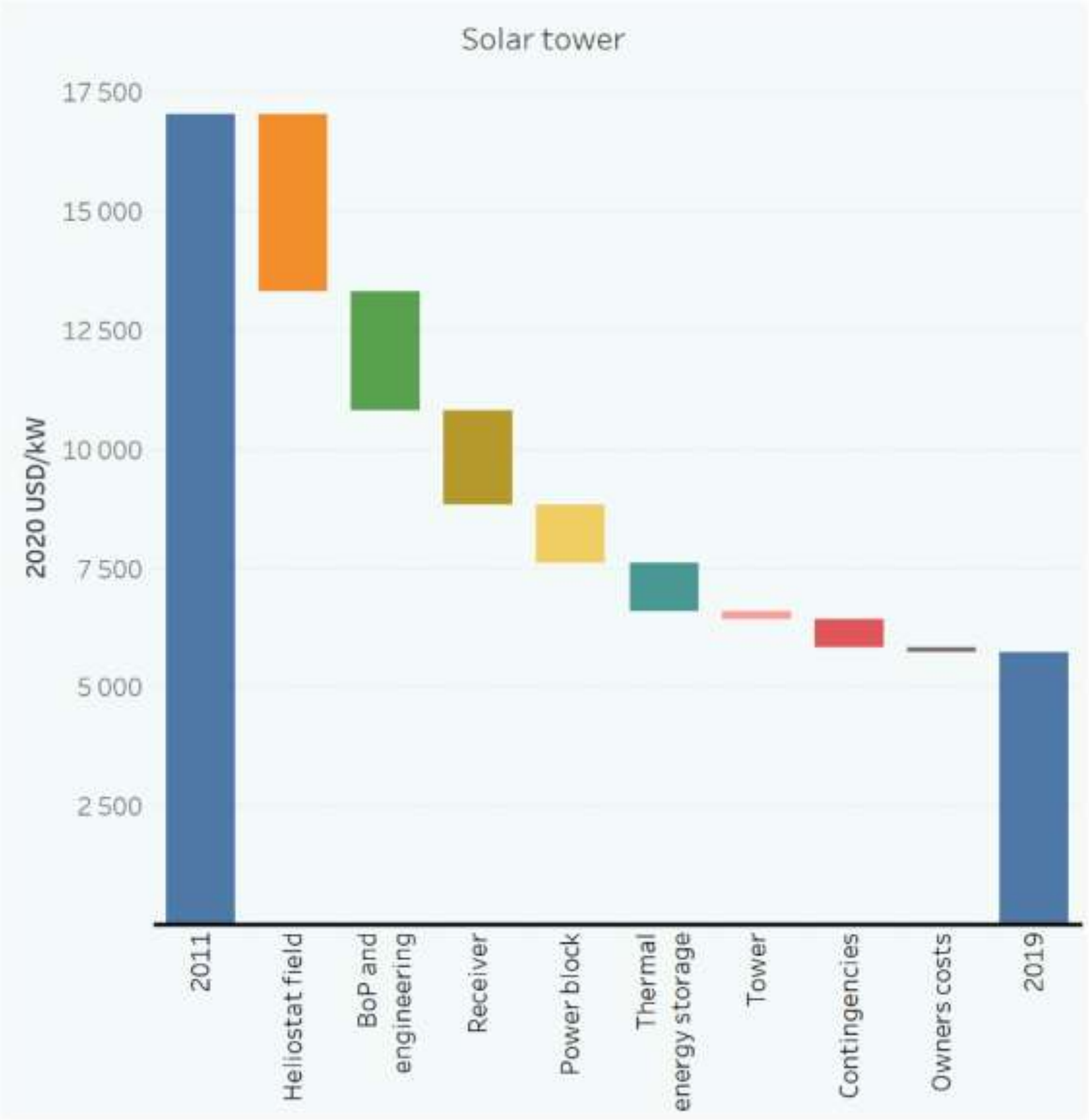


PTC total installed cost breakdown by technology (2010-2020)

Similar caveats apply to the analysis of total installed cost breakdowns for both ST and PTC plants. An additional complication, however, is that during the period 2010 to 2020, ST went from small, commercial plant size (around 20 MW) to true utility-scale projects of 100 MW+. Total installed costs therefore fell by USD 11 324/kW between 2010 and 2020 to USD 5 732 by the end of that period.

Cost reductions were more evenly distributed in ST than for PTC plants. Again, the largest single reduction was the heliostat (solar) field, which declined by USD 3 741/kW. This accounted for a third of the total cost reduction and by 2020 was 70% less than its level in 2010. The next largest contributor was in the balance of plant and engineering category, where costs declined 93%, accounting for 22% of the total reduction in specific costs. Reduction in the receiver, power block and thermal energy storage system costs accounted for 17%, 11% and 9% of the total cost reduction specifically, with costs for these items falling between 58% and 71% over the period.

The cost reductions experienced represent the improved economies of scale of larger plants, greater developer experience, improved technology, more competitive supply chains and a structural shift to markets with lower labour and – in some cases – materials costs.



Project size and storage hours (2010-2020)

Average project sizes have risen over time, in order to unlock economies of scale and as competitive procurement has encouraged greater developer choice in plant specifications. Both the early period of development in Spain and the more recent one in China were characterised by smaller, 50 MW projects. In China's case, these were predominantly technology demonstration projects and among 20 initial pilot schemes. It is likely that future commercial projects will gravitate towards the 100 MW to 150 MW range, which represents the economic optimum in most locations.

As the market has matured, the costs of thermal energy storage have declined. This is the result both of declining capital costs and of higher operating temperatures, which allow larger temperature differentials in the molten salt storage systems, increasing the energy stored for the same volume. The result has been an increase in the weighted-average storage hours through time, with this rising more than three-fold between 2010 and 2020, from 3.5 hours for projects commissioned in 2010 to 11 hours for those in 2020.

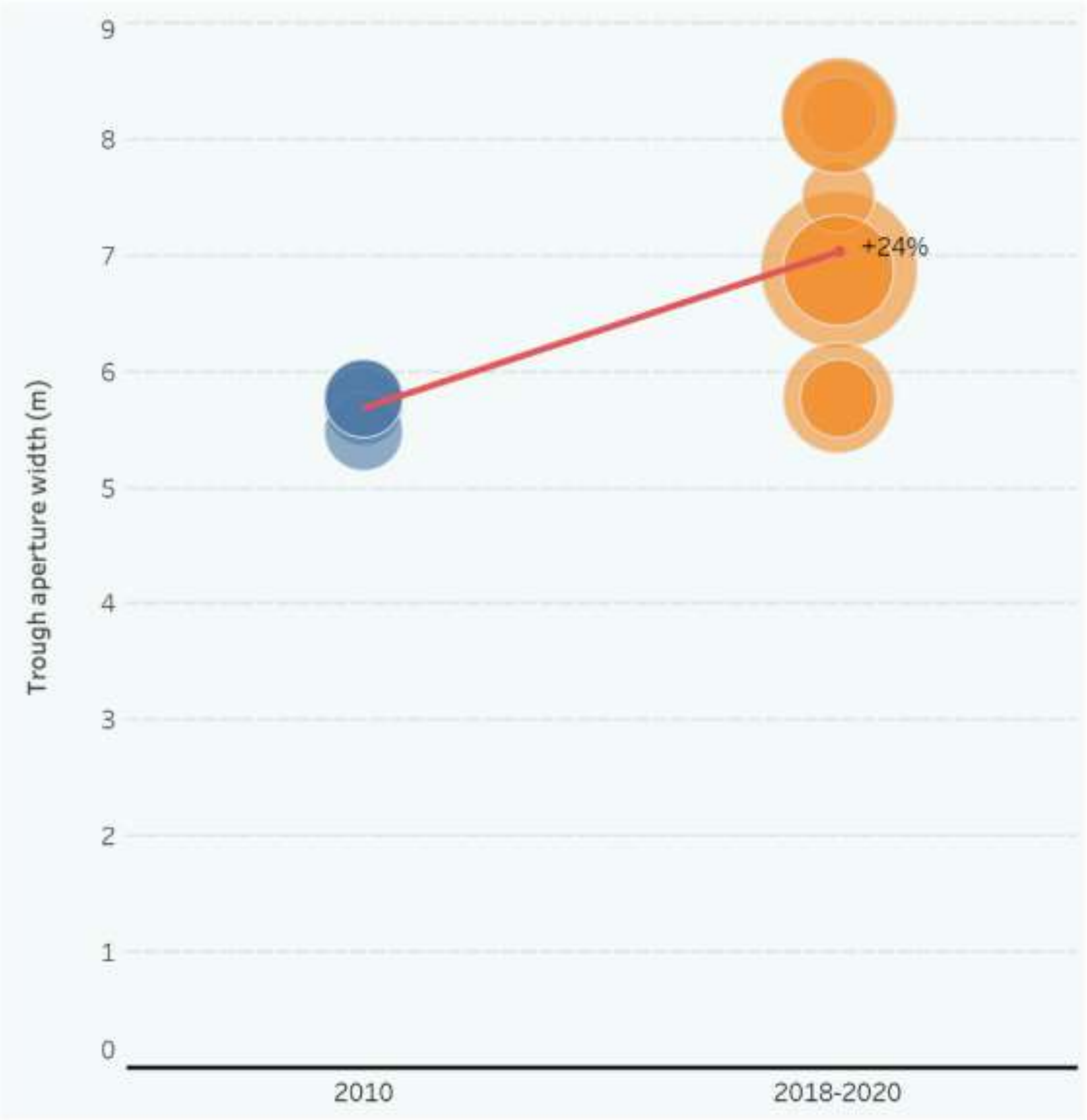
CSP plants are now routinely being designed to meet evening peaks and overnight demand. CSP with low-cost thermal energy storage has the ability to integrate higher shares of variable solar and wind power, meaning that while often underrated, CSP could play an increasingly important role in the future.

Parabolic trough aperture width

Cost reductions have been pursued by trying to reduce the costs of the parabolic troughs themselves and by improving their performance. Essentially, the challenge has been to raise absorption of solar heat and reduce heat losses in the HTF conveyed to the power block, while at the same time, reducing the capital cost of these components.

Improvements in special coatings on the absorber tube and insulation measures for the receiver have helped reduce thermal losses. To reduce capital costs, efforts have focused on reducing materials costs relative to heat generation. To the extent possible, given the loads on the structure, light-weighting of the mirrors and supporting frameworks has been pursued. Aperture widths have also been increased to allow for greater solar radiation to be focused.

Between 2010 and the 2018 to 2020 period, the weighted-average aperture width of the parabolic troughs used in projects increased from around 5.7 metres (m) to around 7 m. In 2010, Spanish projects were dominant, using troughs with widths in the relatively narrow range of 5.5 m to 5.8 m. In the period 2018 to 2020, although deployment had slowed, it was more geographically diverse and used a wider range of troughs. These went from 5.8 m widths – not dissimilar to in 2010 (in two projects) – to larger 8.2 m ‘Space tube’ troughs.



Capacity factors

Between 2010 and 2020, the capacity factor of CSP plants increased 40%, from 30% to 41.9% as the technology improved, costs for thermal energy storage declined and the average number of hours of storage for commissioned projects increased.

The capacity factor of a CSP project is driven by the quality of the solar resource and the technology configuration. The incorporation of low-cost thermal energy storage can increase the capacity factor. Up to a certain point, given that there are diminishing marginal returns, it can also reduce the LCOE.

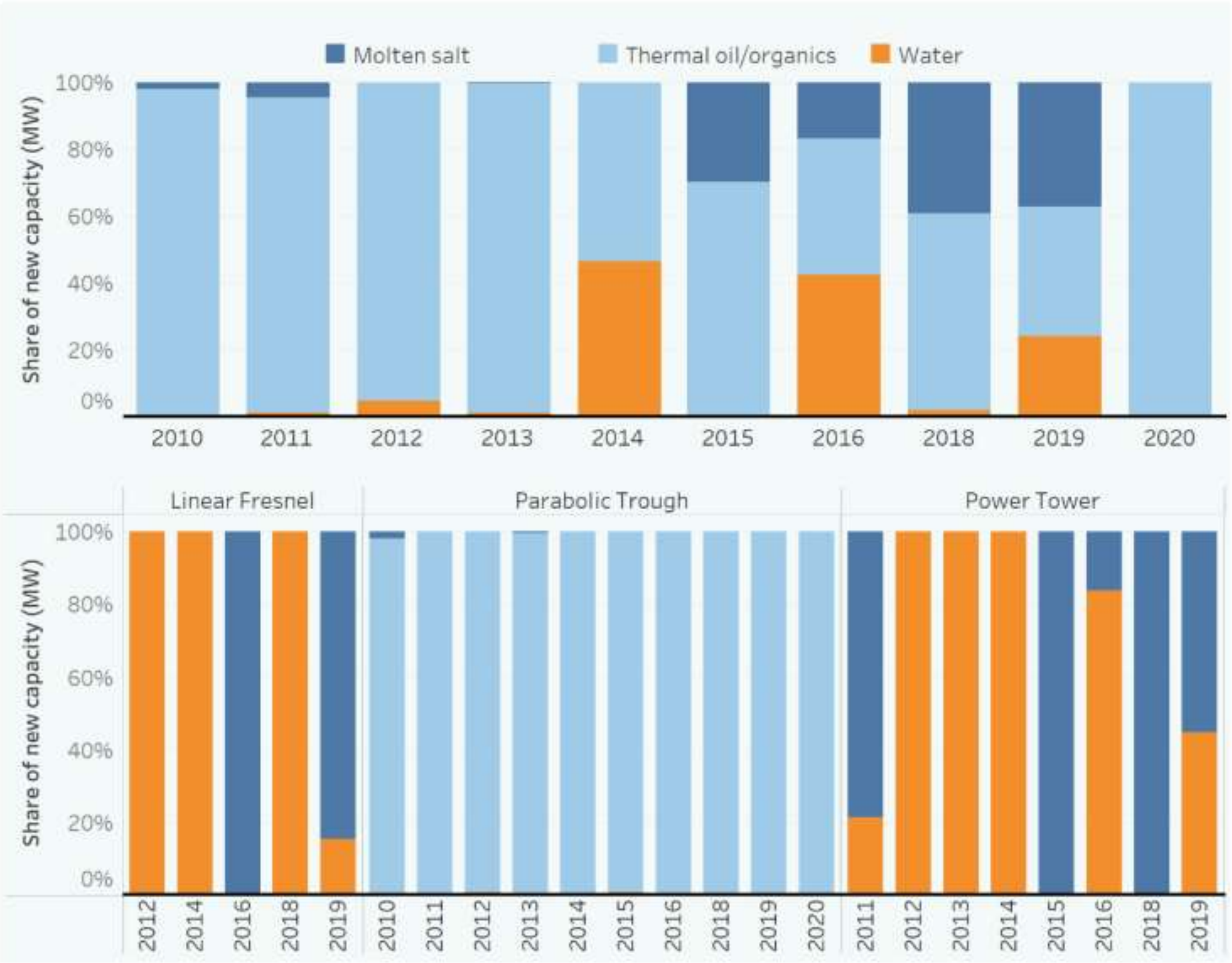
Higher capacity factors from higher levels of storage, do come with trade-offs, however. Increasing solar field size is required to charge the molten salt storage during sunshine hours? As well as maintain daytime generation. Yet, given the increased output helps to amortise all the other capital costs, minimum LCOE is usually achieved with storage in the 9-13 hours range, with a flat curve somewhat before and after. This implies little cost premium for the flexibility of having more or less storage, depending on the needs of the local market.

Heat transfer fluid trends

The HTF fluid plays a vital role in a CSP plant and needs to meet a variety of criteria to be effective, maximising temperatures and minimising losses. The HTF needs to be a liquid that should not degrade at high temperatures and ideally have a low freezing point – in order to avoid expensive freeze protection measures. It should also be highly conductive and have a high specific heat capacity.

The dominant HTF used in PTC plants remains synthetic mineral oils. These have a proven track record and quite high specific heat capacities, but are, however limited to a temperature up to around 400ºC. As they age and begin to deteriorate, these oils also need to be replenished over time, which is relatively expensive.

With STs, two primary solutions to this are: direct steam generation and the use of molten salts. Thus, in years with ST deployment, we see a greater mix of HTF's deployed and thus operating temperatures, as we will see next.

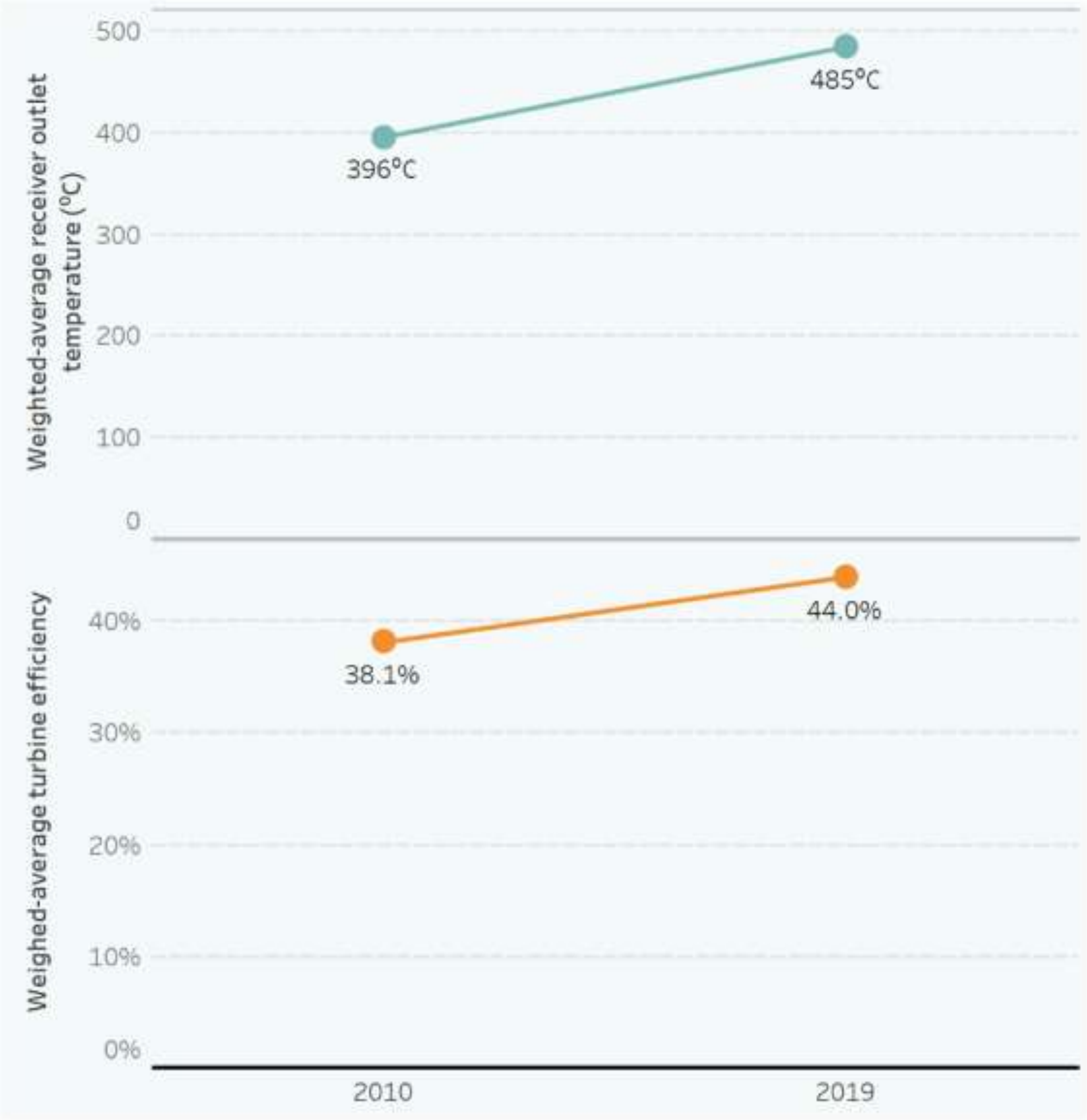


Receiver outlet temperatures and turbine efficiency

With the increased share of STs in deployment, the increased operating temperatures made possible by the use of molten salt HTF's or direct steam generation saw weighted-average receiver outlet temperatures increase. These rose from 396°C in 2010 when PTC plants represented all capacity added for which there is data, to 485°C in 2019, as STs with receiver outlet temperatures ranging from 560°C to 565°C were commissioned.

Higher temperature differentials in the hot- cold tanks allow greater energy to be stored for a given volume. Yet, the benefit of higher operating temperatures is not just lower cost thermal energy storage, but also that they allow for more efficient steam cycles to recover more electricity from the available resource. With the increasing share of STs, the weighted-average turbine efficiency for projects where data is available rose from 38% in 2010 to 44% in 2019.

While efforts continue to commercialise molten salts as an HTF for PTC plants, for the moment, the largest efficiency gains and potential for longer storage remains with ST plants that can already operate at higher temperatures and efficiencies. Greater scale in deployment of STs would help to narrow the installed cost premium over PTC pants they currently face, potentially allowing them a decisive advantage over PTC in LCOE terms, in areas where the air is clear.

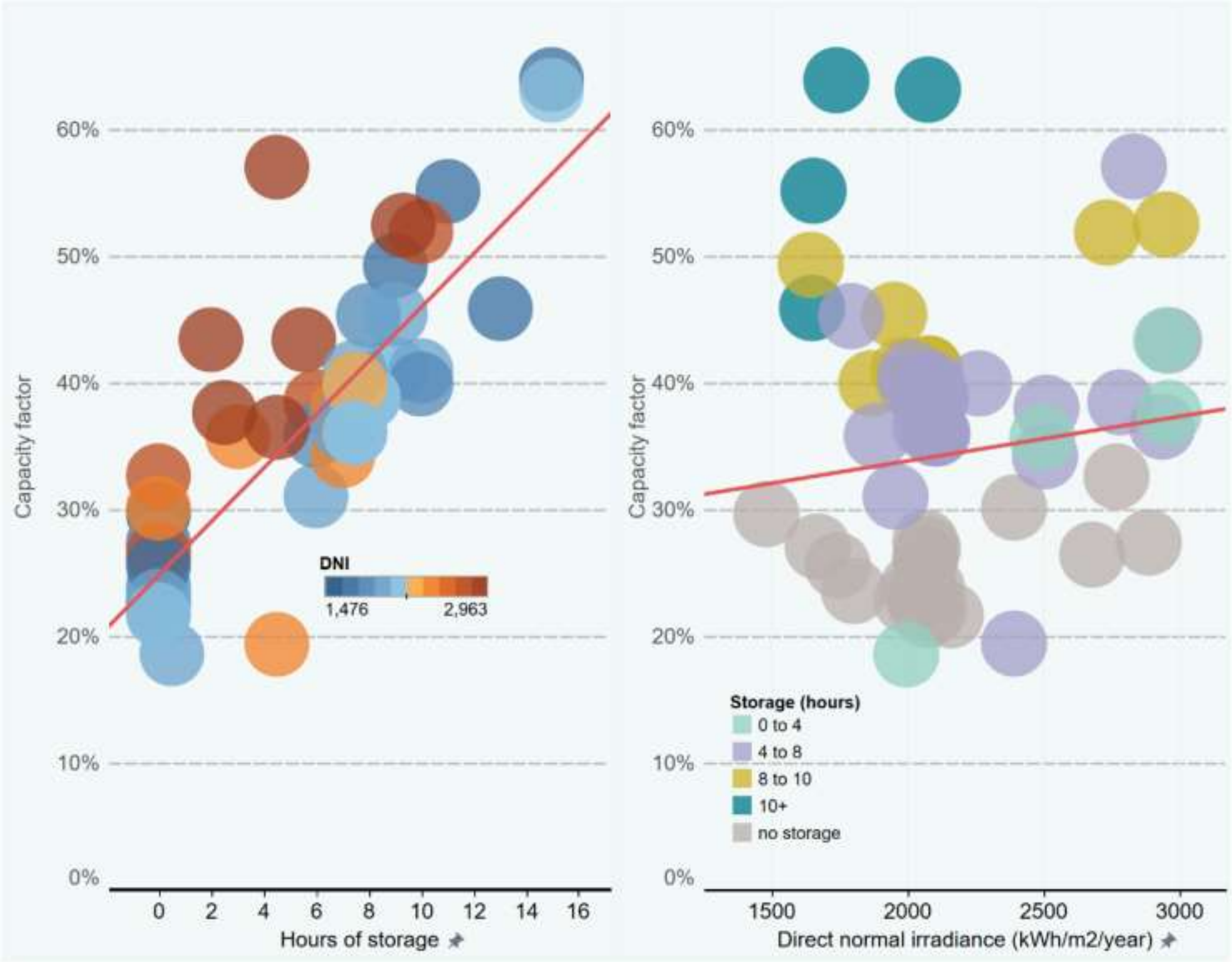


Capacity factors, storage hours and the solar resource

Although higher direct normal irradiation (DNI) leads to larger capacity factors, all else being equal, there is a much stronger correlation between capacity factors and storage hours. This is, however, only one part of the economics of plants at higher DNI locations. Higher DNIs also reduce the field size needed for a given project capacity – and hence the investment.

Yet, technology improvements and cost reductions for thermal energy storage also mean that higher capacity factors can be achieved even in areas without world class DNI.

The impact of higher storage levels is evident in the 2020 data. This shows that newly commissioned plants had a weighted-average capacity factor of 42%, with an average DNI that was lower than for plants commissioned between 2010 and 2013, inclusive. That was a period when the weighted-average capacity factor was between 27% and 35% for newly commissioned plants.

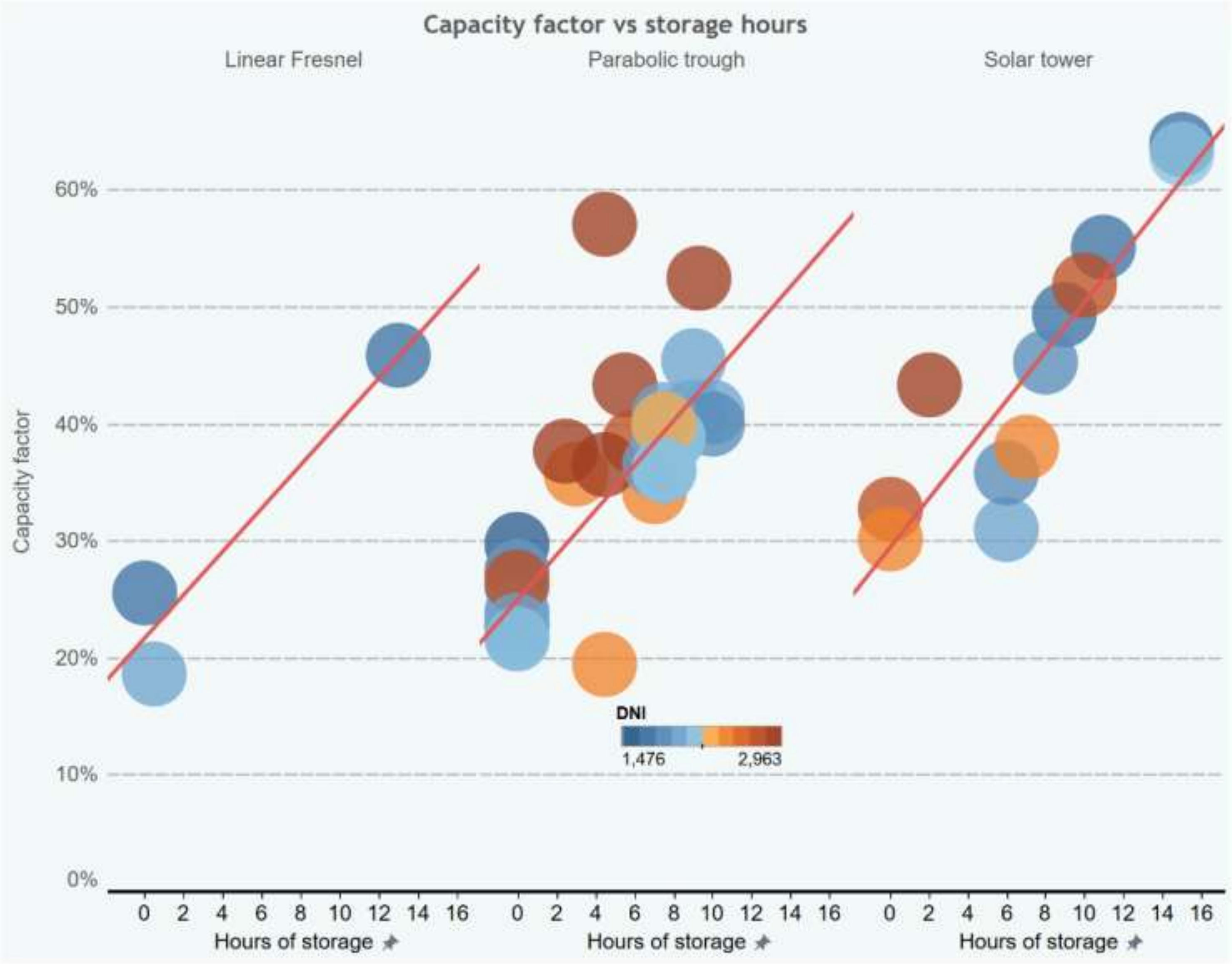


Capacity factors, storage hours and the solar resource by technology

The strong relationship between storage hours and capacity factors holds true even when examining the data for each of the three commercial technologies deployed at utility-scale.

Data for PTC projects are the most numerous, with 54 schemes covered. This data highlights both the importance of DNI and storage on capacity factors, with projects in South Africa in areas with excellent DNI (2 800-2 900 kilowatt hours (kWh)/cubic metre (m^3)/year) having higher capacity factors than projects in lower DNI areas.

The smaller number of ST projects for which there is data (12), suggests a slightly stronger correlation between storage hours and capacity factors than even for PTC plants. This maybe the result of the influence of higher operating temperatures, but care should be taken in interpreting this result, given the large difference in sample sizes for the two technologies.



Operations and maintenance costs

All-in O&M costs, which include insurance and other asset management costs, are substantial compared to solar PV and onshore wind.

Typical O&M costs for early CSP plants still in operation today range from USD 0.02/kWh to USD 0.04/kWh. This is likely a good approximation for the current levels of O&M in relevant markets for projects built in and around 2010.

In collaboration with DLR, analysis by IRENA, however, shows that more competitive O&M costs are possible in a range of projects that achieved financial closure in 2019 and 2020. In many markets, the O&M costs for CSP are high in absolute terms, per kWh, compared to solar PV and many onshore wind farms, but are about 18% to 20% of the LCOE for projects in G20 countries. All-in O&M costs declined from an average of USD 0.03/kWh in 2010 to USD 0.02/kWh in 2020.

Lower CSP O&M costs contributed about 4% to the LCOE reduction for CSP between 2010 and 2020.

All-in (insurance included) O&M cost estimates for CSP, 2019-2020

Country	Parabolic trough collectors (2020 USD/kWh)	Solar tower (2020 USD/kWh)
Argentina	0.025	0.023
Australia	0.027	0.026
Brazil	0.020	0.020
China	0.021	0.018
France	0.032	0.027
India	0.015	0.015
Italy	0.025	0.023
Mexico	0.016	0.015
Morocco	0.013	0.012
Russian Federation	0.024	0.022
Saudi Arabia	0.012	0.011
South Africa	0.013	0.012
Spain	0.024	0.022
Turkey	0.018	0.016
United Arab Emirates	0.018	0.020
United States of America	0.024	0.021

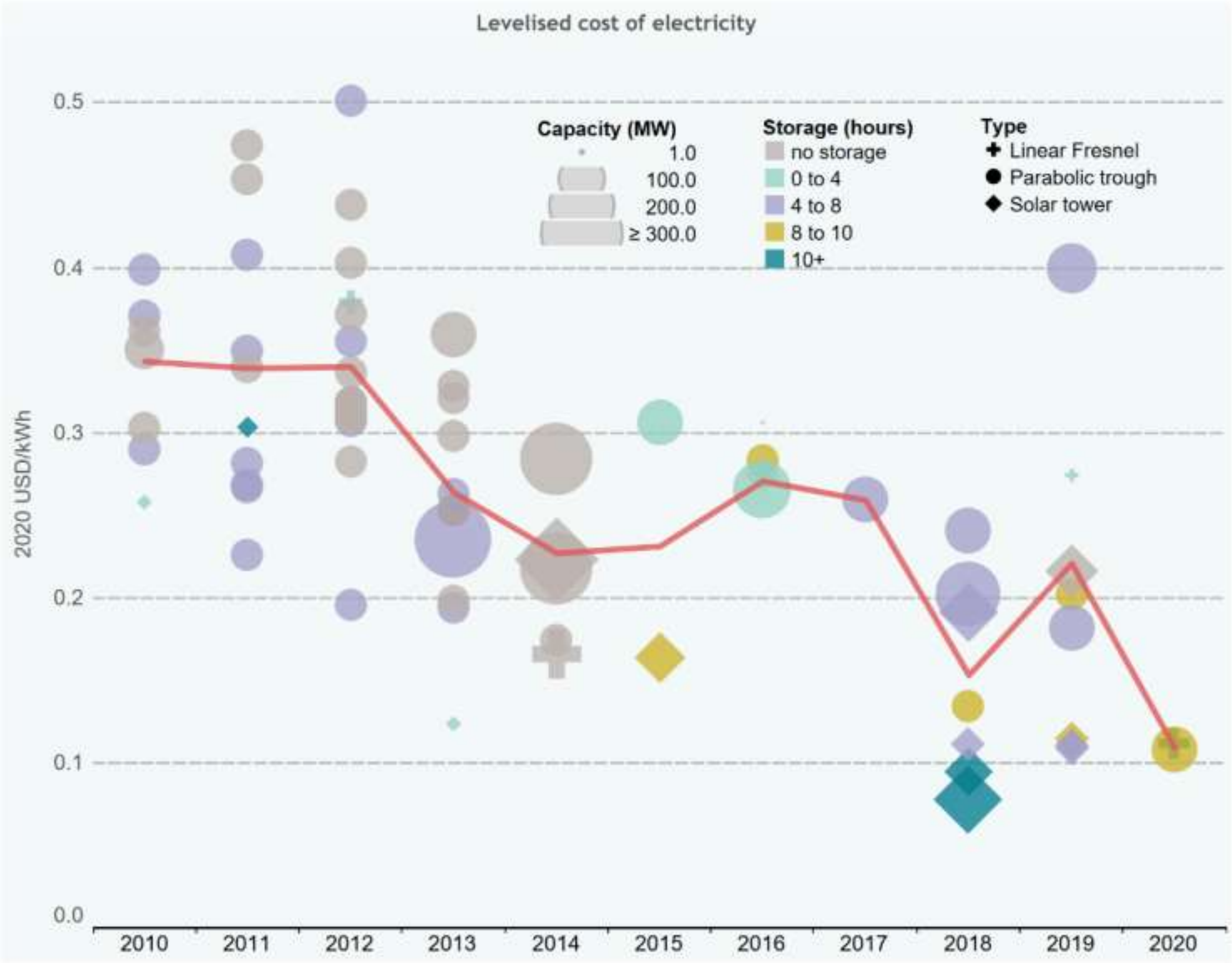
Source: IRENA Renewable Cost Database

Levelised cost of electricity (2010-2020)

The LCOE of newly commissioned CSP plants fell by 68% between 2010 and 2020, as O&M costs declined, capacity factors increased and installed costs fell – in part due to increasing economies of scale at the plant level.

The 50% reduction in the global weighted-average total installed costs of newly commissioned projects was the most important contributor to the overall reduction in LCOE. The increase in capacity factors from 30% to 42% (a 41% increase) was also very important. The overall contribution of a one-third reduction in O&M costs over the period is more muted, and is surpassed by the reduction in the WACC estimated for the period.

The competitive nature of the ST projects that were commissioned in 2018 and 2019, also saw the weighted-average LCOE fall within the range of fossil fuel-fired power costs, in 2018 and 2020 (IRENA, 2020a).

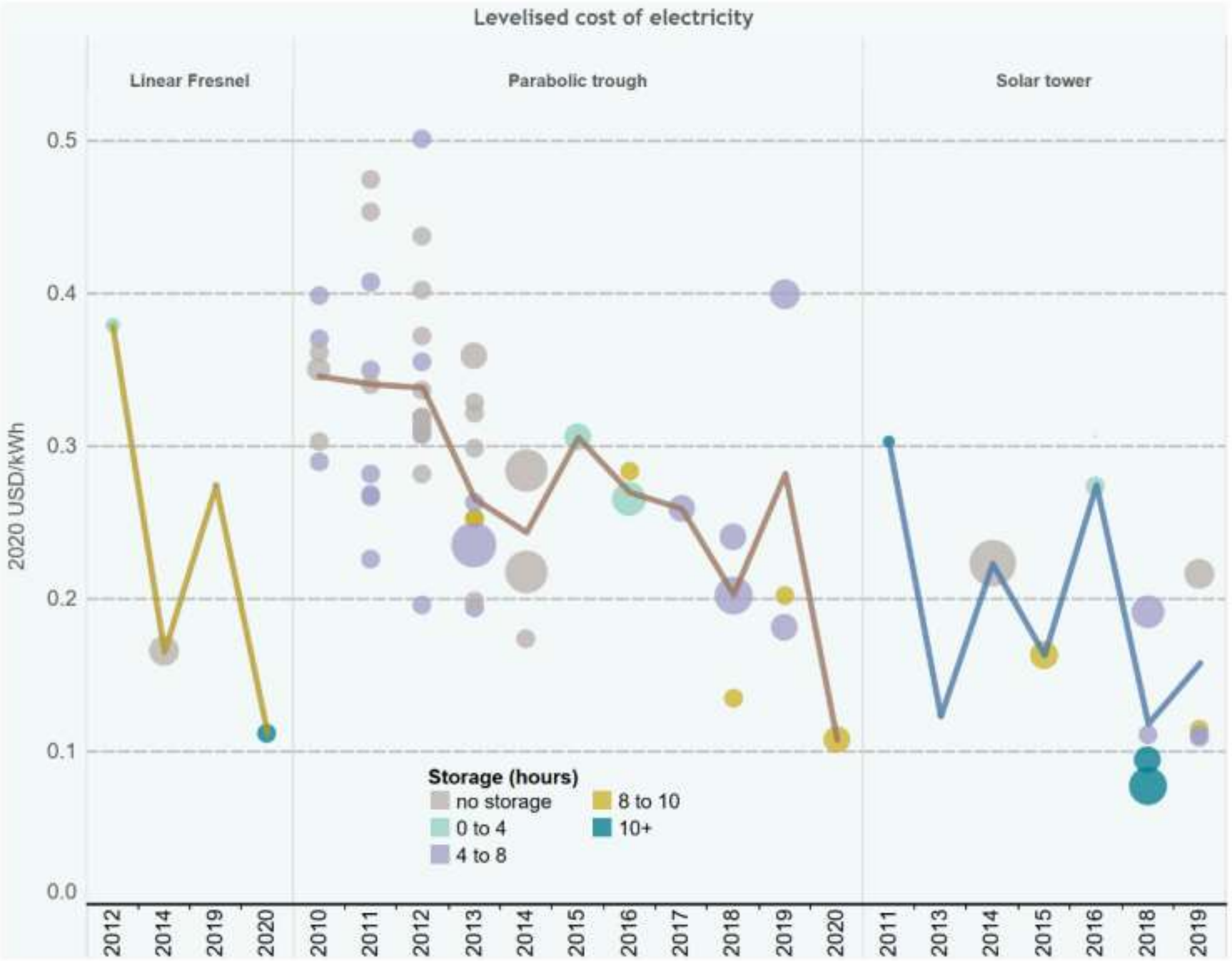


Levelised cost of electricity by technology (2010-2020)

The LCOE of newly commissioned linear Fresnel CSP plants fell by 70% between 2012 and 2020, but to date, the technology remains underrepresented in deployment terms . The LCOE of the projects in the cost database fell from USD 0.379/kWh in 2010 to USD 0.112/kWh in 2020.

Between 2010 and 2020, the weighted-average LCOE of PTC plants fell by 69%, from USD 0.346/kWh to USD 0.108/kWh. With thinner deployment after 2014, the weighted-average LCOE was heavily influenced by individual projects, and in 2019 the commissioning of a much-delayed Israeli project raised the average.

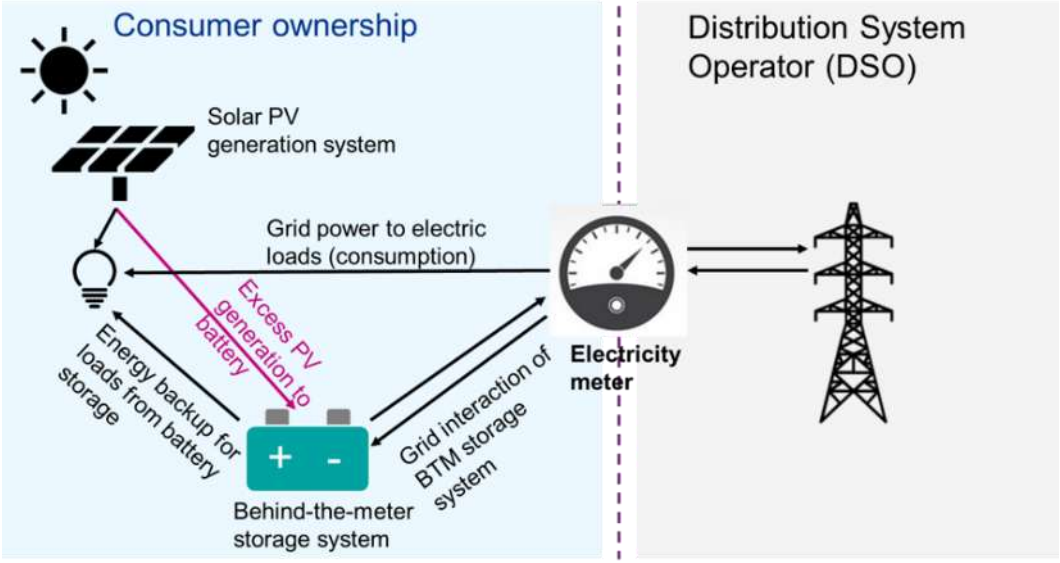
Between 2011 and 2019, the LCOE of ST projects fell by 48% from USD 0.303/kWh to USD 0.158/kWh. If the delayed Israeli ST project, which has costs more in line with the 2015/2016 period, is excluded, the reduction increases to 63%, which may be considered a more reasonable estimate of progress.



Behind-the-meter batteries

Growth drivers

- Significant potential for growth in behind-the-meter applications remains. Notably, this is in small-scale systems associated with PV, enabling an increase in self-consumption, or, potentially, in response to incentives from grid operators and/or distribution companies to manage grid feed-in.
- Currently, where the right regulatory structure is in place (*e.g.* Germany), or in areas with high electricity prices, excellent solar resources and relatively low grid feed-in remuneration (*e.g.* Australia), significant battery storage associated with new PV installations continues to emerge.
- In Germany, recent years have seen as much as 40% of total annual small-scale solar PV installations undertaken together with battery storage. The share of new PV systems installed with storage rose to about 60% during 2019, with preliminary reports putting this figure closer to 70% during 2020 (Figgener *et al.*, 2021; BVES, 2021). PV systems help insulate home owners from experiencing brown-outs and blackouts that occur on a regular basis, not to mention the smaller off-grid market for solar home systems.
- In terms of the services provided by battery energy storage (BES) systems, the economics of behind-the-meter storage opportunities — notably for new PV installations — are likely to be a key driver of battery storage growth.
- In an era of lower feed-in remuneration to the grid, this technology will predominantly provide an electricity time-shift service to increase self-consumption. Given the arbitrage opportunity between electricity tariffs that are higher than feed-in remuneration, BES, associated with new installations of solar PV, is likely to grow rapidly as a result of these drivers. This growth will also include parts of the developing world, where battery and solar can be combined.
- As BES deployment increases and costs fall, retrofits of BES systems with small-scale solar PV are likely to emerge as an important source of energy storage demand. This is a story of economic opportunity that will arise from continued cost reductions.



Key insights

- Systems based on lithium-ion cells dominate electricity storage deployment. Available data for major markets shows that this is overwhelmingly true in the residential sector, where lithium-ion systems are installed almost exclusively.

- Available data for representative datasets of the price of lithium-ion cells shows them declining about 98% between 1991 and 2018 as global manufacturing has scaled up. During this period, performance improvements have centered on improving energy density, (which more than tripled) and specific energy (which almost tripled).

- Time series data available for major markets like Germany and the US state of California can also give some insights into the evolution of project characteristics in the residential sector. The storage capacity of German residential battery systems, for example, grew 38% between 2013 and 2021. Since 2018, the system capacity of residential battery storage in California has risen 63%. Other project characteristics can also be partly tracked from available data and suggest system capacity and basic design often seem to follow market signals.

- The energy-to-power ratio (storage duration) in Germany doubled between 2010 and 2020. Typical residential systems in both Germany and in California have storage durations of about two hours.

- Independent data for specific technical performance characteristics is much harder to come by. Manufacturers are often hesitant to participate in independent test efforts led by research institutes that can verify their data, and participate only partially, anonymously or not at all. Some data are available, however, though there is a risk of it being skewed towards 'best-in-class' manufacturers, which, given higher confidence in their products, are the ones typically participating in research efforts.

- Data for round-trip battery storage system efficiency in Germany suggest a confirmation that efficiency levels have improved in recent years, as markets have grown in scale. This analysis shows that the round-trip efficiency of residential battery storage systems in Germany improved from 94.4% in 2018 to 96.1% in 2021.

Behind-the-meter batteries

-98% **lithium-ion cell price** 1991-2018

COSTS

Residential battery system price

-71% 2014-2020, Germany

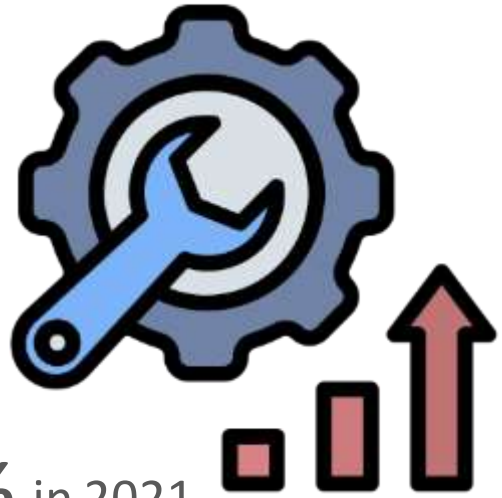
-33% 2018-2021, California

PERFORMANCE

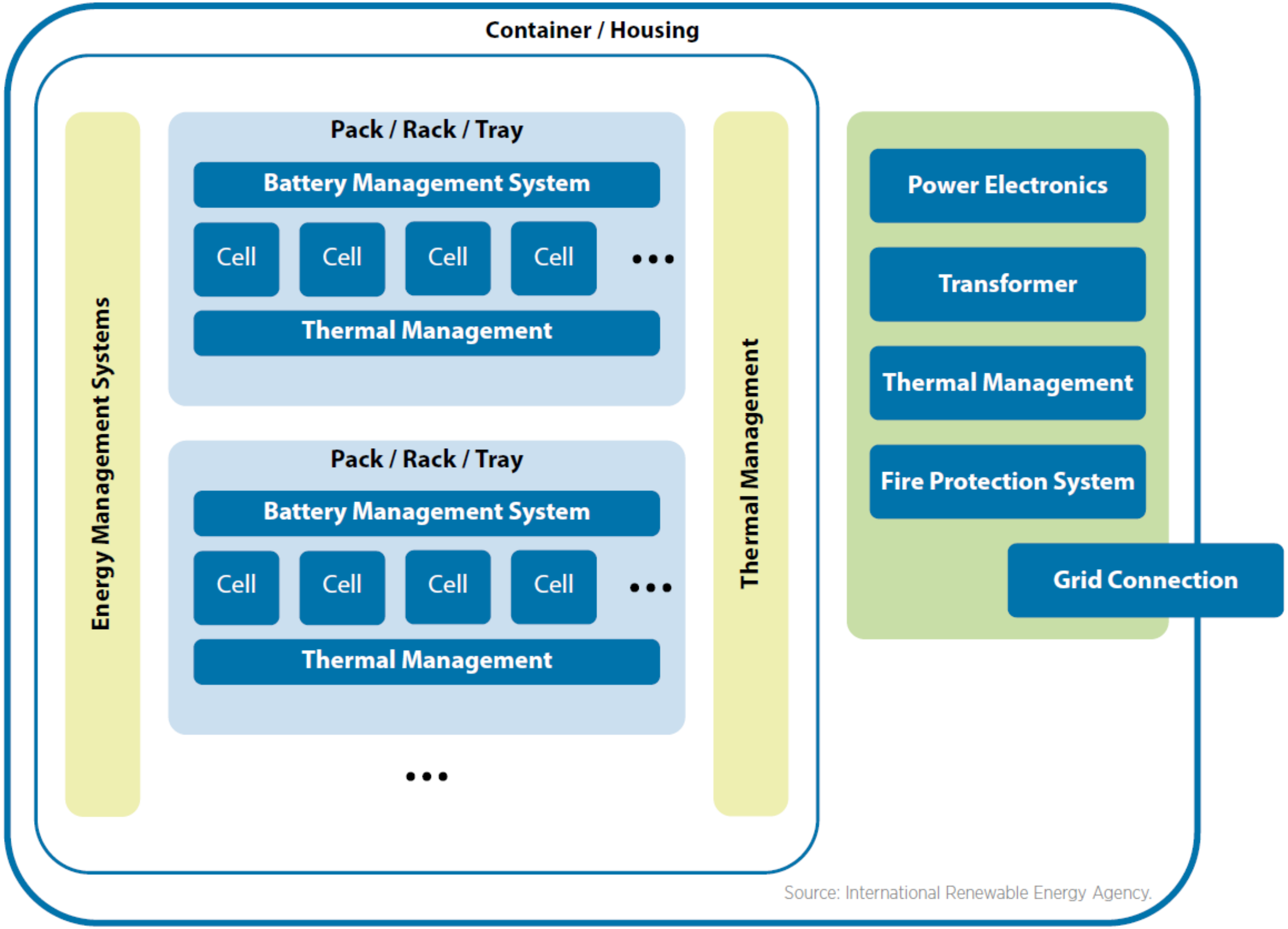
Cell energy density (1991-2018) +239%

	Residential
Storage capacity	
Germany (2013-2021)	**+38%**
California (2018-2021)	**+63%**
Storage duration	
Germany (2010-2020)	**+100%**

Round-trip efficiency
Germany best-in-class **94.4%** in 2018 to **96.1%** in 2021



Schematic of the different components of battery storage systems and BoS

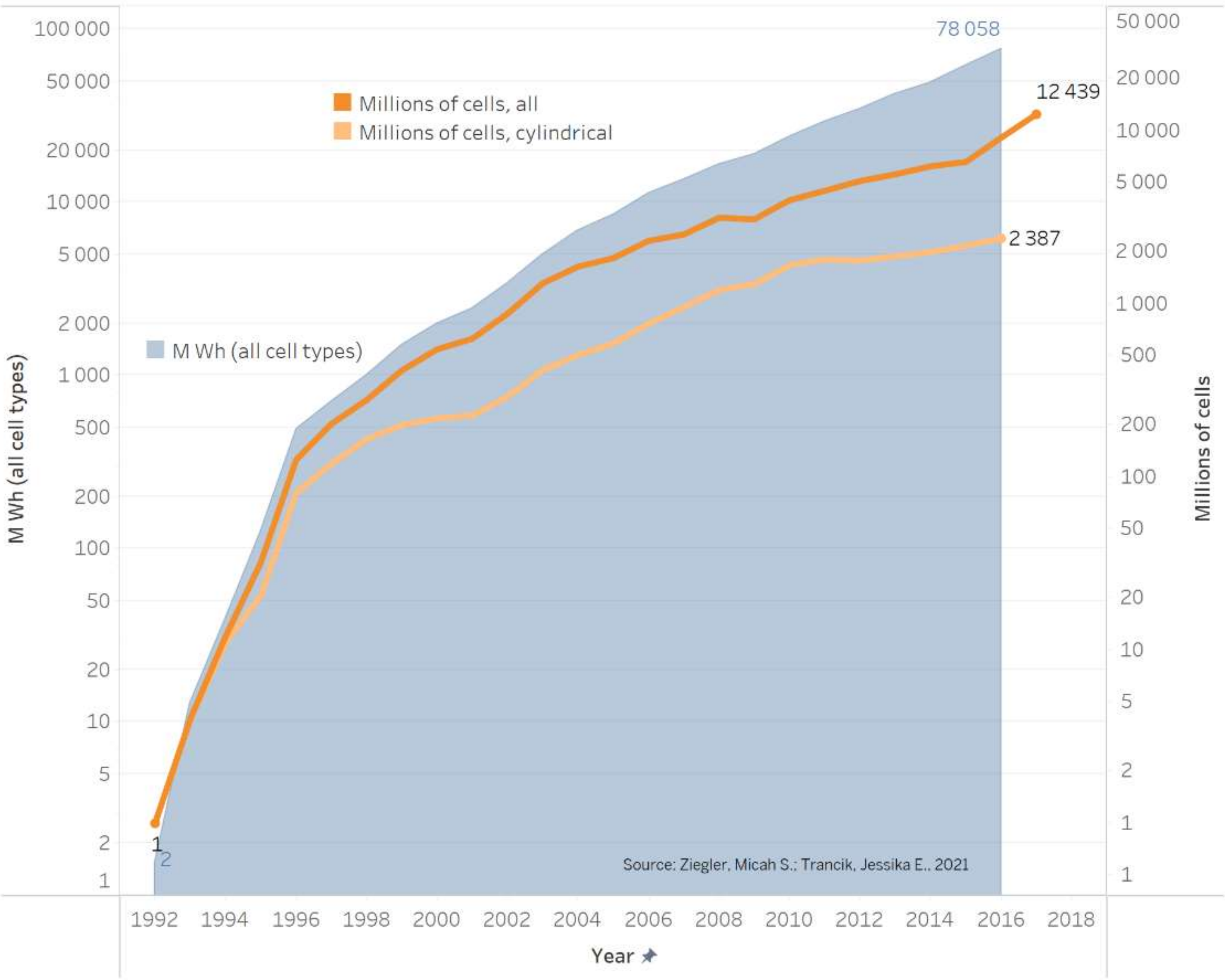


Battery cell deployment by type

First commercialised in the early 1990s, use of lithium-ion batteries grew quickly, given their performance advantages (*e.g.* their improved energy density) over the other rechargeable chemistries deployed at the time.

The setting up of a strong manufacturing base in Asia enabled quick scale-up capabilities for major players, with improved products and diversification. The latter included addressing the automotive market, which has been a major growth driver (Lebedeva *et al.*, 2021).

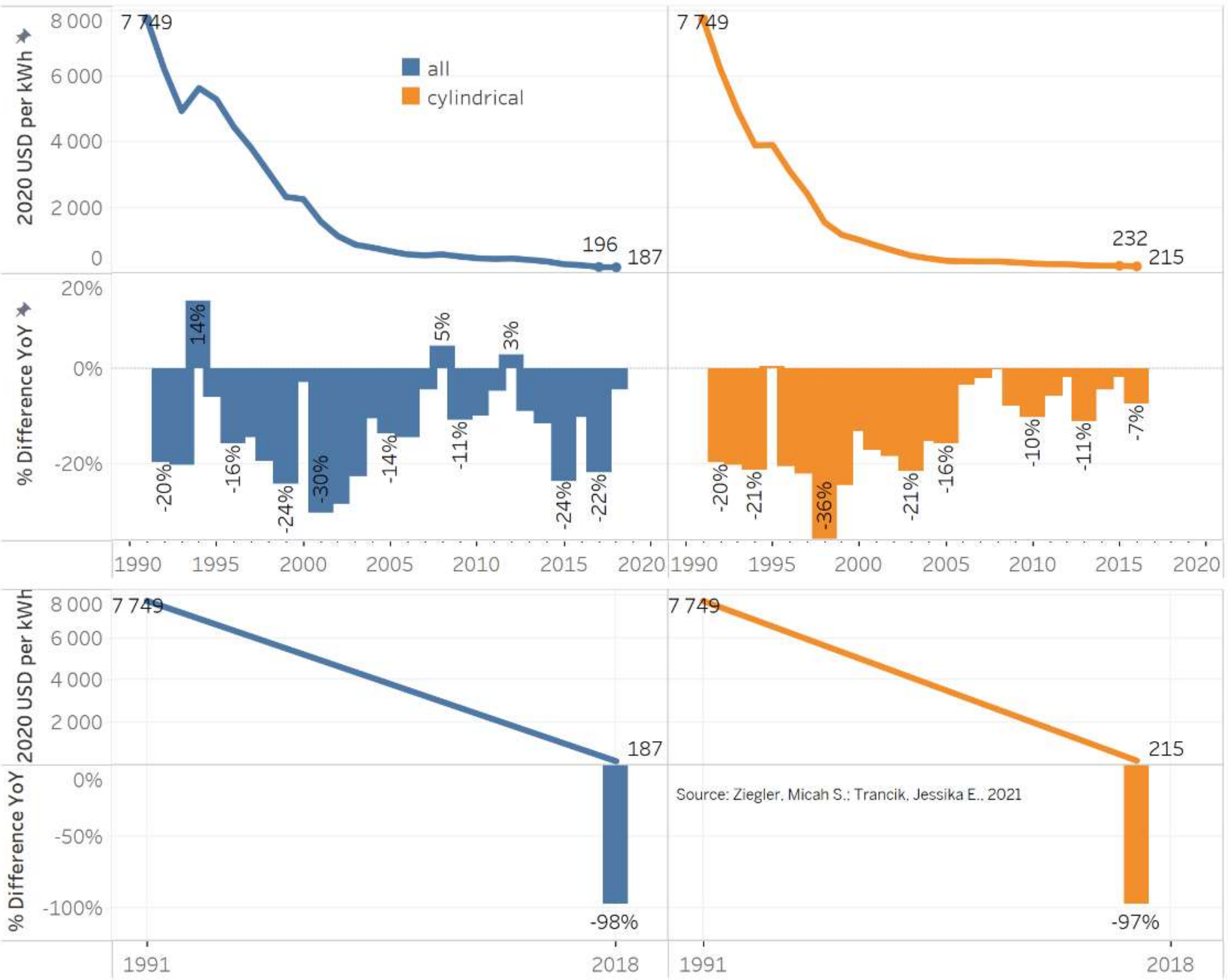
Accordingly, the lithium-ion global battery market has grown rapidly in recent years. The cell market for cylindrical cells has reportedly grown by about 3.4 times since 1992, while the market for all cell types suggests a growth by about 4.1 times over the same period. In terms of energy capacity, the market size grew about 4.7 times between 1992 and 2017, to reach 12 439 megawatt hours (MWh) (Ziegler and Trancik, 2021).



Battery cells: Benchmark costs by type

- Taking into account various research efforts, a representative dataset for the price for all lithium-ion cell types can be built. Between 1991 and 2018, that representative price of all lithium-ion cell types decreased 98% from between USD 7 749 to USD 187/kWh. The annual rate of decrease for all cell types was 14% for that period. Representative data for cylindrical cells is available, but only from 1991 to 2016.

- The price of cylindrical cells declined 97% over that period, to USD 215/kWh in 2016, giving a 13% annual rate of decline. The analysis of cost metrics that take into account energy density in the definition of service results in much faster technological changing rates than the one obtained from price per energy capacity alone. (Ziegler and Trancik, 2021)

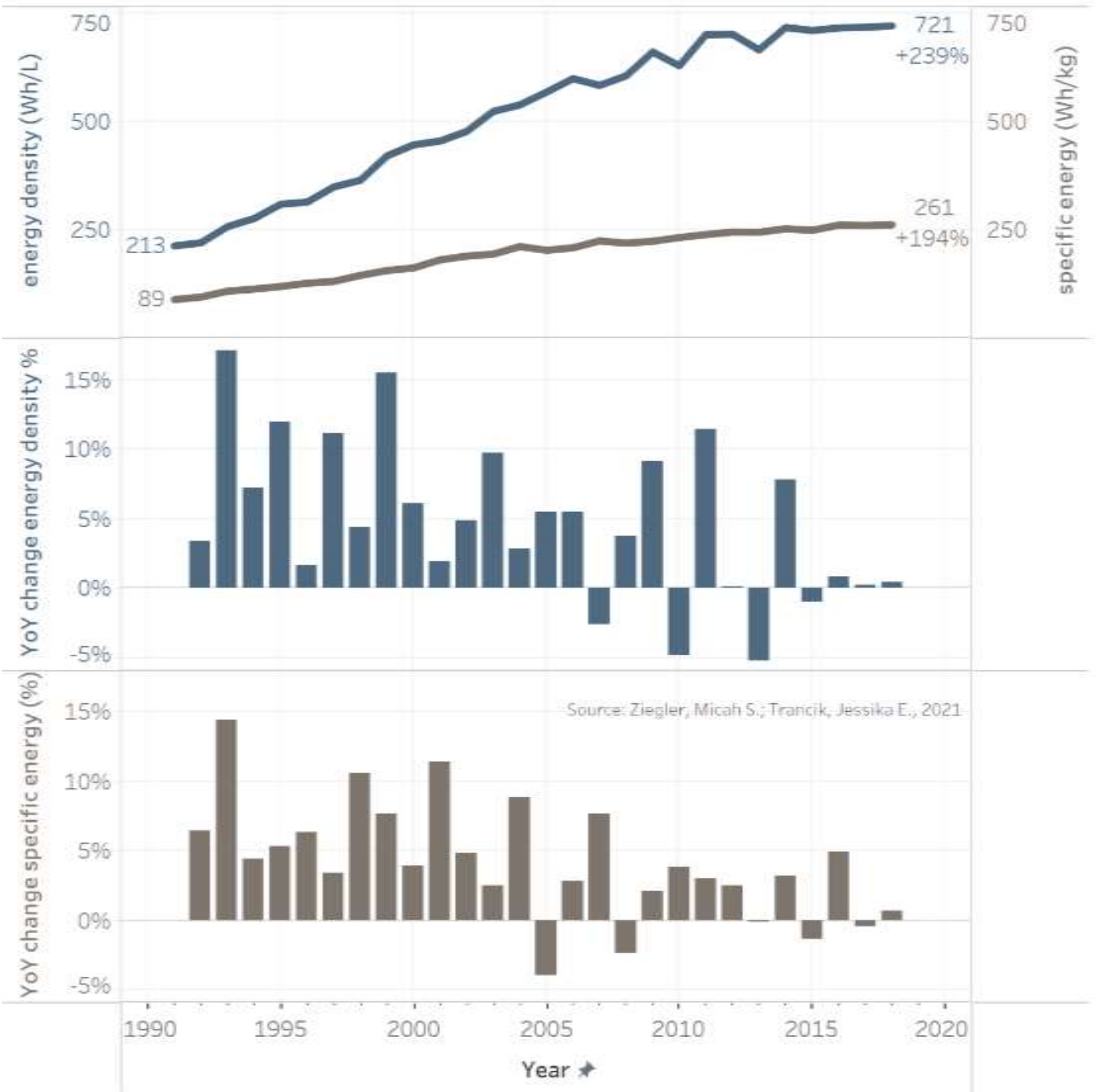


Battery cells: Energy density metrics

- Higher energy density enables the manufacturing of batteries of equal capacities, using less active materials, and thus unlocks cost savings in much the same way higher efficiency solar cells do for solar PV modules.

- Since the 1990s, the energy density of very small lithium-ion consumer electronics cells has increased by a factor of more than two. This means that for the same amount of energy, less material is required and fewer production steps may be needed, resulting in lower costs. Energy density improvements can therefore contribute to further price decline.

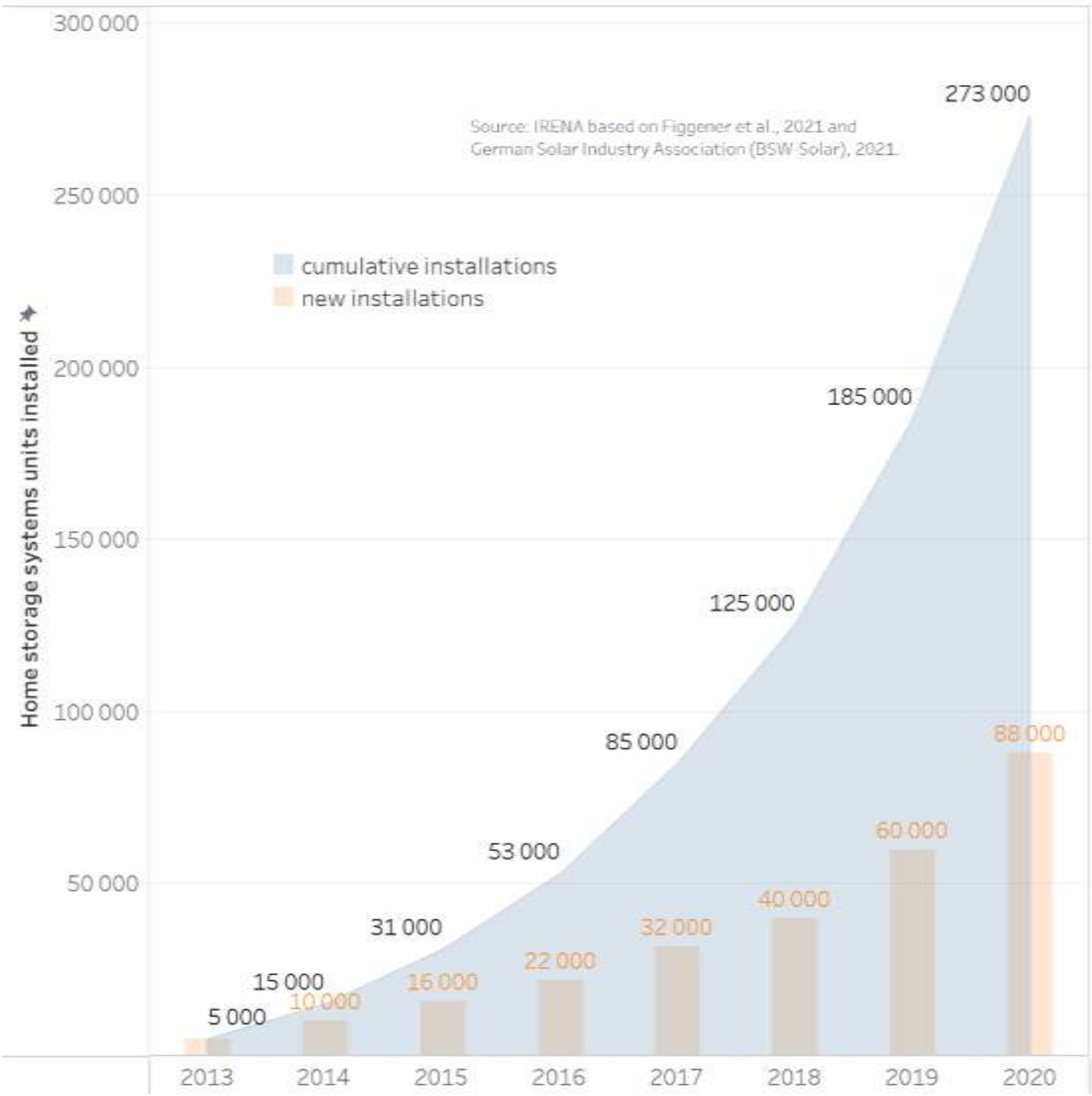
- The achievable energy density of a representative dataset of all lithium-ion cell types increased by close to two and a half times between 1991 and 2018, from 213 watt hours/litre of volume (Wh/L) to 721 Wh/L. The specific energy almost tripled, from 89 Wh/kg to 261 Wh/kg, over the same period. The trend in this metric for the cylindrical cell type is very similar to that of all cell types. This is due to the fact that among all cell types, cylindrical cells tend to have the highest energy density and specific energy.



Residential battery storage systems: German market

- The market for residential battery storage systems in Germany continues to grow. Preliminary estimates for BSW-solar show that new installations grew by 47% between 2019 and 2020. This places the 2020 cumulative installed stock at about 273 000 systems. Data for new residential systems installed during 2019 had total battery power of about 250 MW, corresponding to a storage capacity of 490 MWh (a duration of about 1.96 hours).

- For the cumulative stock up to 2019, these values were 750 MW and 1 420 MWh, respectively (a system duration of 1.89 hours). During 2013, the market share of new residential battery storage installations was about 37% for lithium-ion systems, while the rest of the systems corresponded to lead-acid technology. Since the global uptake of lithium-ion technology, its share of the German home storage market has experienced sharp and sustained growth. Since 2017, that share has remained at about 99% (Figgener *et al.*, 2021).

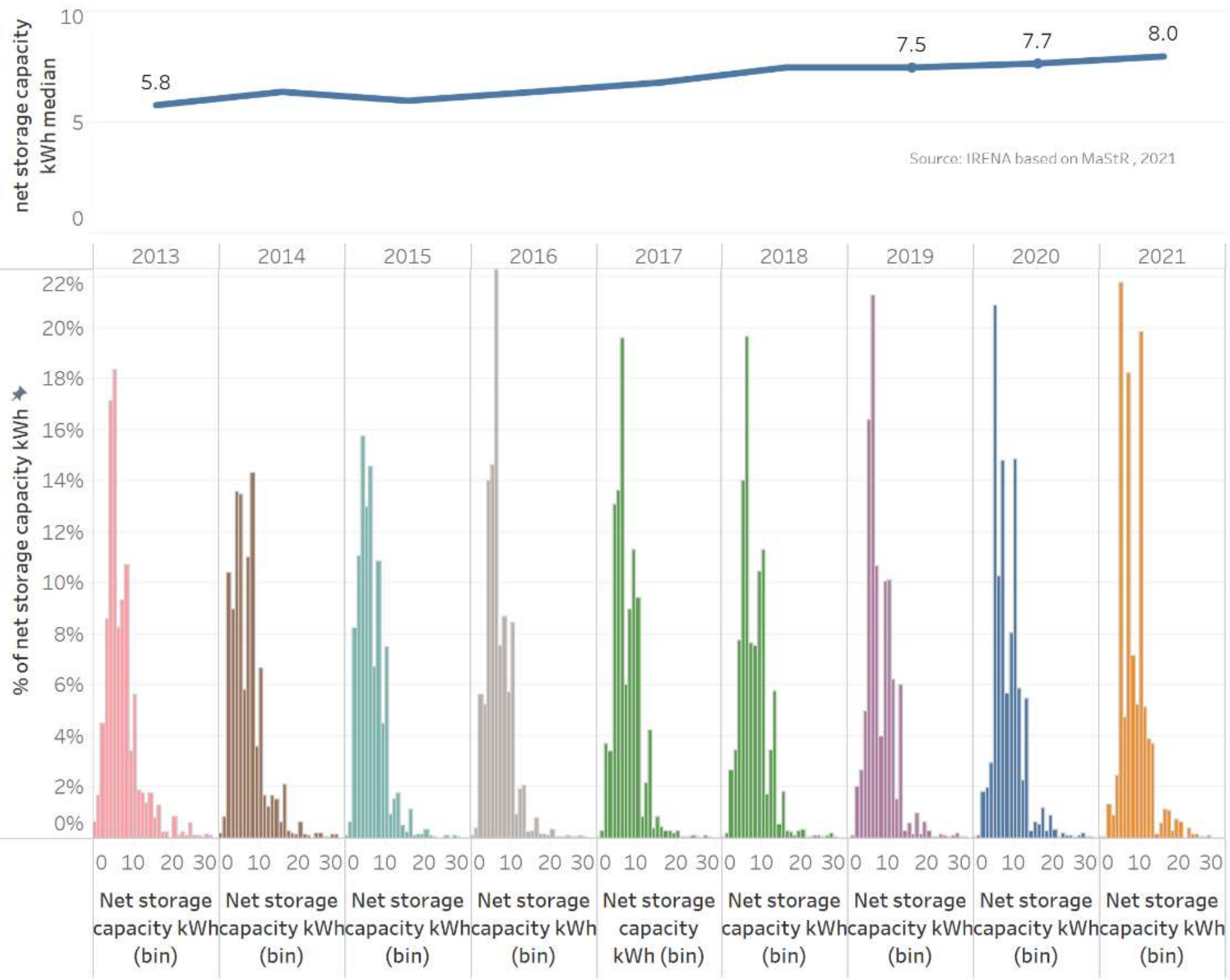


Residential battery storage systems: Storage duration in Germany (2005, 2010, 2015, 2020)

Analysis of the core energy market database for energy storage systems at the German Federal Network Agency, MaStR, can yield additional insights into the evolution of residential battery storage system characteristics.

For systems with net capacity below 30 kWh, the database shows that the median storage capacity of residential systems rose from 5.8 kWh in 2013 to 7.7 kWh in 2020. Preliminary data for 2021 shows a median energy capacity of 8.0 kWh. The dataset shows a median net power of 4.0 kW for residential battery systems installed in 2019. The ratio of battery storage capacity to PV power has been estimated at 1.1 hours (Figgener *et al*, 2021).

The rise in storage capacity has coincided with improved competitiveness of residential battery storage systems and a shift towards increased sector coupling in the private sector.

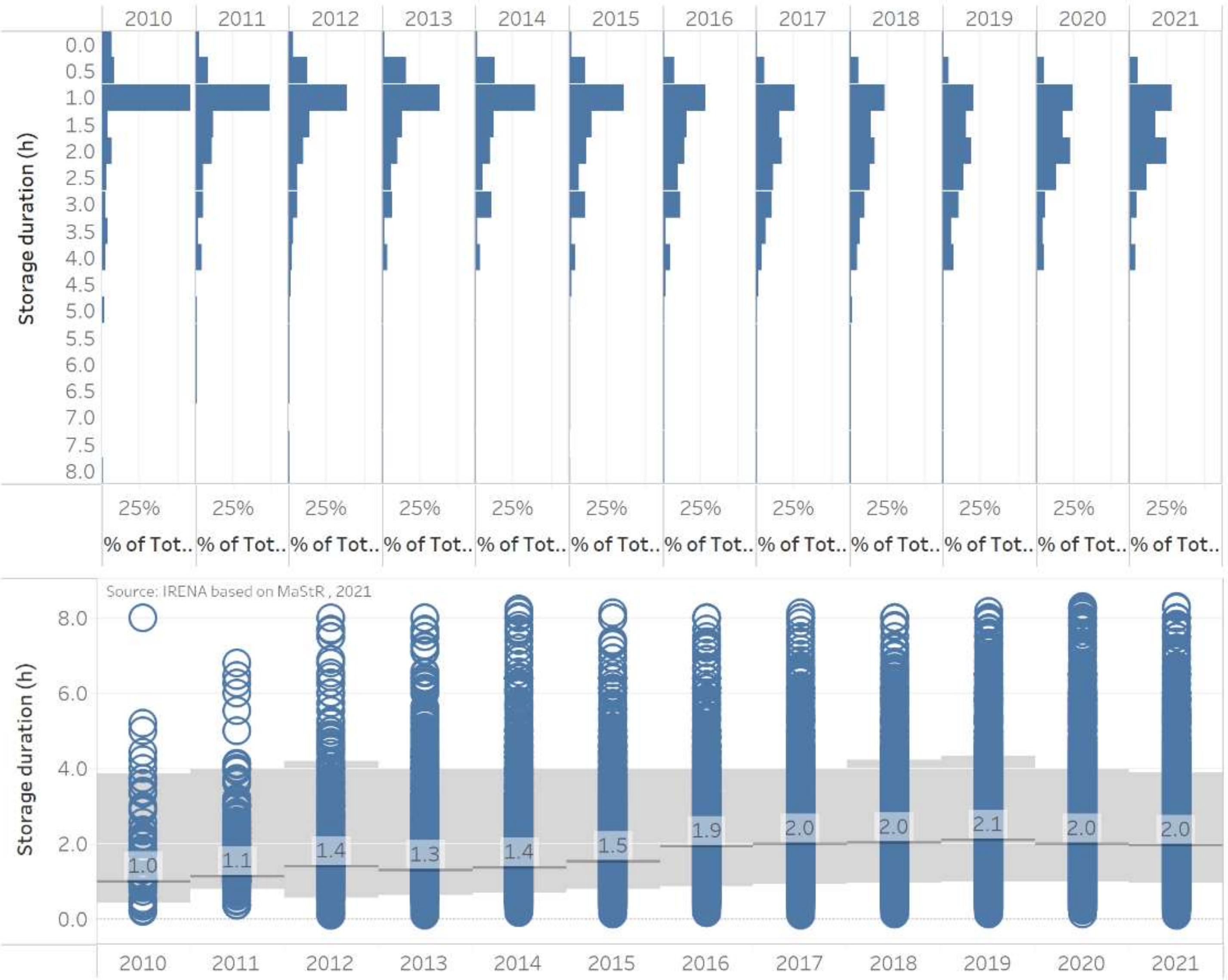


Residential battery storage systems: Storage duration in Germany (2010 to 2020)

- Data from the MaStR core energy market database also makes evident that the median storage duration (also known as the energy to power ratio (EPR) of residential systems doubled between 2010 and 2020. Since 207, the EPR has remained rather flat, at around 2.0 hours, after having increased steadily since 2013.

- A shift towards higher storage duration, increased energy capacity in residential battery systems and their declining costs has coincided with a higher uptake of heat pumps in the residential sector.

- About 40% of all new residential battery storage systems installed in 2019 were operated in combination with heat pumps. This share had roughly doubled since 2013 (Figgener *et al.*, 2020).

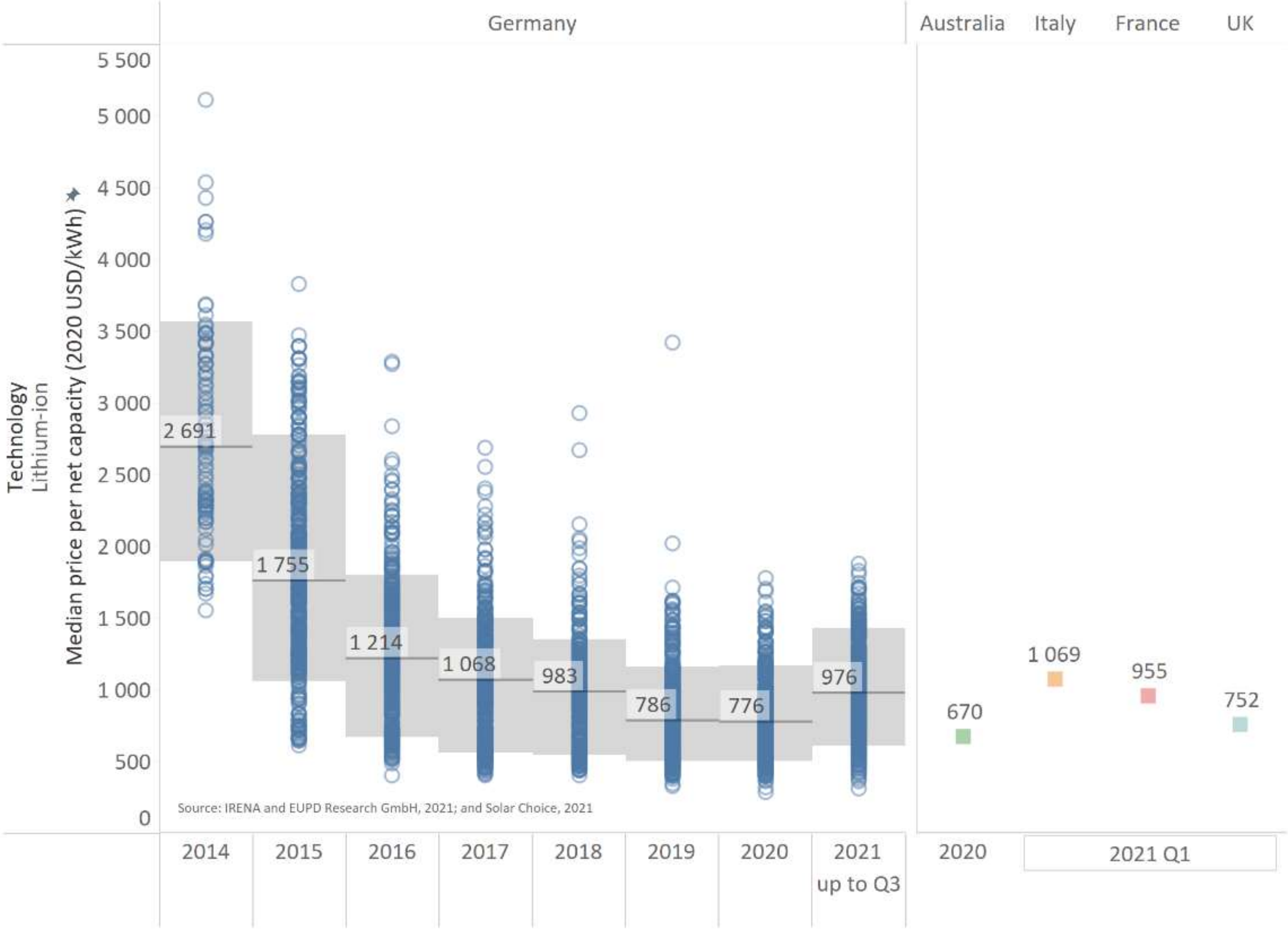


Residential battery storage systems: Total installed system costs

Time series data based on offers for small-scale residential battery systems in the German market suggest that between 2014 and 2020, prices fell by 71%, to USD 776/kWh. Data for 2020 in Australia suggest prices somewhat lower than those experienced in Germany during that year.

In the first quarter of 2021, IRENA surveyed the battery markets in the United Kingdom, Italy and France. Prices in the United Kingdom were the lowest amongst those markets and cheaper than full year 2020 estimates for Germany.

That systems in Italy and France are more expensive matches the experience in those countries with rooftop solar PV pricing. Data up to third quarter 2021 shows prices in Germany at almost the same level they were in 2018. The rise in battery prices in 2021 is likely related to a combination of various factors. These are: increasing raw materials exposure (driven by soaring demand); a shortage of electronics (chips) for controlling units/battery inverters; and increased freight costs.



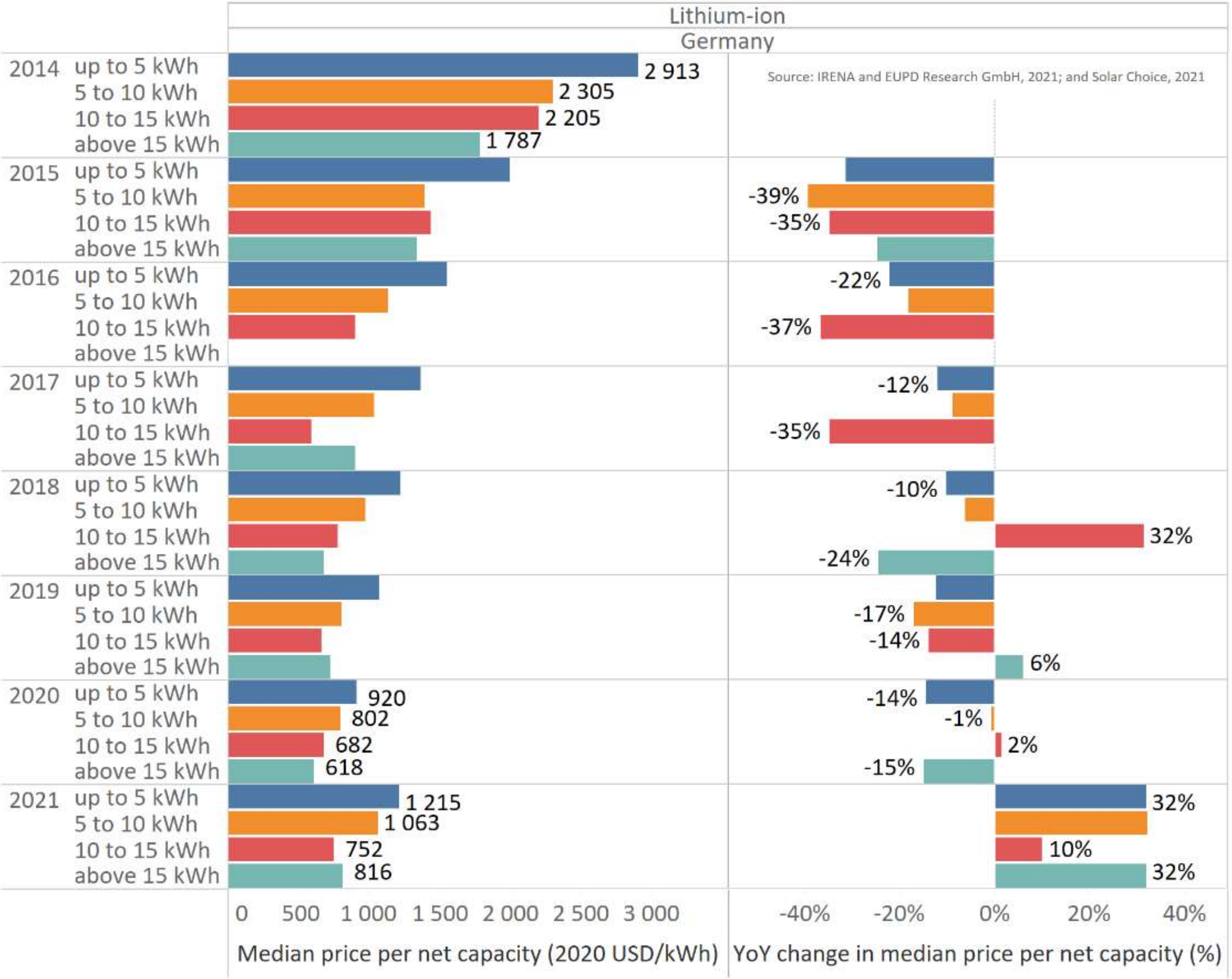
Residential battery storage systems: economies of scale

The time series of Germany's residential battery storage system costs shows the impact of economies of scale.

Between 2014 and 2020, the cost range by net capacity category declined from between USD 1 787/kWh and USD 2 913/kWh, to a much narrower range of between USD 618/kWh and USD 920/kWh. This represents a decline of between 54% and 58%, in reference to the smallest (up to 5 kWh) and largest (15 kWh-30 kWh) categories.

The rise in prices up to the end of third quarter 2021, however, shows the cost range by category declining to between USD 816/kWh and USD 1 215/kWh. That equates to a narrower decline of between 54% and 58% between 2014 and 2021.

In 2014, systems above 15 kWh were about 39% cheaper than systems up to 5 kWh. During both 2020 and 2021, the difference declined slightly in comparison to 2014. In both years, systems above 15 kWh were only 33% cheaper than those up to 5 kWh.

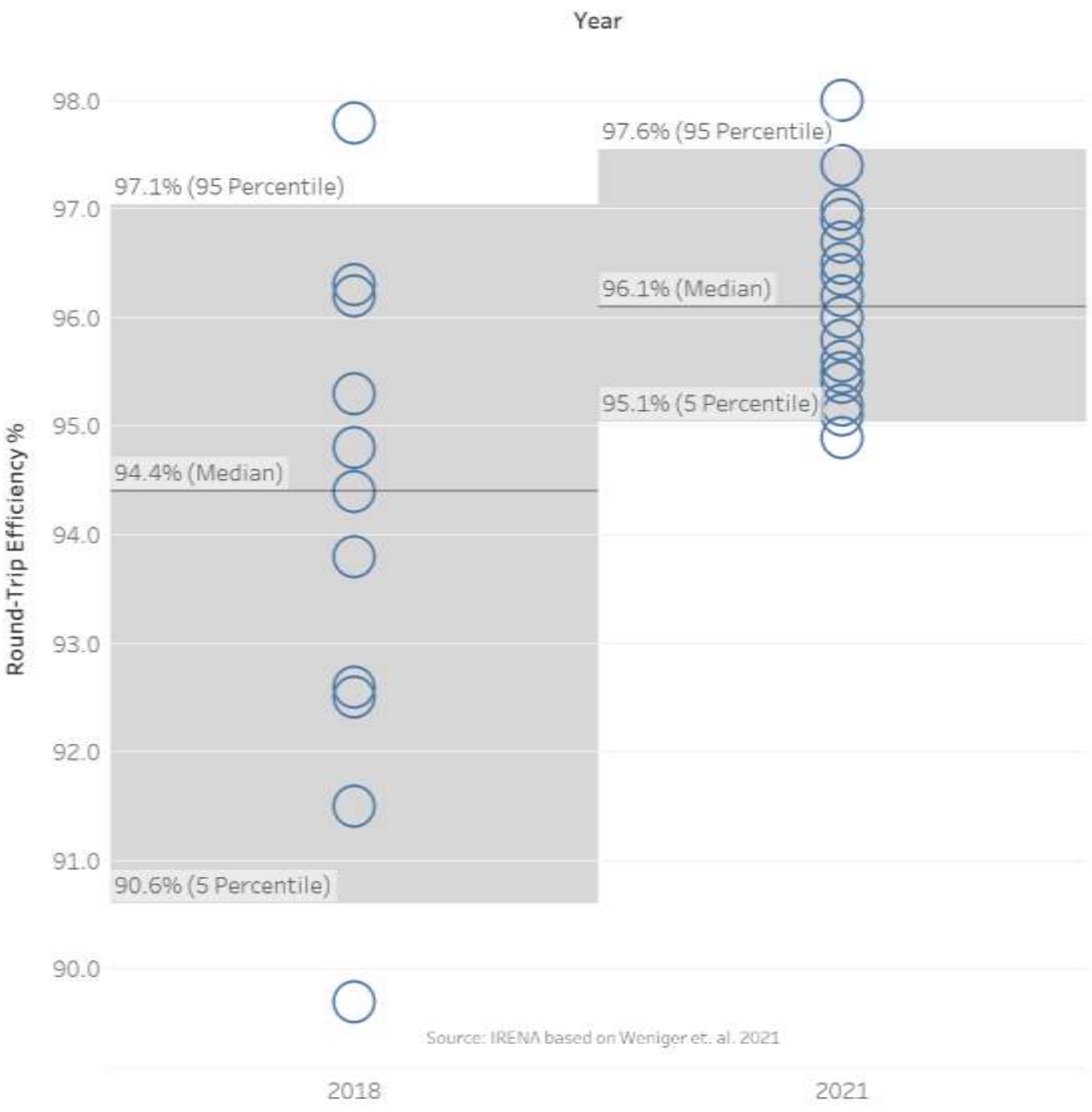


Residential battery storage systems: Efficiency metrics

- Some data from the German market on home storage systems and their performance is also available (Weniger *et. al*, 2021). The estimated range of battery round-trip efficiencies for home storage systems there rose from between 89.7% and 97.8% in 2018 to between 94.9% and 98.0% in 2021.

- The inverter efficiencies of these systems have also improved with time and now lie between 90.2% and 97.6%. The increased market presence of higher efficiency inverters can be attributed to the uptake of silicon carbide-based power semiconductors in the inverter design.

- At the same time, dynamic control deviations have improved. Very low settling times of between 0.3 and 0.5 seconds can now be achieved. Available standby power consumption data ranged between 2 W and 48 W in 2021 (Weniger *et. al*, 2021). Some of this data needs to be treated with caution, however, given that not all manufactures participated in the independent testing efforts used to create it. Results may often be skewed towards manufacturers with better performing systems, who are often more willing to participate.

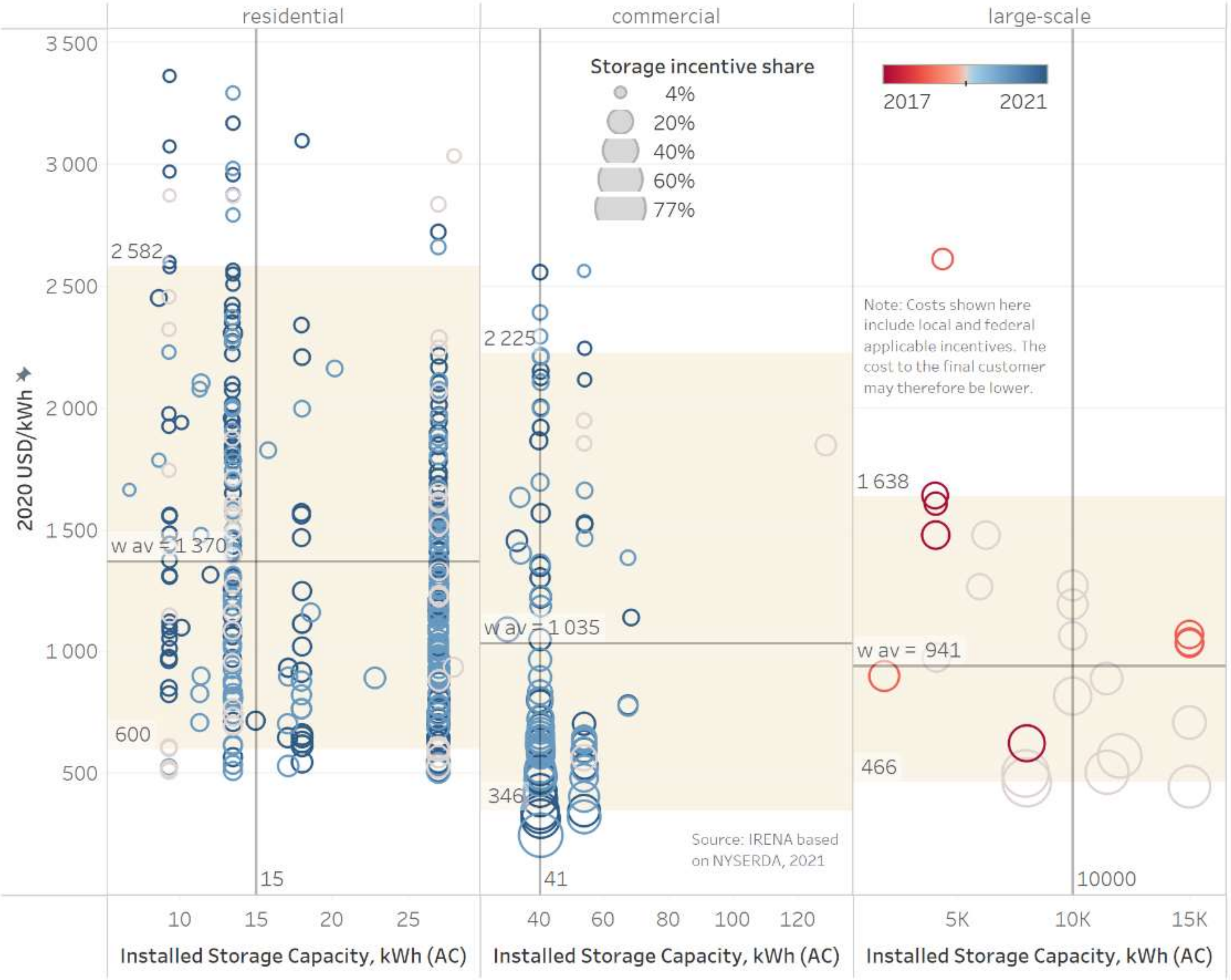


Source: IRENA based on Weniger et. al. 2021

Residential battery storage systems: New York

Analysis of cost data from the New York State Energy Research and Development Agency (NYSERDA) on battery storage, or PV plus battery storage systems shows that the energy capacity weighted average cost of residential storage systems (below 30 kWh) was USD 1 370/kWh between 2017 and 2021. For PV plus storage costs (for which the cost of PV systems was not available directly from the dataset), IRENA's solar PV total installed costs data for the year has been assumed, in order to deduct PV's share of the cost. Therefore, the costs shown here are to be interpreted as including only the storage system. During the 2017 to 2021 period, the weighted average incentive share in the residential sector was 18%, while data for the smaller commercial sector, with energy capacity between 30 kWh and 1 MWh, yields a weighted average of USD 1 035/kWh (about a quarter lower than residential storage costs).

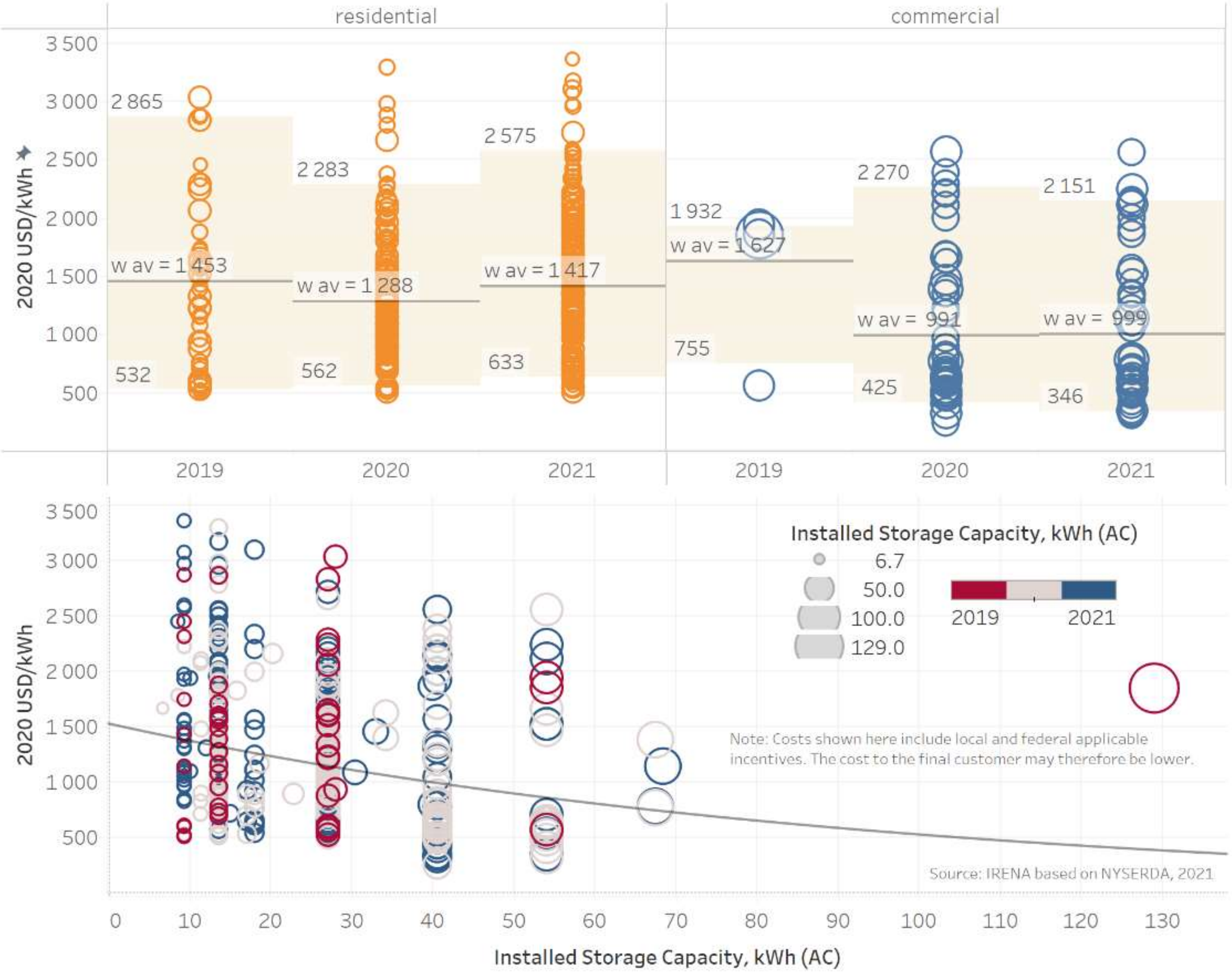
Some data for the large-scale sector (a battery capacity above 1 MWh or battery power above 1 MW) are also available for the period. The weighted average cost of storage systems during that time was USD 941/kWh.



Residential battery storage systems: New York

Sufficient data is available from the dataset covering the period since 2019 to estimate the evolution of battery storage costs over time in the residential and commercial sectors. These data suggest that the energy capacity weighted average cost of residential storage systems declined about 11% in 2020, to USD 1 288/kWh. Preliminary data for 2021 indicates that, alongside other markets globally, the market has suffered a reversal in that downward trend, though costs remain lower than they were in 2019.

Commercial costs declined more heavily between 2019 and 2020 (by about 40%), though these results should be treated with caution, given the low number of projects in 2019. The market does seem to have continued to grow, however, driven by state and federal retail and bulk energy storage incentive programmes in the state. The competitiveness of the commercial market seems less affected by the recent challenges, staying relatively flat in comparison to its 2020 value. Economies of scale exist in both sectors.

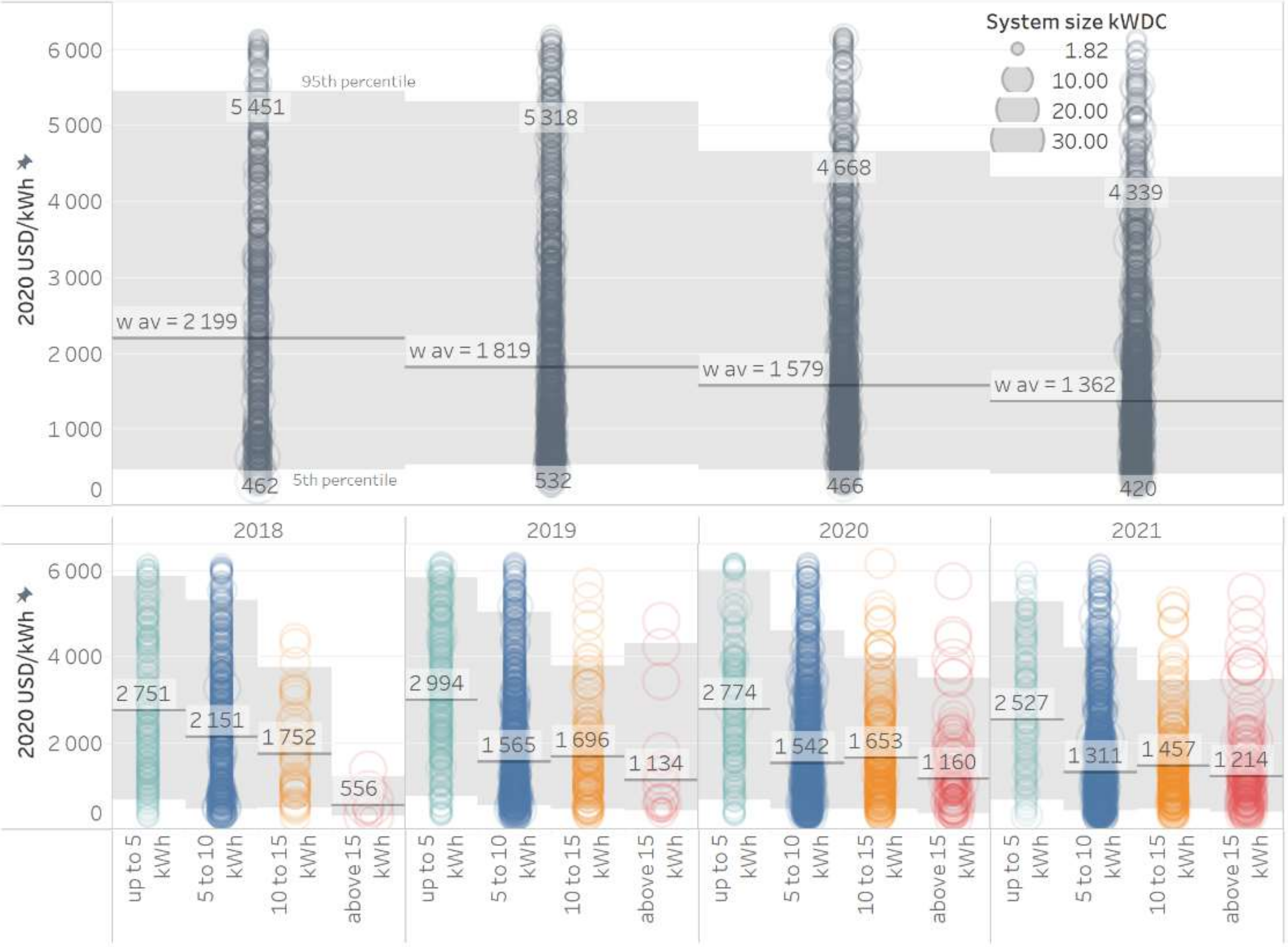


Residential battery storage systems: California

About four-fifths of residential battery systems in the US are paired with PV. The percentage of PV systems that include storage is much lower, however, at about 6% nationally.

Driven by incentives and wildfire resilience issues, the storage attachment rates of PV systems in California have grown. In 2020, about 8% of PV systems installed in the state included battery storage, up from below 1% in 2016 (Barbose *et al.*, 2021).

Following the analytical approach described in the case of the above data for New York State, it is possible to arrive at estimates of the evolution of residential storage costs in California. That analysis shows that between 2018 and 2021 (using preliminary data for the first three quarters), the energy capacity weighted average cost of residential battery storage systems declined 33% from USD 2 199/kWh to USD 1 362/kWh. Systems in California also show economies of scale, particularly notable when comparing systems with capacities below 5 kWh with systems between 5 kWh and 10 kWh.



Source: IRENA based on CaliforniaDGStats, 2021.
Note: Costs shown here include local and federal applicable incentives. The cost to the final customer may therefore be lower.

Residential battery storage systems: California

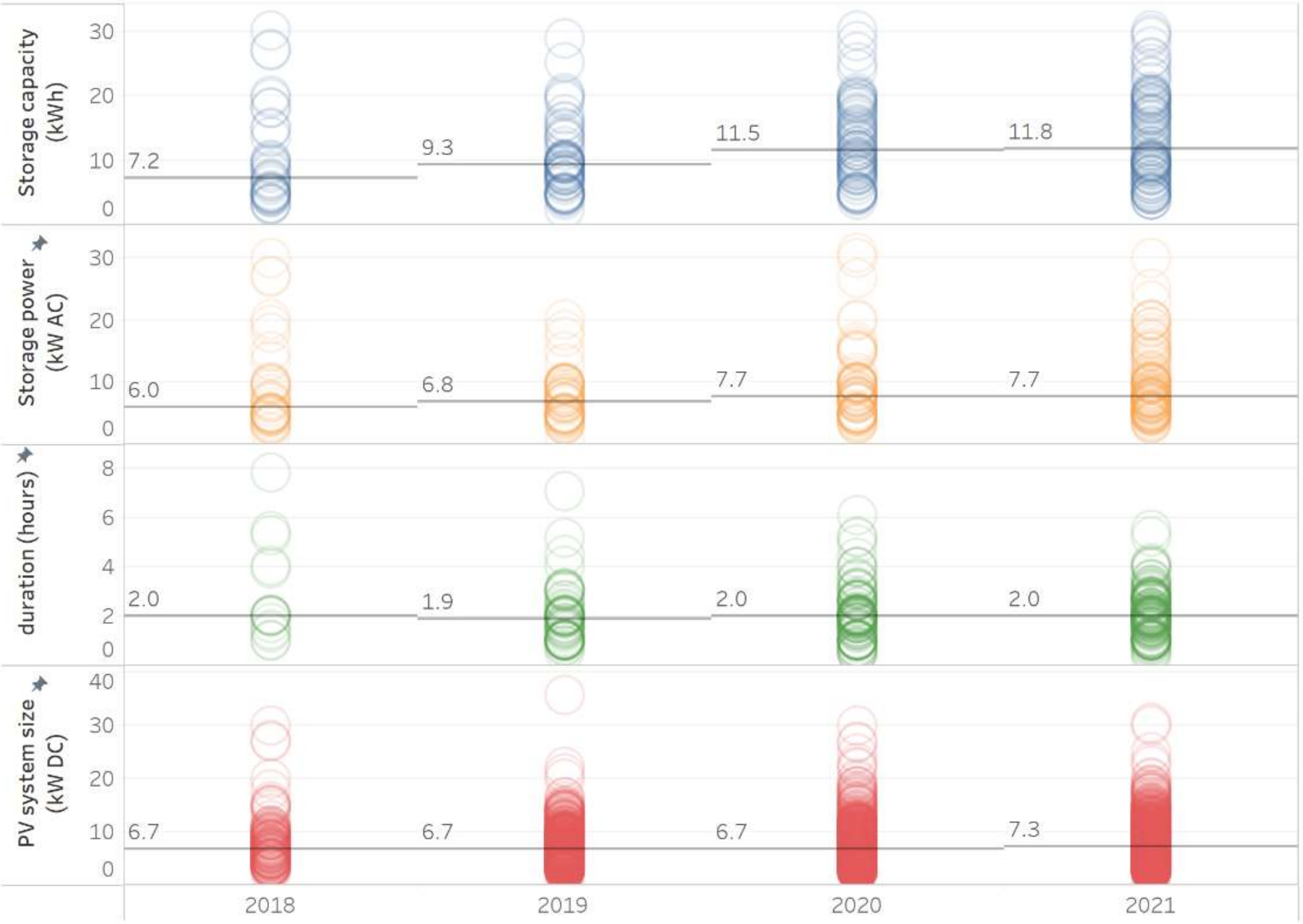
- As the number of residential storage installations has expanded, project characteristics have also evolved, largely following market signals.

- For example, available data suggests that between 2018 and 2021 (looking at the preliminary data from the first three quarters), the median storage capacity grew 63% from 5.3 kWh to 11.8 kWh.

- During the same period, storage power rose 28% from 6.0 kW_{AC} to 7.7 KW_{AC}.

- The energy-to-power ratio of systems has stayed relatively stable in the residential sector with a median duration of about two hours during the period. This is largely determined by leading products that dominate the market.

- Over the same period, the size of residential PV systems in that subset of data grew from 5.1 kW_{DC} to 7.3 kW_{DC}.



Source: IRENA based on CaliforniaDGStats, 2021. Note: Costs shown here include local and federal applicable incentives. The cost to the final customer may therefore be lower. Central estimates shown the median value for each metric.

Onshore wind

Key insights

- The global weighted-average total installed cost for onshore wind fell 32% between 2010 and 2020, from USD 1 971/kW to USD 1 349/kW. The 2020 cost was also down 10% on the 2019 value of USD 1 491/kW. The country/region weighted-average total installed cost for onshore wind in 2020 ranged from around USD 1 038/kW-USD 3 189/kW. China and India have weighted-average total installed costs between 20% to 67% lower than other regions.

- Most markets experienced a peak in wind turbine prices between 2007 and 2010, with these falling between 44% and 78% by the end of 2020. That year, prices were in the range USD 700/kW to USD 910/kW in most major markets, excluding China, where prices were around USD 540/kW due to contracts there that typically exclude logistics and towers.

- Technology improvements in turbines and the drive for cost reductions saw the global average rotor diameter increase from 82 m in 2010 to 119.4 m in 2020, a 46% increase. At the same time, the global average hub-height increased 27%, from 81.3 m in 2010 to 103.2 m in 2020.

- Over that period, average turbine sizes also increased in every major market, with the largest increase in turbine capacity in percentage terms observed in Sweden (113%) followed by Brazil (105%) and Canada (101%).

- With higher hub heights and larger swept areas, there was an almost one-third increase in the global weighted-average capacity factor of onshore wind, from just over 27% in 2010 to 36% in 2020.

- Technology improvements, have, however, likely been larger than this growth implies, given that for the major markets for which IRENA has data, all but the Netherlands saw projects in locations with poorer wind resources in 2020 than in 2010.

- Driven by the cost reductions from wind turbines and balance of plant costs, and technology improvements that have seen capacity factors increase, the global weighted-average LCOE of onshore wind fell 56% between 2010 and 2020, from USD 0.089/kWh to USD 0.039/kWh.

- In 2020, with the exception of Japan, all the 15 countries for which IRENA had robust time series data (sometimes going back to the mid 1980s) had weighted-average LCOEs below USD 0.055/kWh – the lower range for fossil fuel-fired power generation. A number of countries now have LCOEs of USD 0.04/kWh, or lower.

Market development

The onshore wind market has grown almost fourfold from a total installed capacity of 178 GW in 2010 to 698 GW in 2020. Total electricity generation from onshore wind grew by 993 TWh between 2010 and 2019, and by 1 061 TWh over the 10 years from 2009 to 2019. As for other renewable technologies, China has played a large, sometimes dominant role in driving capacity additions. Of the 105 GW added in 2020, China accounted for 69 GW, with the next largest market – the United States – adding 14 GW, or just one-fifth of China's new additions.

In terms of generation, however, China is less dominant, given the excellent wind resources being exploited in the mid-west of the United States. In 2020, US onshore wind generation increased by 22.4 TWh, compared to the 37.7 TWh in China. This includes the year-on-year variation in wind quality across the entire fleet but illustrates the difference in capacity factors which are documented in this section.

Onshore wind from 2010 to 2020

-39% Wind turbine prices

-31% Total installed costs

-56% Levelised cost of electricity

COSTS

PERFORMANCE

Turbine capacity **+32%**

Rotor diameter **+43%**

Capacity factor **+31%**

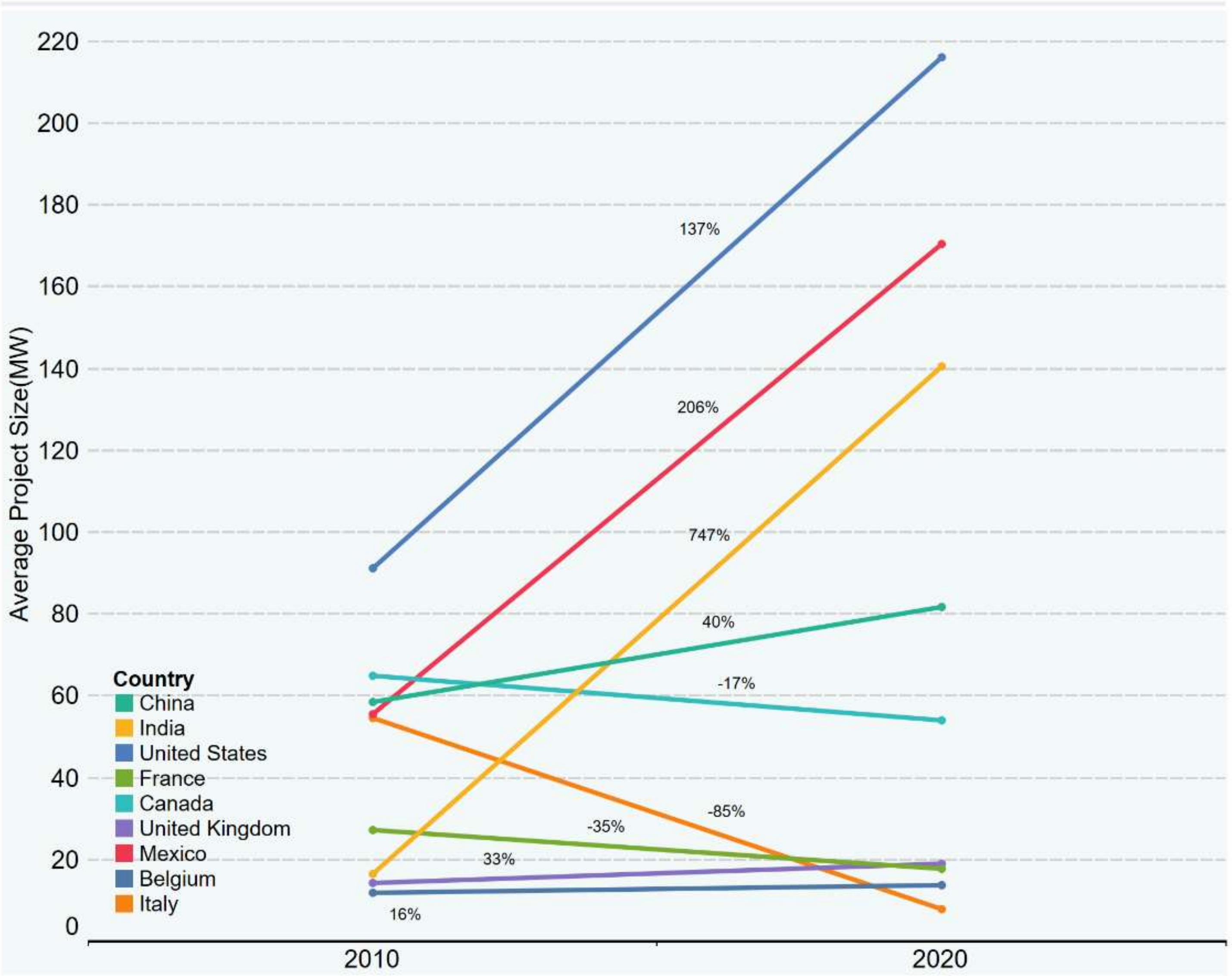
Onshore wind projects average size (2010 and 2020)

Between 2010 and 2020, the average project size has increased tremendously in India, growing 747%, from 17 MW in 2010 to 141 MW in 2020.

A similar trend can be seen in both Mexico and the United States, where average project sizes increased from 56 MW to 171 MW, and 91 MW to 216 MW, respectively.

Belgium and United Kingdom also showed an increase in average project size. In the former, average size increased from 12 MW to 14 MW, while in the United Kingdom, it increased from 14 MW to 19MW.

France and Italy both showed declines in average project sizes, of 35% and 85%, respectively.



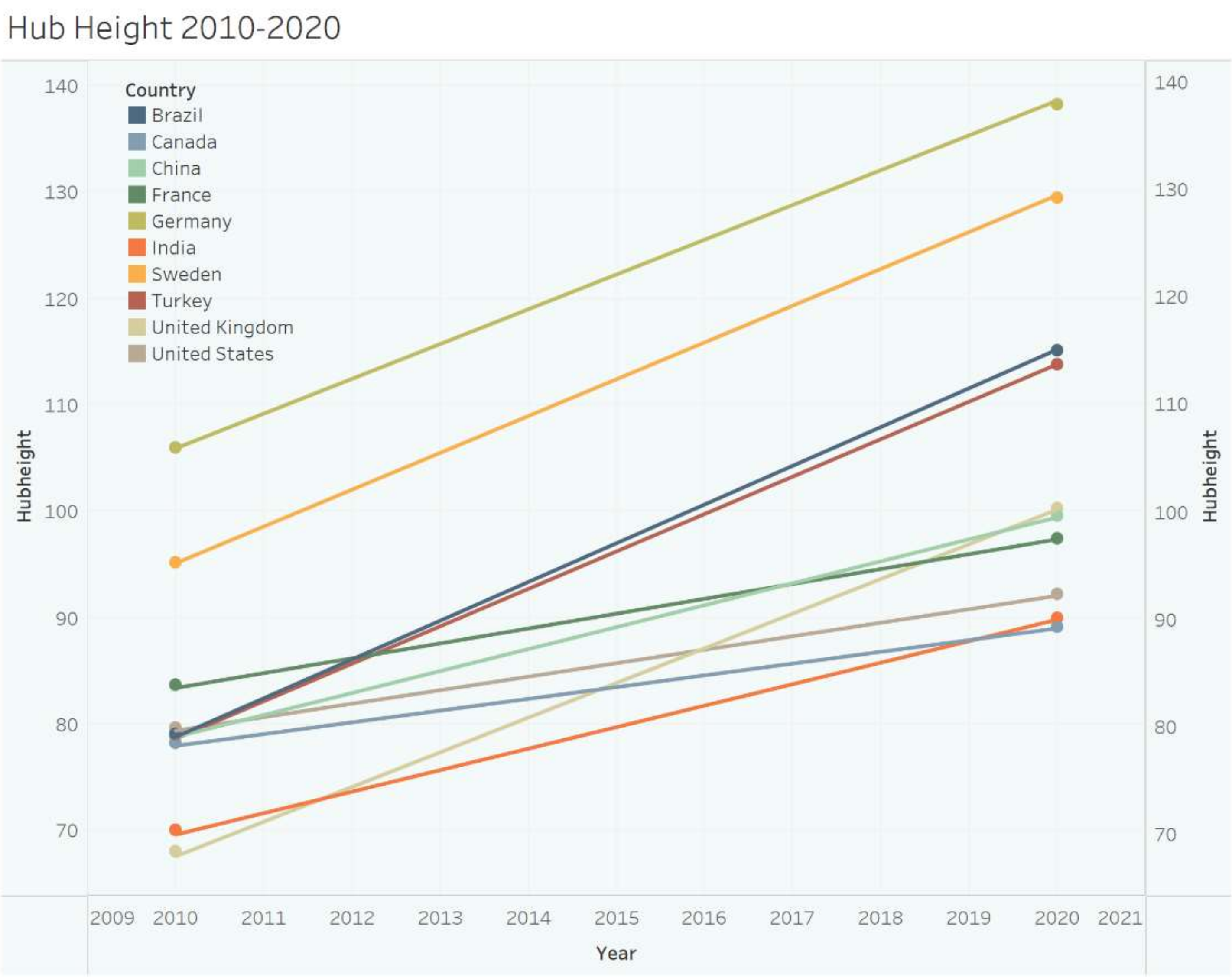
Hub Height (2010 to 2020)

Onshore wind turbine weighted-average hub height experienced an increase in all major onshore wind markets.

Between 2010 and 2020, the United Kingdom had the highest increase in the weighted-average hub height, at 47%, increasing from 68 m to 100 m.

The second highest increase in the weighted-average hub height was in Brazil, at 46%, followed by Turkey, at 44%.

Germany had the highest weighted-average hub height in 2020, at 138 m, followed by Sweden, at 129 m. This gave percentage increases of 31% and 36% respectively. France had a 17% increase from its 2010 value of 84 m, reaching 97 m in 2020.



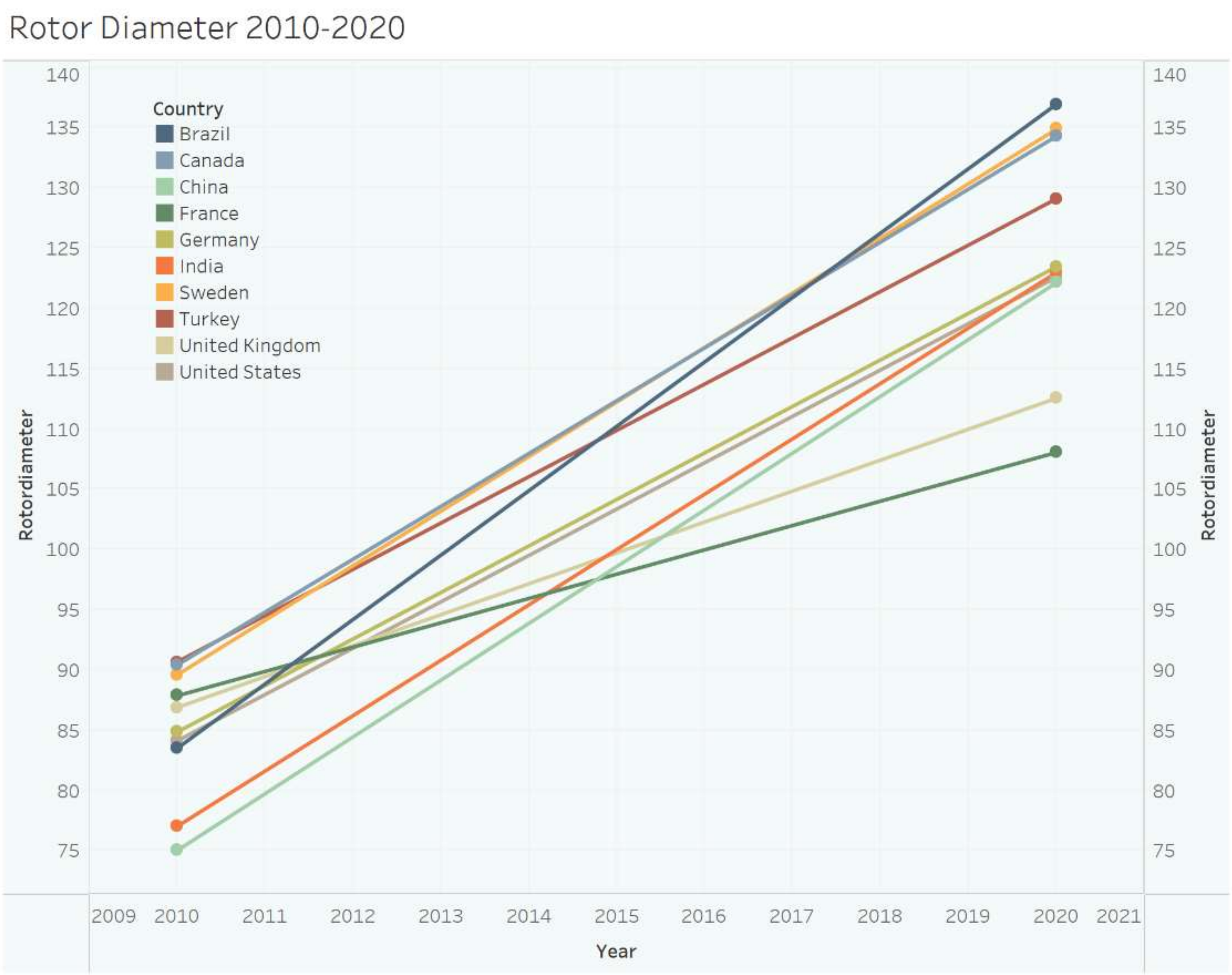
Rotor Diameter (2010 to 2020)

Similarly, onshore wind turbine weighted-average rotor diameters also experienced increases between 2010 and 2020.

Brazil had the highest weighted-average rotor diameter value in 2020 and the highest percentage increase, at 64%, with the value increasing from 83 m in 2010 to 137 m in 2020.

China had the second-highest weighted-average rotor diameter value in 2020 and the second highest percentage increase, at 63%. This value increased from 75 m in 2010 to 122 m in 2020.

Germany and the United States both had a weighted-average rotor diameter value of 123 m in 2020, increasing from 2010 values of 85 m and 84 m respectively. This was a percentage increase of 46%. France and the United Kingdom had weighted-average rotor diameter values that increased from 88 m and 87 m to 108 m and 113 m respectively. This was a percentage increase of 23 % for France and 30% for the United Kingdom.



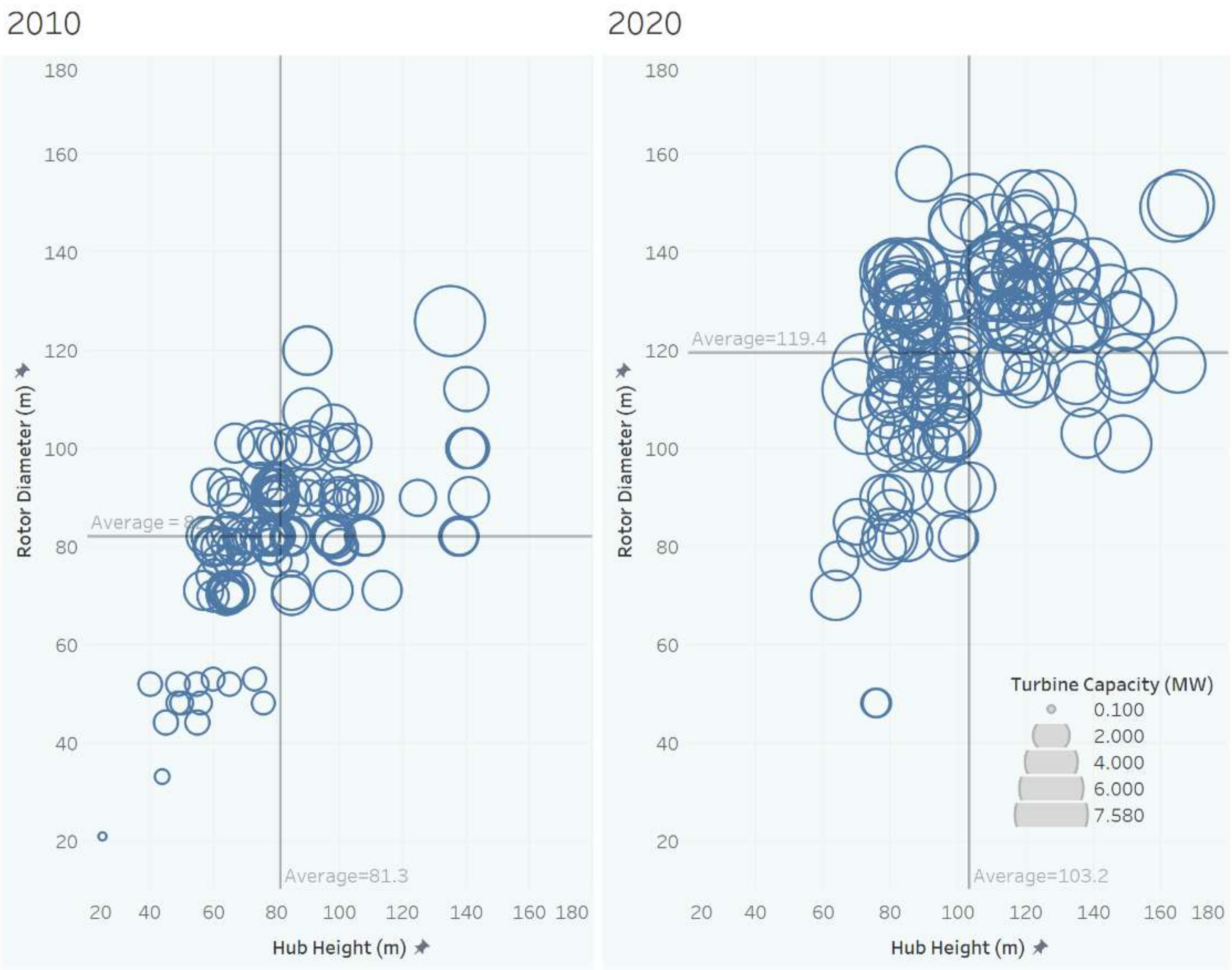
Rotor Diameter vs Hub Height

The trend towards more advanced and more efficient turbine technologies with larger rotor diameters and hub-heights has seen energy outputs and capacity factors rise in most markets over the last ten years.

The shows that the global average of onshore wind turbine rotor diameter and hub height both experienced an increase during the period 2010 to 2020.

The global average rotor diameter for 2010 was 82 m . By 2020, this had increased by 46%, reaching 119.4 m. Meanwhile, global average height increased 27% between 2010 and 2020, from 81.3 m to 103.2 m.

This is in line with the increase in the turbine capacity/rating (in MW) over the same period.



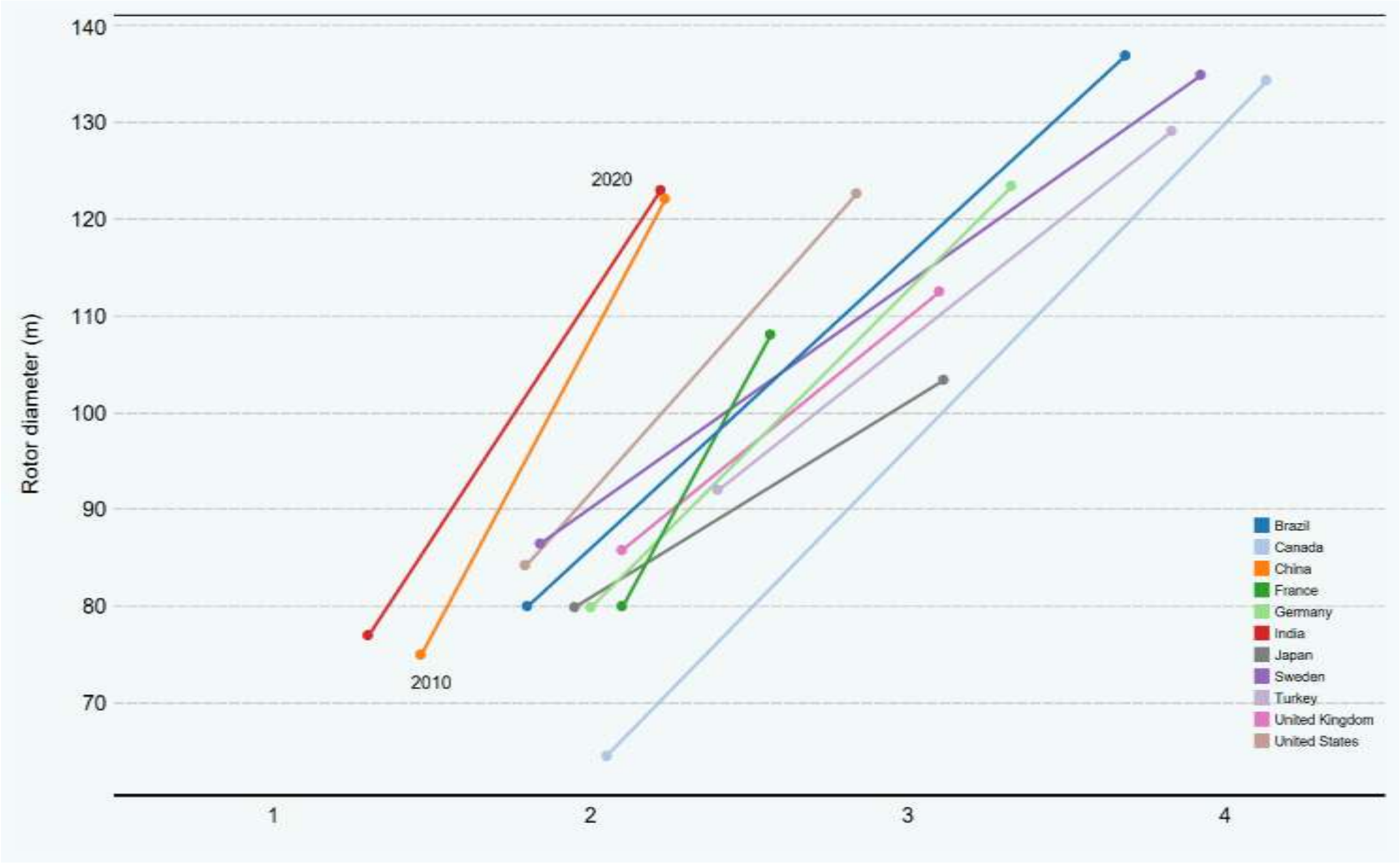
Rotor Diameter vs Turbine Capacity

Between 2010 and 2020, the evolution in average turbine ratings and rotor diameters in Brazil, Canada and Sweden stands out, with increases of greater than 50% in both the average rotor diameter and turbine capacity of their commissioned projects.

In percentage terms, the largest increase in turbine capacity was observed in Sweden (113%) followed by Brazil (105%) and Canada (101%).

The largest increase in rotor diameter occurred in Canada (108%) followed by Brazil (71%) and China (63%). On average, in 2020, Canada and Brazil had the largest turbine rating and rotor diameters, respectively. That year, India had the lowest turbine rating and Japan had the lowest rotor diameter.

Overall, in 2020 the country-level average turbine capacity ranged from 2.22 MW to 4.13 MW, and rotor diameter from 103 m to 134 m.



Wind turbine price trends

Most markets experienced a peak in wind turbine prices between 2007 and 2010. These then fell by between 44% and 78% by the end of 2020. That year, prices ranged from USD 700/kW to USD 910/kW in most major markets, excluding China.

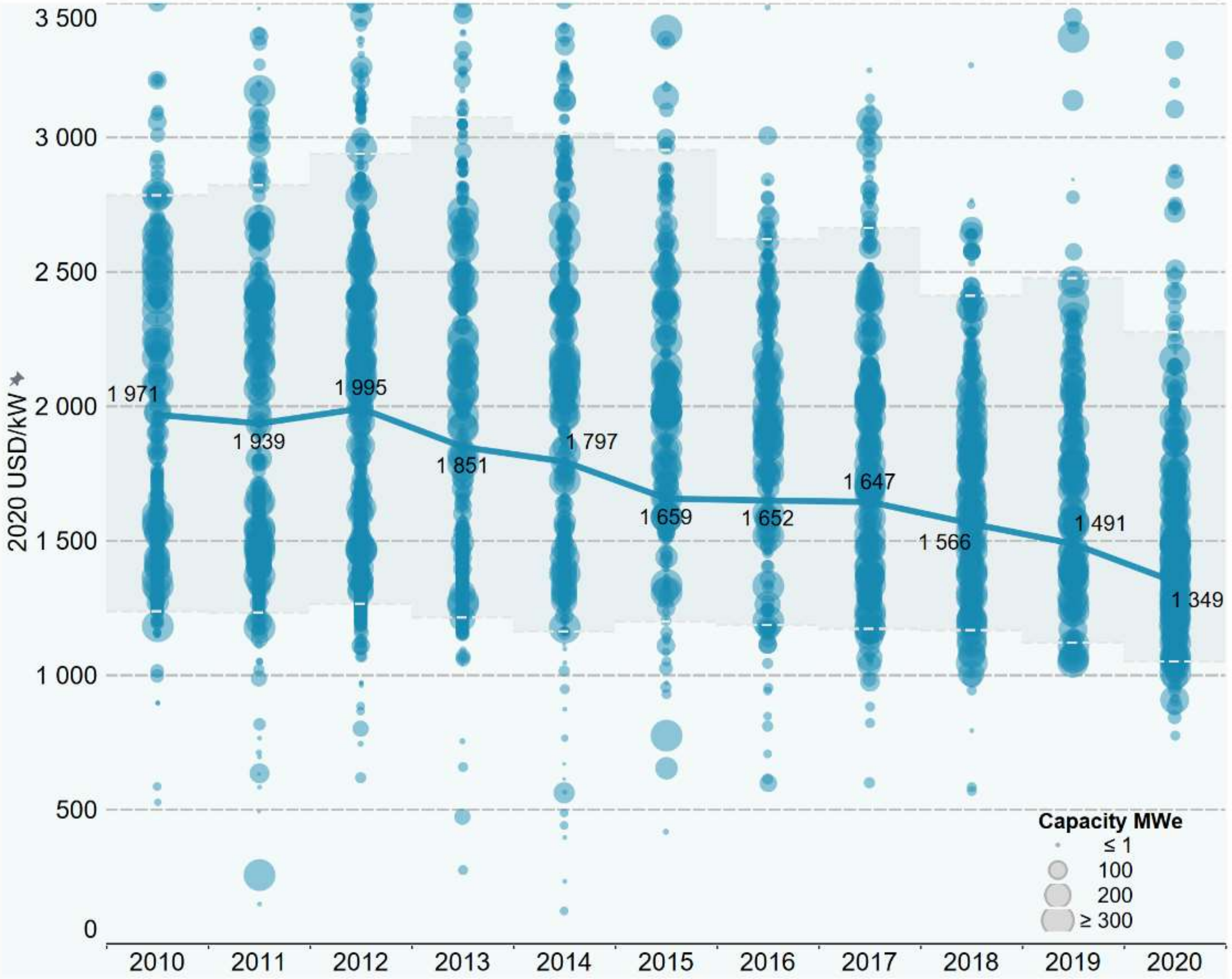
China's experience was one of a dramatic price fall between 1998 – when the wind turbine price was around USD 2 520/kW – and 2002. As the supply chain became deeper and more competitive and manufacturing capacity grew, supply constraints eased and wind turbine prices peaked.

Prices then declined in an irregular, step-wise fashion until the price reached an average of around USD 540/kW in 2020. This was somewhat above the 2019 level, due to tight supply during the surge in deployment in 2020.

Total installed costs, capacity factors and LCOE (2010 to 2020)

The global weighted-average total installed cost for onshore wind fell by 32%, between 2010 and 2020, from USD 1 971/kW to USD 1 349/kW. In 2020, it was also down 10% on the 2019 value of USD 1 491/kW.

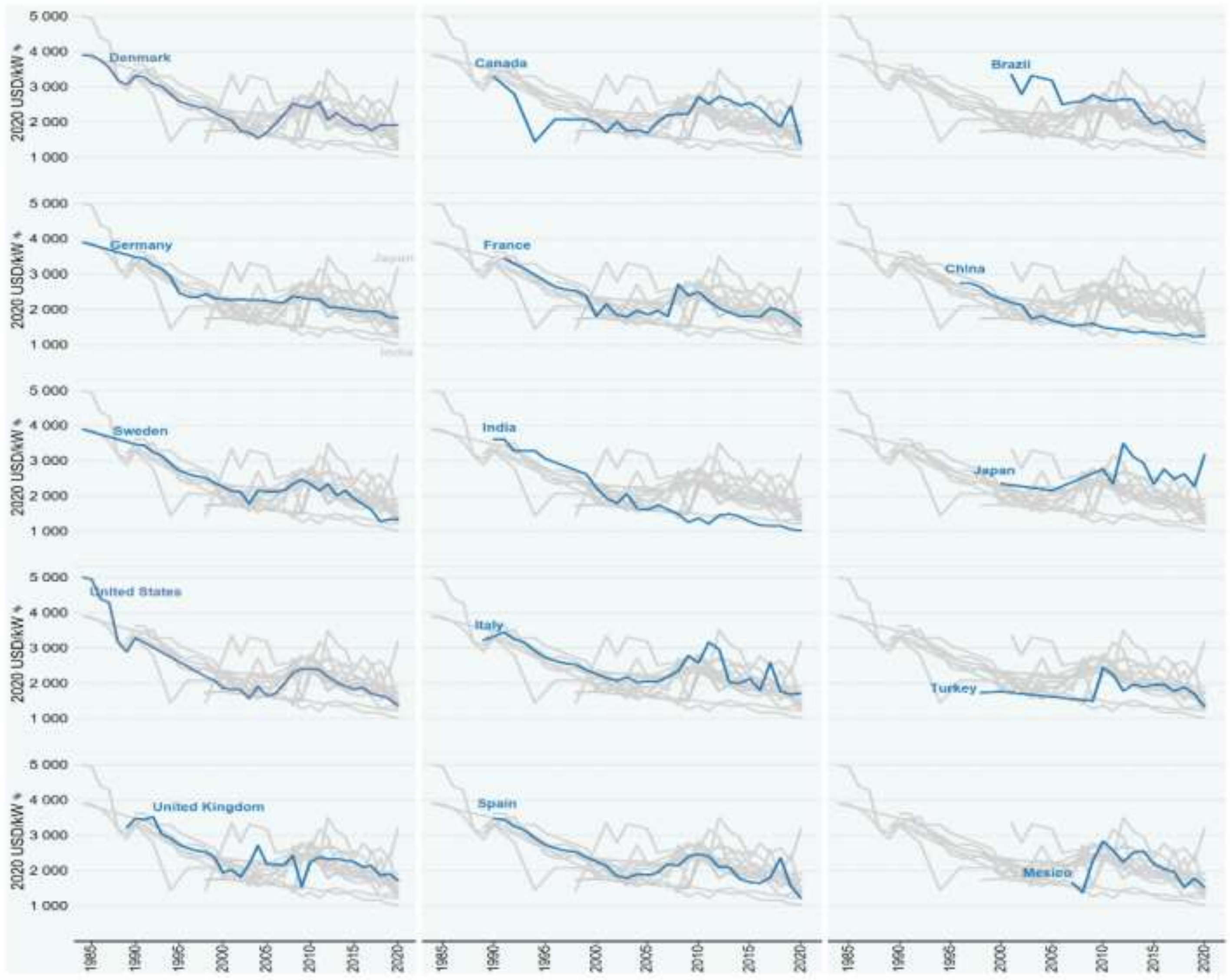
The country/region weighted-average total installed cost for onshore wind in 2020 ranged from around USD 1 038-USD 3 189/kW. China and India have weighted-average total installed costs between 20% and 67% lower than other regions.



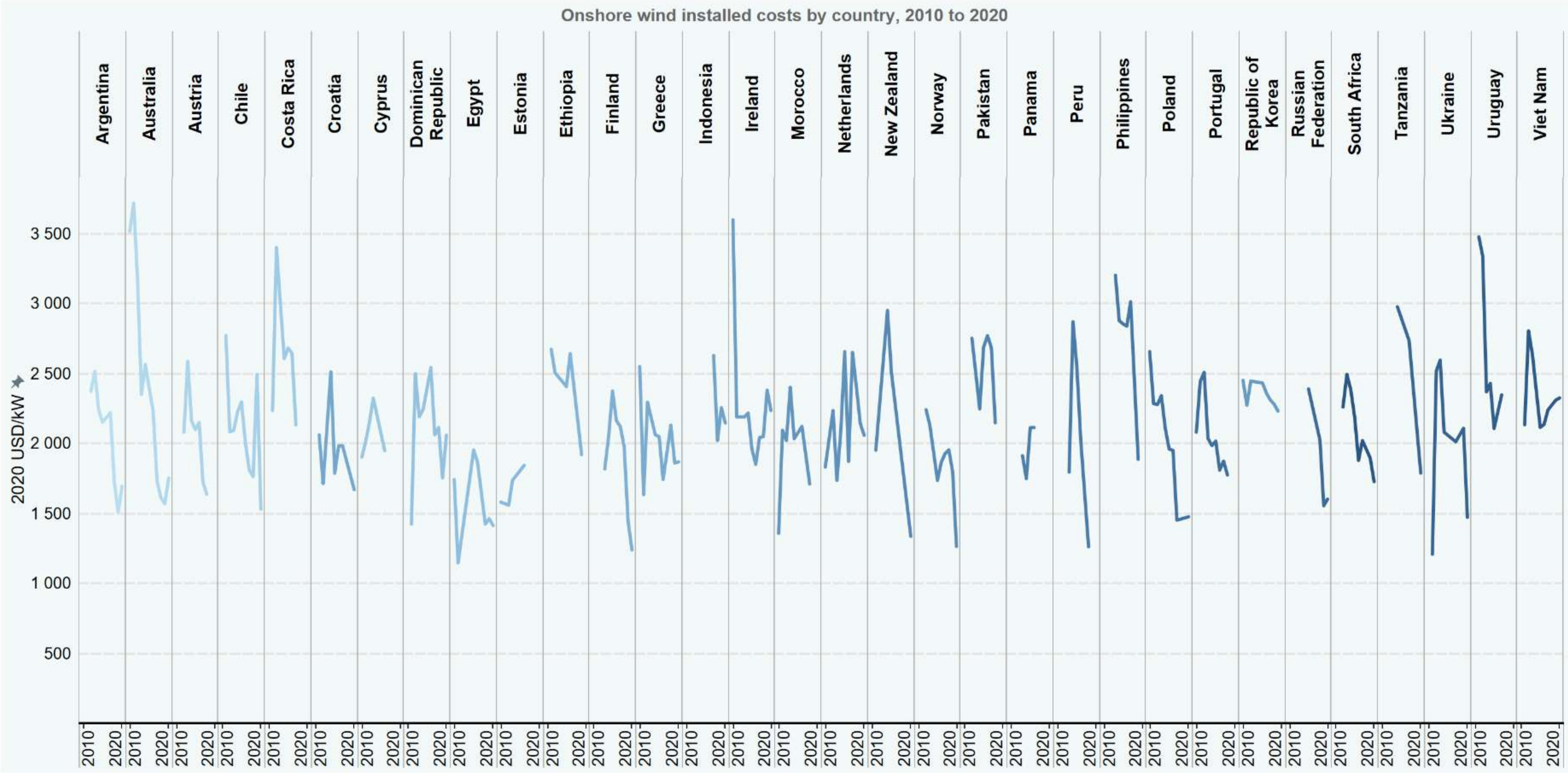
Total installed cost trends in 15 countries (1984 to 2020)

Major wind markets saw a range of cost reductions, stretching from just 8% in Mexico to 72% in the United States. Japan saw a 35% increase over the period shown, with the first cost data point in 2000. The more competitive, established markets show larger reductions in total installed costs over longer time periods than newer markets. The United States, followed by India, had the highest decrease in total installed costs, with reductions of 72% and 71%, respectively. Spain and Sweden each saw a reduction of 65%, while Brazil and China saw reductions of 55% and 53%, respectively. There is, however, a wide range of individual project installed costs within a country and region due to different country and site-specific requirements. These include logistics limitations for transportation, local content policies, land-use limitations and labour costs.

The following page shows trends in 32 countries with smaller wind markets. These provide less data and a shorter time series. This data is often more volatile and should be treated with caution.



Total installed costs by country (2010 to 2020)

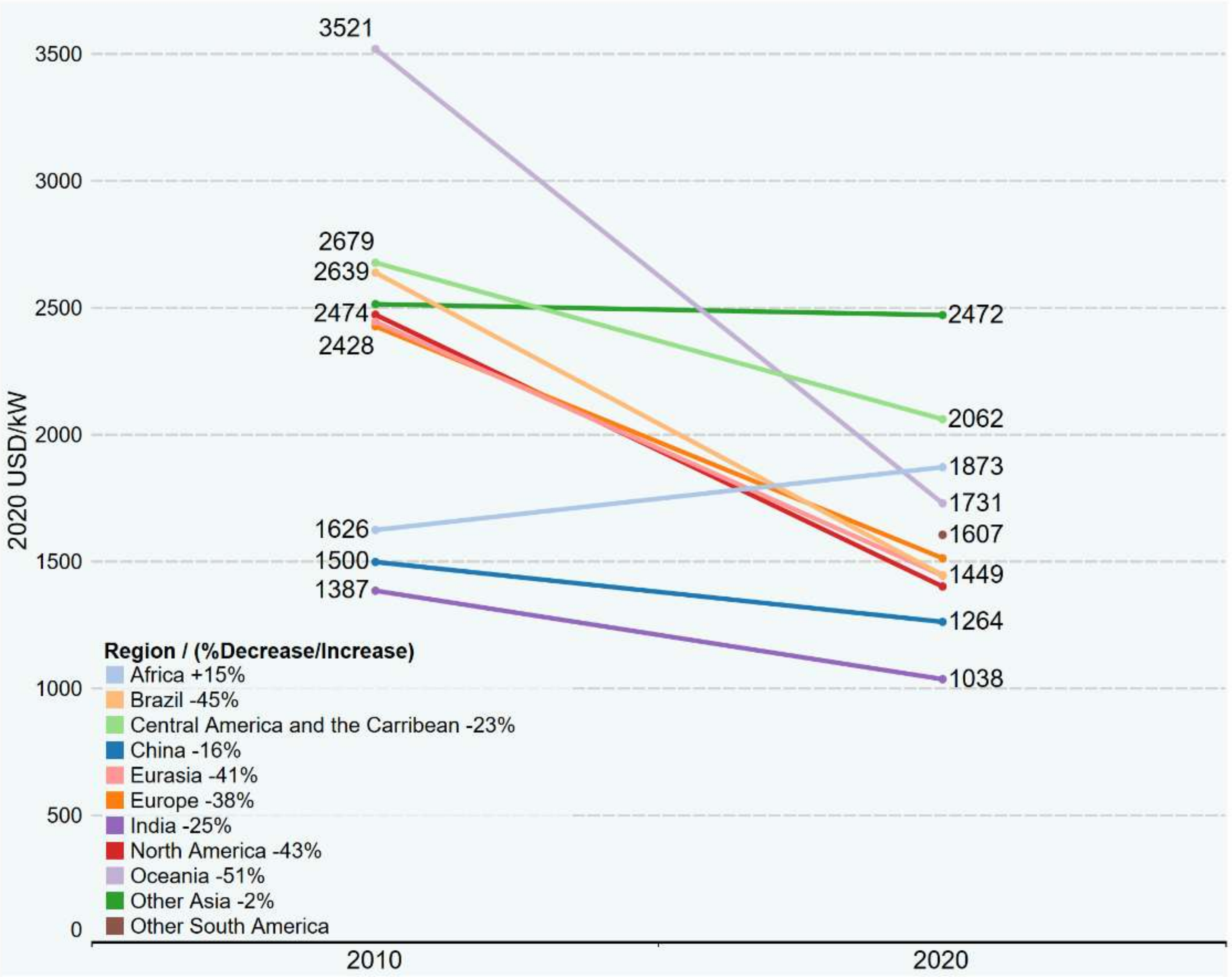


Total installed cost trends by region and country (2010 to 2020)

Looking at the data at a regional level, the regions with the highest weighted-average total installed costs in 2020 were (in descending order): Other Asia (that is to say, Asia excluding China and India); Central America and the Caribbean; and Africa, Oceania and South America (excluding Brazil). The regions with the next highest weighted-average total installed costs in 2020 were Europe, Brazil, Eurasia and North America.

Between 2010 and 2020, Europe showed a 38% decrease in weighted-average total installed costs.

In 2020, India and China, which have more mature markets and lower cost structures than their neighbours, showed lower average installed costs for onshore wind. India and China had the most competitive weighted-average total installed costs – USD 1 038/kW and USD 1 264/kW, respectively. Between 2010 and 2020, installed costs fell by 25% in India and 16% in China.

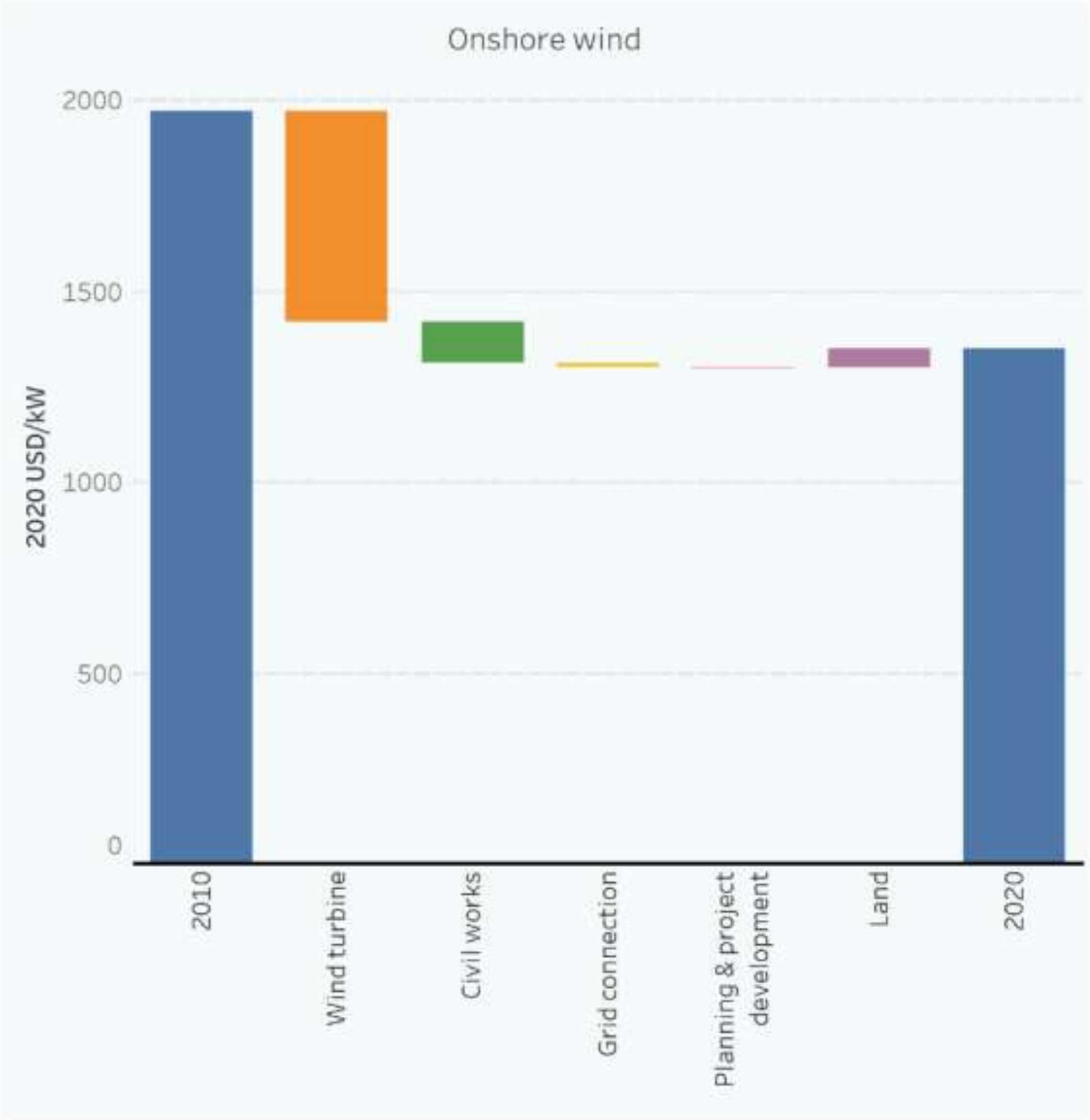


Total installed cost reduction by component (2010 to 2020)

For the period 2010 to 2020, IRENA has estimated the contributions made by four different categories to the reduction of total installed costs. These estimates are based on data in the IRENA Renewable Costs Database and in the literature. The results should be treated with caution, however, as it is not clear how representative some of the cost breakdown data is for a particular market.

Between 2010 and 2020, global weighted-average total installed costs fell 32% (USD 622/kW), from USD 1 971/kW to USD 1 349/kW. The largest contributor to this reduction was wind turbine prices, which fell by USD 551/kW over this time period. The next largest contributor was civil works, where the reduction in global weighted-average values was USD 107/kW. Grid connection costs declined by USD 13/kW over the period, while planning and project development was largely unchanged.
Estimated capital costs associated with projects increased by USD 48/kW, but this was largely due to the implied changes in cost shares for projects in China, which dominated 2020 deployment.

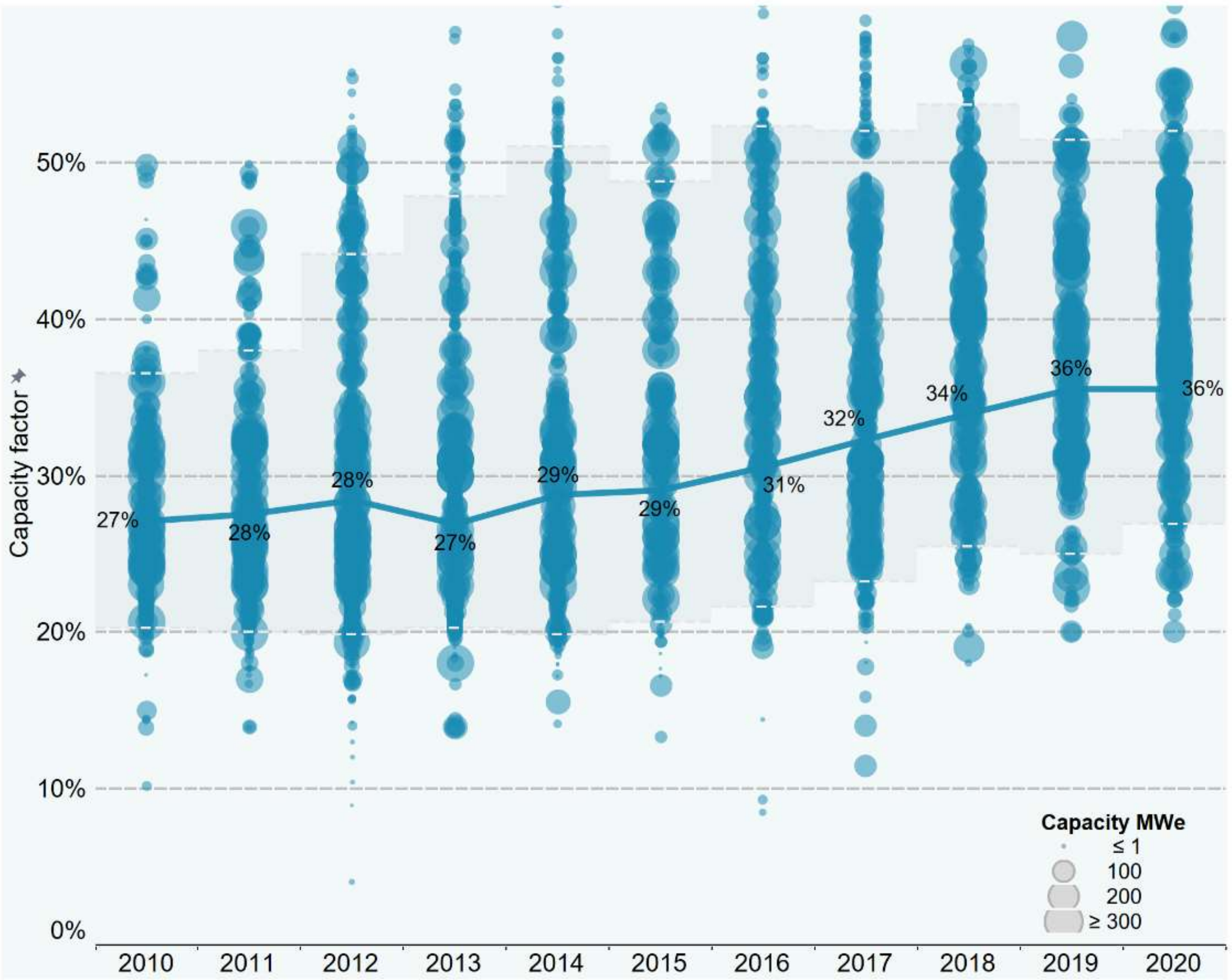
The following slide shows the changes in values by country, which allows for a more balanced view of the impact of total installed cost changes on individual markets. Many of these rely on leasing models, so land acquisition costs do not figure in the breakdown (land development costs being allocated elsewhere).



Capacity Factors (2010 to 2020)

During the 2010 to 2020 period, there was an almost one-third increase in the capacity factor of onshore wind, from just over 27% to 36%. Between 2019 and 2020, the capacity factor remained at 36%.

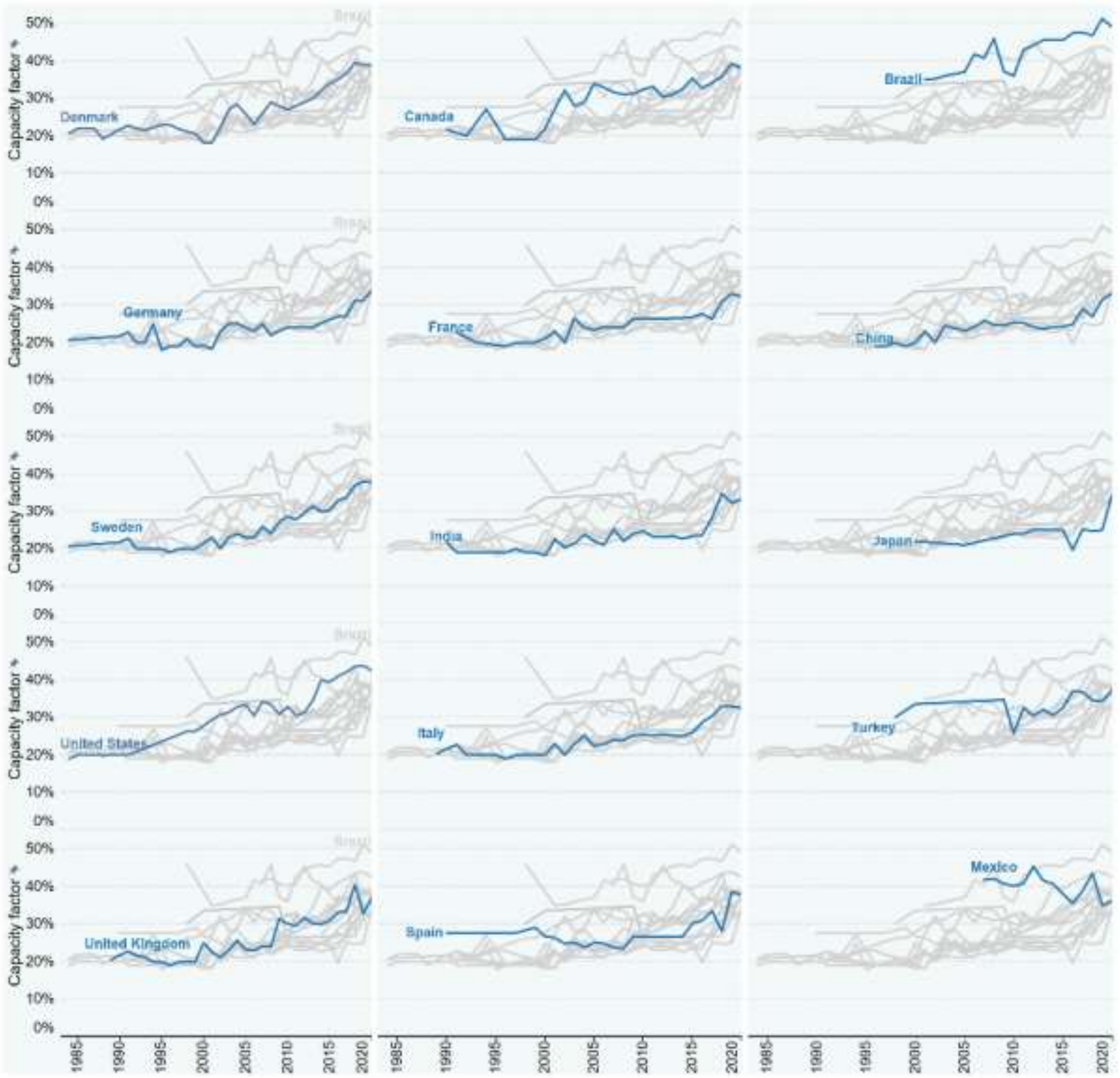
With its poorer wind resources, China's higher share of global deployment in 2020 had a significant impact on the global weighted-average capacity factor.



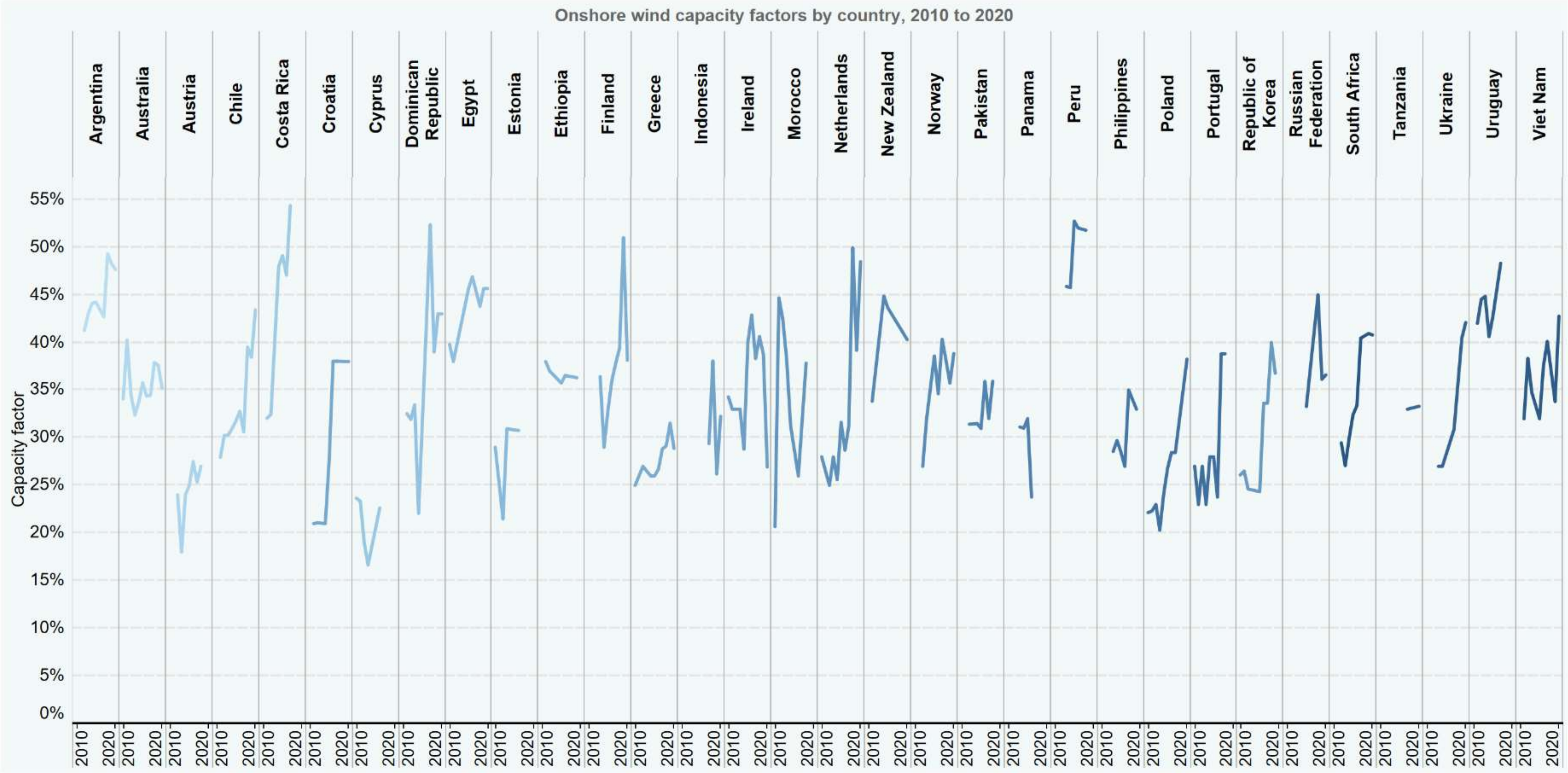
Capacity factor by country for new capacity (1984 to 2020)

Compared to the earliest commissioned projects in China – from 1996 – capacity factors in 2020 were 74% higher, while capacity factors in Denmark, Sweden, and the United Kingdom all increased by more than 80% between their earliest deployment and 2020. In the United States, the capacity factor of newly commissioned projects increased by over 120% between earliest deployment in 1984 and 2020, from 19% to 43%. Brazil, like the United States, has excellent onshore wind resources and in 2020, newly commissioned projects had a weighted-average capacity factor of 49% – 40% higher than in 2001. Technology improvements in wind turbines that have driven growth in capacity factors have had a significant impact on the competitiveness of onshore wind, as we will see later in this section.

The following page shows the trends in smaller wind markets. There is less data and a shorter time series available for these countries, with data often more volatile and best treated with caution.



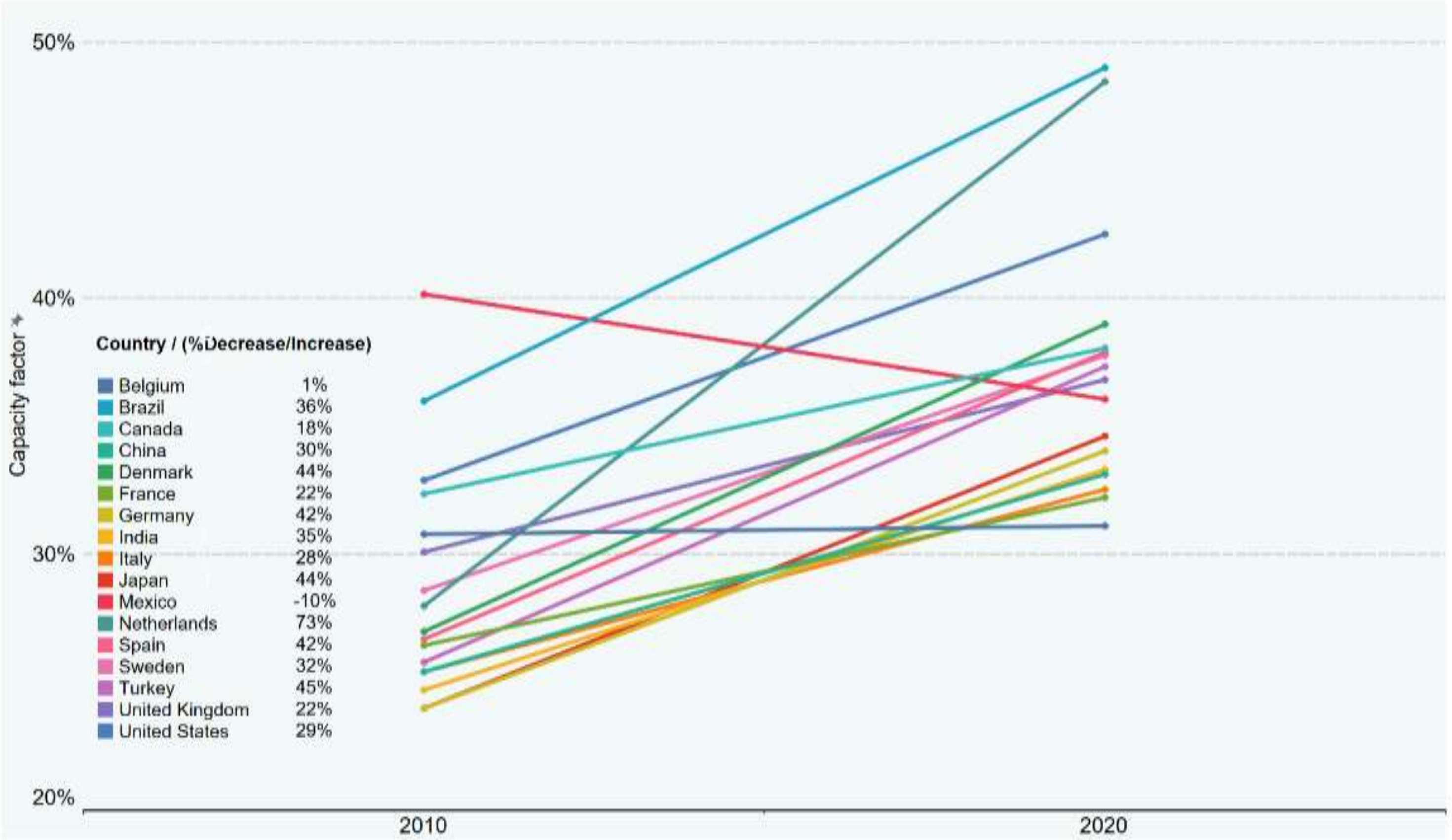
Capacity factor by country for new capacity (2010 to 2020)



Capacity factor by region and country (2010 to 2020)

Country-specific average capacity factors for projects commissioned in major onshore wind markets show that almost all the countries in this group experienced improvements in their weighted-average capacity factors over the 2010 to 2020 period. Increases ranged between 1% in Belgium and 73% in the Netherlands. The exception was Mexico, which saw a 10% decline in its weighted-average capacity factor.

Between 2010 and 2020, Denmark, Germany, Spain and Turkey showed increasing trends, of between 42% and 45%, while Italy and Sweden saw smaller increases of 28% and 32%, respectively. France and the United Kingdom both had a smaller 22% increase in their weighted-average capacity factors.

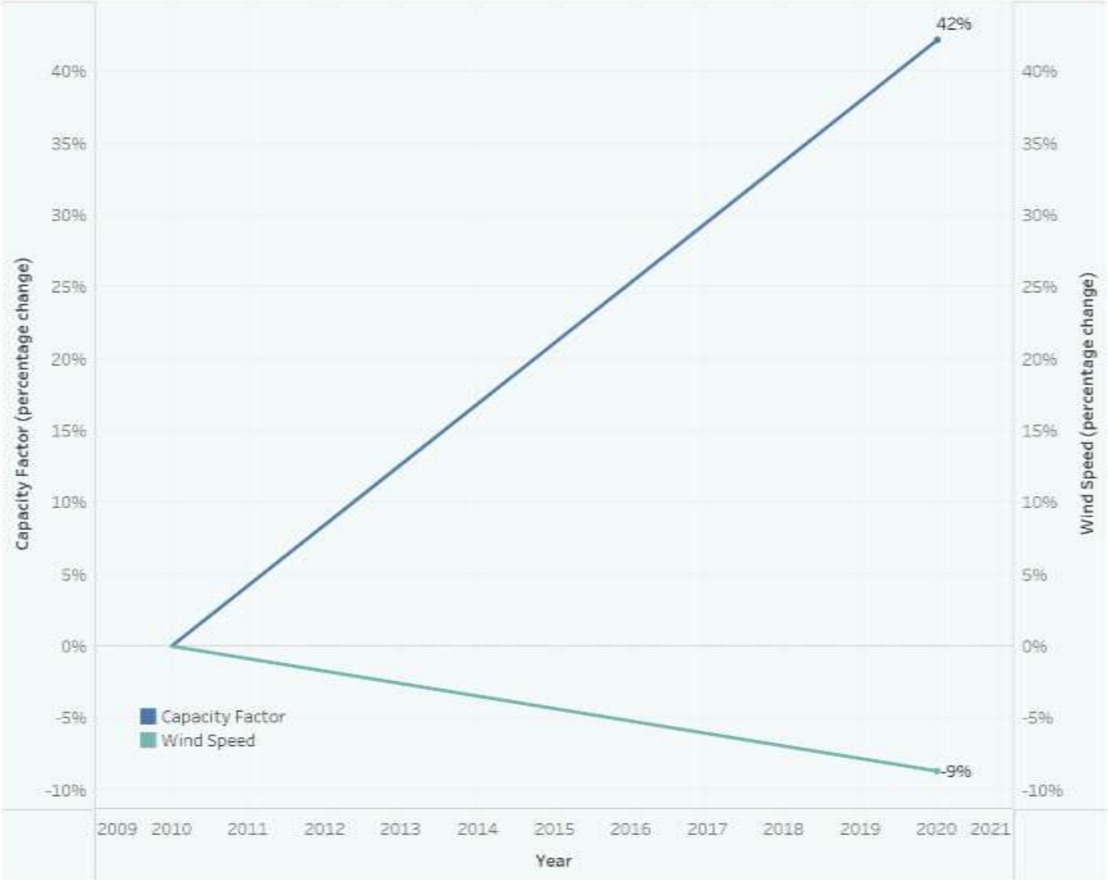


Capacity factors and wind resource quality (2010 to 2020)

The figure on the right shows the percentage change of weighted-average capacity factor and weighted-average wind speed for Brazil, Canada, France, Germany, Japan, Netherlands, Sweden, Turkey and the United Kingdom.

Between 2010 and 2020, the weighted-average capacity factor for this subset of countries increased by 42%, while the weighted-average wind speed declined by 9%.

Detailed weighted-average capacity factor and weighted-average wind speed data for the selected countries can be found in the next slide.



Capacity factors and wind resource quality by country (2010 to 2020)

A detailed breakdown of the previous slide shows that all the countries selected experienced an increase in their weighted-average capacity factors, despite a decline in the weighted-average wind speed. This could be due to less access to better wind resources in some countries.

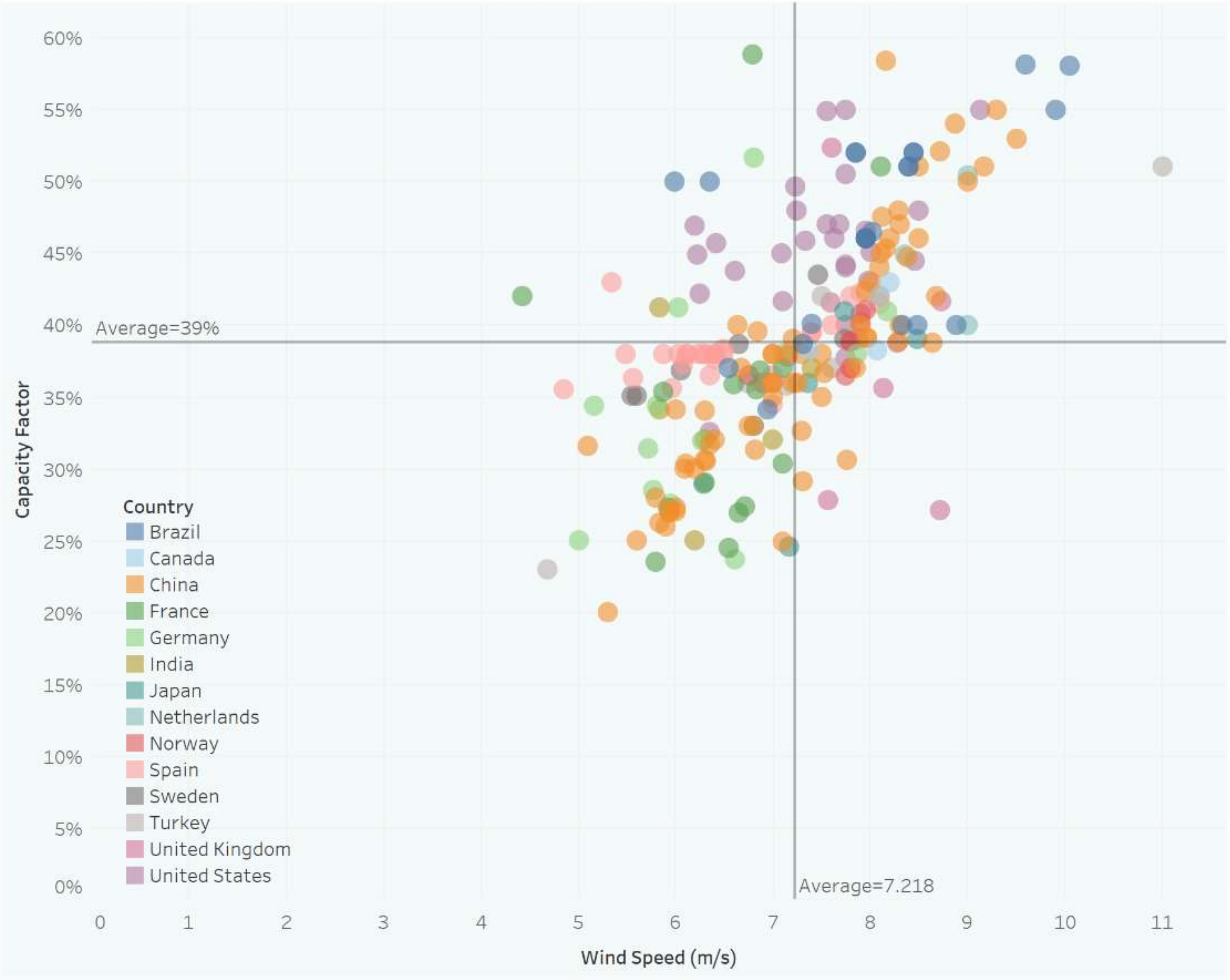
This trend confirms that technology improvements, including larger turbines and longer blades with higher hub heights, contributed greatly to an increase in the global weighted-average capacity factor.

The highest weighted-average capacity factor increase was in the Netherlands, at 73%, followed by Turkey and Japan, which saw increases of 45% and 44% respectively.

France and the United Kingdom both showed an increase of 22% in their weighted-average capacity factors, while Canada had the lowest weighted-average capacity factor increase, at only 18%.

Capacity Factor vs Wind Speed (2020)

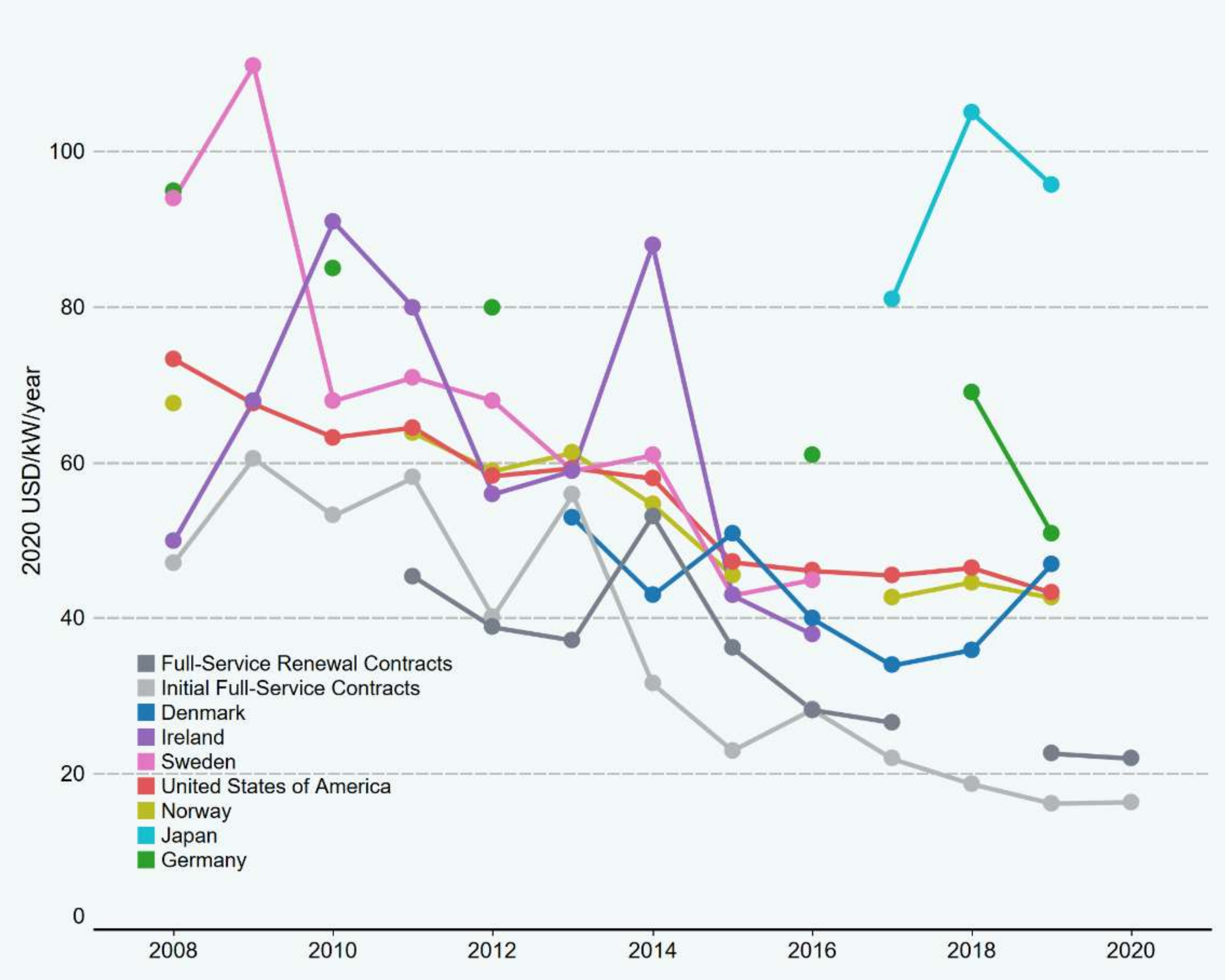
This figure shows the correlation between capacity factors and estimated wind speeds for the selected projects commissioned in 2020 for which IRENA was able to identify the exact wind farm site. While the results should be considered indicative only, they do show a clear correlation. It is important to note, however, that this represents a subset of the total projects commissioned in 2020, with the global average capacity factor at a lower value.



Operations and Maintenance (O&M) costs

This figure shows O&M costs in selected countries, along with Bloomberg New Energy Finance (BNEF) O&M price indexes. The latter are represented as either initial full-service contracts, or full-service contracts for already established wind farms. The latter are more expensive because they factor in the ageing of turbines. The data show a downward trend in O&M costs, reflecting the maturity and competitiveness of the market.

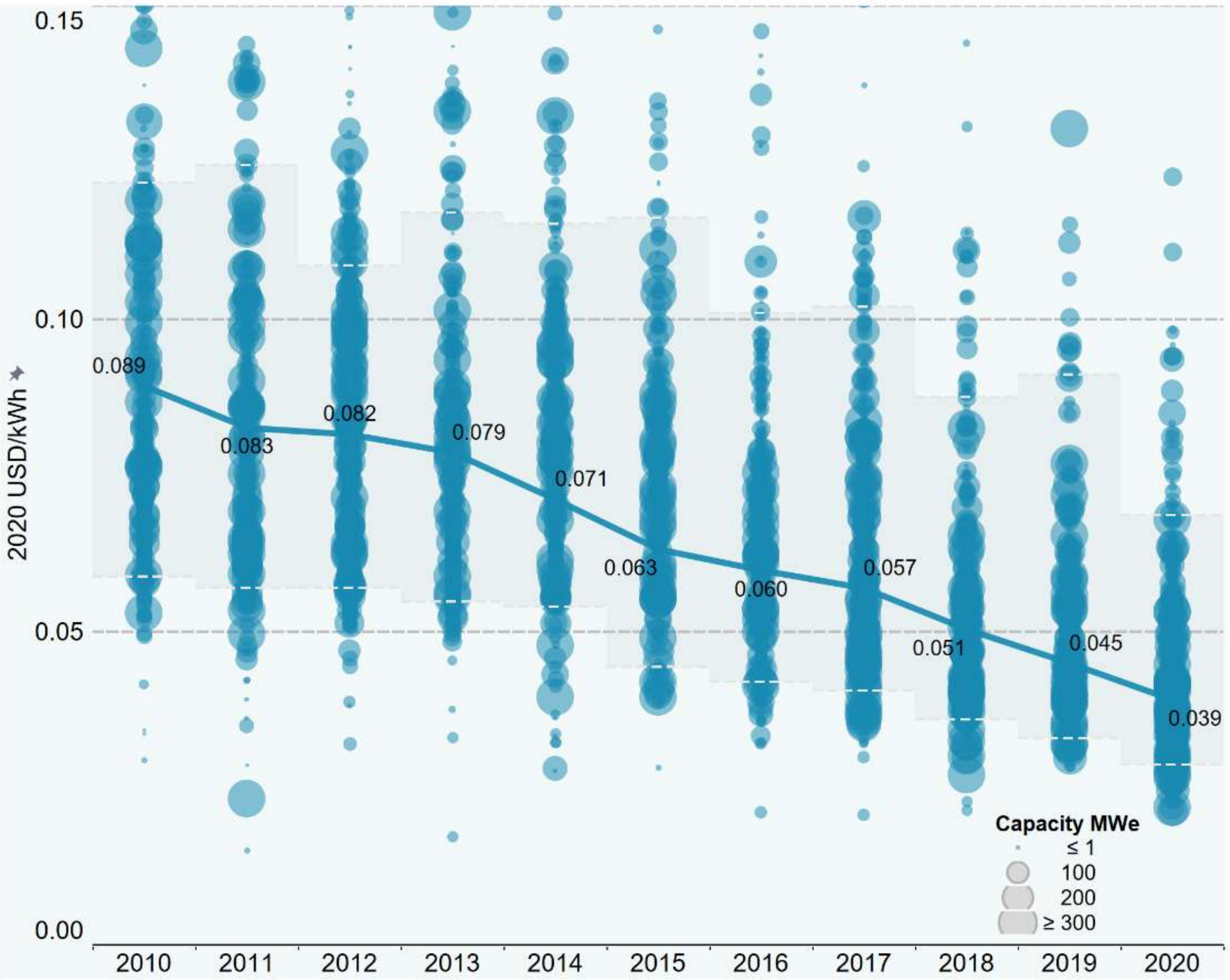
Initial full-service contracts fell 66% between 2008 and 2019, while full-service renewal contracts declined by 50% between 2011 and 2019. At the country level, between 2016 and 2018, O&M costs for onshore wind ranged from USD 33/kW per year (in Denmark) to USD 56/kW per year (in Germany). The latter country is known for its higher than average onshore wind O&M costs. The difference between the contract prices and observed country O&M costs is explained by the additional, predominantly operational expenses not covered by service contracts (*e.g.* insurance, land lease payments, local taxes, etc.).



Global trend in levelised cost of electricity (2010 to 2020)

In 2020, around 100 GW of the new onshore wind projects commissioned had an LCOE lower than the cheapest new source of fossil fuel-fired power generation.

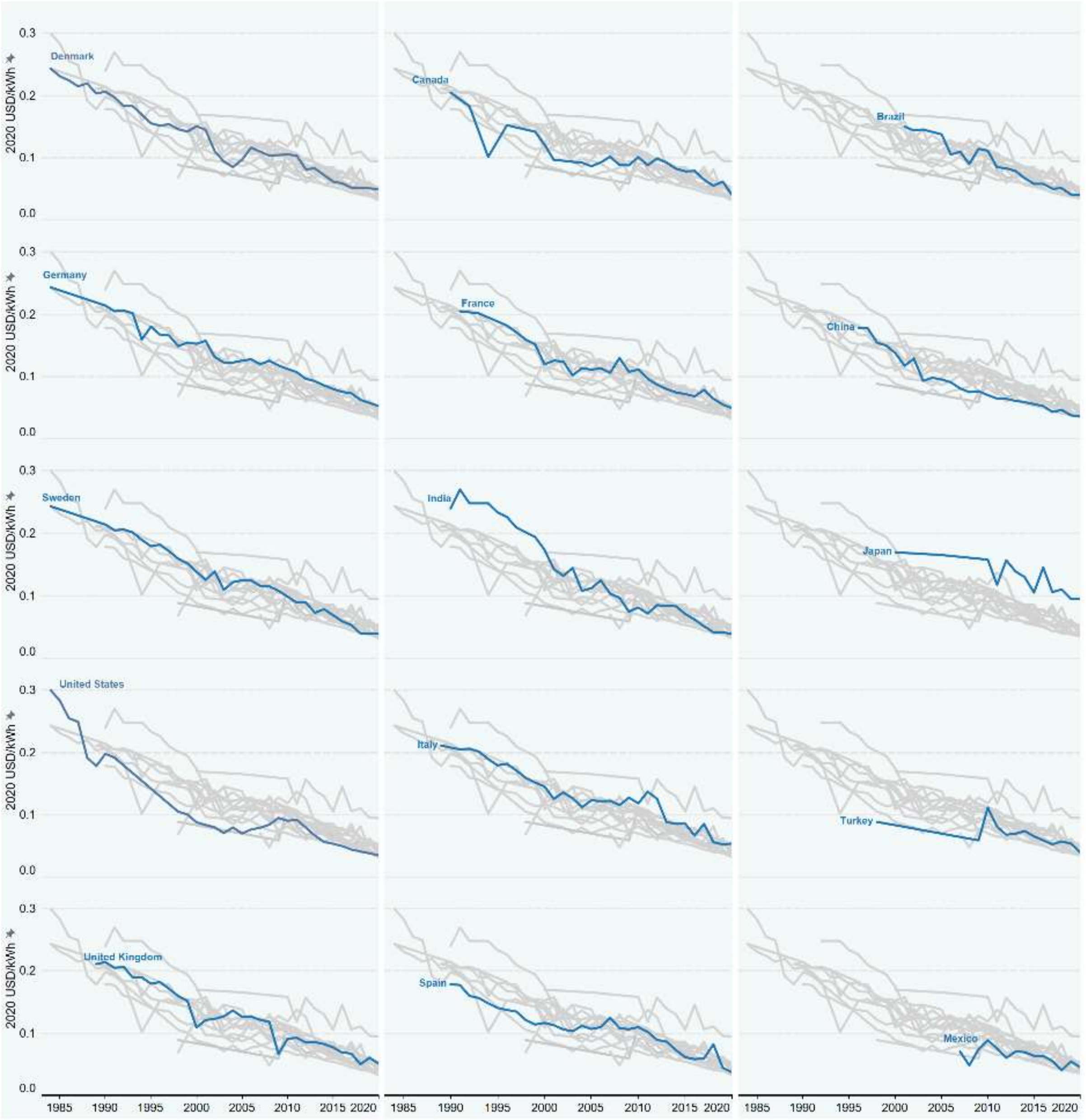
Between 2010 and 2020, the global weighted-average LCOE of onshore wind fell 56%, from USD 0.089/kWh to USD 0.039/kWh. In 2020, there was a 13% year-on-year reduction.



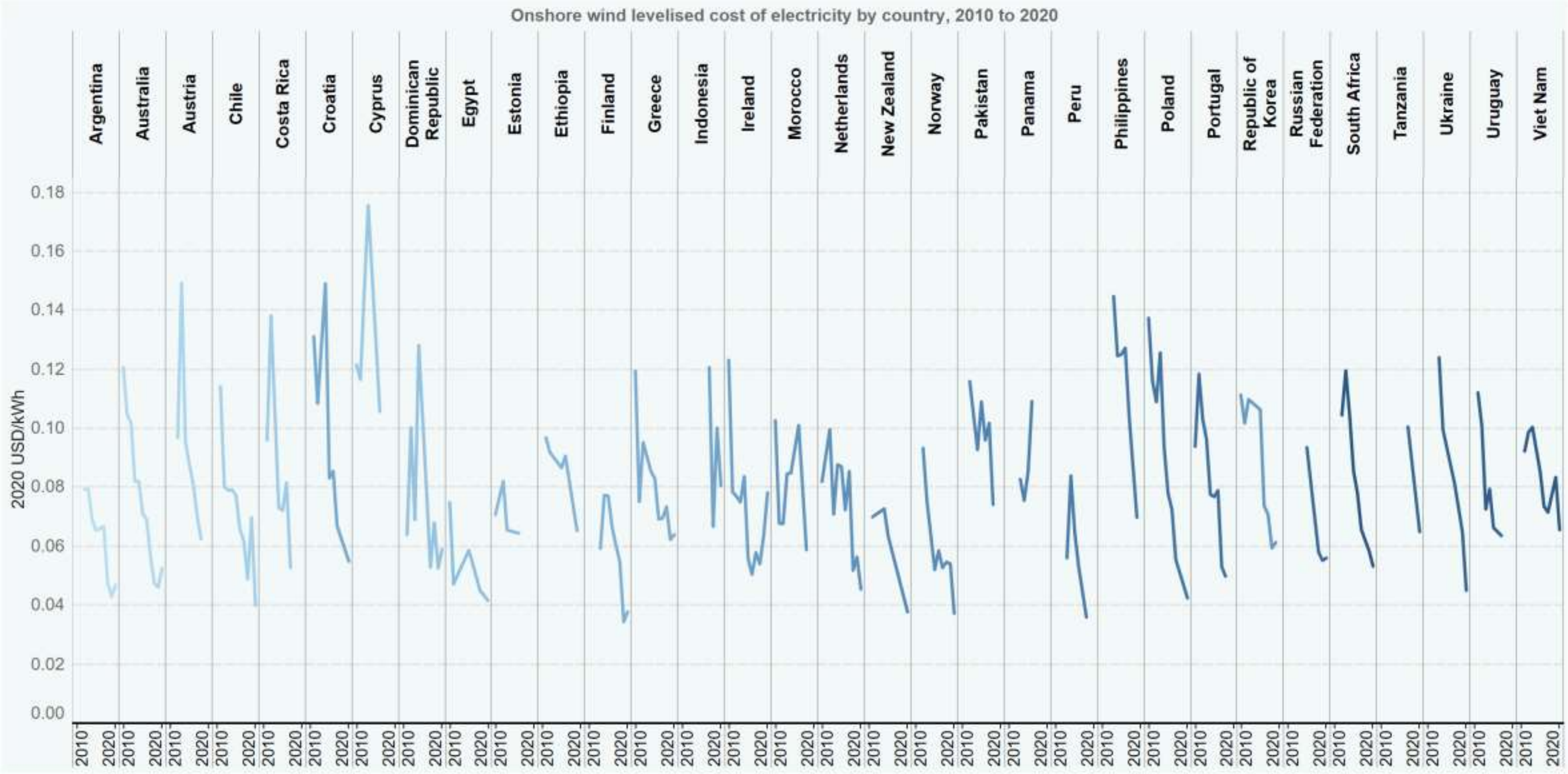
Levelised cost of electricity by country (1984 to 2020)

Of the 15 countries analysed on the right, the largest LCOE reduction – 88% – was in the United States, which also had the largest reduction (72%) in average total installed costs. The average capacity factor in the United States also saw a 120% improvement. Sweden and India had the second and third largest weighted-average LCOE reductions, at 84% and 83%, respectively, followed by China, which had a weighted-average LCOE reduction of 79%. In 2020, with the exception of Japan, all the 15 countries analysed on this page had weighted-average LCOEs below USD 0.055/kWh – the lower range for fossil fuel-fired power generation.

The following page shows the trends in smaller wind markets, where there is less data and a shorter time series. This data is often more volatile and should be treated with caution. In 2020, newly commissioned projects in Finland, New Zealand, Norway and Peru all had LCOEs below USD 0.04/kWh – comparing favourably with China, India and the United States of America.



Levelised cost of electricity by country (2010 to 2020)



Offshore wind

Key insights

- Offshore wind has experienced a decade of rapid growth and the arrival of competitive offshore wind projects. Average project sizes increased from 136 MW in 2010 to 301 MW in 2020, as turbine sizes grew and projects moved into deeper waters further from shore.

- Focusing on Europe, the most mature market, the global weighted-average water depth for newly commissioned offshore wind projects increased 76% between 2010 and 2020, from 21 m to 37 m. Over the same period, projects moved from an average distance from shore of 18 km to 40 km and the weighted-average turbine size increased 158%, from 3.1 MW to 8 MW. Rotor diameters increased 46%, from 112 m to 163 m, over the decade.

- With higher hub-heights and swept blade areas, capacity factors have increased over time. This is due to technology improvements in the turbine, wind farm layout and connections, and to improved O&M practices that have reduced downtime in the windiest periods. The global weighted-average capacity factor grew from 38% for projects in 2010 to 40% for projects in 2020. In Europe, however, there was a 13% increase, from 39% in 2010 to 44% in 2020.

- Between 2010 and 2020, the global weighted-average total installed costs fell 32%, from USD 4 706/kW to USD 3 185/kW. In 2011,the global weighted-average total installed cost peaked at USD 5 390/kW , representing a figure 41% higher than its 2020 level.

- Offshore, turbines (including towers) generally account for between 33% and 43% of the total installed cost. Installation costs, from the estimates available, range from 8% to 19% of total installed costs, while contingency/ other costs range from 10% to 14%, electrical interconnection from 8% to 24% and foundation costs from 14% to 22%. Development costs, which include planning, project management and other administrative costs, comprise between 2% and 7% of total installed costs.

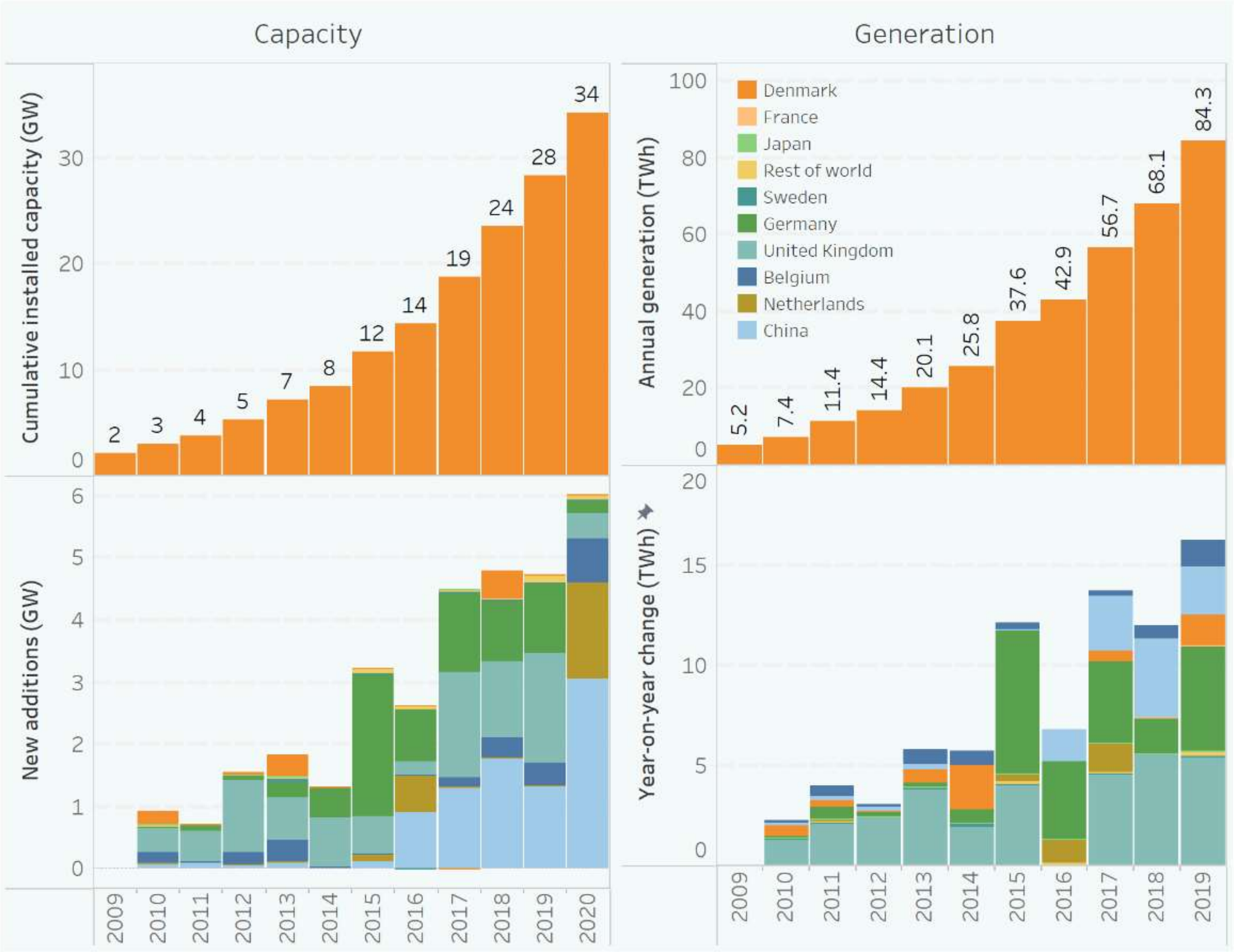
- The cumulative installed capacity of offshore wind grew from just 3 GW in 2010 to 34 GW in 2020. Over the same time period, the LCOE of newly commissioned offshore wind projects fell by around half (48%). The Netherlands had the lowest weighted -average LCOE for projects commissioned in 2020, at USD 0.067/kWh and the Republic of Korea the highest, at USD 0.122/kWh. Between 2010 and 2020, China had the second lowest weighted-average LCOE, at USD 0.084/kWh, while it also had the second highest percentage reduction in country weighted-average LCOE values, at 52%.

Market development

Over the period 2010 to 2020, the total cumulative installed capacity of offshore wind grew from around 3 GW to 34 GW.

In 2010, slightly less than 1 GW of new capacity was commissioned, predominantly in the United Kingdom. By 2020, however, this had grown to 6 GW of newly commissioned capacity, with China accounting for around half of that. Despite modest capacity additions in 2020, the United Kingdom remains the country with the largest offshore wind capacity, with 10.4 GW installed. With 3 GW added in 2020, however, China is now in second place, with 9 GW, and Germany in third place, with 7.7 GW. The Netherlands, with 2.5 GW, and Belgium, with 2.3 GW, round out the top five countries by installed capacity.

Offshore wind generation data was heavily influenced by a windy Northern Europe in 2020, with the UK capacity performing particularly well, belying its modest capacity additions.



Offshore wind from 2010 to 2020

-32% Total installed costs

-48% Levelised cost of electricity

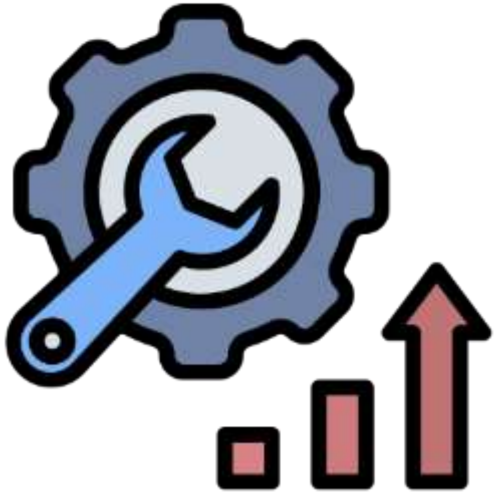
COSTS

PERFORMANCE

Turbine capacity **+143%**

Rotor diameter **+46%**

Capacity factor **+6%**



Project characteristics in Europe (2010, 2015 and 2020)

In 2010, an average offshore wind farm in Europe would have been a 155 MW project in a water depth of 21 m and 18 km from shore. It would likely have had a monopile or gravity foundation and an average turbine rating of 3.1 MW, with an average hub height of 83 m and rotor diameter of 112 m.

By 2020, the average project size had increased to 336 MW with most having monopile/jacket foundation in an average water depth of 37 m, 40 km from shore. The turbine rating had also increased, to 8 MW, with an average hub height of 97 m and rotor diameter of 163 m .

While the 'average' offshore wind farm in Europe is in many ways an artificial metric, an examination of how the weighted-average of newly commissioned projects has changed for different metrics over the period 2010 to 2020 can provide an idea of some of the major changes in the sector, before we examine country-level details in the rest of this section.

The average offshore wind farm in Europe	2010	2015	2020
Water Depth (m)	21	29	37
Distance from shore (km)	18	49	40
Project Size (MW)	155	270	336
Hub Height (m)	83	87	97
Rotor Diameter (m)	112	119	163
Turbine Size (MW)	3.1	4.2	8.0
Foundation	Monopile/Gravity	Monopile/Jacket	Monopile/Jacket

Project characteristics: Water depth and distance to shore

The following pages detail the trend in offshore wind farm characteristics and, specifically, the water depth and distance from shore of these projects. These two parameters have an outsized impact on project economics. Deeper waters mean more expensive foundations, while increased distance from shore and ports increases the cost of the grid connection and the cost of installation, given longer downtimes between port and wind farm for crew and logistics.

Between 2000 and 2020, offshore wind farms moved to deeper waters and farther from shore. Based on project data in the IRENA Renewable Cost Database, the offshore wind farms commissioned in 2001 averaged 25 MW in size in a water depth of 7 m, roughly 5 km from shore. These figures have significantly increased since then. In 2020, the average offshore wind farm reached 336 MW and had a weighted-average distance to shore of 40 km and a water depth of 37 m.

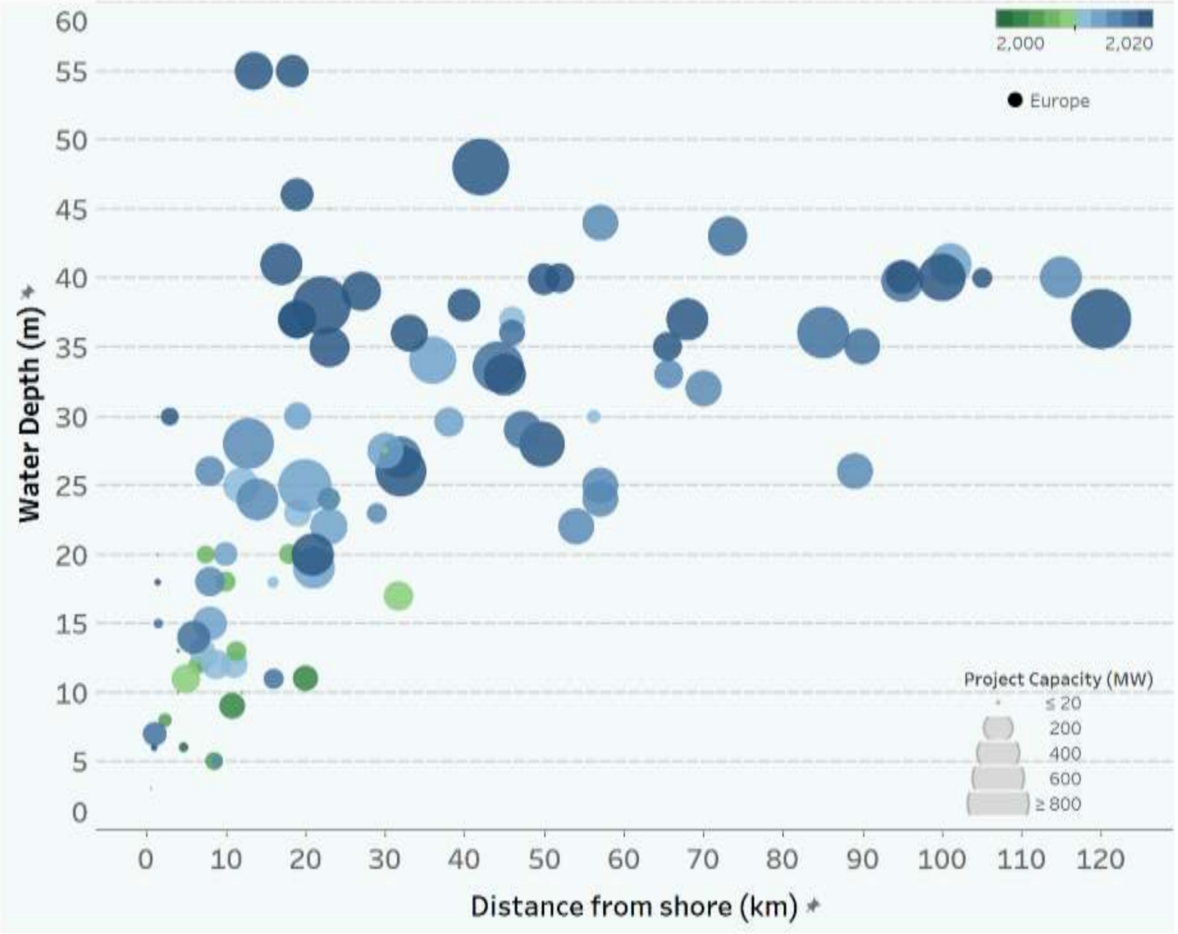
The trend to deeper waters and further from shore is most pronounced in Europe – the most mature market for offshore wind. Most recent projects in Europe are in waters between 30 m and 50 m deep. Many European projects, however, remain relatively close to shore, helping offset the greater water depth. Having said this, in recent years, there has been a trend to greater distances form shore, with an increasing proportion of European projects located between 50 km and 120 km out.

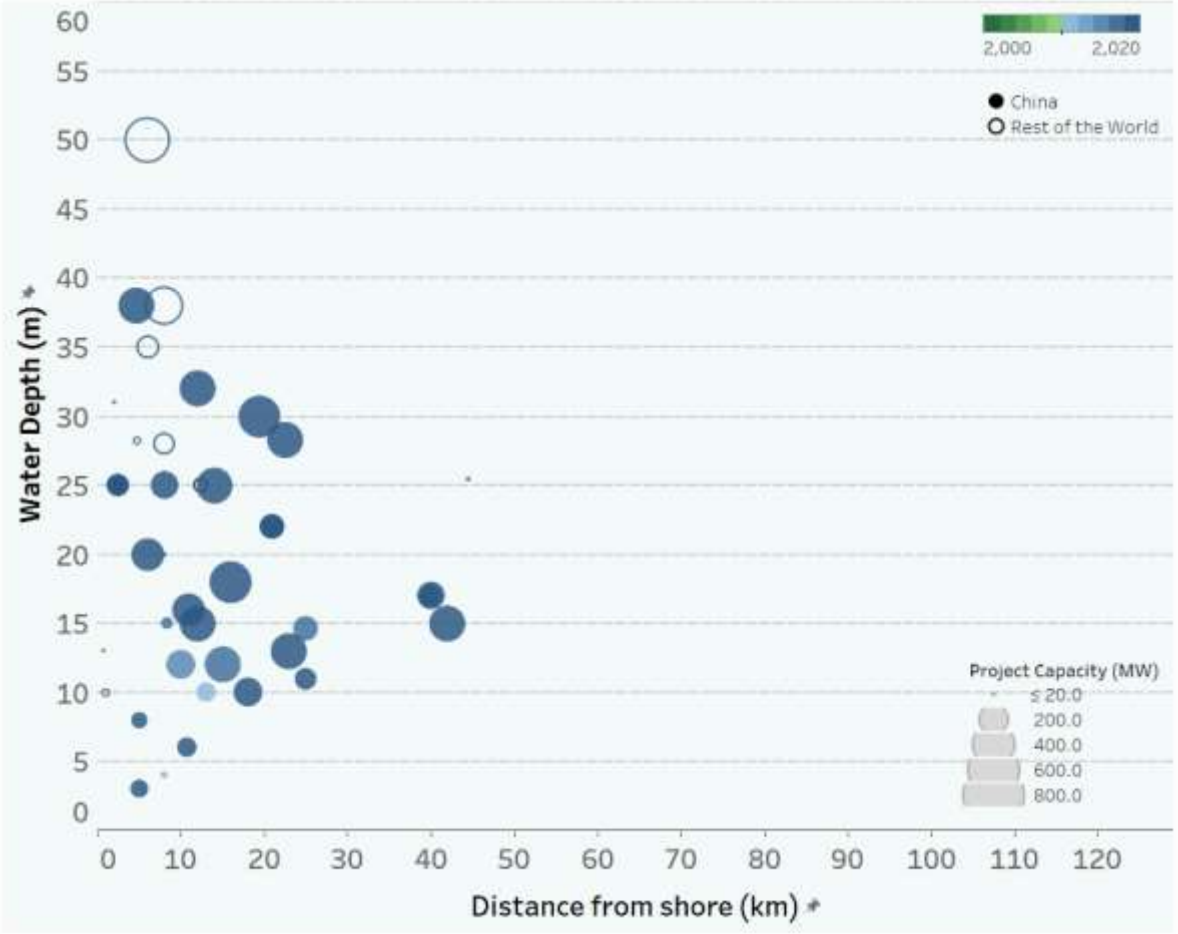
The majority of these projects can be found in Germany and the United Kingdom, the latter being Europe's largest offshore wind proponent, with 10.4 GW of installed capacity at the end of 2020.

Belgium, China, Denmark and the Netherlands are still largely exploiting zones closer to shore. The Netherlands is the main exception, with a significant share of its total wind farms now 50 km or more from shore. All of these countries are, however, currently still able to exploit areas in shallow water, from 20 m to 40 m deep.

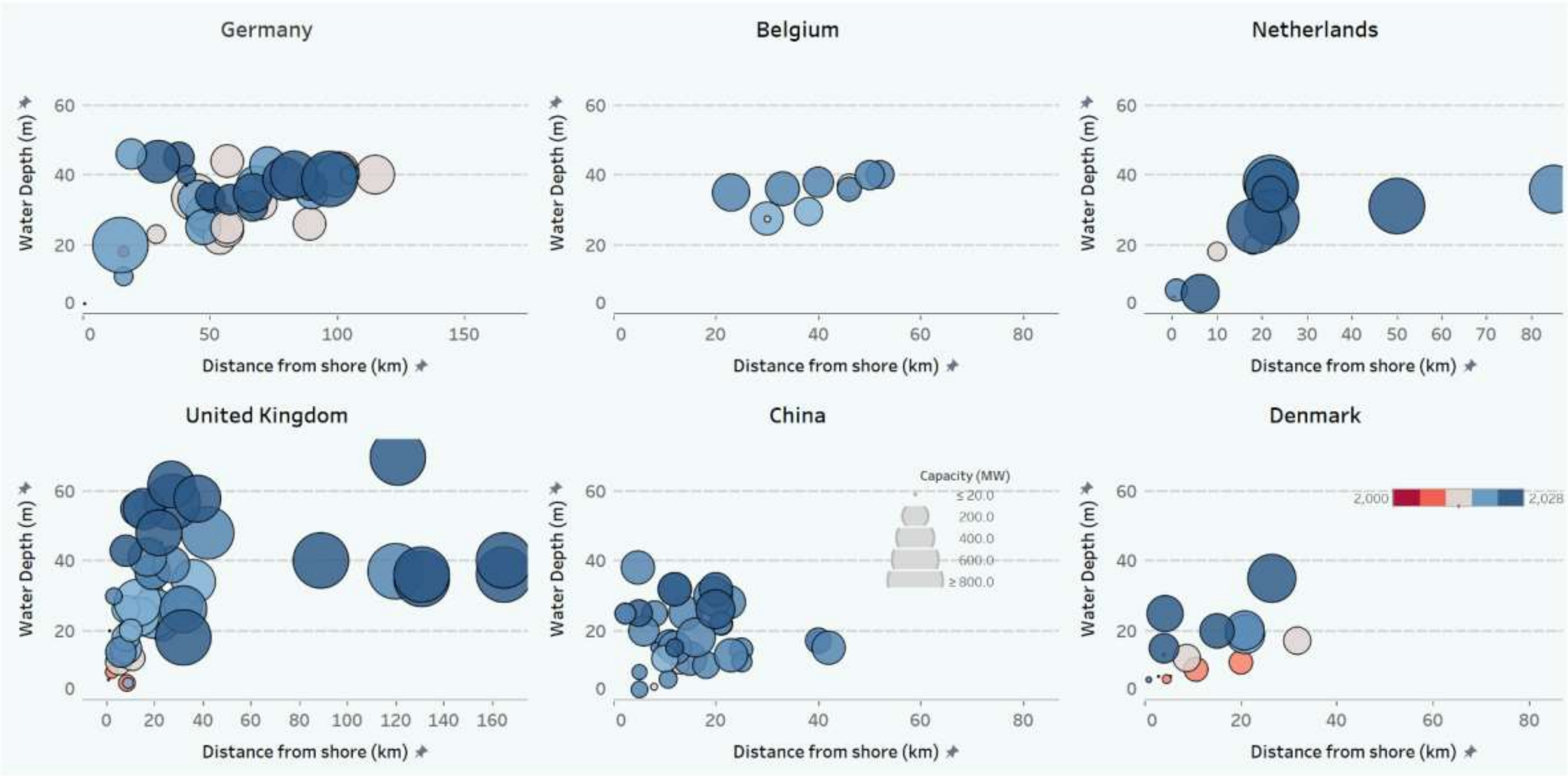
With relatively few commissioned offshore wind farms outside the major markets of Europe and China, there is no real global trend in water depth and distance from shore. However, most countries are prioritising close to shore zones (less than 15 km from the coast), albeit with a very wide spread of water depths (26 m to 50 m for utility-scale projects).

Water depth vs distance from shore in Europe and the Rest of the World





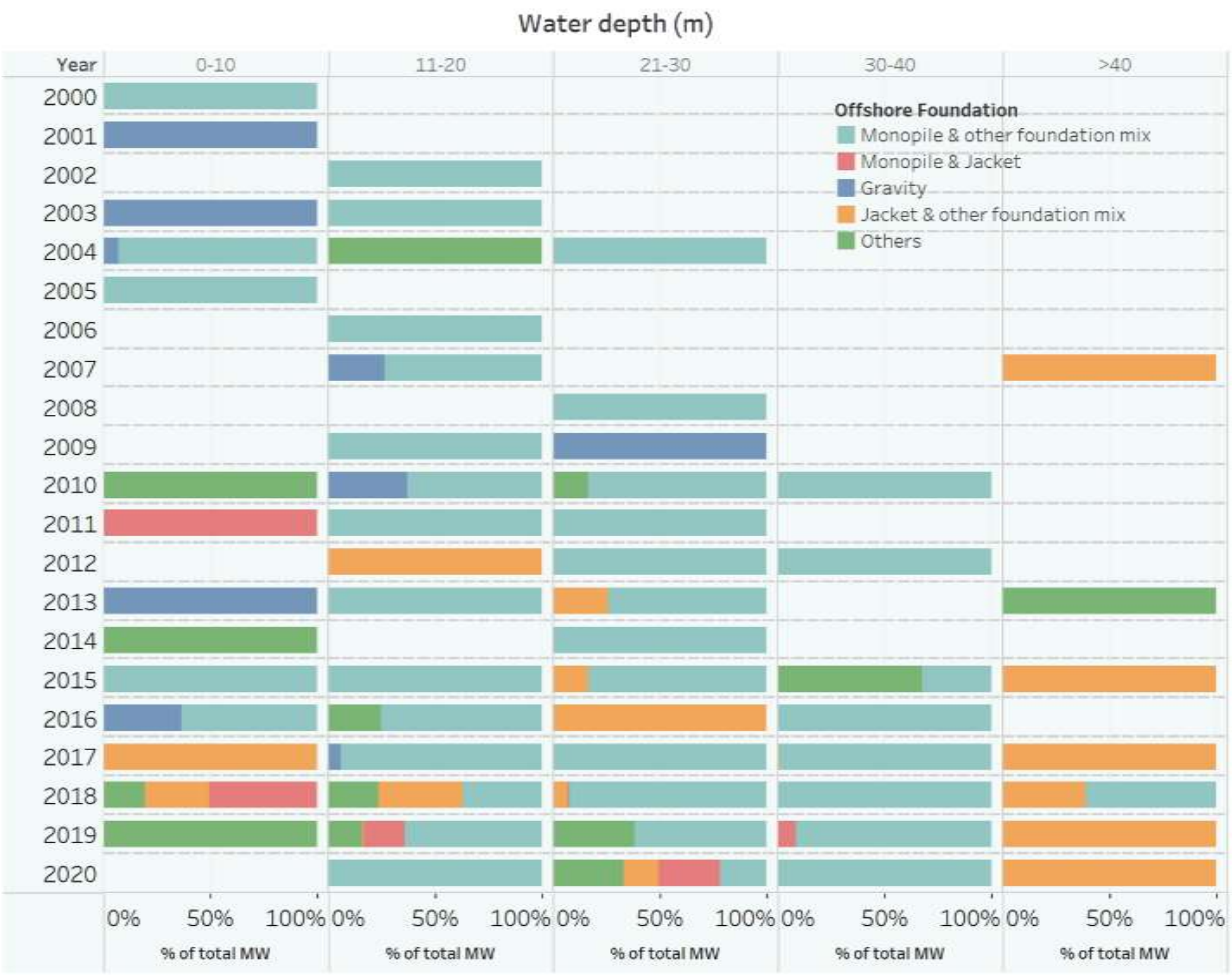
Water depth vs distance from shore by country



Foundation type by water depth

Offshore wind projects use a range of different foundation types depending on sub-surface seabed conditions and economics. The common designs are:
monopile; jacket; a combination of monopile and jacket; gravity; and new foundation designs such as multiple, suction bucket, tripile/tripod (referred to on the right as 'others').

Monopile foundations are simple, well proven and dominate installed capacity in water depths between 20 m and 40 m, for which they are most suited. Jacket foundations dominate water depths beyond 40 m, as they are more suited to deep water and/or high waves. Gravity foundations saw significant shares in shallow water in 2010, 2013 and 2016. In 2017, their deployment was seen in water depths of 10 m to 20 m, while in 2018, they were seen in water 20 m to 30 m deep. Other foundation types, such as suction buckets, multiple or tri-pile/tripod started emerging in shallow waters, predominantly at, or below, 30 m.



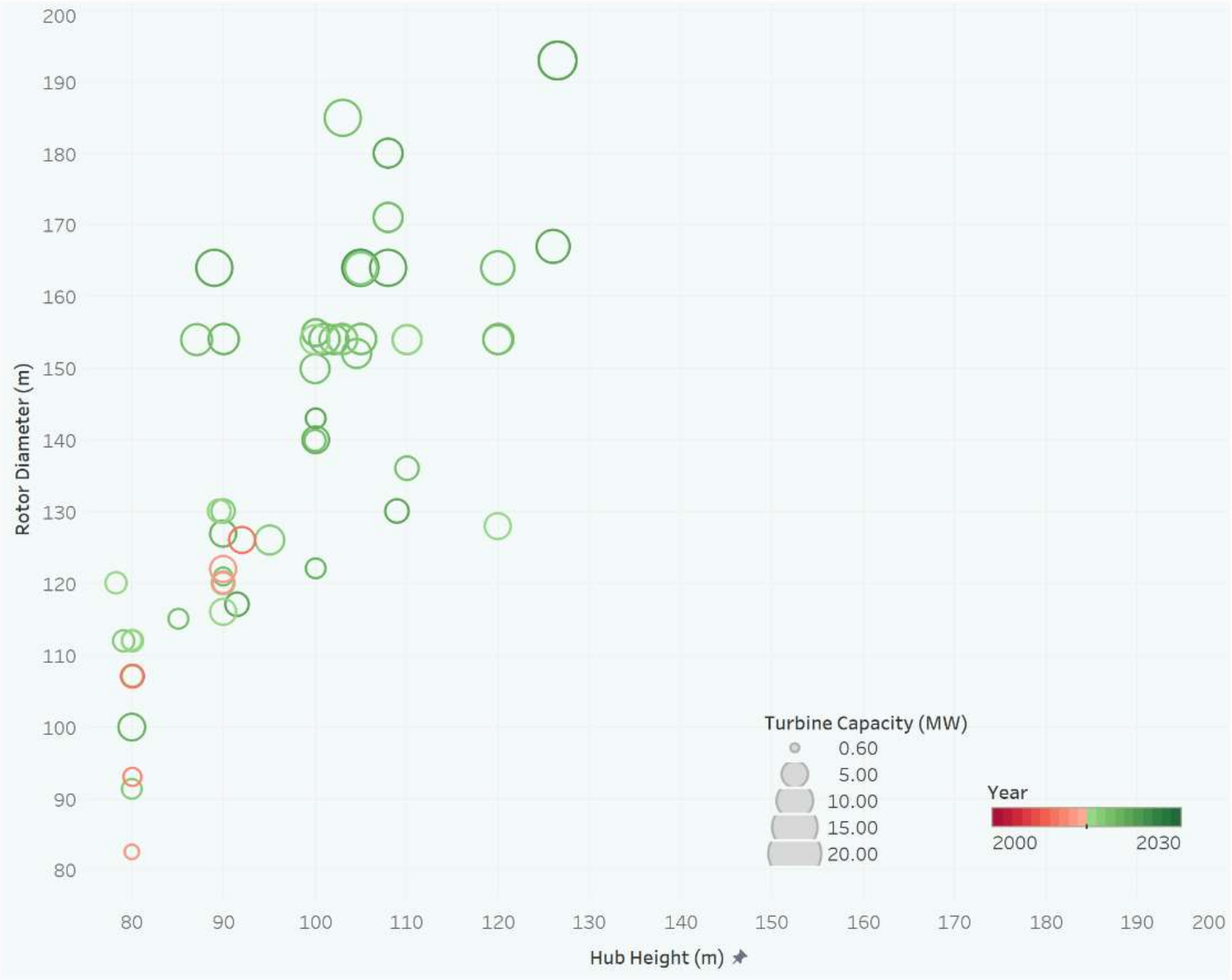
Rotor Diameter vs Hub Height

It is apparent that in more recent years, the rotor diameters and hub heights of offshore wind turbines have increased in line with growing turbine capacity.

Between 2010 and 2020, the weighted-average rotor diameter increased by 44%, while the weighted-average hub height increased by 18%.

Over the same period, offshore wind weighted-average turbine capacity increased by 143%, increasing from 3.1 MW to 7.5 MW.

The next three slides show the trends in weighted-average rotor diameter, hub height and turbine capacity over the 2010 to 2020 period.



Rotor Diameter

With recent years seeing more projects in China, Germany and Belgium – countries where projects tend to use larger rotor diameters – the weighted-average rotor diameter increased by 44% between 2010 and 2020.

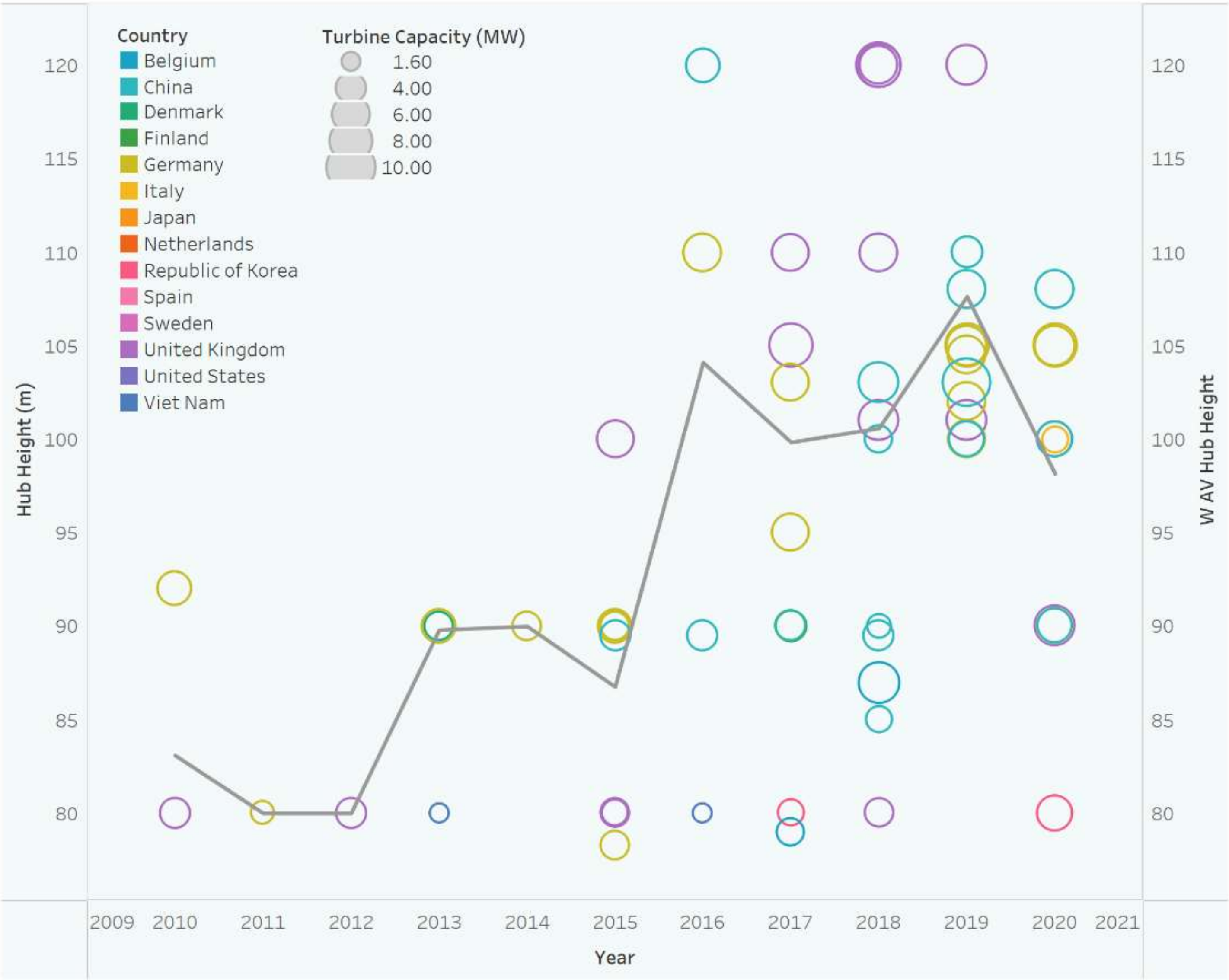
In 2020, Germany and Belgium had a weighted-average rotor diameter of 166 m, while in China it was 162 m.

The weighted-average rotor diameter for Europe was 112 m in 2010. This value reached 163 m in 2020 (a 46% increase).

Hub Height

Between 2010 and 2020, the weighted-average hub height increased by 18%, from 83 m to 98 m. The weighted-average hub height in 2020, however, was 7% lower than its 2019 value of 108 m.

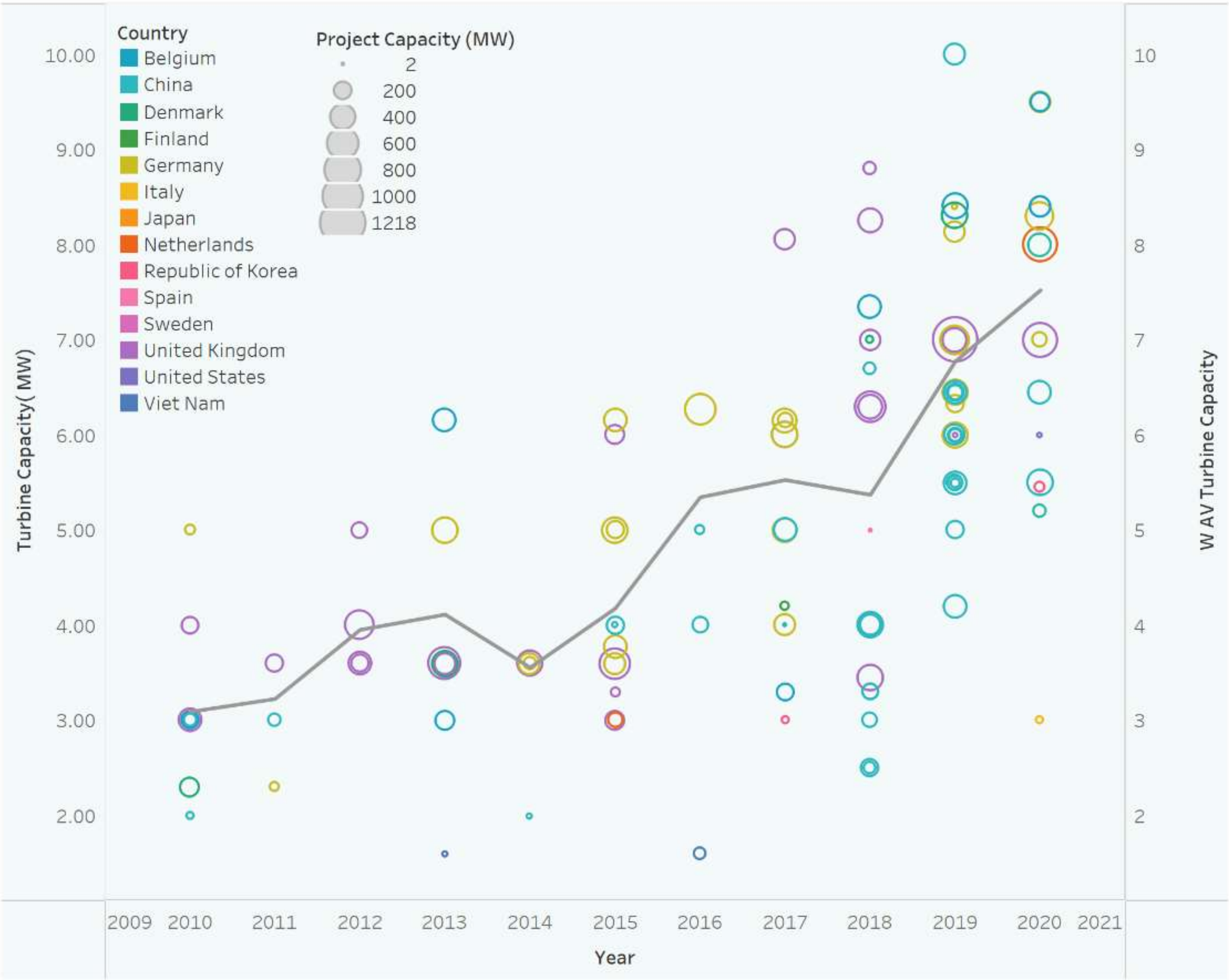
In 2020, Germany had a weighted-average hub height of 105 m, while the weighted-average hub height for Europe was 97 m. China had a weighted-average hub height of 103 m for the same year.



Turbine Capacity

In 2020, the global weighted-average capacity of a deployed turbine was around 7.5 MW, up from 3.1 MW in 2010, or a 143% increase. In 2020, offshore wind turbine capacity for almost all selected countries was more than 5 MW.

An increase in wind turbine capacity increases cost competitiveness, resulting in fewer (and more efficient) turbines. This, in turn, requires fewer maintenance visits and brings improvements in health and safety, reduces installed and O&M costs, and has a positive impact on the environment.

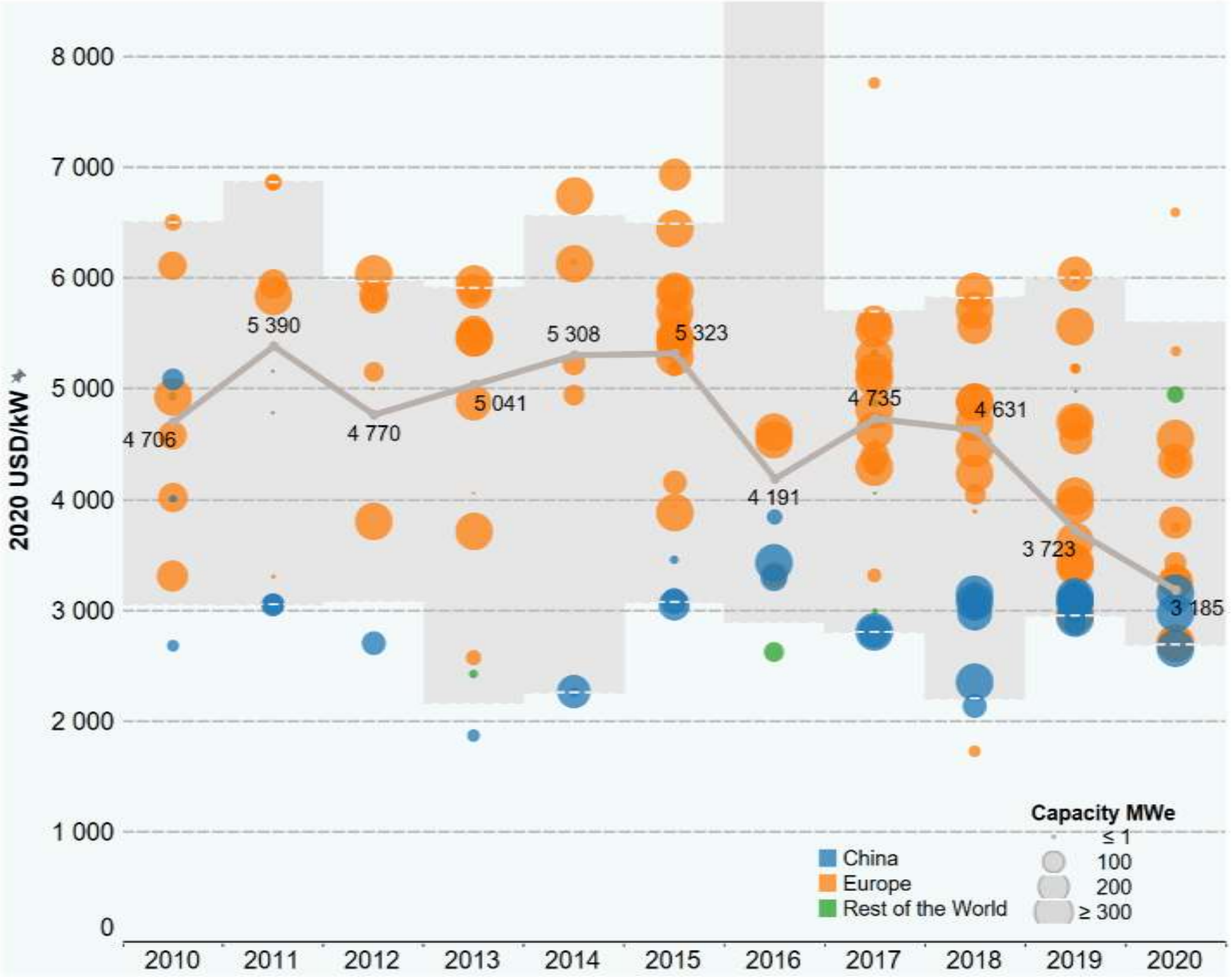


Total installed costs (2010 to 2020)

Between 2010 and 2020, global weighted-average total installed costs fell 32%, from USD 4 706/kW to USD 3 185/kW. The global weighted-average total installed cost peaked in 2011, at USD 5 390/kW, representing a figure 41% higher than its 2020 value.

The global cumulative installed capacity of offshore wind increased more than eleven-fold between 2010 and 2020, from 3.1 GW to 34.4 GW. This was almost equally driven by installations in China and Europe.

In 2020, China accounted for around half of total deployment. Global weighted-average total installed costs are therefore heavily influenced by China's lower costs, which are due to lower commodity prices and labour costs, as well as the near-shore and inter-tidal nature of most Chinese wind farms.



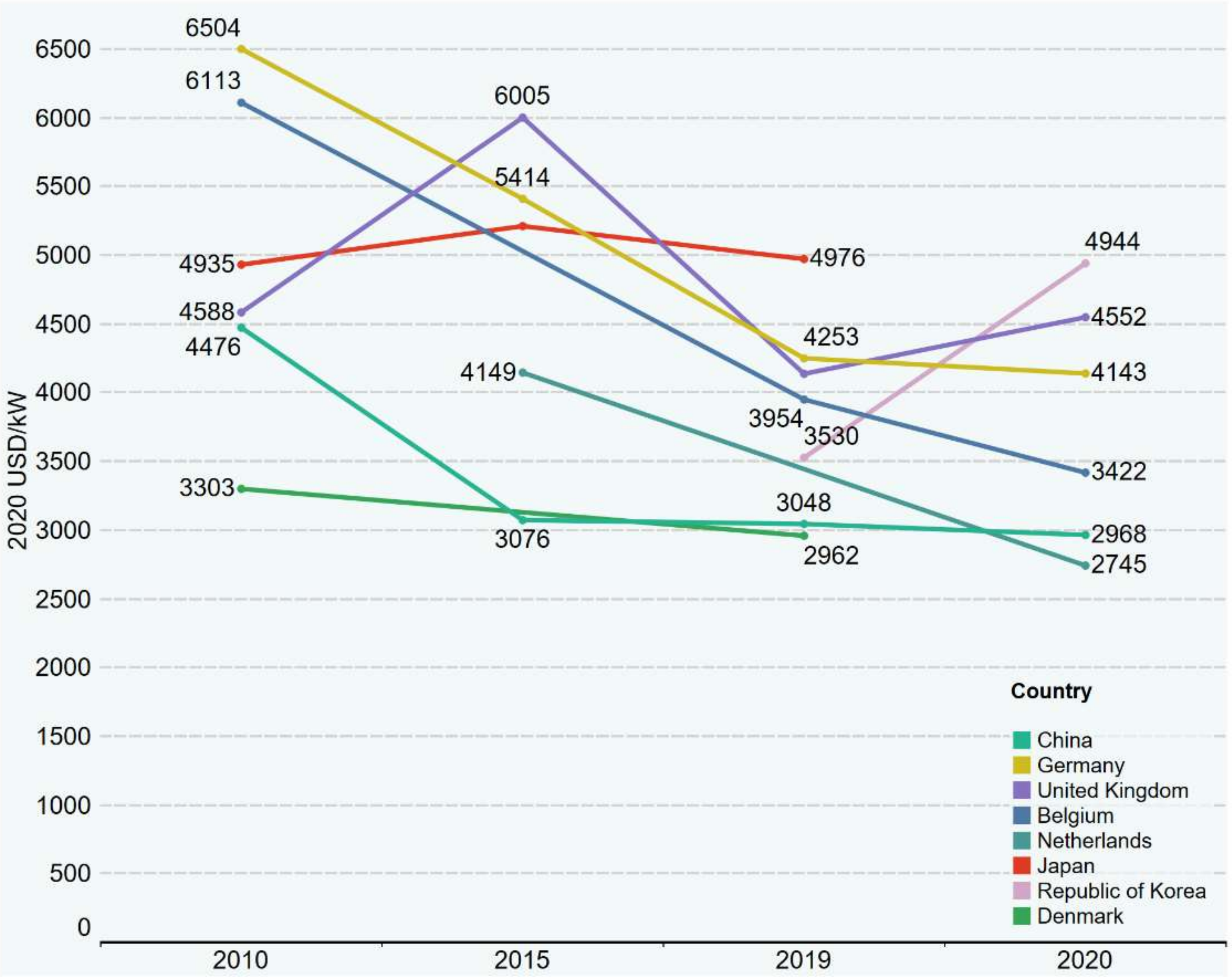
Total installed cost by country (2010 to 2020)

Between 2010 and 2020, Belgium had the highest percentage reduction in country weighted-average total installed, declining from USD 6 113/kW to USD 3 422/kW, or 44%.

Germany had the second highest percentage reduction, from USD 6 504/kW to USD 4 143/kW, or 36%, while China experienced a decline of 34% – from USD 4 476/kW to USD 2 968/kW.

In the Netherlands, which had the second largest added capacity of offshore wind in 2020 (1.5 GW), the project-specific weighted-average total installed cost was in fact the lowest, when compared to other markets. At USD 2 745/kW, this was a 34% decrease on its 2015 value of USD 4 149/kW.

The Republic of Korea saw a 40% increase in its weighted-average total installed cost between 2019 and 2020, from USD 3 530/kW to USD 4 944/kW.

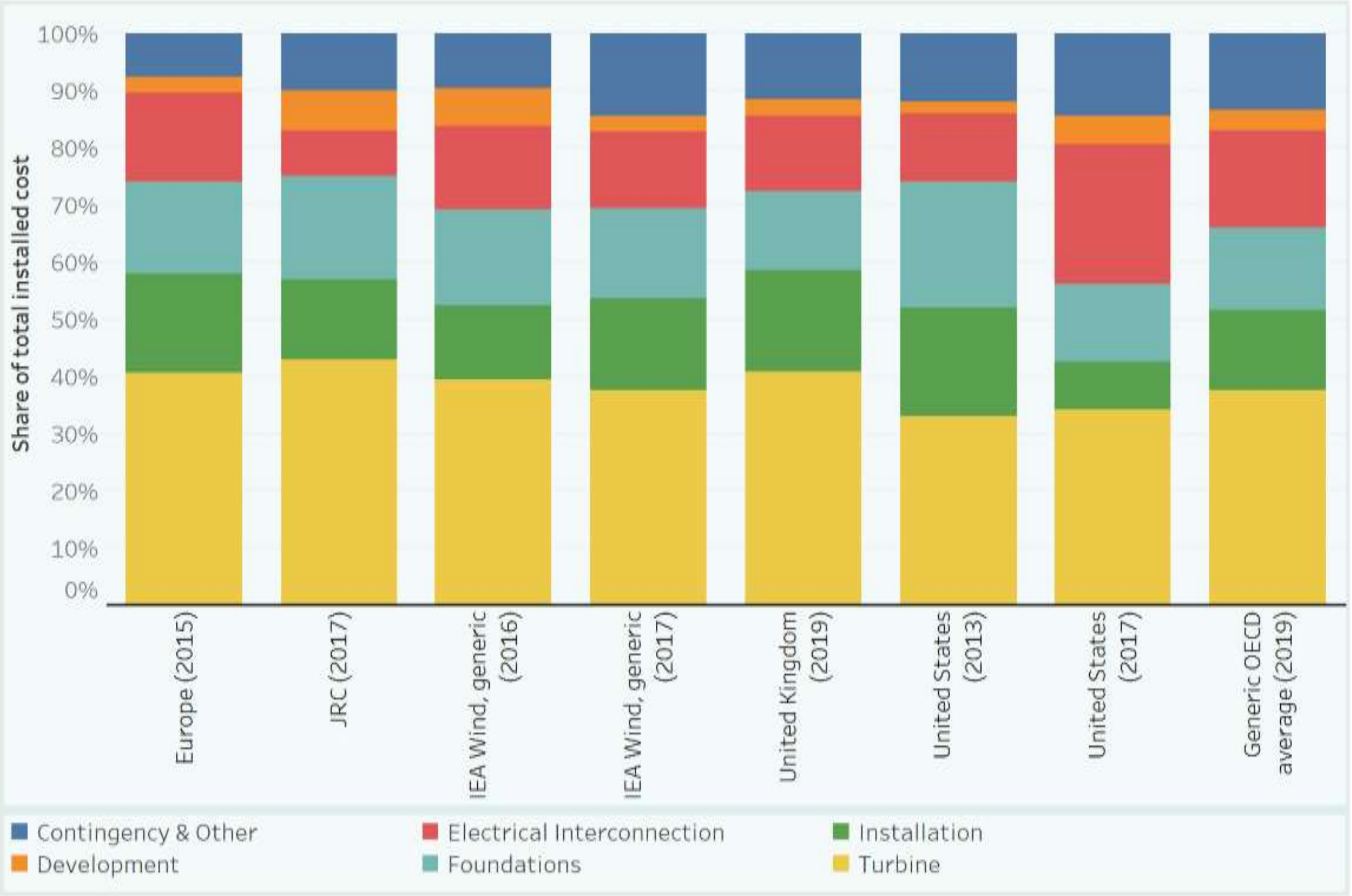


Total installed cost by country (2010 to 2020)

Offshore, turbines (including towers) generally account for between 33% and 43% of the total installed cost. Yet, other costs – including installation, foundation and electrical interconnection – are also significant, and take up a sizeable share of the total.

Installation costs, for the estimates available, range from 8% to 19% of total installed costs, while contingency/ other costs range from 10% to 14%, electrical interconnection from 8% to 24%, and foundation costs from 14% to 22%.

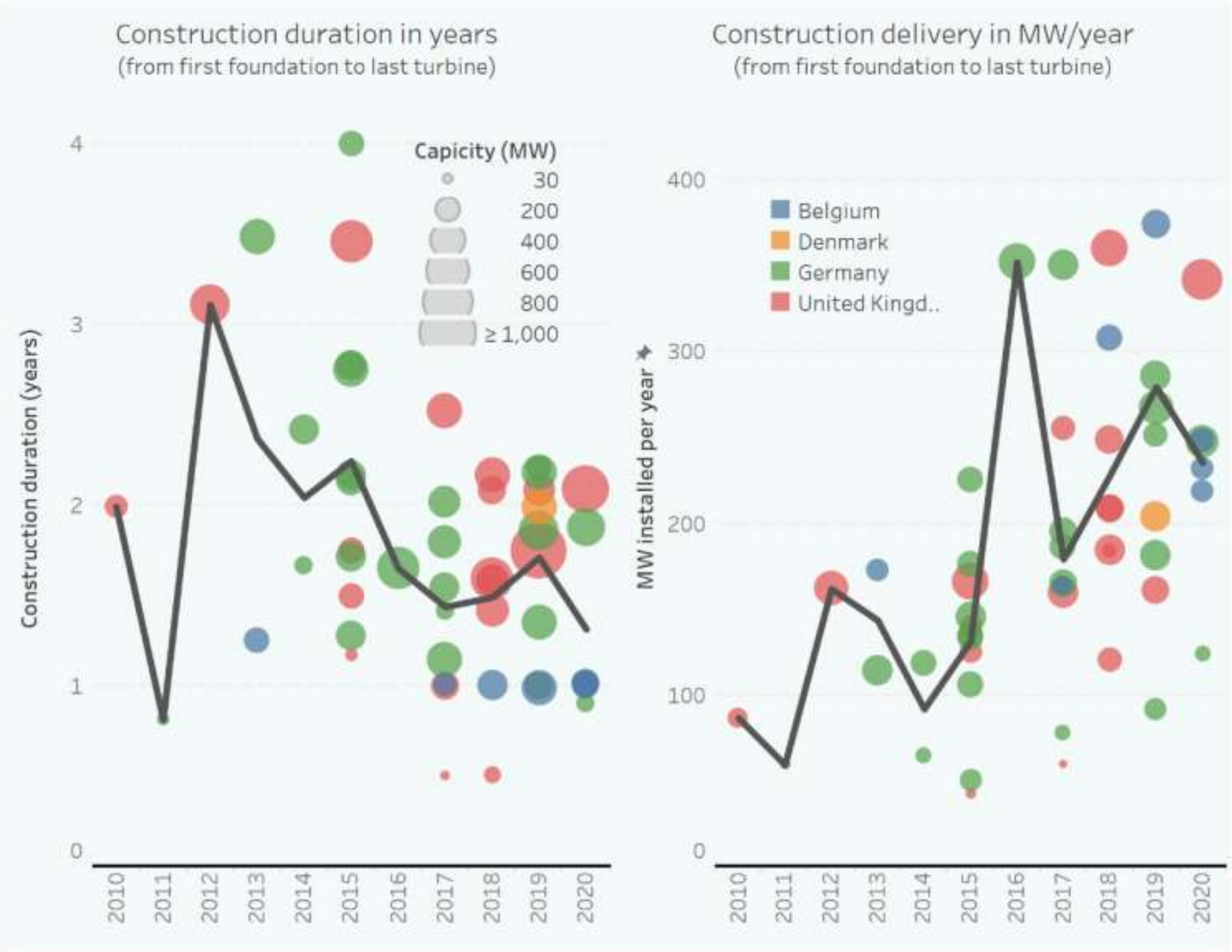
Development costs, which include planning, project management and other administrative costs, comprise between 2% and 7% of total installed costs.



Installation time per project in Europe

As detailed on the previous page, the installation costs for the turbines are a major cost contributor to the overall total. This reflects the expense of transporting, operating and installing foundations and turbines offshore, with distance to port another major contributor.

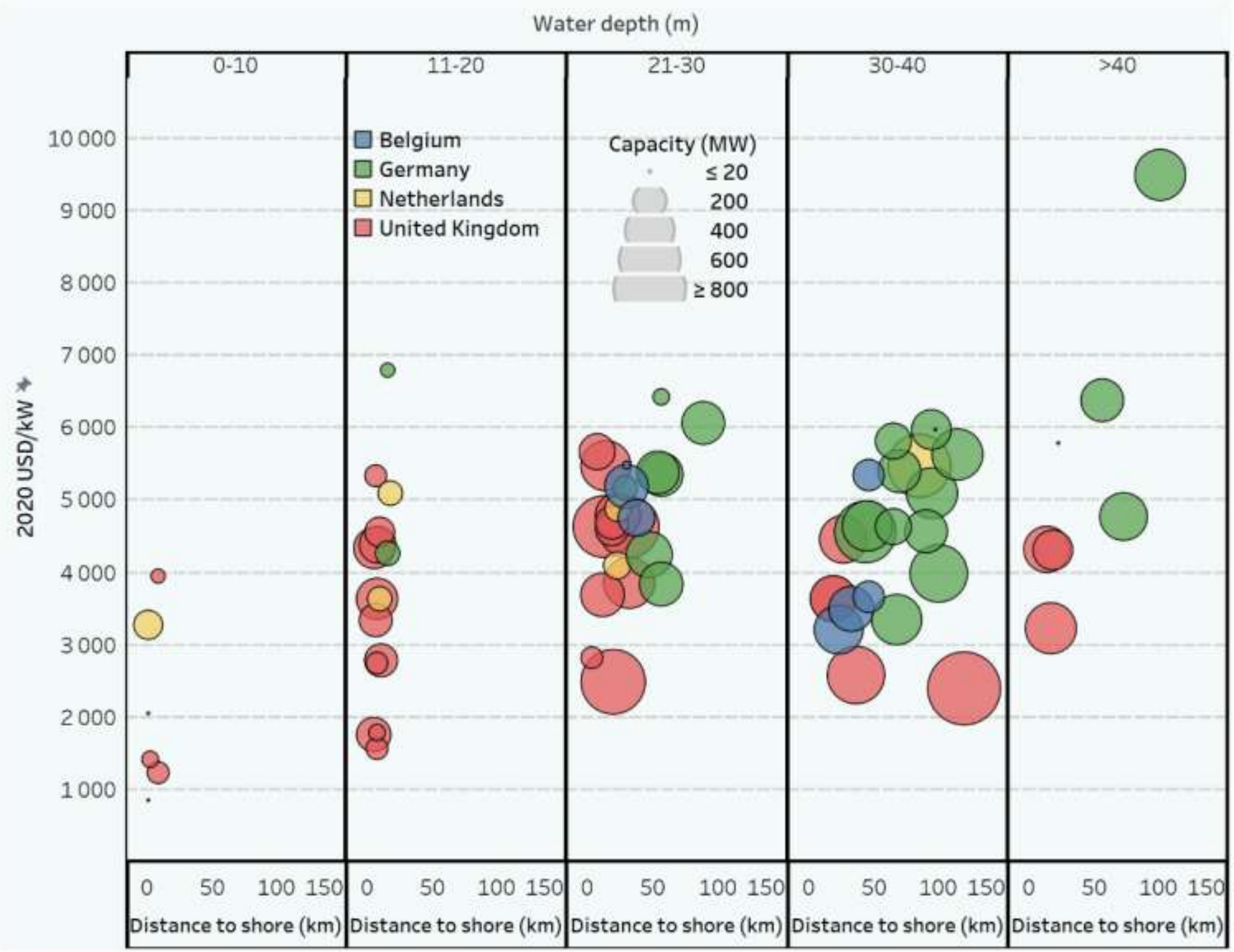
As larger, dedicated installation vessels have become available, experience has been gathered and larger turbines have been employed, however, installation times for projects have fallen. From an average two or more years per wind farm, in 2020, the time was less than 18 months. To capture the dynamics mentioned in the previous paragraph, however – and given varying project sizes – a better metric is MW installed per year by project. In these terms, a much stronger trend can be seen in the data available for Europe since 2018, with the figures increasing from 100 MW to 200 MW per year per project to 200 MW to 300 MW. From 2016, projects also routinely exceeded 300 MW per year.



Total installed cost by country, water depth and distance to shore (2010 to 2020)

With both water depth and distance to shore having a significant impact on total installed costs, it can be difficult to disentangle the influences of these two factors. This is particularly so, given the different cost structures in different markets, individual project characteristics beyond these two metrics and the paucity of data in what is still a relatively small market.

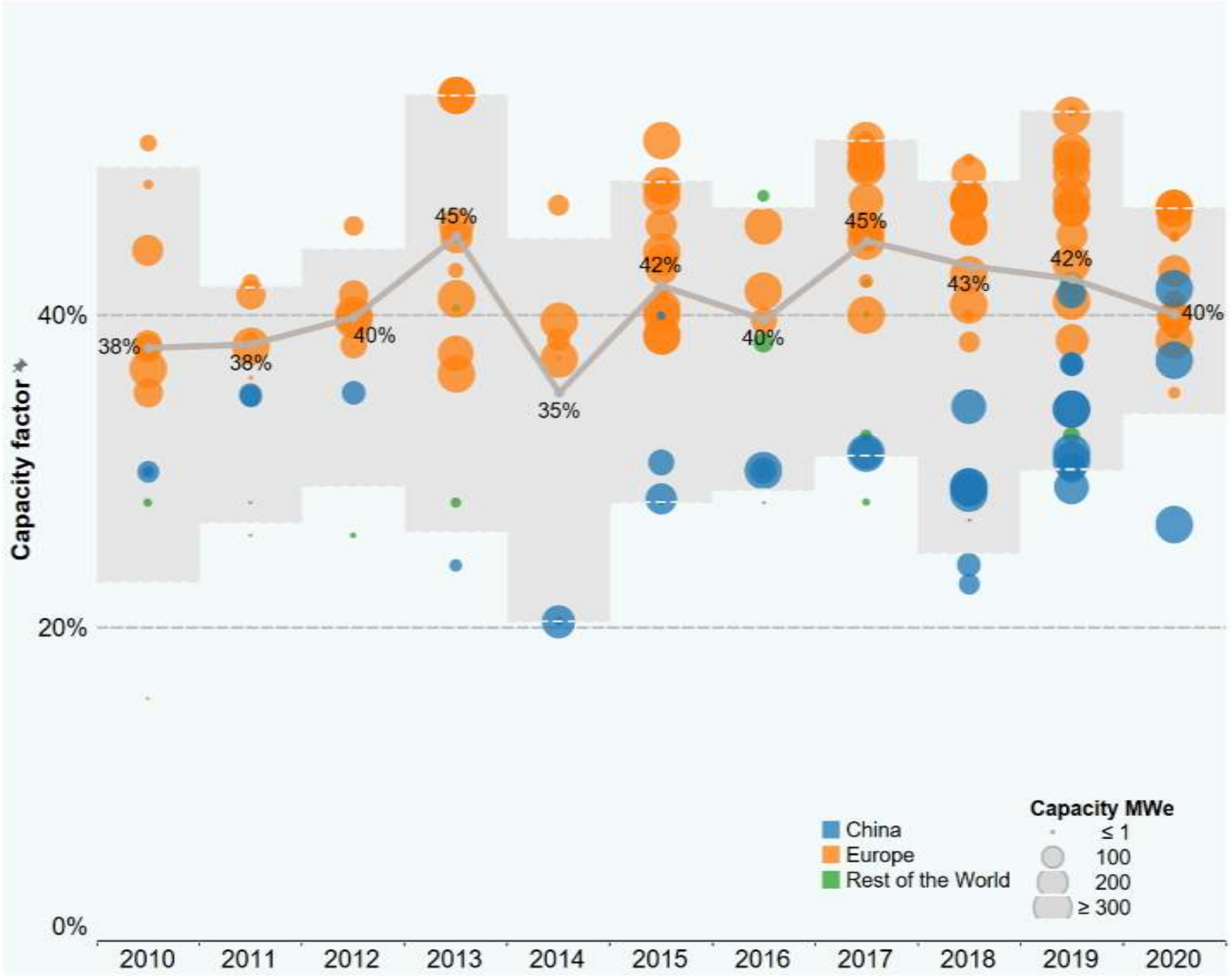
This problem is compounded by the correlation between water depth and distance to shore across the data for Europe, as seen on the right. The relationship for Germany is weaker, however, with a wide range of projects without extremes in water depth, whether or not they are closer or further from shore. In analysis undertaken by IRENA, the results are not clear, though, with the lack of data and confounding factors meaning that further work is required to understand the relative impact of water depth and distance from shore on actual project installed costs. This is so, even if the data, for the UK at least, suggests distance from shore is somewhat more important than water depth.



Capacity Factors (2010 to 2020)

Between 2010 and 2020, the global weighted-average capacity factor of newly commissioned offshore wind farms grew from 38% to 40%.

From 2017 to 2020, however, there was a decline in the global weighted-average capacity factor. This was predominantly, but not entirely, driven by China's increased share in global deployment. Projects in China tend to be near-shore or inter-tidal, resulting in poorer wind resources than those sited further offshore. In addition, China's projects do not use the very large, state-of-the-art turbines being deployed in Europe and elsewhere. Between 2010 and 2020, the weighted-average capacity factor for projects commissioned in Europe increased by 13%, from 39% to 44%. In Europe, the 5th and 95th percentile capacity factors for projects commissioned in 2020 were 37% and 47%. In contrast, the weighted-average capacity factor for projects commissioned in China that year was 37%, while the 5th and 95th percentiles were 28% and 41%, respectively.



Capacity factor and wind speed trends by project in Europe (2010 to 2025)

The data for Europe shows the clear contribution technology improvements have made in boosting the capacity factors of offshore wind farms over the last decade, with this likely to continue for the next few years.

Between 2010 and 2020, the weighted-average capacity factor of newly commissioned projects increased by around 8%, while the weighted-average wind resource for those projects increased by only 2%. However, 2020 was something of an outlier for wind projects in Europe. Looking at 2019 and 2021, the numbers were +22% and +4%, and +13% and +3%, respectively, relative to projects in 2010.

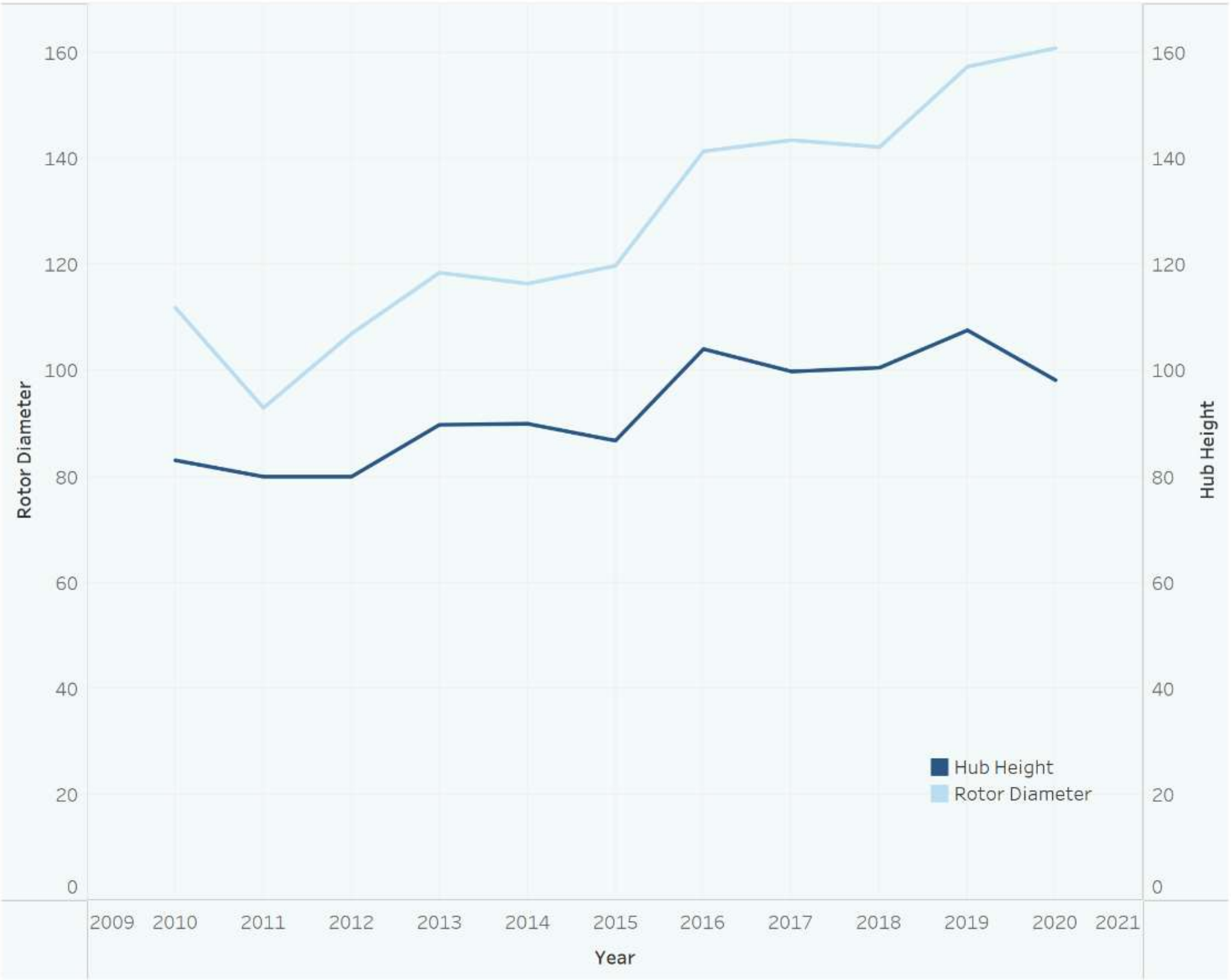
In addition to the improvements in offshore wind turbines that have already been mentioned, including higher hub heights and larger swept areas, increased capacity factors have come from improved wind farm layouts, the increased durability of components and the benefits of big data in developing preventative maintenance programmes to reduce unplanned outages in periods of high wind output.

Rotor Diameter vs Hub Height (2010 to 2020)

Data shows that both offshore wind rotor diameter and hub height followed a similar increasing trend over the period 2010 to 2020.

The turbine rotor diameter experienced a 44% increase over that period, growing from a weighted average value of 112 m to 161 m. Over the same decade, turbine hub height grew by 30%, from a weighted average of 83 m to 108 m in 2019, before dropping to 92 m in 2020. China’s contribution (around half of new capacity added in 2020) drove this reduction, as explained above.

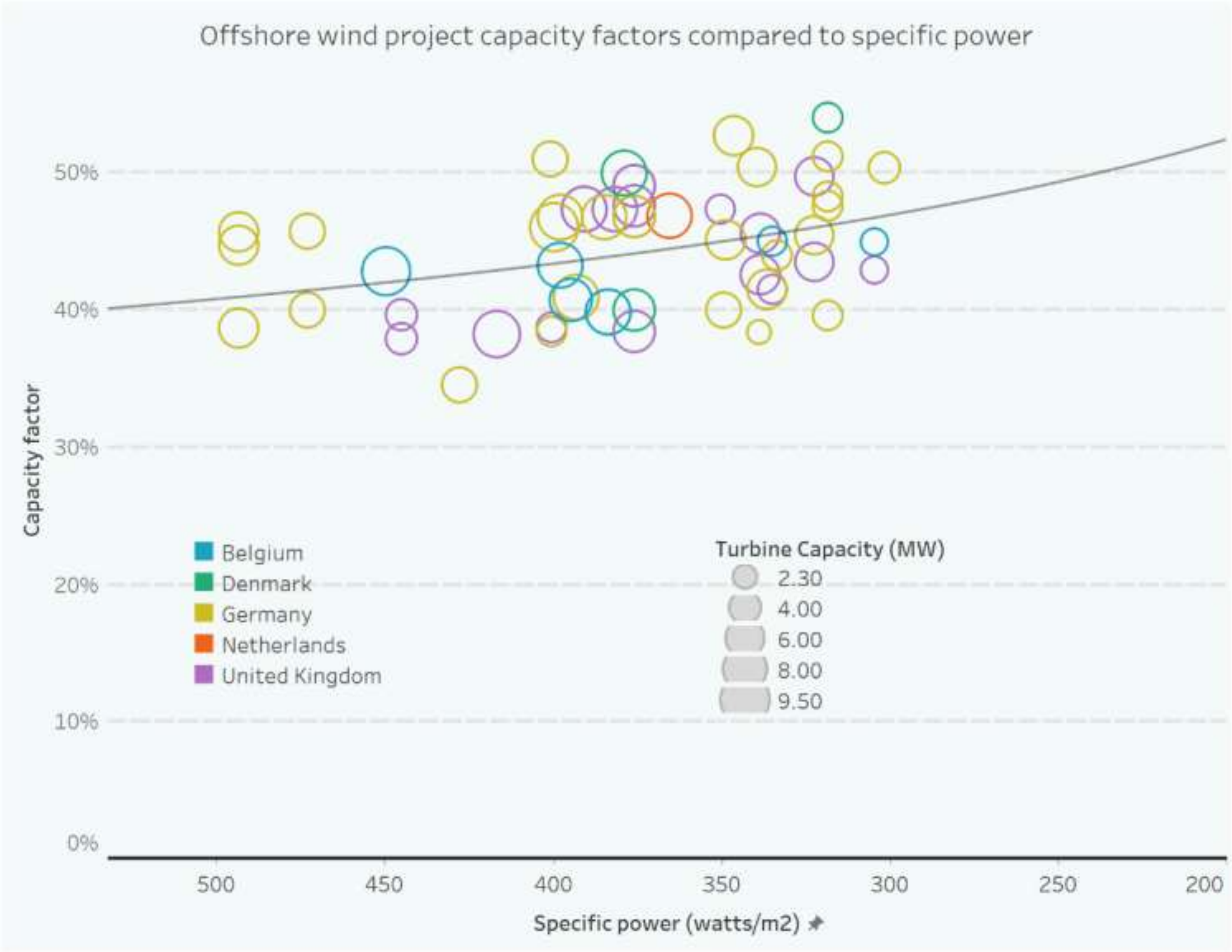
With rotor diameters increasing faster than both hub heights and turbine sizes, the specific power (measured in W/m^2) of wind turbines has fallen over time, particularly in Europe. This has important implications for capacity factor trends, as, all else being equal, in many situations, lower specific power levels will result in higher capacity factors.



Offshore wind capacity factors and specific power

The relationship between specific power (mapped inversely) and capacity factors for offshore wind projects for which IRENA has data is shown at the right. All else being equal, larger rotor blades will harness more energy from the wind, turning the rotor blades at higher rates than with shorter blades. This means turbine generators operate at higher output levels and at maximum rated capacities for longer periods. The combined impact of this will be higher capacity factors.

The data available suggests that over time, this has happened in Europe. There is a statistically significant relationship there – albeit one that does not explain a lot of the variation seen in the chart (*e.g.* a low R-squared), suggesting other factors are also in play. The impact of hub heights and wind resource qualities across the countries represented in the chart are likely having a significant impact, although a full statistical analysis would be required to identify the main drivers.

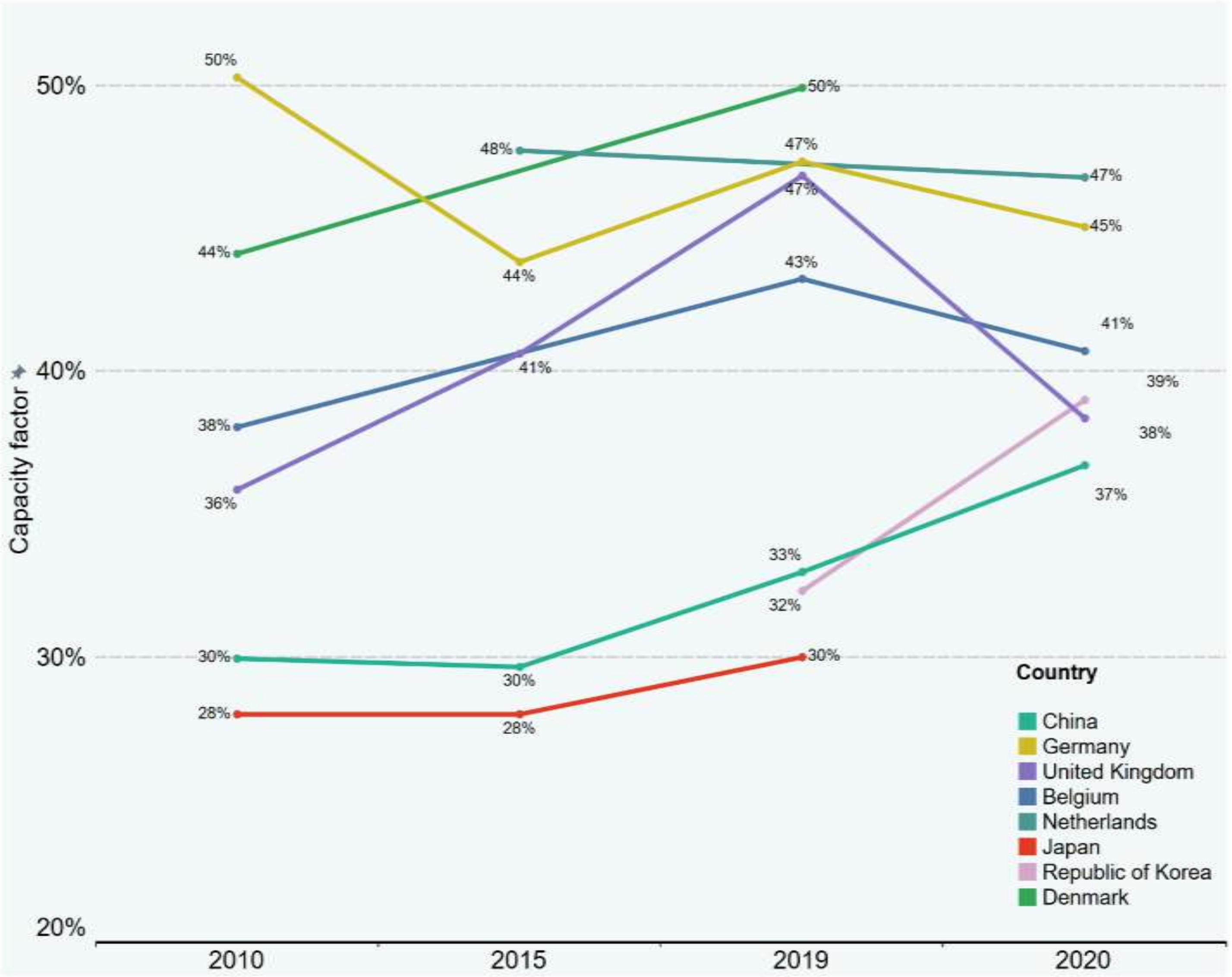


Capacity factors by major market (2010 and 2020)

In 2020, the Netherlands had the highest weighted-average capacity factor for offshore wind, at 47%, followed by Germany and Belgium with values of 45% and 41% respectively.

China had the lowest weighted-average capacity factor, with a value of 37% in 2020 – although this was higher than its 2019 value of 33%. China also had the highest percentage increase in country weighted-average capacity factor values between 2010 and 2020, at 23%.

For the same period, Germany had the highest percentage reduction, at 10%, which was the exception to generally increasing capacity factors over the period. Germany's figure can be attributed to the already relatively high-capacity factor achieved there in 2010, which was significantly above the country's peers, and the growing weight of projects that have been commissioned in the Baltic Sea. There, lower average wind speeds prevail than in the North Sea (Wehrmann, 2020).

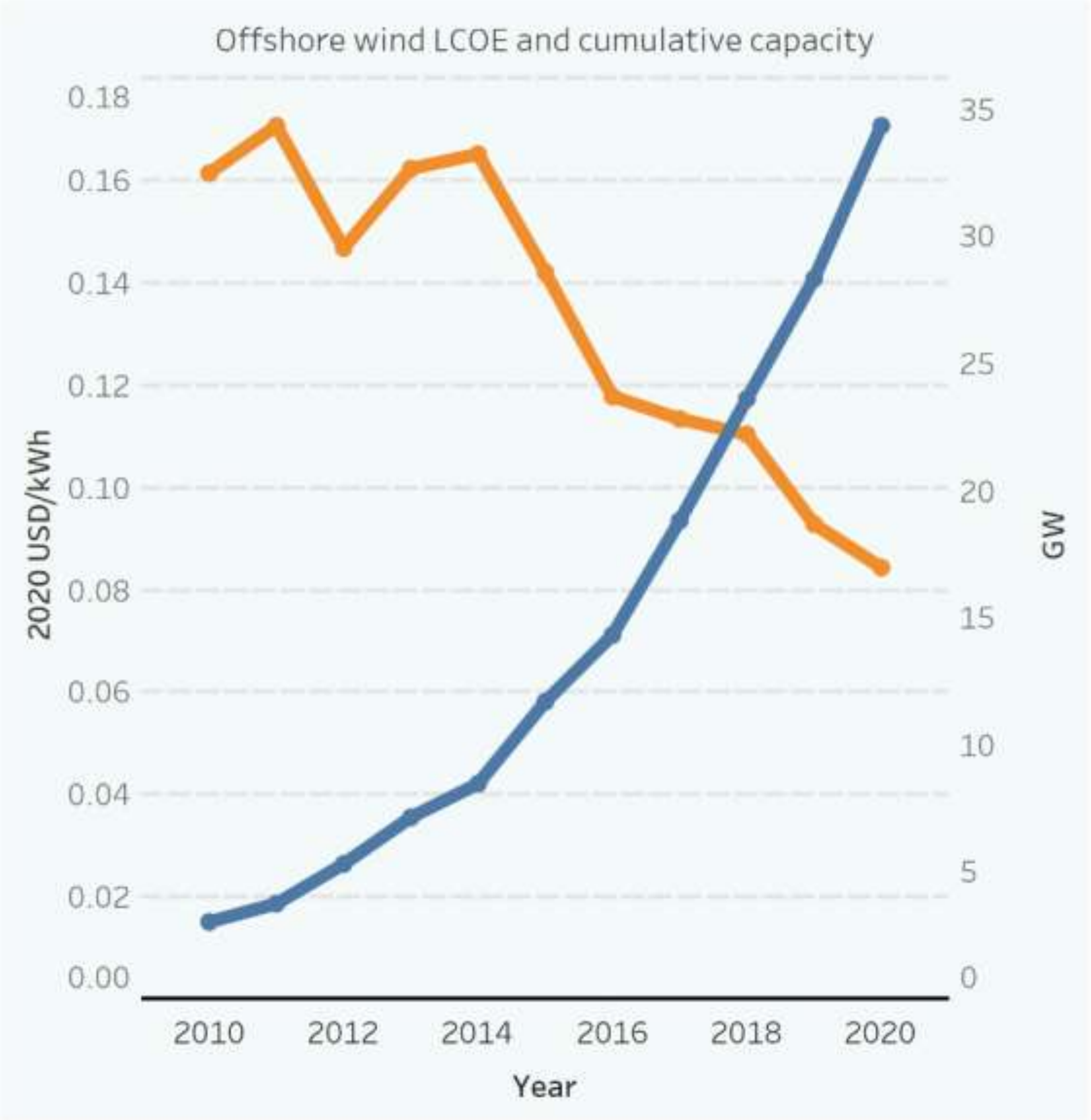


Offshore wind levelised cost of electricity and cumulative installed capacity

The cumulative installed capacity of offshore wind grew exponentially between 2010 and 2020, from just 3 GW to 34 GW. Over the same period, the LCOE of newly commissioned offshore wind projects fell by around half (48%). This was driven by a one-third fall in total installed costs and a 6% increase in the global weighted-average capacity factor.

China was by far the largest market for newly commissioned projects in both 2019 and 2020. This helped lower the global-weighted average cost, given that China has lower cost structures and its projects are predominantly located in shallow waters close to shore. To some extent, China's contribution masked the improvements in capacity factors elsewhere, as China's smaller turbines and poorer wind resources than those available in Europe yielded lower capacity factors.

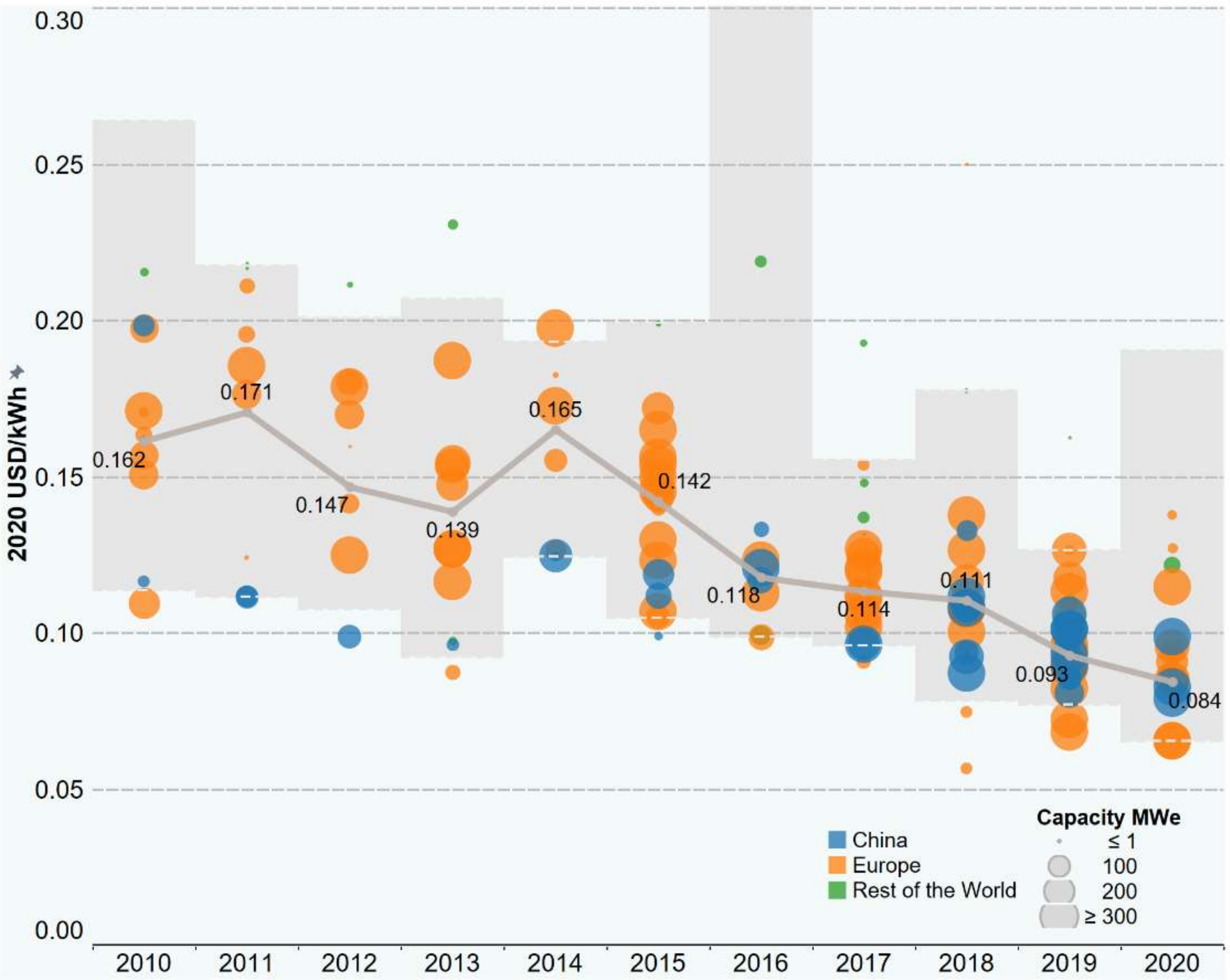
Overall, the decade represents remarkable progress, as in 2020, projects commissioned were at the lower end of the fossil fuel-fired cost range of USD 0.055/kWh to USD 0.148/kWh for new projects. With auction and power purchase agreement (PPA) results signalling costs of between USD 0.05/kWh and USD 0.10/kWh in established offshore wind markets for projects to be commissioned in coming years, offshore wind has achieved competitiveness in a surprisingly short time period. It has also done this with relatively modest cumulative installed capacity.



Levelised costs of electricity (2010 to 2020)

In recent years, increasing experience and competition, advances in wind turbine technology, the establishment of optimised local and regional supply chains, and strong policy and regulatory support have resulted in a steady pipeline of increasingly competitive projects.

Between 2010 and 2020, the global weighted-average LCOE of offshore wind fell 48%, from USD 0.162/kWh to USD 0.084/kWh. Year-on-year, in 2020, weighted average LCOE fell 9% from its 2019 value of USD 0.093/kWh. From its peak in 2007, the global weighted-average LCOE of offshore wind fell by 53%.

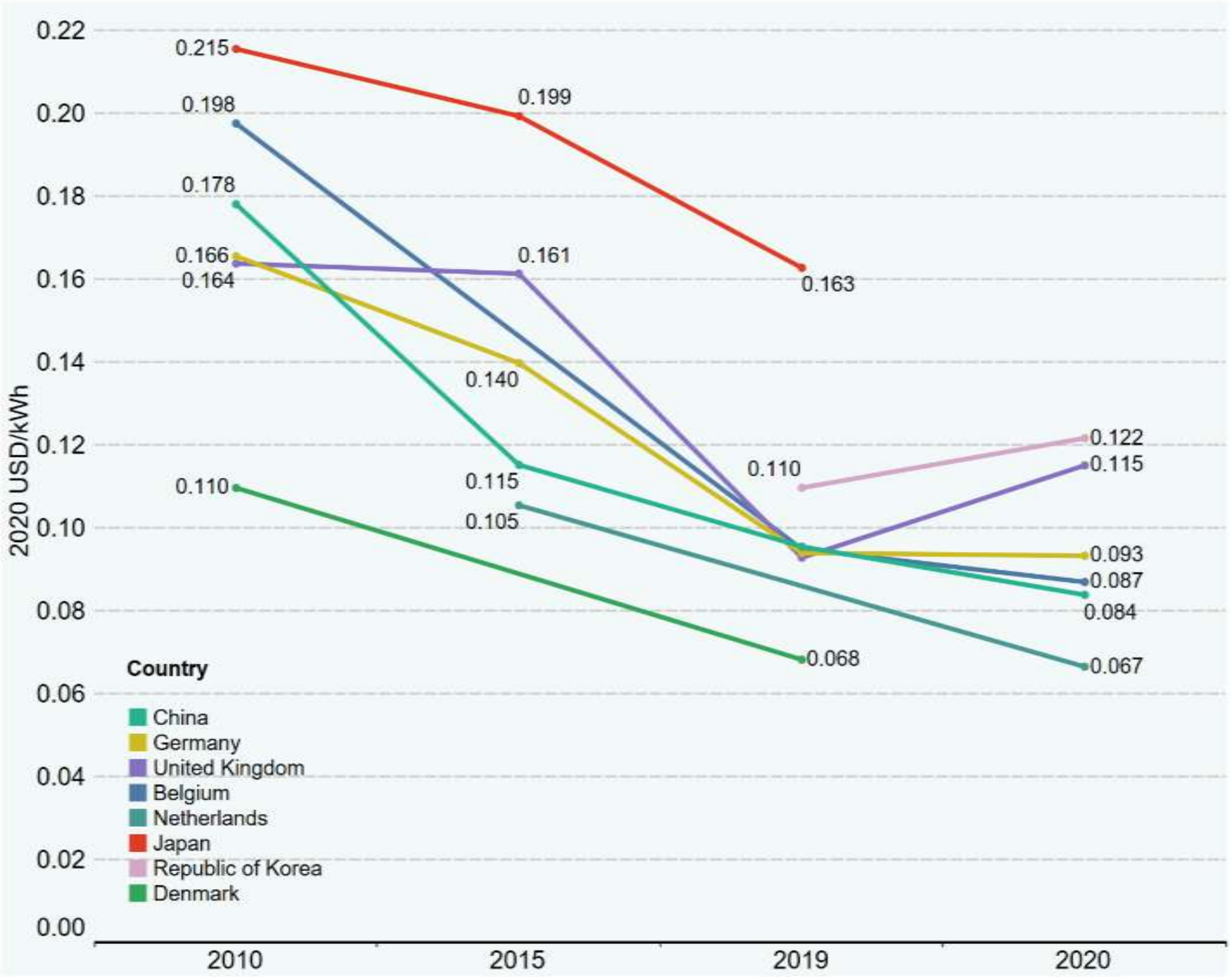


Levelised cost of electricity by major market (2010 and 2020)

The Netherlands had the lowest weighted - average LCOE for projects commissioned in 2020, at USD 0.067/kWh. The Republic of Korea had the highest weighted-average LCOE value, at USD 0.122/kWh.

China had the second-lowest weighted-average LCOE, at USD 0.084/kWh, and it also had the second-highest percentage reduction in country weighted-average LCOE values between 2010 and 2020, at 52%.

Belgium saw the highest percentage reduction (56%) in country weighted-average LCOE values between 2010 and 2020, with the second highest starting point after Japan in 2010, at USD 0.198/kWh.



Hydrogen electrolysers

Overview and key insights

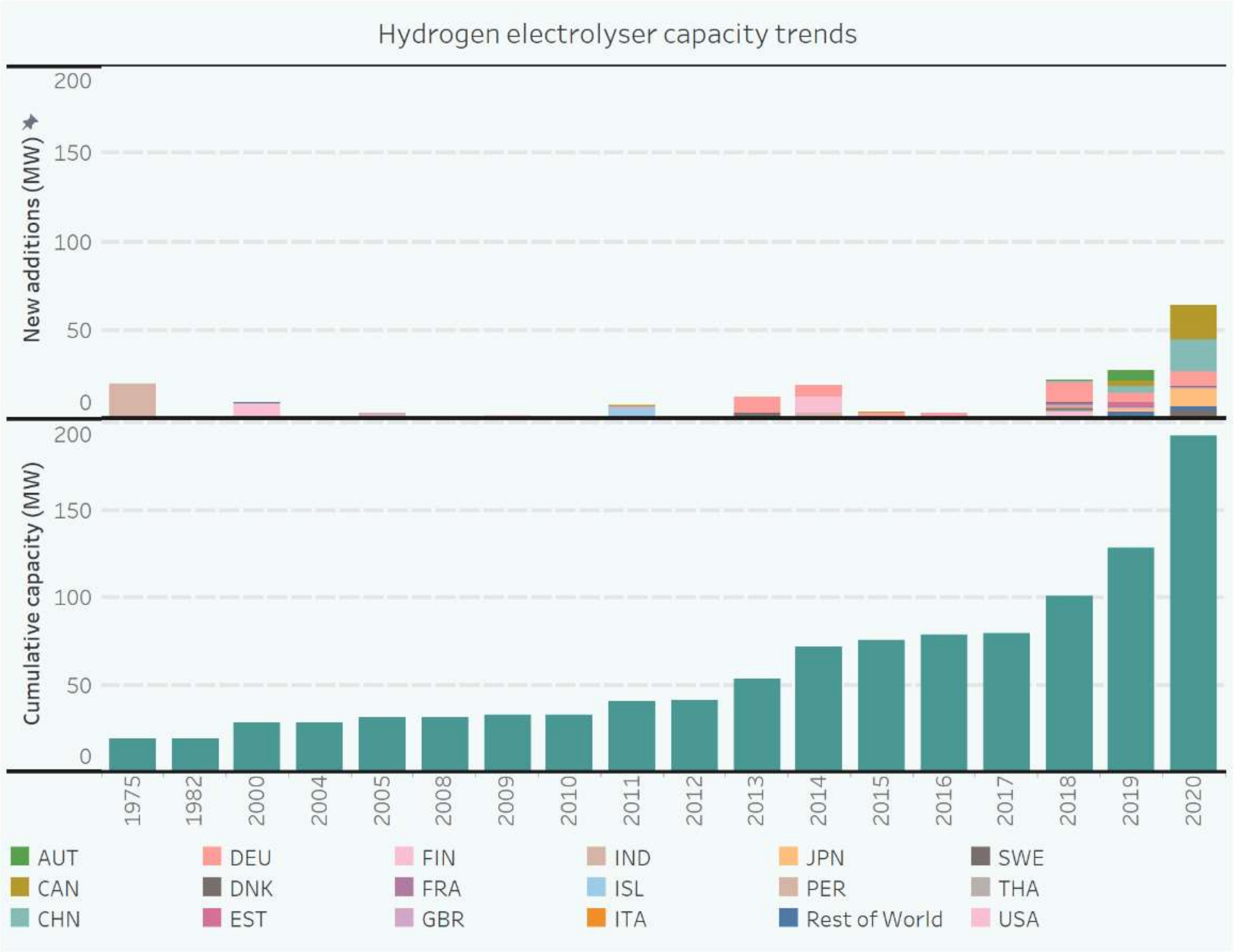
- As the cost of renewable electricity has fallen, interest in renewable hydrogen as an energy carrier and storage medium has grown. Renewable hydrogen could provide an important feedstock for a decarbonised chemicals sector, provide energy in critical industrial processes such as steel making, and be used either directly or in a converted form (*e.g.* ammonia) in transportation, as well as providing seasonal storage to balance variable electricity generation from solar and wind power, over the year.
- Renewable hydrogen can be produced from renewable electricity in electrolysers that process water into hydrogen. These electrochemical devices split water into its constituent components, yielding hydrogen and oxygen by the passage of an electrical current.
- Electrolysers have been commercially deployed since the beginning of last century and a number of different types exist. The main commercial technologies, however, are alkaline (AEL) and proton exchange membrane (PEM) electrolysers. There is significant ongoing R&D activity in the sector, while a relatively small number of companies exist that manufacture, perform system integration, and provide turn-key solutions for customers.
- Between 2003 and 2005, the cost of AEL electrolysers declined to between USD 1 340/kW and USD 2 190/kW, then fell to between USD 350/kW to USD 1 660/kW in 2020. The cost decline was 61% between 2005 and 2020.
- AEL projects remain predominantly in the low MW range, but increasingly, recent projects have capacities from 10 MW to 30 MW.
- PEM electrolysers are still manufactured on a smaller scale than AEL ones and remain costlier in comparison. PEM systems also have a more expensive bill of materials, involving costly transition metals. PEM costs have declined slightly more rapidly than AEL costs, however. Between 2003 and 2005, the cost of PEM electrolysers ranged between USD 2 920/kW and USD 7 450/kW falling to between USD 40/kW to USD 2 940/kW in 2020 (a decline of 68% between 2005 and 2020).
- The electricity consumption of today's AEL electrolysers is around 52 kWh/kilogramme of hydrogen (kg H_2), while PEM systems consume 54 kWh/kg H_2.
- The efficiency difference from stack to system is more pronounced for AEL than for PEM. AEL's system components are more complex and more energy intensive than PEM systems, which show a smaller efficiency gap between system and stack.

Market development

Historically, the market for hydrogen electrolysers was essentially minimal, with data showing that the total operational installed capacity only exceeded 200 MW in 2021 (IEA, 2021).

At the end of 2020, Germany had the largest installed capacity at around 47 MW, followed by Canada, which commissioned a 20 MW PEM system in 2020. That year, China and Peru both had around 20 MW in operation.

BNEF expects around 300 MW of new capacity to be commissioned in 2021 (BNEF, 2021), eclipsing the entire cumulative capacity operating at the end of 2020. The project pipeline suggests that new capacity added could rise to 1.3 GW in 2022, with most of this in the Asia-Pacific region. It could then grow to 2.2 GW in 2023, as Europe deploys significant capacity. The years 2024 and 2025 could see 3.3 GW and 8.7 GW added, respectively, but with a deep valley of lower additions then starting in 2026, before growing to as much as 13 GW of new capacity added in 2030.



Source: IRENA based on IEA, 2021

Hydrogen electrolysers

-60% Reduction in Alkaline electrolyser costs (2005-20)

COSTS

-67% Reduction in PEM electrolyser costs (2005-20)

Alkaline electricity consumption **52 kWh/kg H_2**

PEM electricity consumption **54 kWh/kg H_2**

PERFORMANCE

Electrolyser technology characteristics

Water electrolysis is conducted when a cell consisting of two electrodes (an anode and a cathode) reacts with an electrolyte solution (an electrolyte is the media responsible for transporting the generated chemical charges). This leads to the transportation of anions (-) or cations (+) from one electrode to the other.

The key difference between alkaline electrolysers and the other three is that in the alkaline electrolyser, the electrolyte responsible for transporting the chemical charges is typically a highly concentrated potassium hydroxide solution in liquid form. The other three technologies rely on a solid electrolyte.

Solid oxide and anion exchange membrane (AEM) systems have significant potential, from a technology perspective, but are not yet commercially available at scale. As a result, the data is too sparse to include them in the following sections, so we are focusing instead on AEL and PEM electrolysers.

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or NaHCO3 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Note: Coloured cells represent conditions or components with significant variation among different companies.
PFSA = Perfluoroacidsulfonic; PTFE = Polytetrafluoroethylene; ETFE = Ethylene Tetrafluorethylene; PSF = poly (bisphenol-A sulfone); PSU = Polysulfone; YSZ = yttriastabilized zirconia; DVB = divinylbenzene; PPS = Polyphenylene sulphide; LSCF = $La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$-δ; LSM = $(La_{1-x}Sr_x)_{1-y}MnO_3$; § = Crofer22APU with co-containing protective coating.

Based on IRENA analysis.

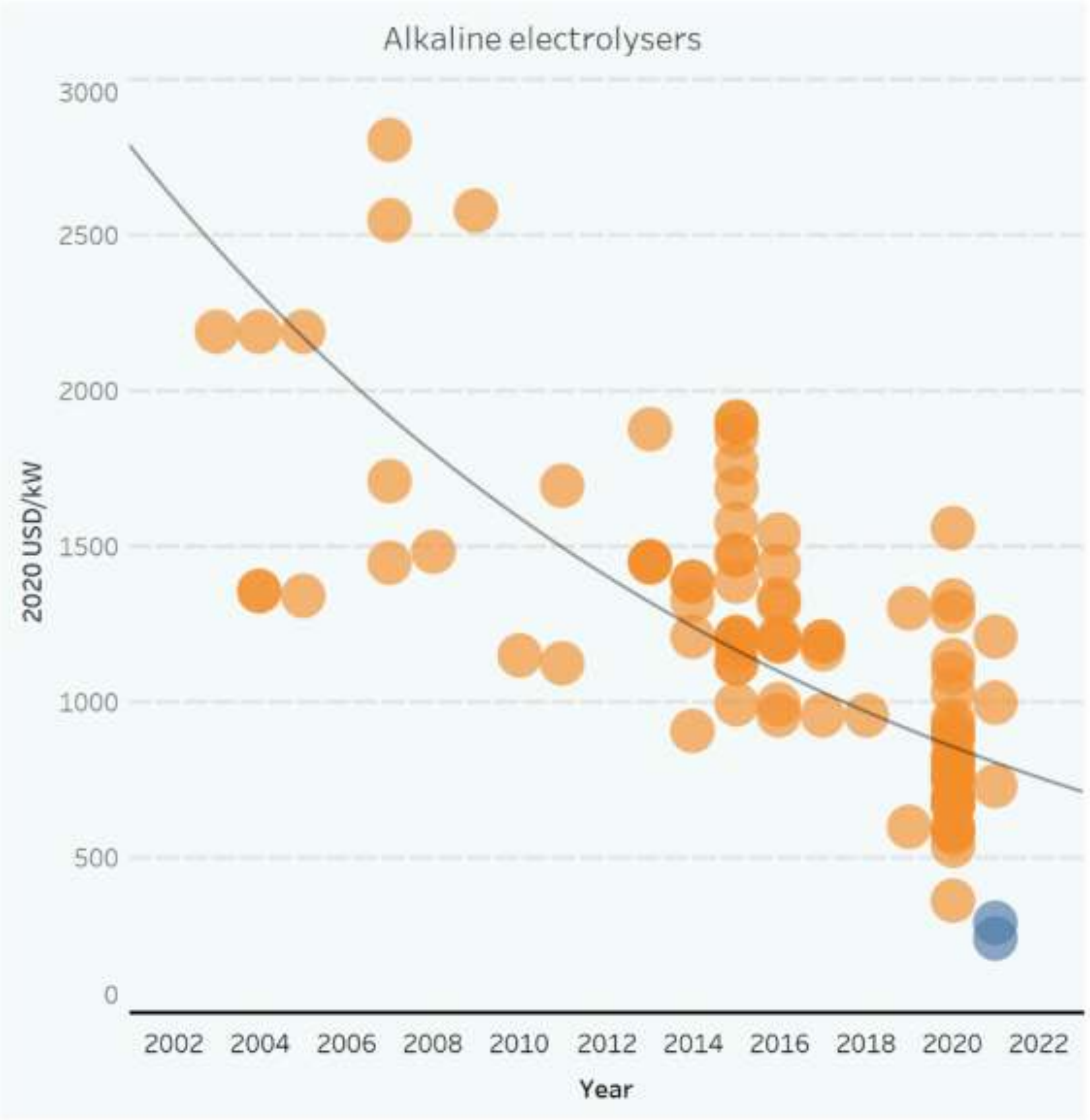
AEL electrolyser cost trends

AEL electrolyser costs have fallen over time. Between 2003 and 2005, they ranged between USD 1 340/kW and USD 2 190/kW, while by 2020, they ranged between USD 350/kW to USD 1 660/kW in 2020. The trendline suggests a 61% reduction in costs between 2005 and 2020. A number of very low engineering, procurement and construction (EPC) quotes have been seen in China (blue dots), but may not have the same boundary conditions as elsewhere.

The data presented here is from primary data sources quoting industry data, news reports, OEM quotes, company reports or cost data from grant reporting. It excludes references to costs based on secondary data. Additionally, any reference where the source of the cost data was unexplained is excluded. An important caveat is that the specific boundary conditions for each project are not always clear. Every effort has been made to ensure homogeneity, but this cannot always be guaranteed.

The available information represents 86 data points. These are a mixture ranging from representative costs to individual electrolyser project costs, or manufacturers' quotes for projects.

Project sizes remain predominantly in the low MW range, but recent projects are increasingly in the 10 MW to 30 MW range. Some representative quotes for 200 MW to 300 MW projects are also now emerging, although the precision of these estimates remains open to question.



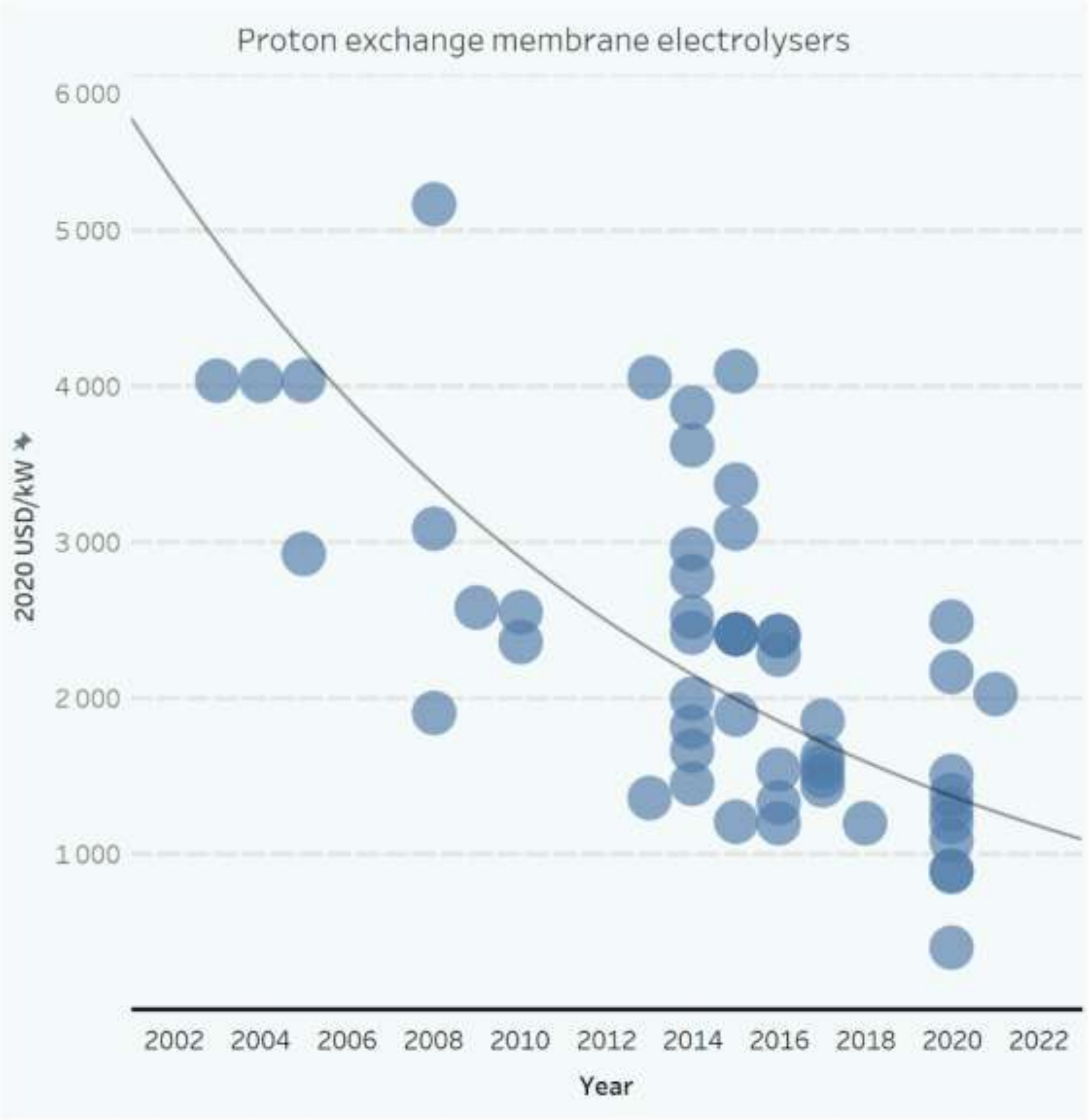
Source: IRENA Renewable Cost Database and Glenk and Reichelstein, 2019

PEM electrolyser cost trends

The data available to IRENA for PEM represents 54 data points. AEL electrolyser costs are currently lower than those for PEM, as the latter is currently costlier to produce today and manufactured on a smaller scale. PEM costs have fallen more rapidly than those for AEL, however, by declining 67% between 2005 and 2020.

PEM electrolysers costs ranged from USD 2 920/kW to USD 7 450/kW between 2003 and 2005. By 2020, they had fallen 68% to between USD 400/kW to USD 2 940/kW. Higher PEM costs are not just related to a lack of economies of scale in manufacturing. PEM also entails a more important materials bill than for AEL, as the technology uses more expensive inputs, such as iridium and platinum. The harsh, oxidative environment inside a PEM cell also necessitates titanium-based materials, noble metal catalysts and protective coatings to halt the degradation of cell components. These components do also ensure optimal electron conductivity and cell efficiency, however.

The average size of new PEM projects added in 2020 was just 2.5 MW, dropping to just 0.9 MW if the 20 MW Air Liquide project in Canada is excluded. Therefore, even before addressing manufacturing scale and R&D efforts to reduce costs and improve performance, increasing the size of projects would help provide economies of scale at the project level and help to reduce costs.

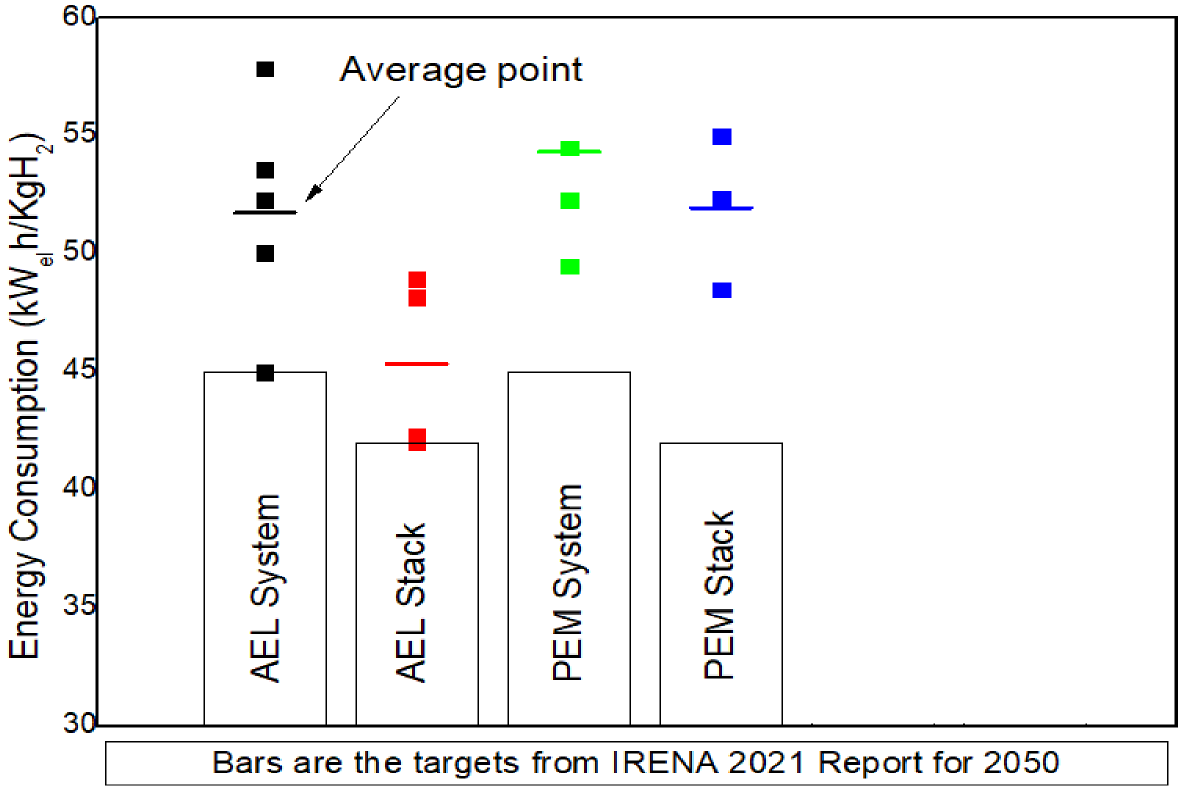


Source: IRENA Renewable Cost Database and Glenk and Reichelstein, 2019

Performance tracking to 2050: Electricity use per kg of hydrogen

IRENA has surveyed existing electrolyser performance and has benchmarked these values against our 2050 targets. This chart shows the energy intensity of electrolysers in terms of kWh per kilo of hydrogen. Today's average technology solution for AEL systems is around 52 kWh/kg H_2 , but with a wide range. With current progress to advance alkaline electrolysers, this represents the emerging gap in efficiency levels between old systems and the more advanced concepts now being deployed. Moreover, the efficiency difference from stack to system is also more pronounced for the alkaline type, as their system components are more complex and more energy intensive than PEM systems. PEM systems tend to be much simpler, and that explains the smaller efficiency gap between system and stack. As alkaline systems are more mature, however, the data tends to suggest that they are slightly more efficient than PEM systems.

In terms of progress towards the 2050 targets, AEL systems currently include models that could achieve the target of 45 kWh/kg H_2, although the simple average of the systems is significantly higher. The challenge for PEM systems remains much more significant, as the gap, even for today's best systems, is much more significant. The potential for efficiency improvements is largely untapped, however, so the goal remains realistic for PEM systems.

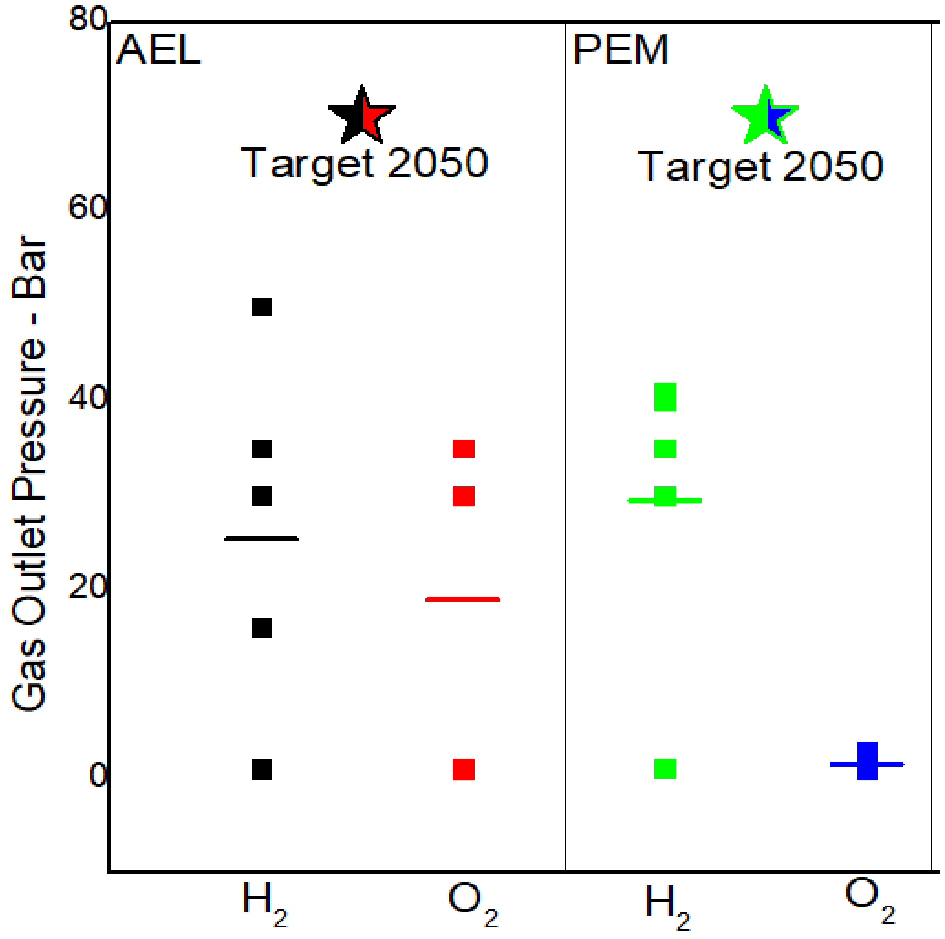


Performance tracking to 2050: Gas outlet pressure for hydrogen and oxygen

The gas outlet pressure data collected for AEL and PEM offerings are summarised on the right. The average values (represented by the dash) show clearly that alkaline electrolysers operate almost entirely at a balanced pressure point, with the anode (O_2) and cathode (H_2) on both sides under the same pressure level – in fact, with the smallest pressure difference possible, in order to reduce gas crossover.

In contrast to AEL, PEM systems work in a state of 'differential pressure', with hydrogen at pressure levels of around 30 bar and the oxygen under atmosphere-like pressure conditions (only a few bars) in order to decrease water vapour formation and therefore increase efficiency in energy consumption.

Both systems operate well below the 2030 targets, which allows for lower compression costs prior to storage or injection into transmission or distribution grids.

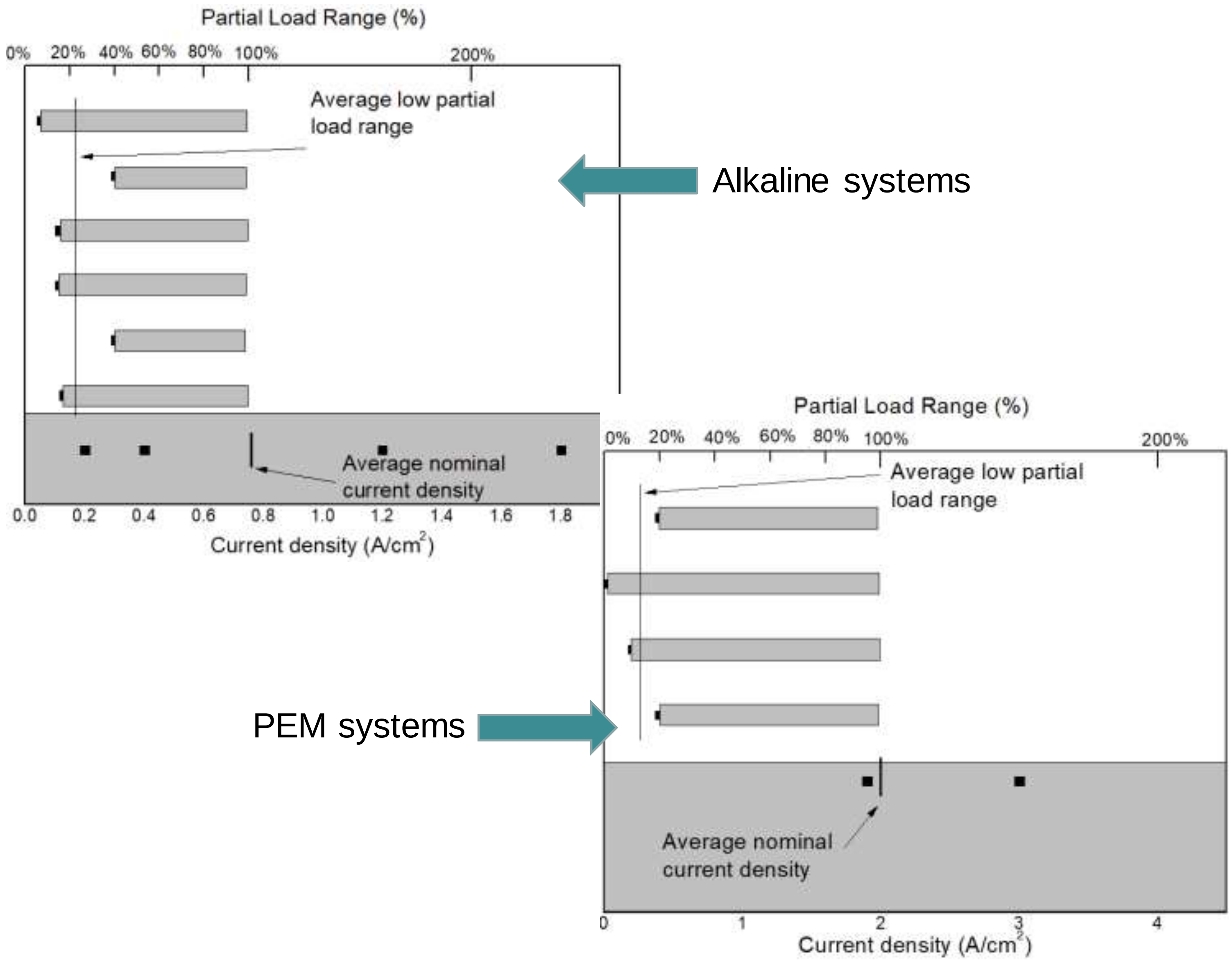


Performance tracking to 2050: Partial load operation and current density

The different reported current density points for alkaline electrolysers means significant variation exists across the systems offered. The average point was used to calculate the load range, showing the possibility of operating alkaline electrolysers under a significantly wider power variation, able to be ramped down to around 20% of capacity.

PEM electrolysers can operate across a wider range of their capacity. Unfortunately, however, data availability is poor for PEM systems. Despite the lack of transparency around current density with PEMs, though, it is clear they can operate at much higher energy densities, allowing them to be more flexible than AEL systems.

This additional more flexibility helps to explain why PEM electrolysis is considered the better option for integration with variable renewable electricity generation and for earning additional revenue in the auxiliary services market.

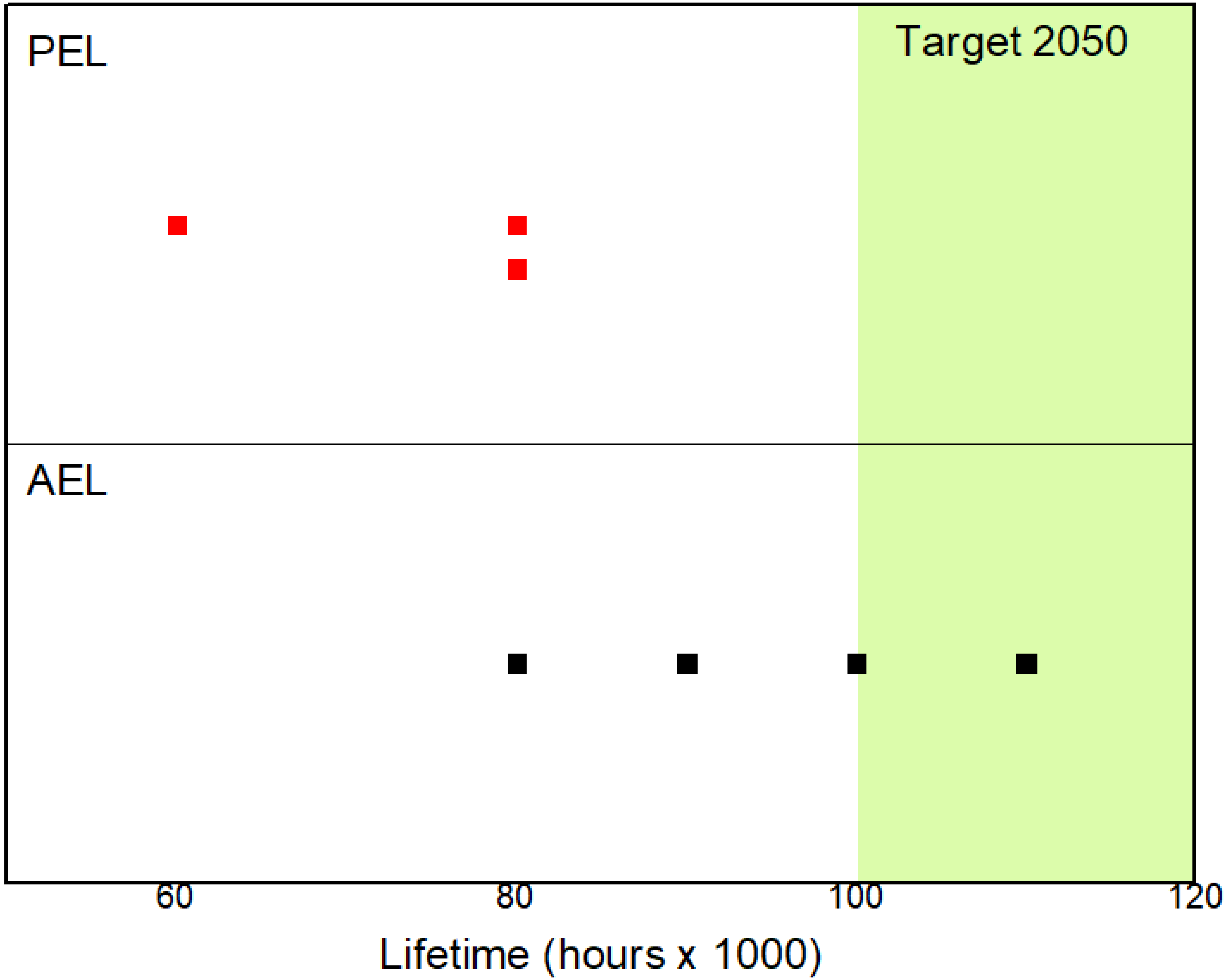


Performance tracking to 2050: Stack operating lifetime

The durability data obtained for both AEL and PEM electrolysers is somewhat modest, with little information available. The information regarding their durability over thousands of hours under real operating conditions is therefore quite uncertain.

Having said this, the consensus among industry participants is that AEL electrolysers already benefit from quite good durability and are capable of running beyond 100 000 hours. This suggests that the targets for 2050 defined by IRENA may have been somewhat conservative.

For PEM systems, only a handful of data points were available, but these suggest a range of 60 000 to 80 000 hours. More data is needed to prove this is representative of the range of offerings on the market today, however. More importantly, the existing data suggest PEM systems have some ground to make up in order to reach the IRENA target for 2050.



Large-scale solar thermal

Key insights

Over the period of this project, IRENA has benefitted from collaboration with a range of partners. This has allowed IRENA to enrich the data and analysis presented in this report, without having to call on European Commission (EC) project funds. The material included here was therefore not financed by the EC.

Together with Solrico and the Solar Payback project, financed by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, IRENA has collected actual project cost data for large-scale solar thermal systems for the provision of water heating and process heat/steam in industry.

The data represents a unique dataset, and the most comprehensive collection of cost and performance data for large solar thermal projects around the world. It includes data for 1 633 projects providing space or hot water heating, and heat for industrial processes covering 250 MW. It also provides data for 122 solar thermal district heating projects, accounting for 687 MW. The data available represents between 50% and 90% of the projects installed in the last ten years in most of the major solar thermal markets. The exceptions are China and India, where data availability remains poor.

With the support of the German Federal Ministry for Economic Affairs and Energy, IRENA has also collected data on heat pumps for the provision of space and water heating in residential and commercial buildings.

Data availability remains generally poor, however. Comprehensive cost data is available for Germany and the United Kingdom from support programmes, while IRENA surveyed a number of other markets in Europe, albeit with limited success.

The data presented here for heat pumps and solar thermal is therefore not as comprehensive as that presented in the previous sections but is designed to provide some indication of progress in technology performance and cost metrics for these end-use technologies. IRENA plans to continue this data collection, if resources become available, given the importance of a better understanding of these technologies (and others). This is especially so in the context of the goals of the Paris Agreement and countries' need for advice on end-use decarbonisation pathways, given the increasing number of net-zero policy goals that have emerged over the last 18 months.

Large-scale solar thermal for heat

-68% Reduction in installed costs of solar thermal systems for industrial processes in Europe (2014-2020)

-33% Reduction in levelised cost of heat from solar thermal district heating in Denmark (2010-2019)

COSTS

16-19% Learning rate for solar district heating in Denmark

PERFORMANCE

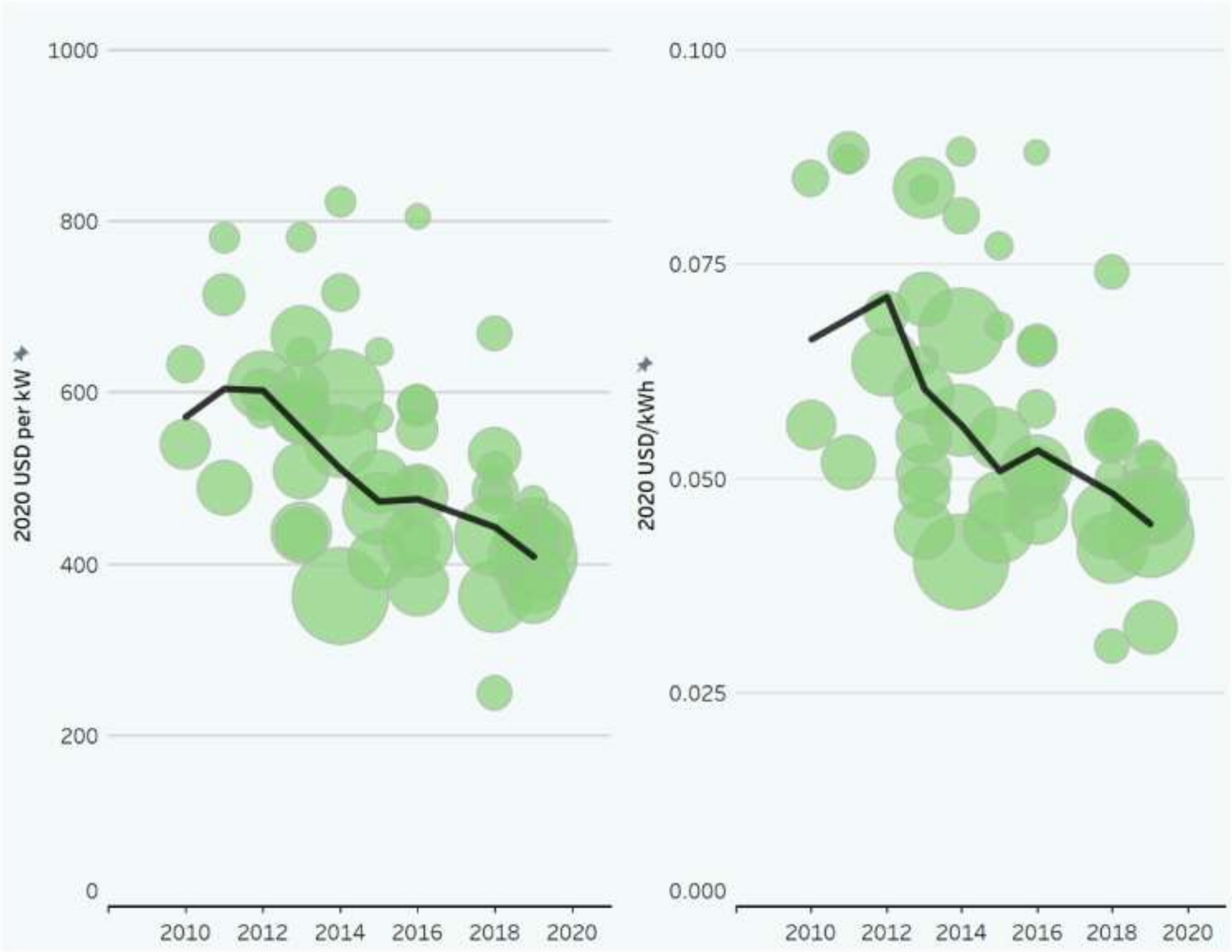
Increase in average project size in Europe of systems for industrial processes **x12.7**

Increase in annual yield of Mexican systems **+32%**

Solar thermal district heating in Denmark

Denmark is a world leader when it comes to solar thermal district heating, with more than 1 GW thermal (GW_{th}) in operation at the end of 2020. Around 120 villages, towns and cities use solar heat in their municipality-owned district heating networks.

The total installed cost of district heating scale solar heat in Denmark fell from a weighted average of USD 573/kW in 2010 to USD 409/kW in 2019. This was quite a remarkable achievement, given the market for new capacity was shrinking over this period. These installed cost reductions have made solar thermal heating systems a competitive source of heat for district heating, as the weighted-average levelised cost of heat (LCOHEAT) fell from USD 0.066/kWh in 2010 to USD 0.045/kWh in 2019. With no fuel price volatility, this allowed solar thermal district heating to achieve competitive results for consumers in Denmark.

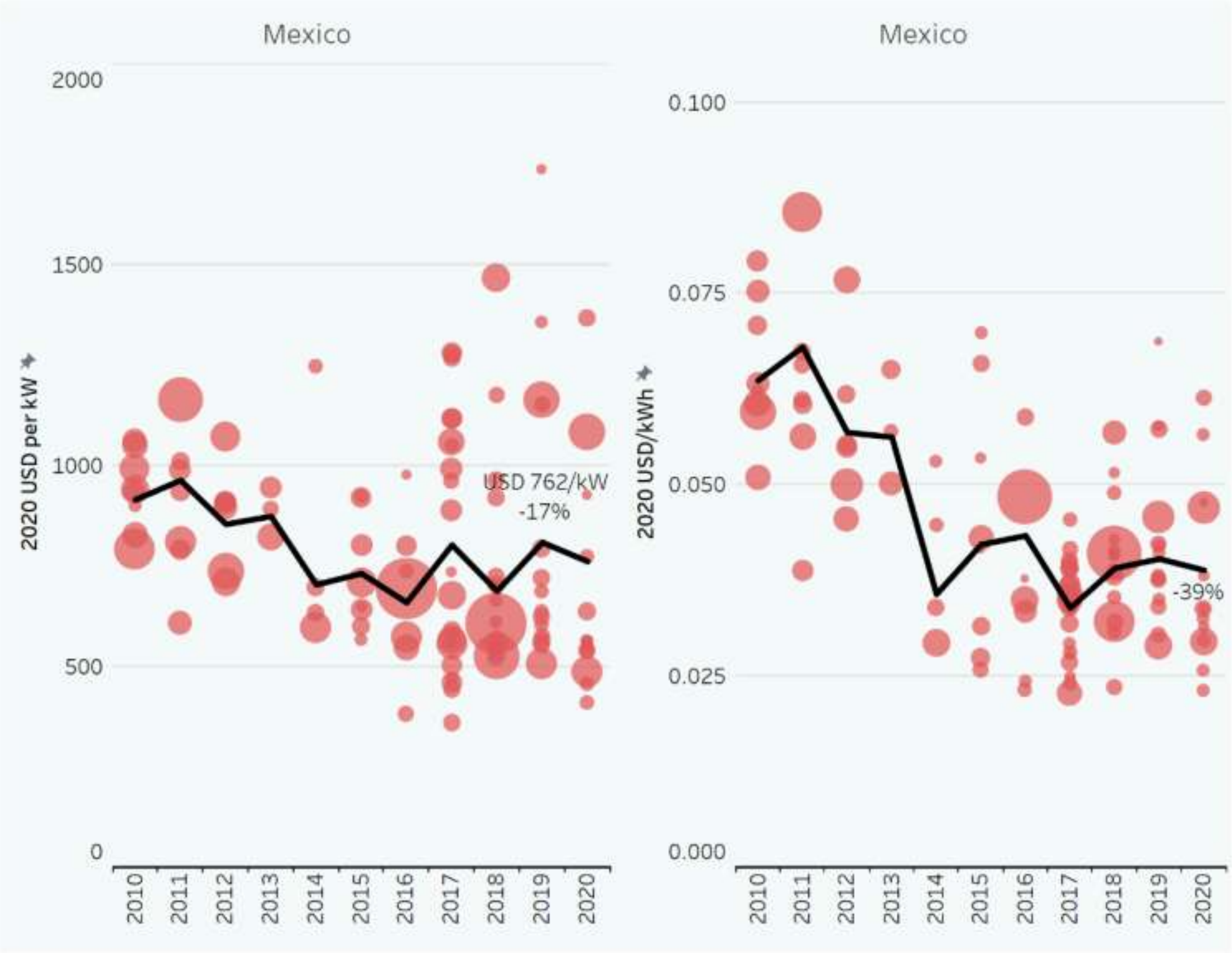


Solar thermal in Mexico

Mexico has an established solar thermal market, with competitive equipment costs and excellent solar resources helping it to achieve very competitive heat costs.

The total installed cost of solar heat projects in Mexico fell from a weighted average of USD 916/kW in 2010 to USD 762/kW in 2020, a reduction of 17%. Project sizes remain relatively modest, with most projects in the 50 kW to 500 kW range, serving hospitals, schools and other commercial activities with hot water.

System component improvements and optimisation of the overall system design has seen yields increase over time, ensuring that in Mexico, the weighted-average LCOHEAT fell faster than total installed costs, from USD 0.064/kWh in 2010 to USD 0.039/kWh in 2020. Over the decade, this represents a reduction of 39%.

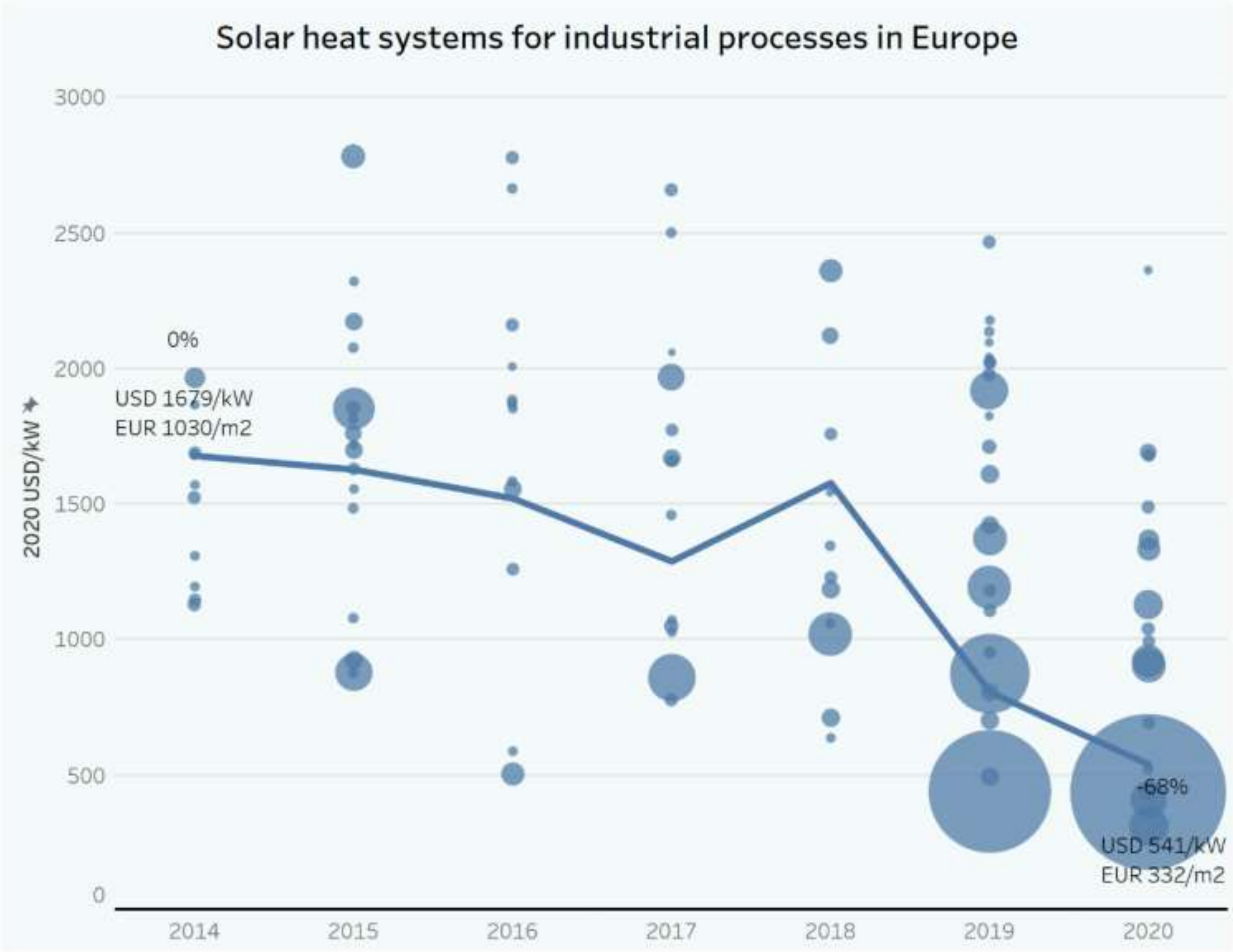


Solar heat for industrial processes in Europe: Total installed costs

Europe has supported the development of solar heat for industrial process (SHIP) projects over the last ten years, albeit in small numbers.

The total installed cost of new European SHIP projects fell from a weighted average of USD 1 670/kW in 2010 to USD 541/kW in 2019. This was a decline in installed costs of more than two-thirds – and on the back of modest deployment. This highlights not only the benefits of policy support, but the importance of also achieving plant-level economies of scale to help drive down costs in the early years of commercial deployment.

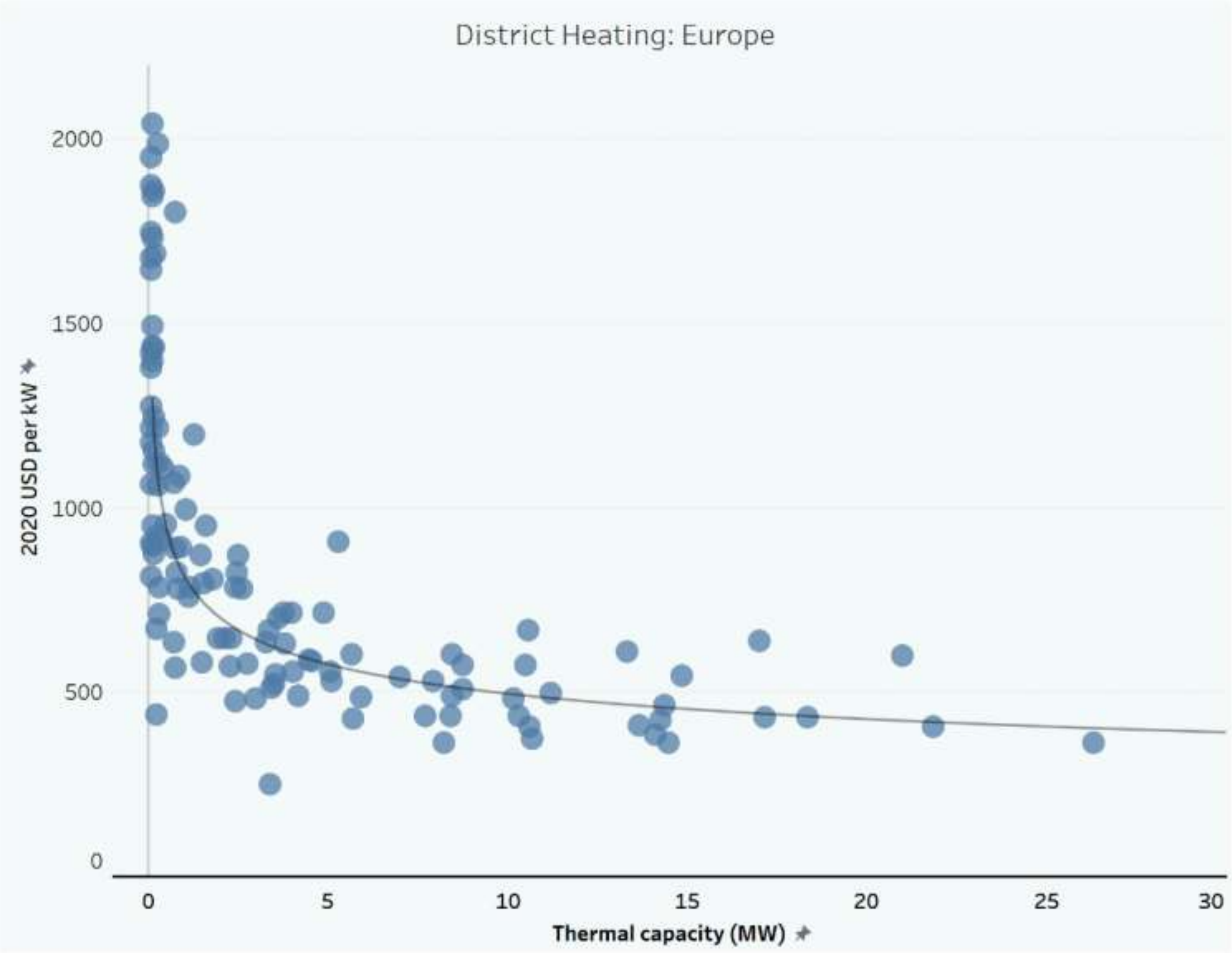
The data clearly shows the benefit of moving from smaller projects to larger ones. In the latter category, project development, design and engineering and customer acquisition costs can be spread out, in addition to the benefits of procuring and manufacturing at larger volumes.



Economies of scale in solar thermal: District heating systems in Europe

The Danish district heating sector has been marked by experienced suppliers and manufacturers, competing to deliver competitive MW-scale projects to district heating schemes. Between 2010 and 2020, the weighted-average project size for the projects in our database for Denmark ranged from a low of 5.4 MW thermal (MW_{th}) in 2010 to a high of 17 MW_{th} in 2016, with 12 MW_{th} in 2019.

The figure on the right shows the total installed cost data for 121 district heating projects, plotted against the project capacity in MW. Austria, Denmark and Germany account for 97% of the district heating projects in the database. The clear economies of scale in project size are quite evident. The fitted line for economies of scale suggests that for every doubling in the size of the plant, total installed costs will decline by 14%. A clear message is that policies to support larger-scale projects would likely have immediate benefits for consumers in terms of lower renewable heat costs.

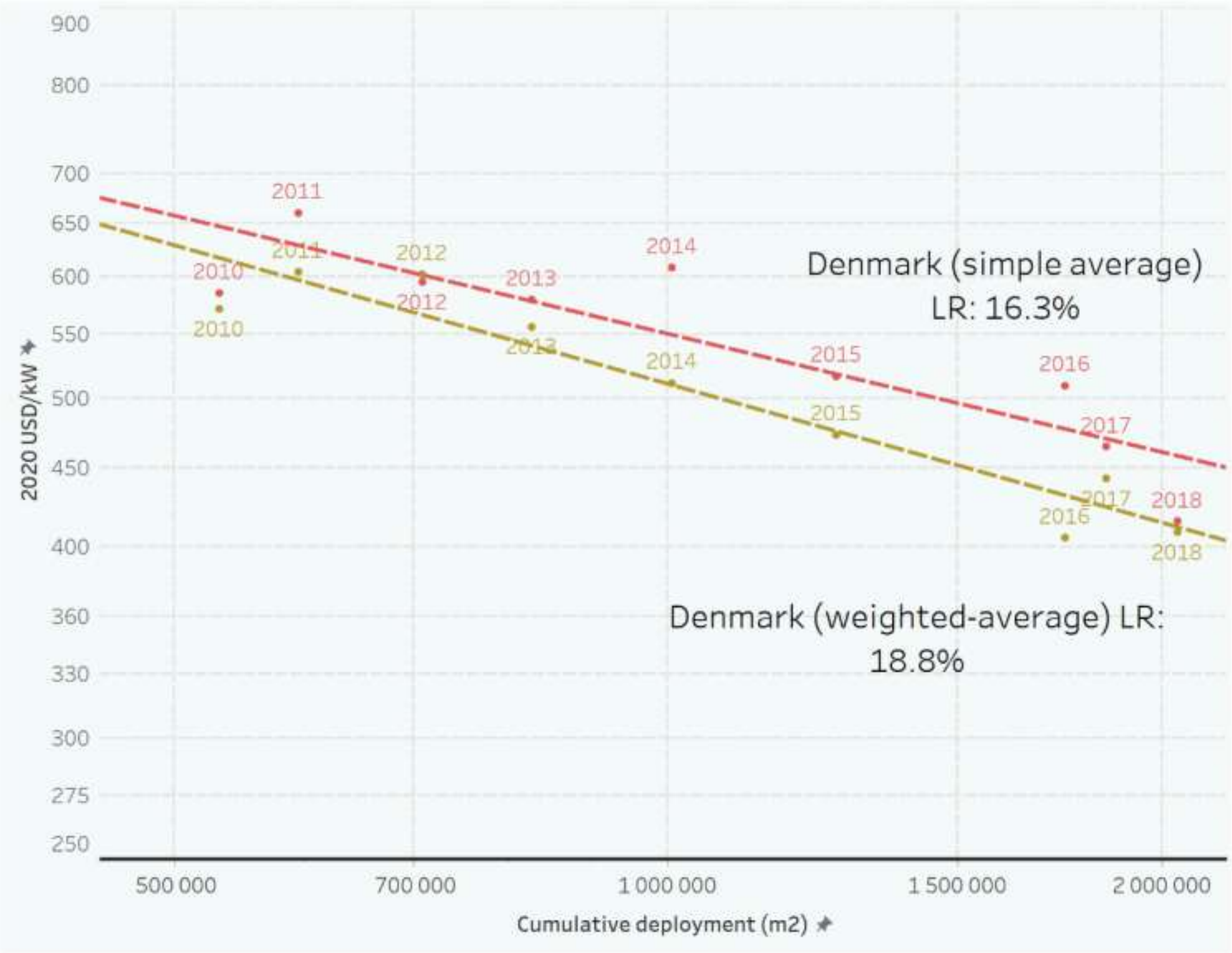


Learning rates for solar thermal: District heating systems in Denmark

With small markets and a slowing in the rate of new deployments in recent years, it is difficult to calculate meaningful learning rates for solar thermal in most markets. For the Danish district heating market, however, IRENA and Solrico have successfully managed to collect representative data that allow a calculation of the learning rate.

The figure on the right shows the total installed cost data for Denmark's district heating projects, plotted against the cumulative installed capacity, in terms of square metres of collector area.

The learning rate for the period 2011 to 2019, based on the weighted-average total installed cost, was around 19%. For the simple average, it was somewhat lower, at 16%. These are impressive learning rates, given the modest size of the market (121 projects totalling 687 MW in our database) and the fact that the new capacity additions per year were slowing over this period.



International Renewable Energy Agency

IRENA Innovation & Technology Centre

PART II
Datasets and analysis on patents and standards in energy technologies

Patents are legal documents that define the intellectual property rights sought for a technological invention and give exclusive permission for exploitation for commercial purposes, hence preventing others from imitation.

Patents are granted for inventions that are new and bring an inventive step concerning industrial applications. Patents protect an invention for a limited time (usually 20 years) and in the specific territory where patents are filed, implying that more than one patent application is necessary to protect the same invention in multiple countries. The decision on where to file a patent is driven by the market potential of the technological invention in a specific country.

Patents are considered a core output of RD&D activities and present an important, though imperfect, proxy indicator to measure and inform the rate of technological progress. As such, they play an important role in the early stages of innovation. Collecting and analysing patent data helps to monitor technology development on a global, national and local scale.

Patent data are used to detect global trends in technology development, as they provide insights on the progress generated by nations and their innovation systems, including the level of internationalisation of their inventive activity and the level of countries' technology specialisation.

International technical standards are developed once a potential market is identified and is closer to the commercialisation stage.

International technical standards are documents that emerge from internationally harmonised requirements for the development of a reliable and effective design, the production and use of goods and services. They provide useful information by documenting and disseminating information on state-of-the-art technologies and allow RD&D efforts to build upon the best-known technology practices and facilitate the transition to the commercialisation stage.

Standards increase the global tradability and compatibility of products and services and provide an extra layer of consumer protection in addition to government policies and protection organisations. Technical committees that are developing standards can serve as a platform for discussions between experts, which in turn can foster further innovation.

International technical standards are associated with providing enabling conditions for broader technology deployment and commercialisation and represent an indirect sign of technology progress. International standards may contribute to faster deployment of the technology and serve as an indicator of technology readiness and the stage of commercialisation. They are a strong indicator that innovative technologies are being deployed.

Six Patent Sub-Indicators

1) A **patent family (or inventions, or patent)** is a set of patent applications protecting the same invention in different countries. Therefore, a patent family is a proxy of inventive activity.

2) **An international patent family** considers patent applications in a family filed by applicants' resident in a country that is different from the jurisdiction where this patent is filed. This metric reveals the interest in establishing an international flow of inventions and helps to assess global trends in technology transfer.

3) **Patent families of high value** refer to the patent families that include patent applications filed in more than one patent office. Each application comes at a certain cost, and therefore an applicant that files more than one application (in multiple patent authorities) is willing to spend more than if only filing one patent application. This implies that applicants foresee high value for their invention.

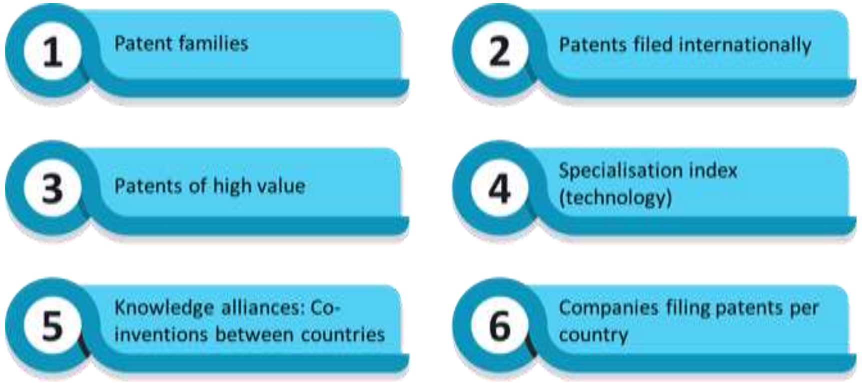
4) **Specialisation index** represents patenting intensity in technology for a given country compared to global activity. As such, it offers further insights into the country's patenting activity (hence specialisation) when compared to global patenting activity.

5) **Knowledge alliance** defines co-inventions (patent families) that are produced among two or more applicants from different countries. This indicator helps to assess knowledge co-operation and industrial cross-country collaboration.

6) **Companies filing patents per country** is an indicator measuring the market dynamic of countries in respect to a specific technology sector. When this indicator is combined with the number of inventions developed (the Herfindahl–Hirschman Index [HHI]) it measures the market concentration and gives an indication of the competition in that sector.

Data provision

Patent data have been provided by the European Commission's Joint Research Centre (JRC). JRC follows the methodology that applies fractional counting in order to avoid double counting of the same invention (Fiorini et al., 2017; Pasimeni et al., 2021). Patent indicators are complemented by information from the European Patents Office (EPO) and the IRENA platform on International Standards and Patents in Renewable Energy (INSPIRE).



Five International Standards Sub-Indicators

1) The **number of international standards** developed indicates the level of maturity of a technology in reaching commercialisation. This takes into consideration efforts to standardise best practices and common criteria for the technology to enter the market.

2) **International standards under development** are a direct response from the industry and consumer groups and indicate the readiness of the technology to be broadly deployed.

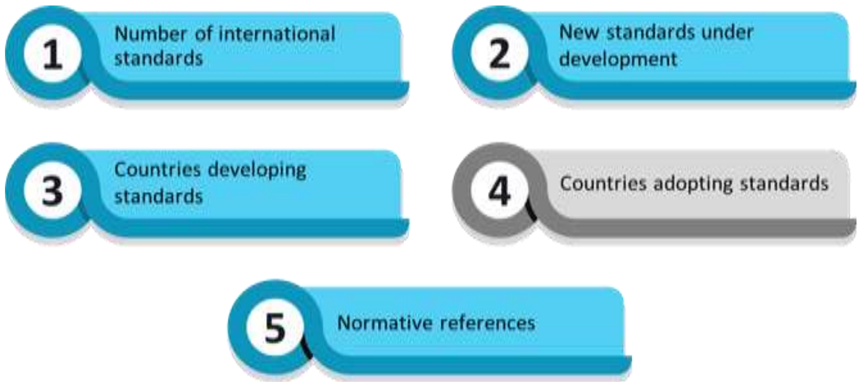
3) **Countries developing international standards** and their participation in standardisation committees present an insightful indicator that sheds light on countries and key stakeholders (industry, researchers, consumers and regulators) looking to collaborate in developing global markets for the incumbent technology.

4) **Countries adopting international standards** provides an insight into the diffusion of best practices experience of key stakeholders (industry, researchers, consumers and regulators) worldwide, and the degree of the removal of technical barriers to trade. Unavailability of data, however, makes it impossible to analyse this sub-indicator.

5) **Normative references**. The European Committee for Standardisation defines a normative reference as, "A document to which reference is made in the standard in such a way as to make it indispensable for the application of the standard." The use of normative references sheds light on innovations and best practices from the same and/or a different technology/category or industry and allows spill over knowledge that eventually leads to the broader deployment of the current technology.

Data provision

International standards data have been extracted from IRENA's in-house database, which includes technical standards from the main international standardisation bodies, namely the International Electrotechnical Committee (IEC) and the International Organisation for Standardisation (ISO).



Methodology applied to two emerging technologies

OFFSHORE WIND

Offshore wind has received increasing attention in the last decade because of its potential for exploiting high wind resources offshore through large-scaled offshore wind parks. Technology innovation has enabled development of key components (*e.g.* floating wind turbines or subsea power transmission cables) that have driven a rapid cost reduction.

Patent data relative to offshore wind are extracted considering the Cooperative Patent Classification (CPC) that provides specific codes for offshore wind technology within the overall sector of wind energy. Offshore wind is analysed here via one specific component, that is offshore wind turbines (CPC code Y02E10/727).

GREEN HYDROGEN (ELECTROLYSERS)

Hydrogen technology is gaining momentum nowadays thanks to its potential for decarbonising energy-intensive industries and other sectors such as transport and heating. To reach climate targets, production of hydrogen needs to be green, hence powered by renewable energy sources and originated via an electrolysis process.

Patent data relative to hydrogen (electrolysers) are extracted considering the Co-operative Patent Classification (CPC) that provides specific codes for water electrolysers within the overall sector of hydrogen. The analysis of hydrogen (electrolysers) concerns hydrogen production from non-carbon containing sources (*e.g.* by water electrolysis – CPC code Y02E60/36).

Wind Energy – Patent code	
Y02E10/70	• Wind energy
Y02E10/72	•• Wind turbines with rotation axis in wind direction
<u>Y02E10/727</u>	•• Offshore wind turbines
Y02E10/728	•• Onshore wind turbines
Y02E10/74	•• Wind turbines with rotation axis perpendicular to the wind direction
Y02E10/76	•• Power conversion electric or electronic aspects

Hydrogen Technology – Patent code	
Y02E60/30	• Hydrogen technology
Y02E60/32	•• Hydrogen storage
Y02E60/34	•• Hydrogen distribution
<u>Y02E60/36</u>	•• Hydrogen production from non-carbon containing sources, e.g. by water electrolysis
Y02E60/50	•• Fuel cells

Offshore wind

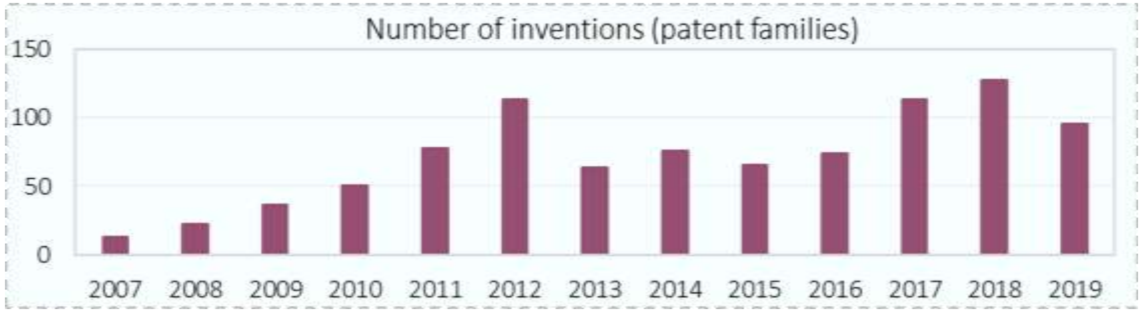
Patents: 1) Patent Families

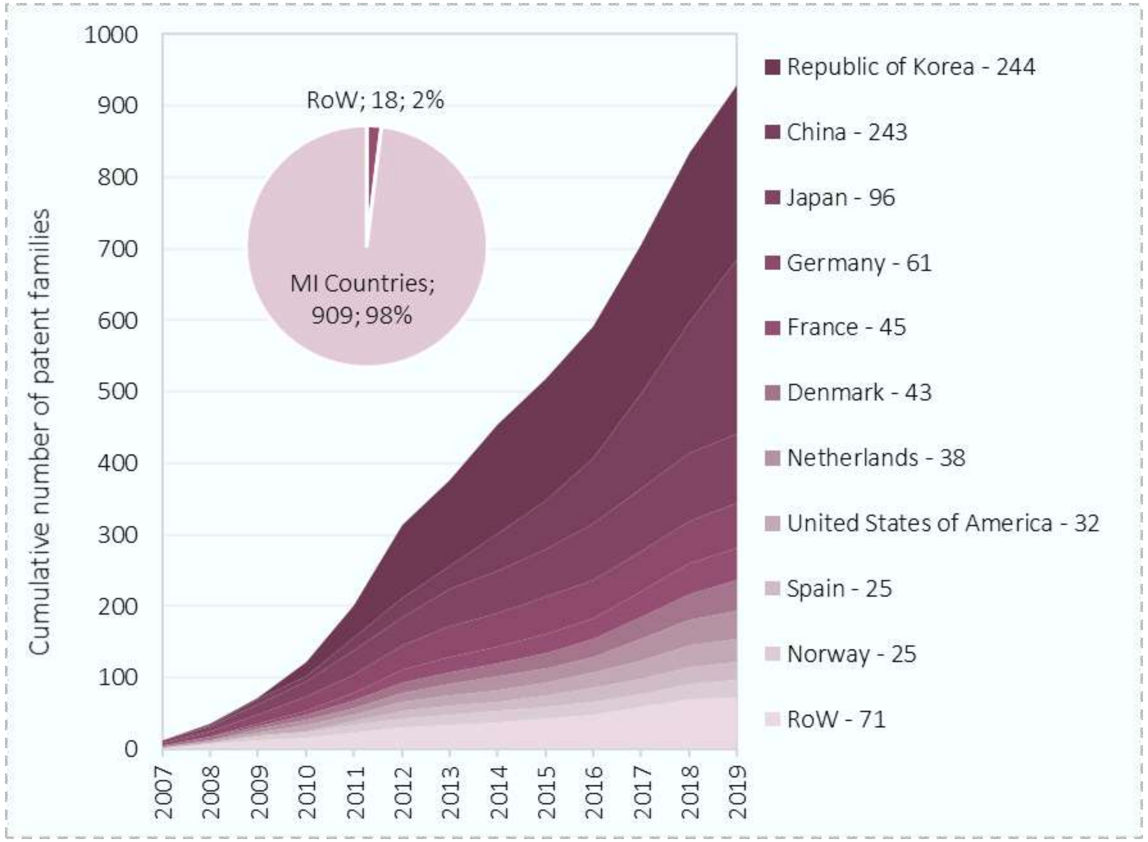
Between 2007 and 2019, patent activity in offshore wind turbines (as per the Y02 code) experienced ups and downs with two peaks during that period. The first, highest patenting activity was recorded in 2012 (114 inventions), with the trend increasing again from 2016, reaching 128 offshore wind inventions in 2018.

Between 2007 and 2019, more than 900 new offshore wind inventions were filed globally. In the five years from 2015 to 2019, the number of new inventions equalled the number of inventions filed in the previous eight years, from 2007 to 2014, showing a renewed interest in offshore wind technology.

On a country level, countries with the highest number of patent families – in total, as well as on an annual basis – were the Republic of Korea, followed by China, Japan and the top European Union countries, namely Germany, France, Denmark and the Netherlands. This indicates an increased interest from countries other than the European front-runners in inventive activity in offshore wind technologies.

Overall, Mission Innovation (MI) countries dominate the top 10 list, representing approximately 98% of the global offshore wind activity. Almost half of these inventions were developed in China or the Republic of Korea.





Patents: 2) International Patent Families

Patent families filed internationally in offshore wind exhibited two peaks, in 2012 and 2017. On average, international inventions represented 14% of total inventions.

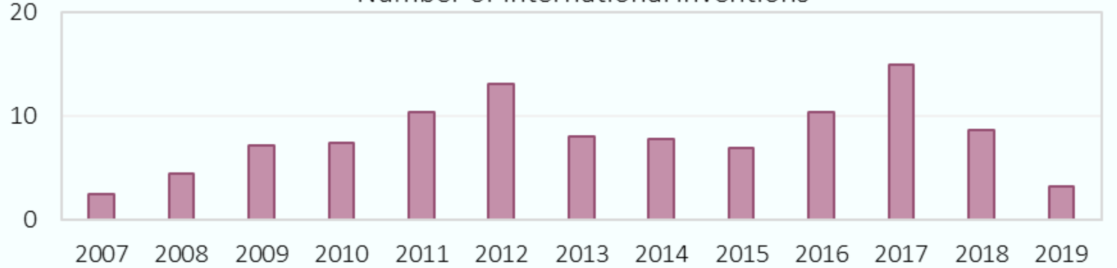
All the top 10 countries filing international patents were MI countries. At individual country level, from 2007 to 2019, the highest cumulative numbers of international patent families belonged to Japan, the United States and European countries (Denmark, France, Germany, the Netherlands and Spain). These seven countries account for about 66% of the total number of inventions protected internationally.

China was not among the top countries that filed patents internationally: only 4% of Chinese inventions were protected in other jurisdictions, with these accounting for about 4% of total international inventions.

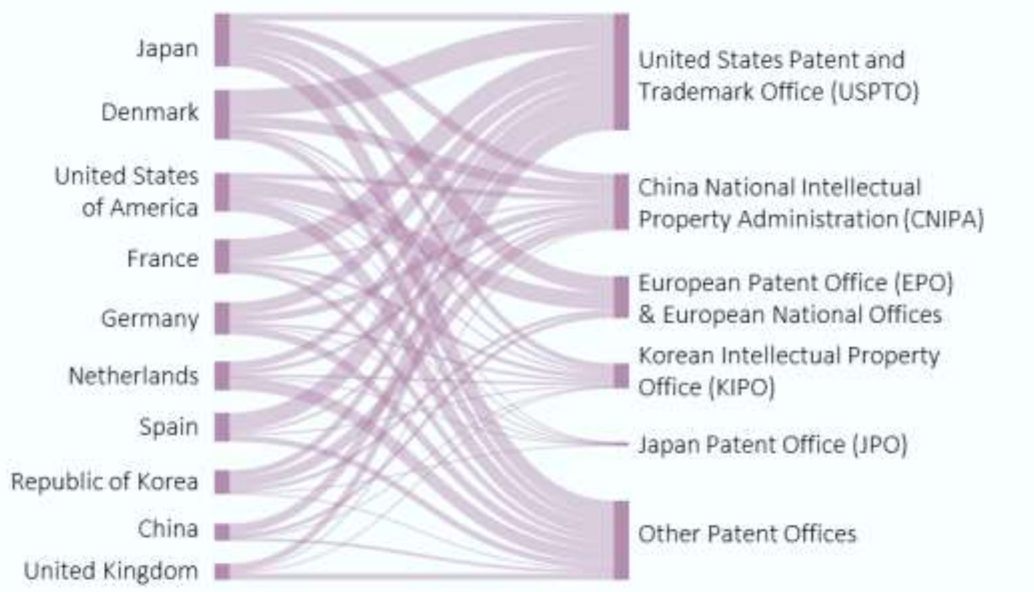
China was second after the United States in attracting inventions from other countries. Some 17% of total international inventions are protected in China. A possible interpretation for this trend is the number of market opportunities foreseen in China, hence the need to protect inventions in this geographical area.

Japan was the main country producing and protecting internationally offshore wind inventions: 14% of Japanese inventions were international and represented 30% of total international inventions. Japan attracted less than 1% of total international inventions, indicating high technological capacity, but less market opportunity in the country.

Number of international inventions



Top 10 countries (on the left) protecting inventions internationally in top jurisdictions (on the right). 2007-2019



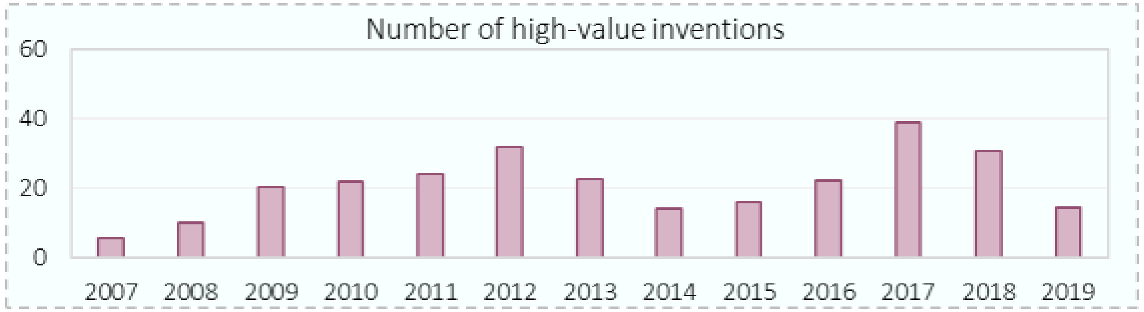
Patents: 3) Patent Families of High Value

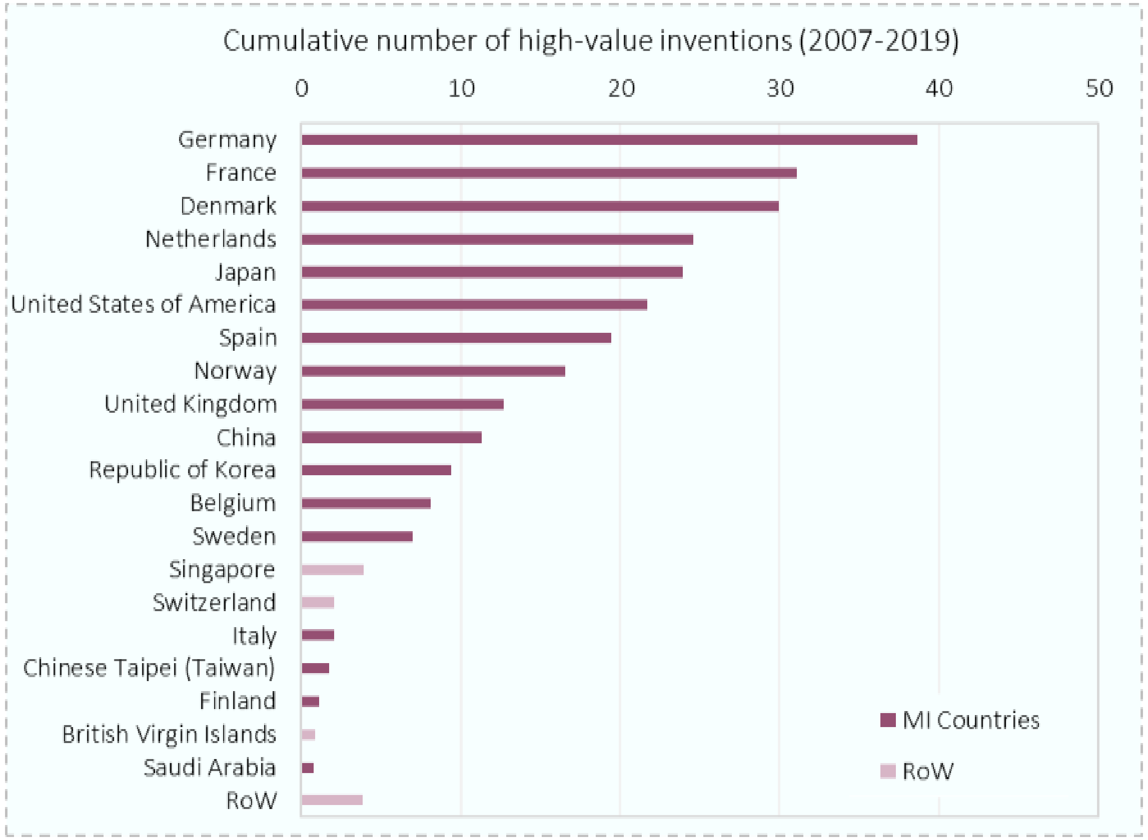
At the country level, the top 10 countries filing high-value inventions were all MI members. The Europeans, namely Germany, France, Denmark, the Netherlands, Spain and Norway, accounted for about 59% of the total high-value inventions and, overall, 64% of their inventions in offshore wind were of high-value.

Japan and the United States were fifth and sixth respectively in this ranking. Countries such as France and Spain, which have low offshore deployment levels, possess knowledge gained from their development of onshore wind farms that they can apply to offshore wind technologies.

An interesting observation can be made about China and the Republic of Korea. These countries lead in their domestic patenting activity and tend to file their inventions in only one patent office (mostly a domestic one) rather than multiple offices. This translates into lower levels of filed patent families of high value. Their shares of total high-value inventions were 9% and 3% respectively.

This can be attributed to various possible factors, including the large size of their country/market, the quality level of patents, or incentivising mechanisms in these countries to file domestic patents.





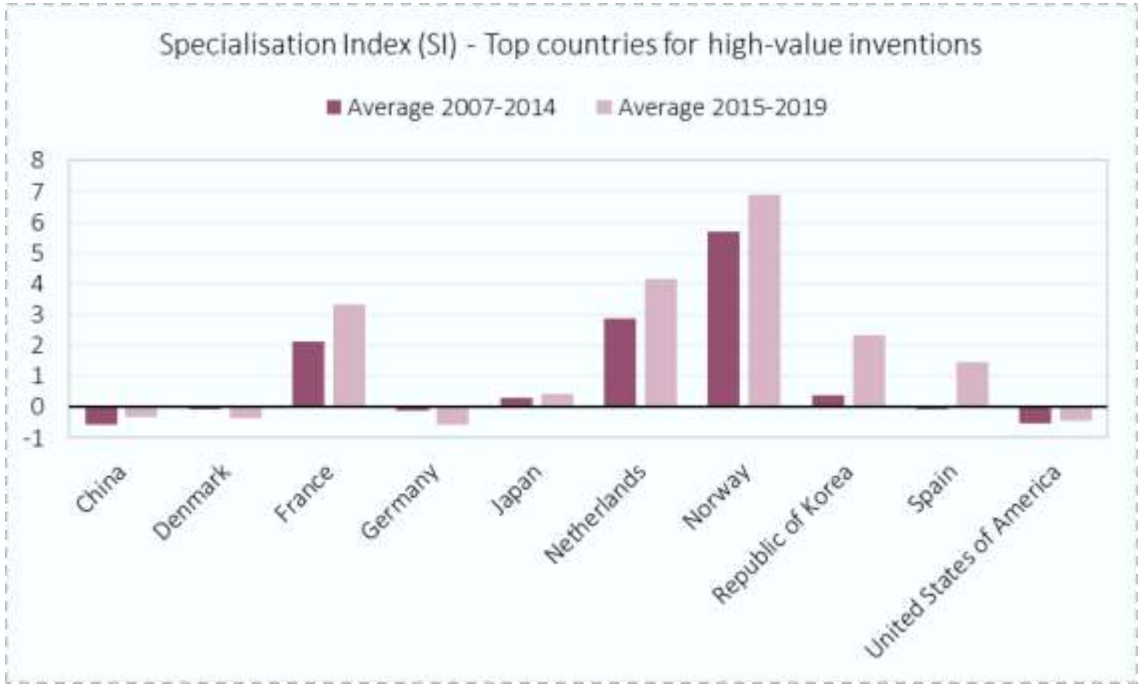
Patents: 4) Specialisation Index (SI)

The specialisation index (SI) takes a particular country's share of offshore wind-related inventions in its total number of wind sector inventions and compares this to the global share of offshore wind inventions over total global wind inventions. Inventions related to the entire wind sector are detected via the Y02E10/70 CPC codes (and sub codes), that together define wind energy technologies. Globally, the share of offshore wind inventions within the wind sector grew from about 1.6% in 2007 to about 4.5% in 2019, reaching its maximum in 2012 (5%).

Countries that had a positive SI in the first period (2007 to 2014) increased the level of specialisation in the most recent time-frame (2015-2019).

Norway was the most specialised country in offshore wind, signalling its ability to transfer knowledge from the offshore oil and gas industry to offshore wind (*e.g.* in offshore foundation construction).

The Netherlands and France show a very high SI, indicating their specialisation in offshore wind technology. Between 2007 and 2019, their shares in offshore patenting production were 15% and 13%, respectively. The level of specialisation in these countries was significantly higher than in the Republic of Korea, Spain or Japan. Nevertheless, both the Republic of Korea and Spain showed the highest improvement of their specialization between the 2007 to 2014 and 2015 to 2019 periods, indicating how these two countries are fast growing players in the offshore wind sector.



China, Denmark, Germany and the United States had a negative SI during the period in question, despite being at the top for the number of patent families in offshore wind.

In addition, while China and the United States improved their specialisation over time, the SI for Germany and Denmark fell in the period 2015 to 2019. This indicated that the amount of inventive activity dedicated by these countries to offshore wind within the wind energy sector was lower than the global average.

Patents: 5) Knowledge Alliance

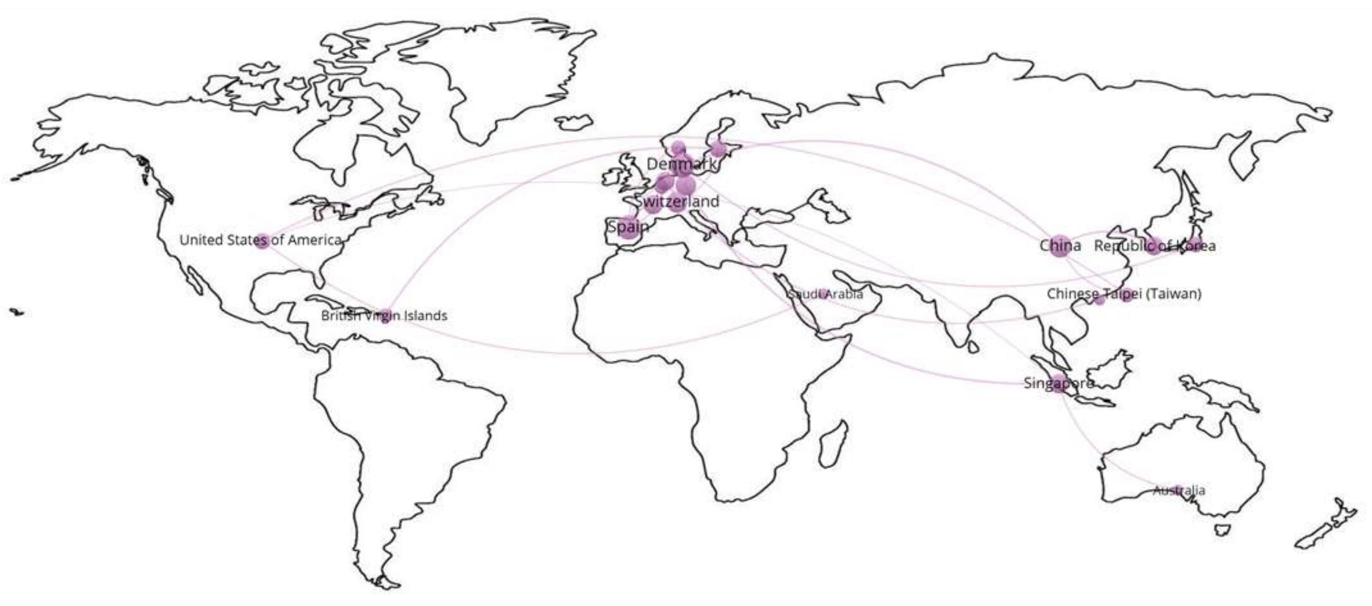
Between 2007 and 2019, about 30 inventions related to offshore wind were the result of collaborations among two or more countries. Fifteen out of the 21 countries undertaking international collaborations were MI countries.

Europe is at the centre of several international knowledge alliances in the offshore wind sector. This highlights its leading position in this technology, and constant activity to take advantage of the full potential of Europe's coastal regions.

During the period examined, Denmark, Spain and Switzerland were the countries with the highest number of collaborations, co-operating with four other countries.

Asian countries, namely, China, Japan, the Republic of Korea and Chinese Taipei, engage in mutual alliances, indicating the relevance of geographical proximity when it comes to knowledge alliances and the development of co-inventions.

International network of co-inventions in offshore wind (2007-2019)



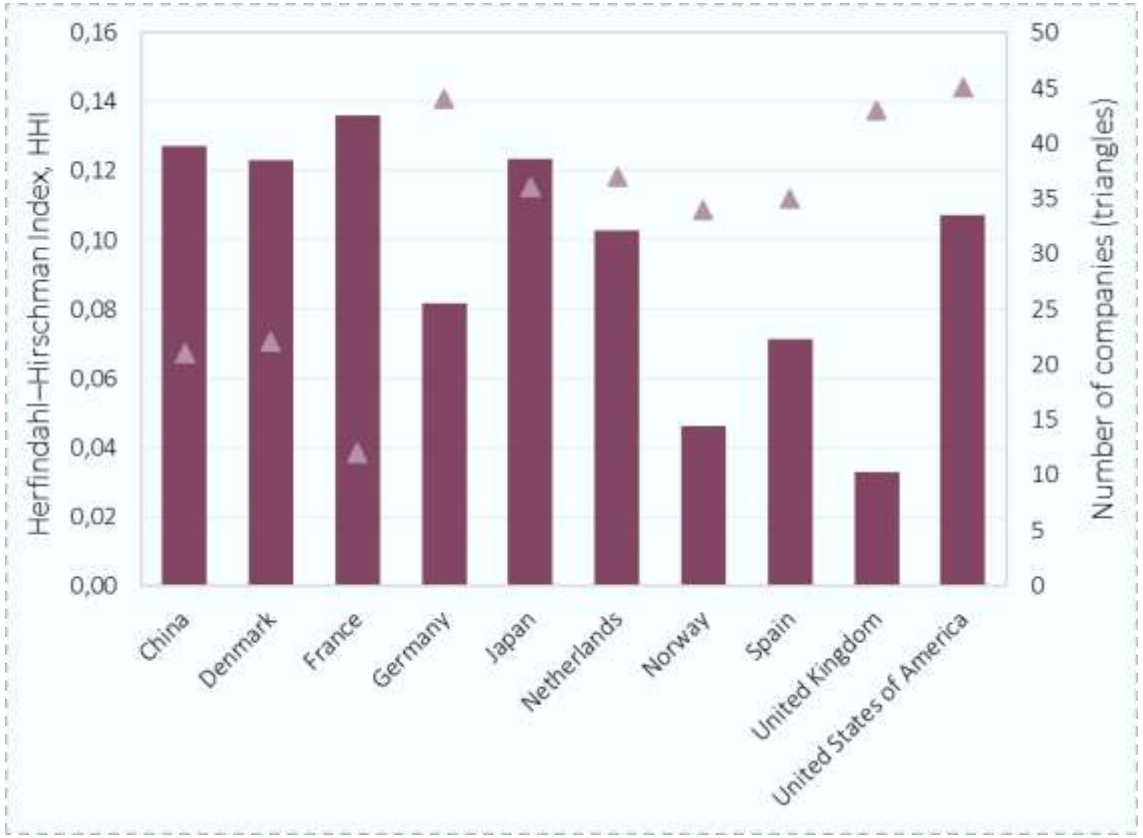
Patents: 6) Companies filing patents per country

Looking at the top 10 countries developing high-value inventions related to offshore wind, the United States, Germany and the United Kingdom had around 45 companies that were active in the offshore wind technology sector. Japan, the Netherlands, Norway and Spain followed with about 35 active companies, while Denmark, China and France were at the bottom of this ranking (see right axis in the figure).

The Herfindahl-Hirschman Index (HHI) measures the level of market concentration in a country and, as it moves towards 1, indicates a fully monopolised market where one company covers the entire production of patents (the left axis in the figure).

In the data examined here, overall, national markets were not very concentrated (the HHI averaged 0.10 among the top 10 countries). This indicated a good balance among national players producing offshore wind inventions.

A negative relation between the number of companies and the HHI is of high probability (more companies result in a less concentrated market). This condition was true, for example, in the United Kingdom (43 companies and 0.03 HHI) and in France (12 companies and 0.14 HHI). It did not hold true, however, in Japan (36 companies and 0,12 HHI), where just two companies produced about 44% of the country’s total high-value inventions.

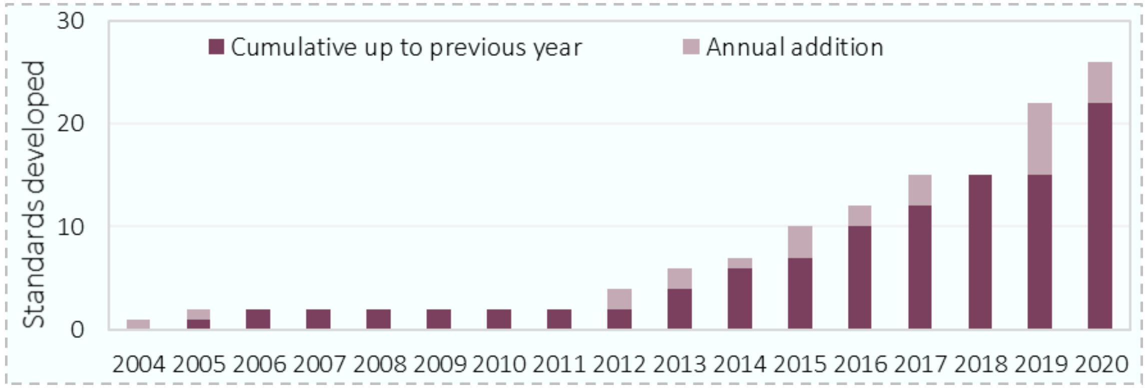


Standards: 1) Number of International Standards

The international technical standardisation of offshore wind covers different areas and aspects that contribute to optimised operations, from design, production, performance, safety and testing to analysis.

The data used here were collected through the IEC, ISO, DNV, Microgeneration Certification Scheme and the American Wind Energy Association databases.

Between 2004 and 2020, 33 international standards were developed for wind energy technologies. Between 2004 and 2020, 26 standards were published which are applicable to both onshore and offshore wind energy technologies and 5 which were applicable either only to offshore wind or floating wind. An important part of these standards was published after 2012, as shown in the following column diagram. This indicates that the technology is on the path to maturity, reaching commercialisation and gaining momentum over time.



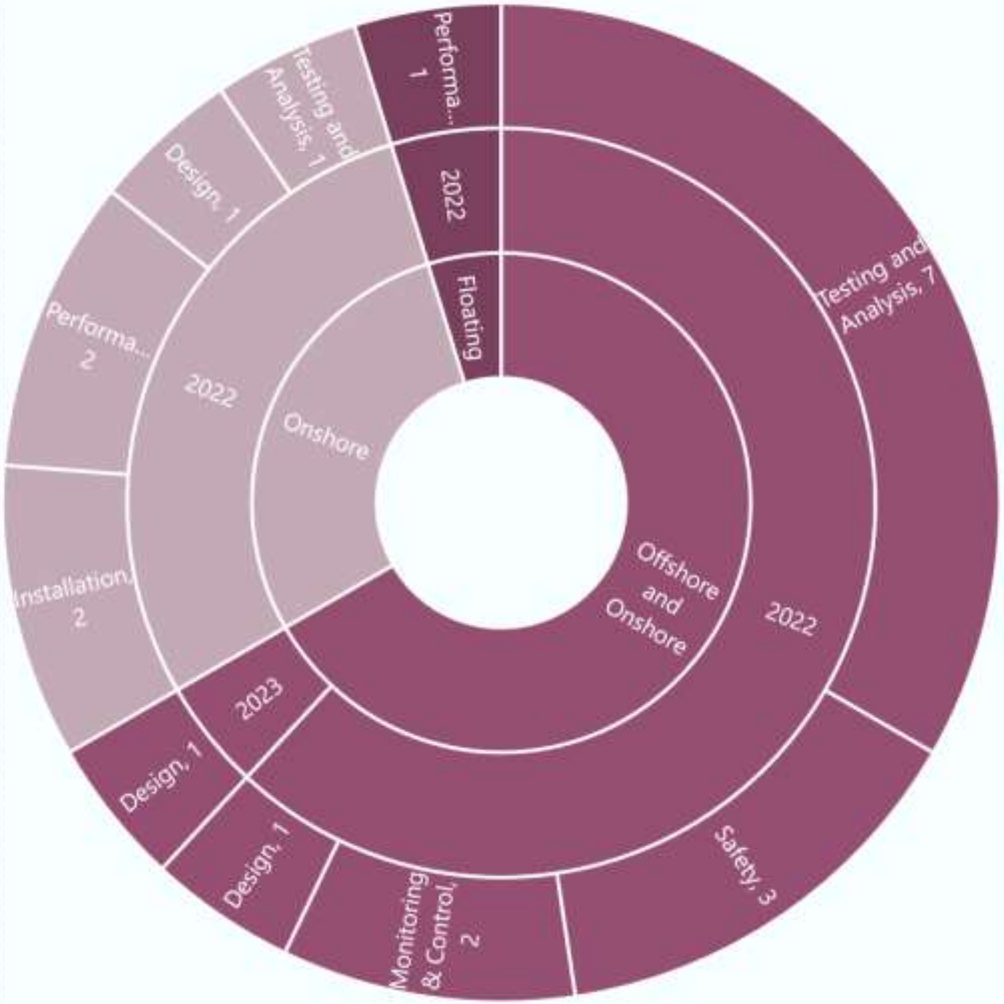
Standards: 2) New Standards Under Development

Currently, 21 new international standards for wind technology are being developed. These cover several different categories, with their finalisation expected between 2021 and 2023. It takes approximately three years from the initial proposal to the final adoption of the standard.

Currently, one international standard is under development specifically for offshore wind, focusing on the design requirements for floating offshore wind turbines. The working group looking at this is focusing on the assessment of external conditions at an offshore site and on specifying essential design requirements to ensure the engineering integrity of offshore wind turbines.

Conveners of this working group are the United States and the Republic of Korea. Sixty-six experts are members of the group, with these coming from 13 different countries: China, Denmark, France, Germany, Japan, the Netherlands, Norway, the Republic of Korea, Spain, South Africa, Sweden, the United Kingdom, and the United States. Japan is the most represented country, with 17 experts, followed by Germany and Spain with 9 each.

International technical standards under development in offshore wind technology

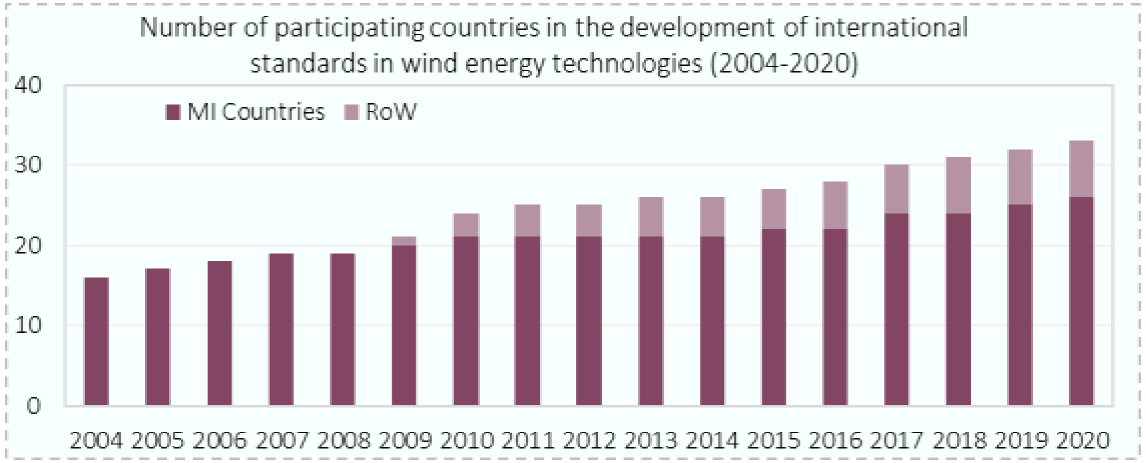


Standards: 3) Countries developing international standards

From the data collected on countries developing international standards, offshore wind technology has attracted interest from many countries. The number of member countries (excluding observer countries) participating in the development of international technical standards in wind energy technology (both onshore and offshore) increased steadily from 2004 to 2020, from 16 to 33. Including observer countries, in 2020, the number of countries participating in international standards development was 41.

These countries are broadly distributed geographically, as shown in the map on the right. In addition to the historical frontrunners with the highest installed capacities (Europe and China), the list includes Japan and the Republic of Korea.

MI countries – including Denmark, which chairs Technical Committee 88 for wind energy generation systems (the committee was established in 1988) – are strongly engaged in international standards development for wind energy technologies. In 2020, they represented 29 countries out of the total 41 countries (about 71% of the total). While MI countries were strongly engaged during the 2004 to 2016 period, participation from other countries started growing only after 2010. Increasing interest in international standards development from a wider group of countries denotes growing confidence in the technology, which in turn may contribute to the expansion of the technology to other markets, in the future.

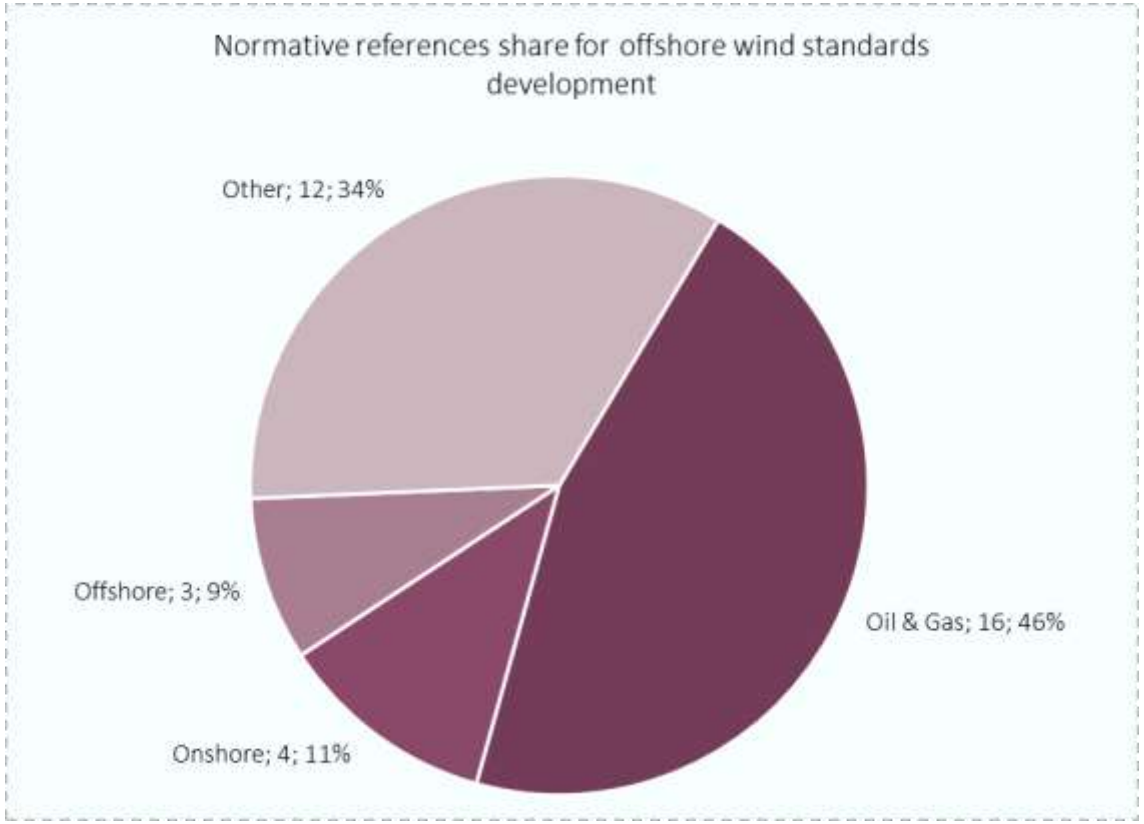


Standards: 5) Normative References

International technical standards in offshore wind have relied upon international standards developed for different technologies in different sectors and environmental conditions.

A significant number of normative references, representing more than 46%, came from the oil and gas (O&G) industry as shown in the diagram on the right. Normative references from O&G are mainly used for foundation design, material and marine operations.

In addition, environmental standards played a role in the development of offshore wind standards. These include standards concerning exposure to different weather conditions, and chemicals for the production and installation of the electrical components for offshore wind turbines.



Hydrogen electrolysers

Patents: 1) Patent Families

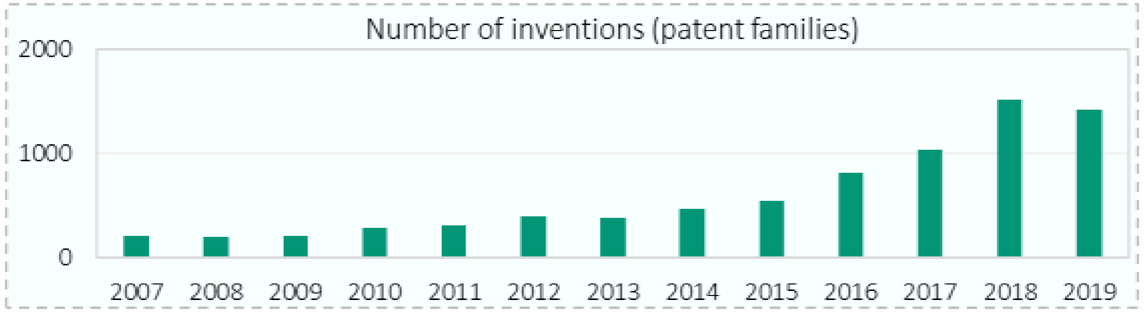
Between 2007 and 2019, patenting activity relative to hydrogen (electrolysers) grew rapidly, particularly from 2014 onwards, with 30% average annual growth.

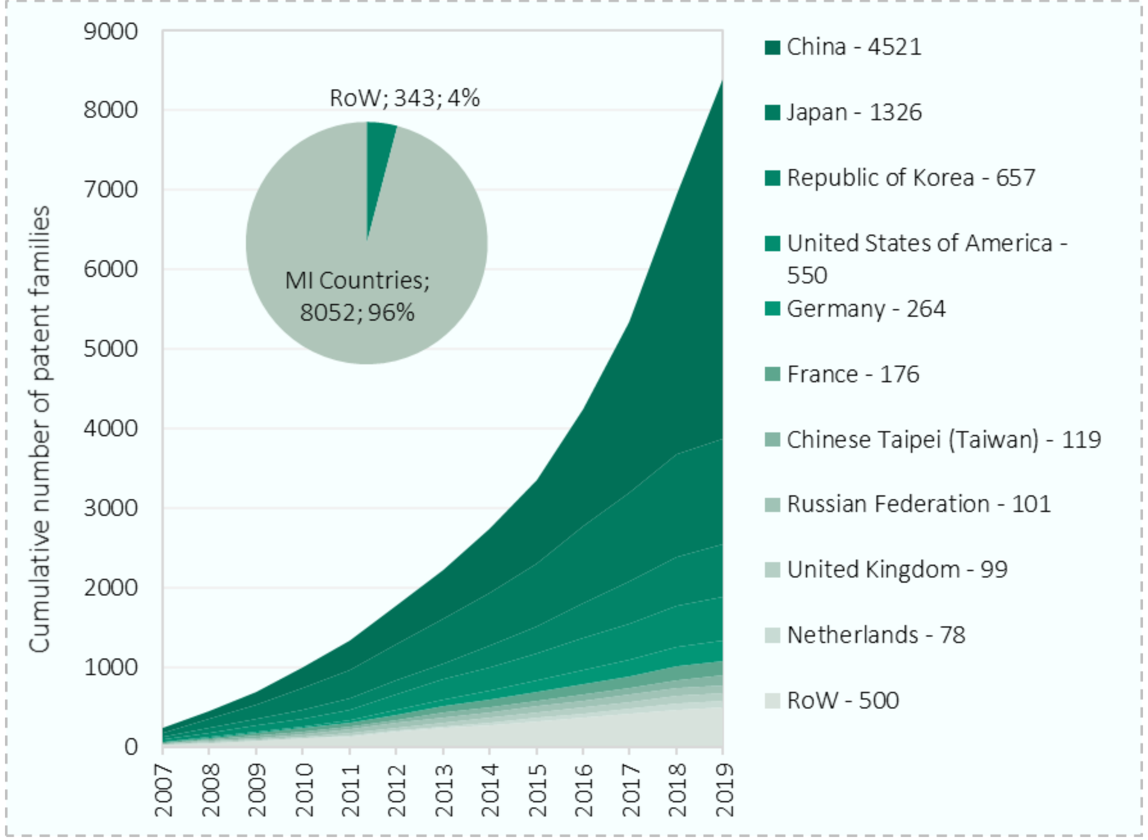
About 1 600 new inventions were produced in 2018 alone. This rising trend is expected to continue, given that 2019 data are incomplete and that there is growing interest in this technology. In the period 2007 to 2019, more than 8000 new inventions were filed globally, half of these developed in the last three years.

On a country level, in 2019, China accounted for more than half of the total number of inventions – a leading position gained just recently, given that in 2015 China's share was around 30%.

Japan and the Republic of Korea also registered a large number of inventions in hydrogen (electrolysers), indicating these countries' growing interest in developing green hydrogen related innovation.

The United States followed these leading Asian countries, while the European presence among the top countries was limited to Germany, France, the United Kingdom and the Netherlands. Overall, MI countries represented approximately 96% of global inventive activity in relation to hydrogen (electrolysers).





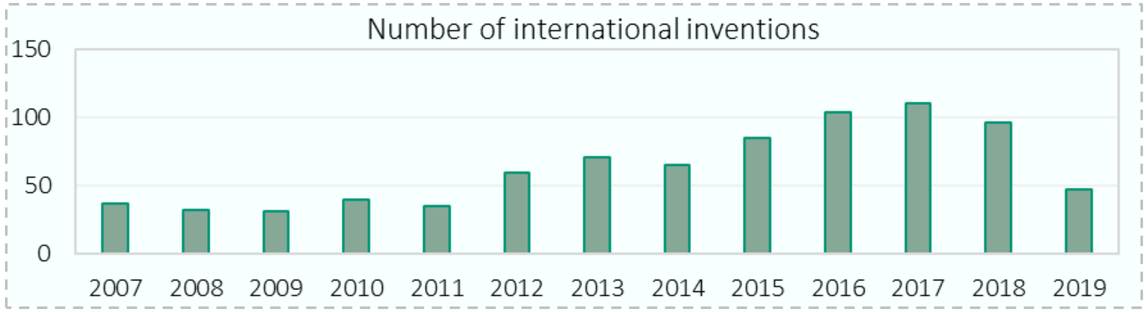
Patents: 2) International Patent Families

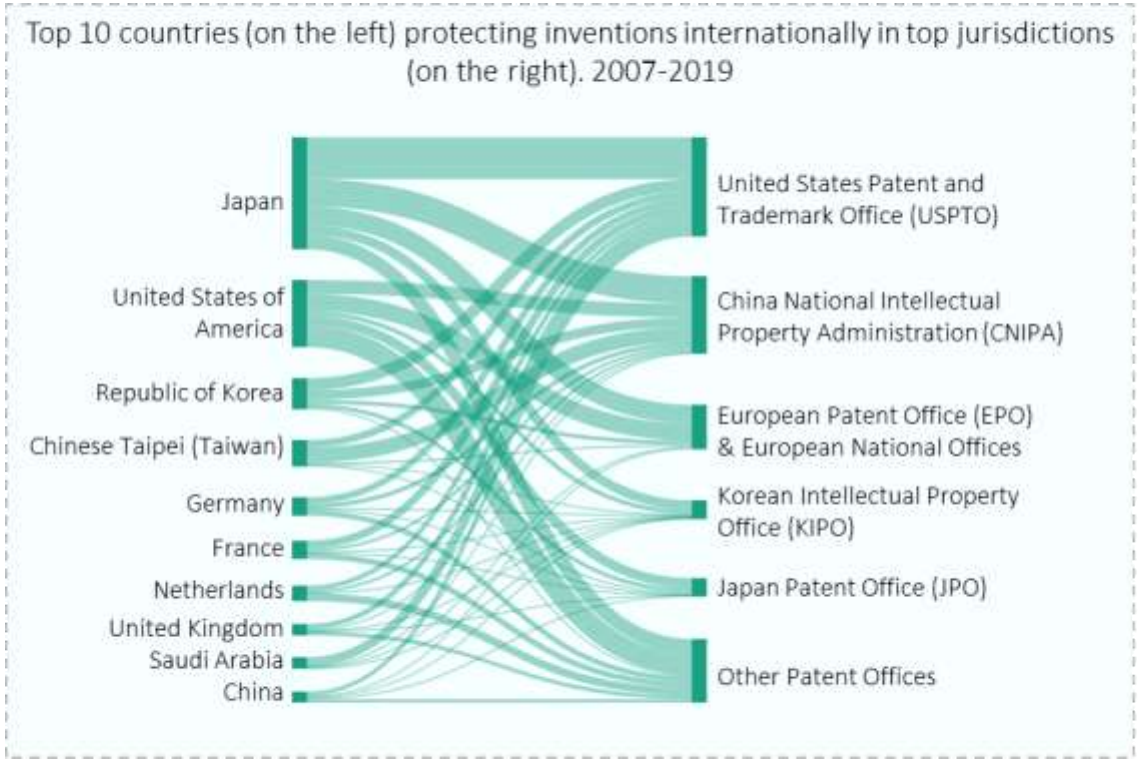
Patent families related to electrolysers and filed internationally exhibited growing numbers after the period 2012 to 2014. These accounted for about 15% of annual total inventive activity.

Almost 90% of total international inventions were developed by MI members. At the country level, from 2007 to 2019, the highest cumulative numbers of international patent families were developed in Japan, the United States, the Republic of Korea and Chinese Taipei. Altogether these countries covered more than 60% of the total number of inventions protected internationally. European countries – namely Germany, France, the Netherlands and the United Kingdom – followed, covering 17% of the total, with about 26% of their inventions protected in patent jurisdictions outside European borders.

China was not among the very top countries protecting inventions internationally: only 1% of Chinese inventions were protected this way, with these representing 3% of total international inventions related to hydrogen (electrolysers). In contrast, China comes second only to the United States in attracting inventions from other countries: 22% of international inventions are protected in China.

About 14% of international inventions were protected in European patent jurisdictions, with that figure about 6% in the Republic of Korea and Japan, respectively, despite the latter two countries being among the top nations seeking international protection for their inventions.





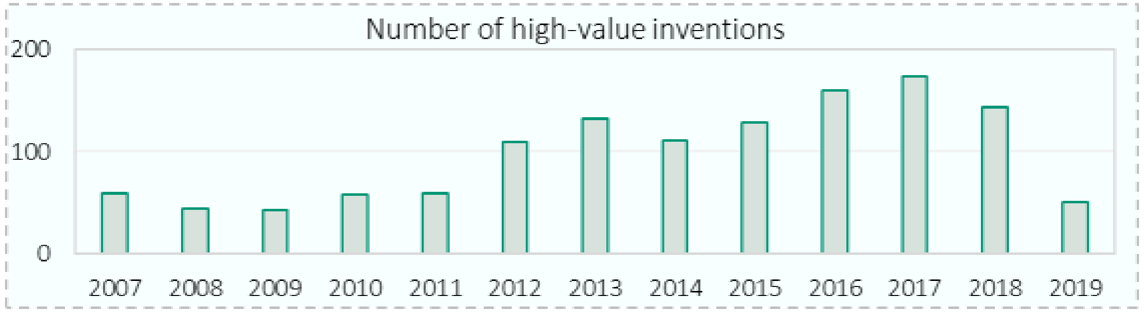
Patents: 3) Patent Families of High Value

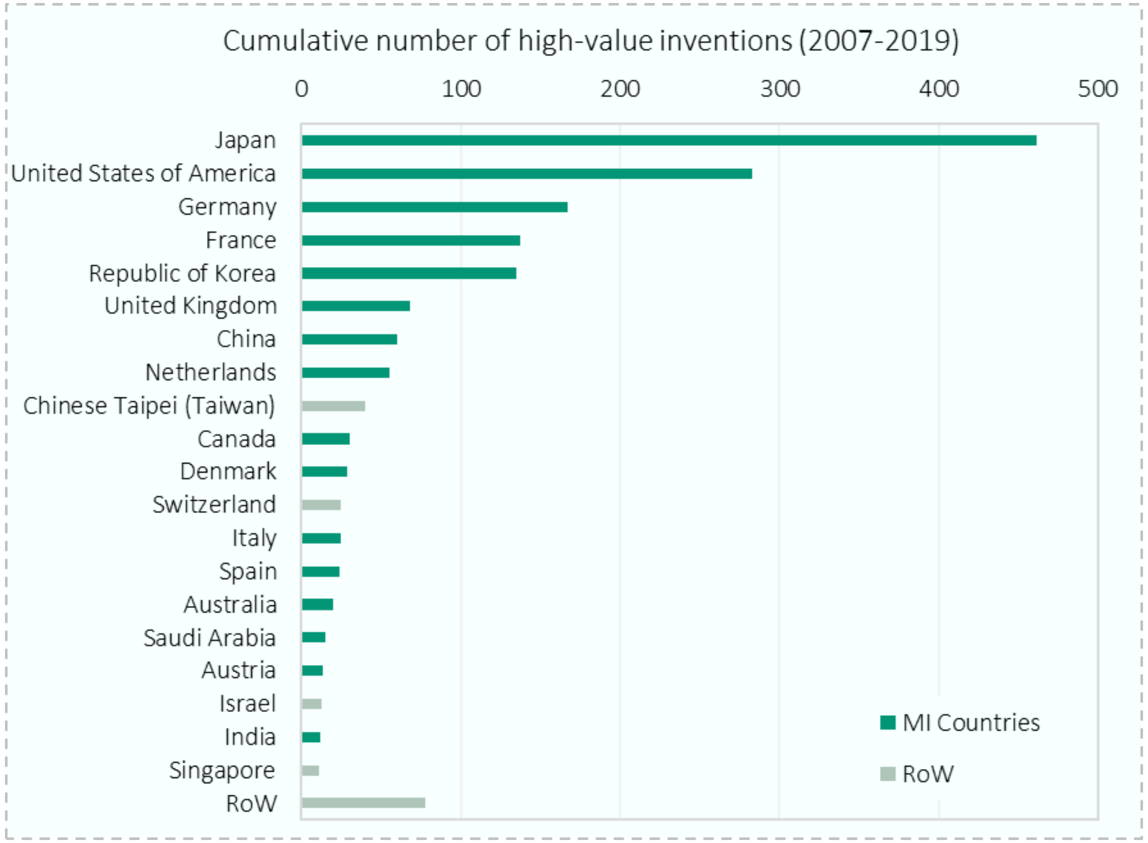
The number of patent families of high value in the area of hydrogen (electrolysers) increased in 2014, following the international invention trend. On average, between 2007 and 2019, 25% of total inventions related to hydrogen (electrolysers) were of high-value.

Japan and the United States were the two leading countries in terms of high-value inventions (31% and 53% of their total inventions, respectively), implying their inventions were protected in more than one country. Germany was third, followed by France, the Republic of Korea and the United Kingdom, with these four together accounting for 26% of total high-value inventions.

Only 2% of the Chinese inventions were of high-value, showing the interest of Chinese patenting companies in protecting their inventions related to hydrogen (electrolysers) domestically, rather than going to international markets. This could have been driven by incentivising mechanisms for domestic patent applications in place in the country.

On average, between 2007 and 2019, European countries had the highest share of high-value inventions among the total number of inventions, with France at 77%, the Netherlands, 70%, the United Kingdom, 63%, and Germany at 61%. This shows the quality of European technological know-how, which easily finds fertile ground in multiple countries.





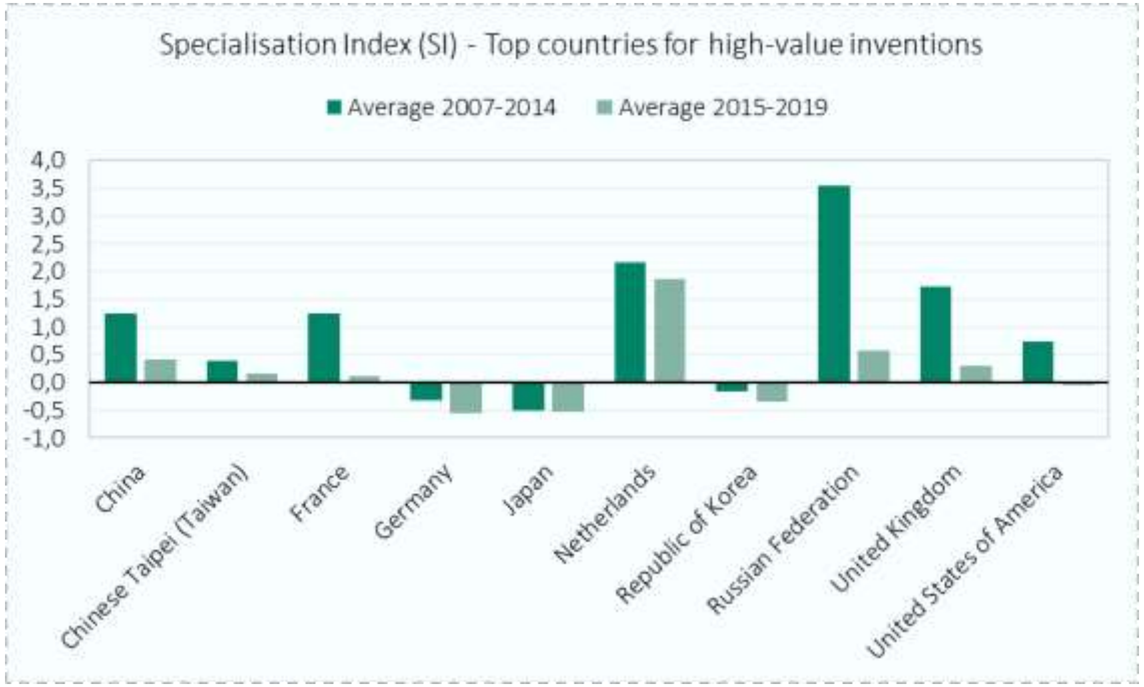
Patents: 4) Specialisation Index (SI)

The Specialisation Index (SI) takes the proportion of a country's total, hydrogen sector-related inventions made by electrolyser inventions and compares it to the global share of electrolyser inventions over the total hydrogen inventions. Inventions related to the entire hydrogen sector are detected via the Y02E60/30 CPC codes (and sub codes), that together define hydrogen energy technologies.

Globally, the share of electrolyser inventions within the hydrogen sector grew from about 5% in 2007 to about 31% in 2019, showing the high level of interest in this area of technology.

On average, between 2007 and 2014, the Russian Federation showed the highest SI, but this level of specialisation then fell drastically in the second period, from 2015 to 2019. The Russian Federation produced around 70% of its total inventions in water electrolysis in the 2007 to 2014 period, with about 37% of these inventions within the hydrogen sector. Globally, this share was 9%, explaining the high Russian SI. But, while the global share of water electrolysis then increased, it fell in the Russian Federation, explaining the subsequent reduction in its country specialisation.

Between 2015 and 2019, the Netherlands had the highest value SI in electrolysers. This value did not fall, compared to the earlier period, in contrast with other countries that experienced drastic reductions. On average, the annual share of electrolyser-related inventions in the hydrogen technology area in the Netherlands was 41 %.



During the period examined, specialisation was rather low in other countries. China, Chinese Taipei, the United Kingdom and the United States dedicated about 20% of their hydrogen-related patenting activity to electrolysers. Germany, Japan and the Republic of Korea had negative SIs, despite being top for the number of patent families in water electrolysis. This indicated that the focus on electrolysers in these countries was lower than the global average.

Patents: 5) Knowledge Alliance

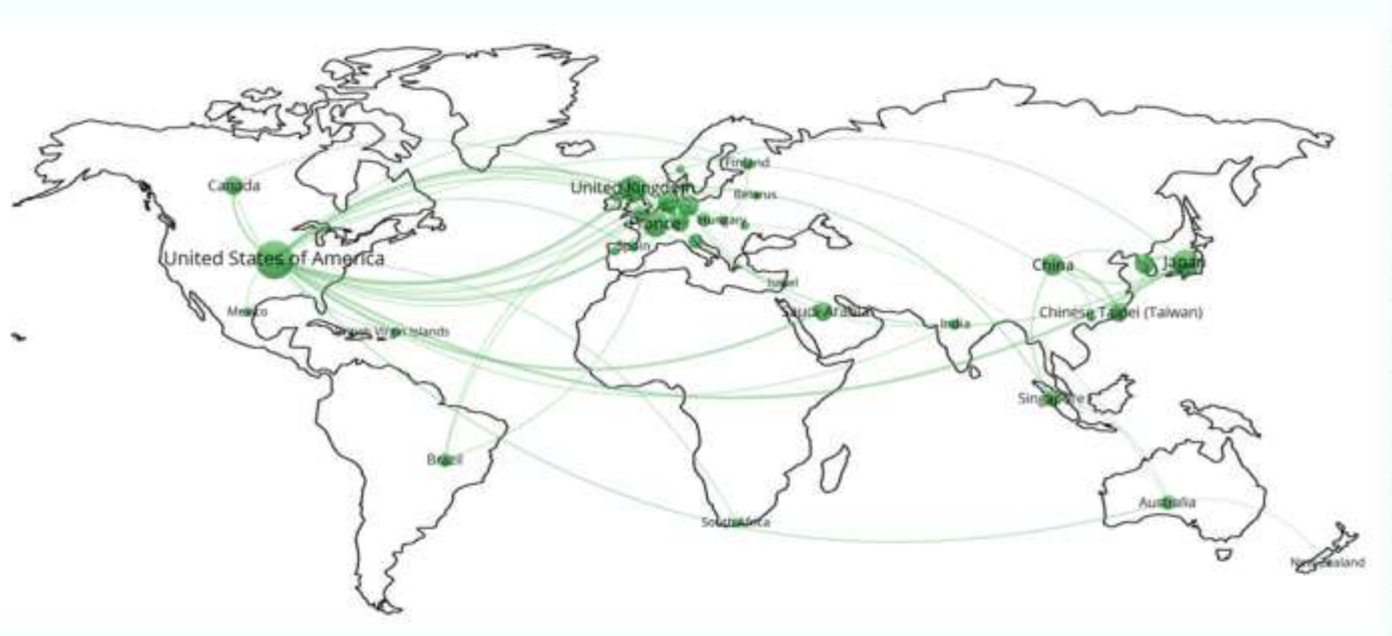
Between 2007 and 2019, about 113 inventions related to hydrogen (electrolysers) were produced, thanks to collaboration between two or more countries.

MI countries were involved in all 55 international alliances; 35 of theses were between two MI countries, with these producing 76% of total co-inventions. The remainder were alliances between MI countries and non-MI countries.

The United States was the network hub for electrolysers; producing the highest number of co-inventions (around 30). It also had the largest number of international ties in this technology area. In total, the United States collaborated with 21 other countries.

The second country, in terms of international links was France, with 9 countries and 9 co-inventions.

International network of co-inventions in electrolysers (2007-2019)



The United Kingdom and Japan had more the 10 co-inventions each, despite having fewer links to other countries (5 and 6 respectively). Japan produced the majority of its co-inventions in alliance with the United States and the Republic of Korea (73% of its total) while the United Kingdom produced the majority with the United States (56% of its total).

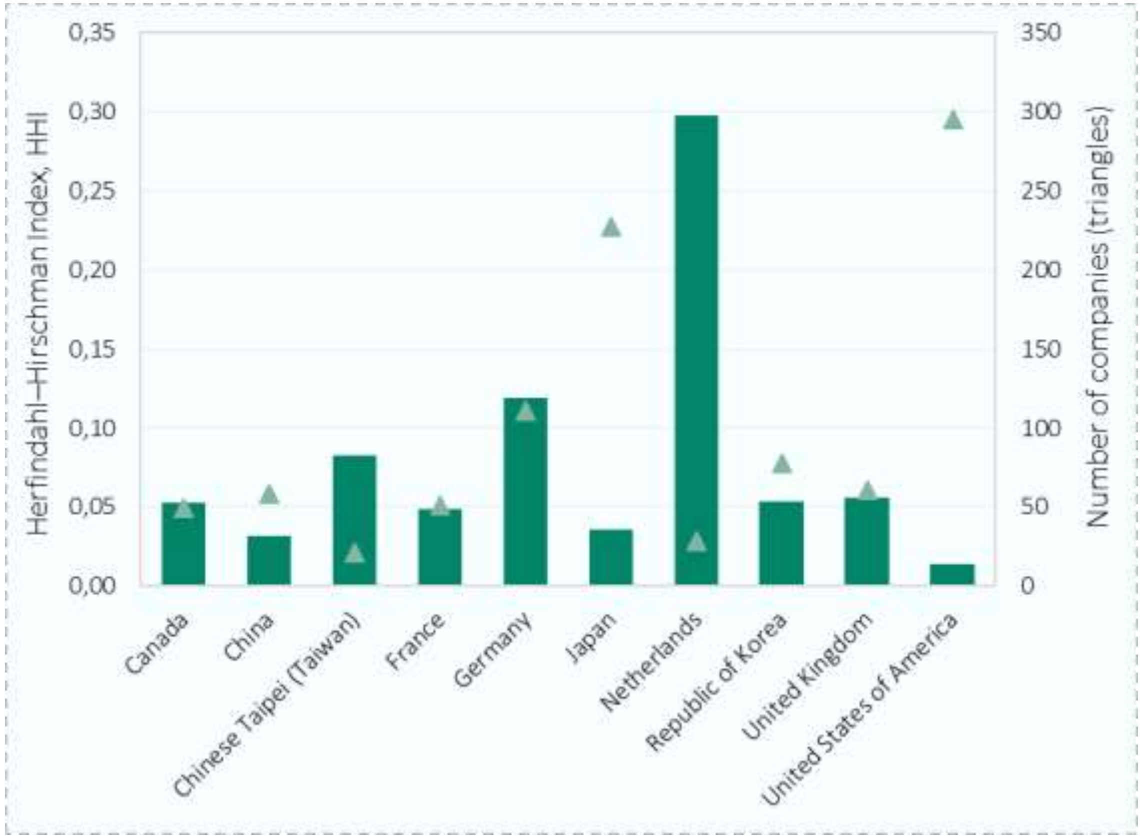
European and Asian countries tended to participate in knowledge alliances with neighbouring countries, indicating the importance of geographical proximity for technology collaboration.

Patents: 6) Companies filing patents per country

Looking at the top 10 countries developing high-value inventions related to electrolysers, the United States and Japan had hundreds of companies that were active in this field (295 and 277 respectively). All the other countries, average around 50 companies each (right axis in the adjacent figure).

As mentioned above, the HHI measures the level of market concentration in a country. As it moves towards 1, it indicates an increasingly monopolised market, ultimately in which one company covers the entire production of patents (left axis in the figure).

On this scale, the Netherlands, with an HHI of 0.30, had the most concentrated market among the top countries. There, 53% of inventions related to electrolysers were produced by just one company. In other countries, the market related to electrolysers was not very concentrated, with an HHI average of around 0.05.

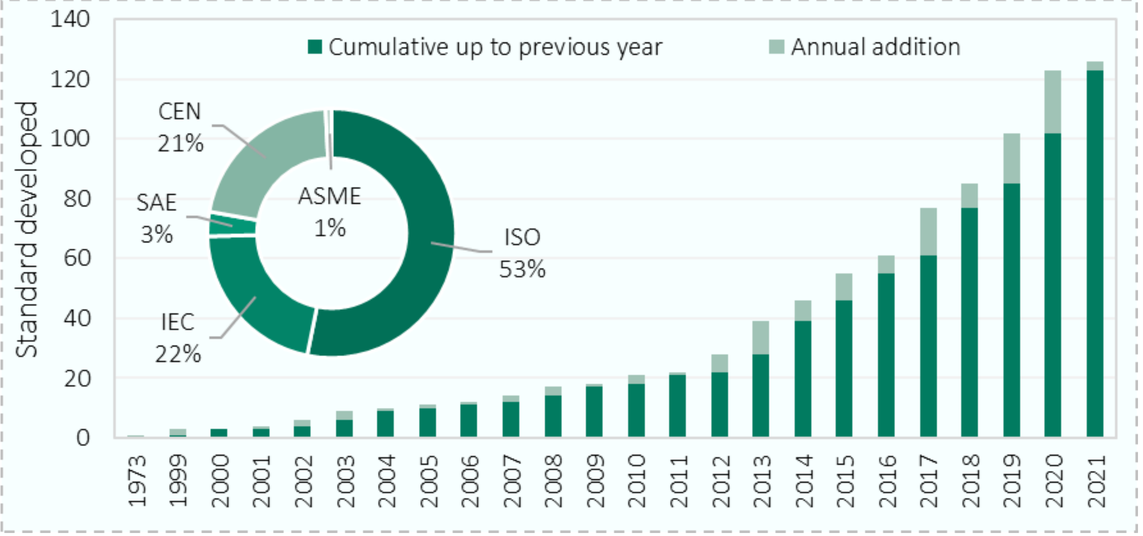


Standards: 1) Number of international standards

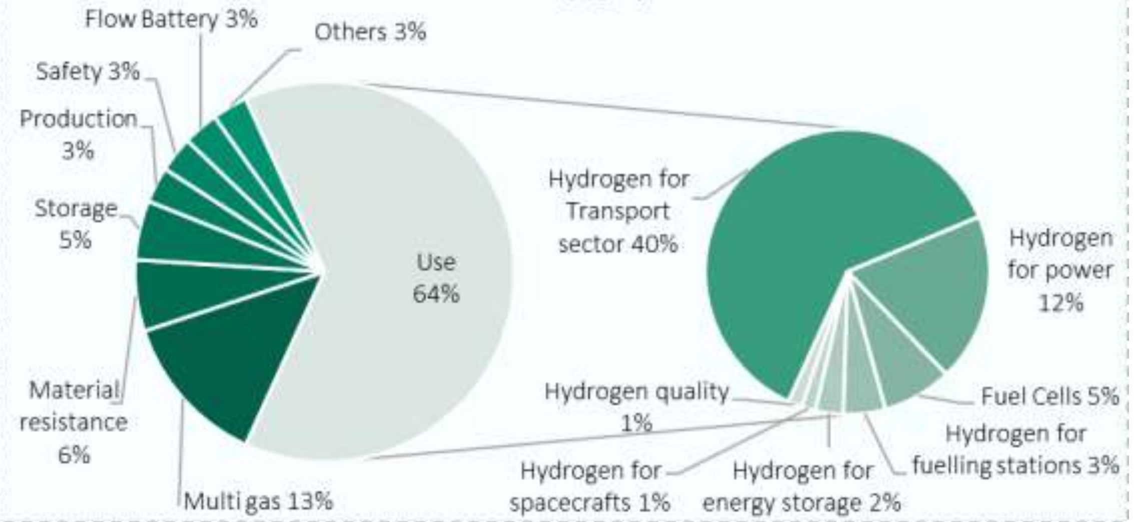
To conduct our analysis of international standards for hydrogen (electrolysers) and to map emerging trends to the maximum extent possible, we consulted both international and regional organisations. Some 78% of total published standards are accounted for by three international bodies – namely, the International Standard Organisation (ISO), the International Electrotechnical Commission (IEC) and the Society of Automotive Engineers (SAE). The remaining standards are from two regional bodies: the European Committee for Standardisation (CEN) and the American Society of Mechanical Engineers (ASME).

More than half of the standards surveyed were added in the last five years of the analysis period (2017 to 2021). Considering the time lag between a standard being proposed and its publication, this trend strongly coincides with the establishment of the most active committees, in 1990, 1996 and 2014. Such a steep increase in the publication of standards in the last decade illustrates hydrogen's growing momentum in the energy sector.

Most of the published international standards on hydrogen are dedicated to its usage. The diverse applicability of such standards, however, makes it impossible to differentiate between blue, green, grey or other types of hydrogen. Some 62% of the standards on the use of hydrogen (that is about 40% of the total) are dedicated to transport sector applications, such as cars, lorries, and 2- and 3-wheelers.



Breakdown of international standards on hydrogen (left), and focus on use (right)



Standards: 2) New Standards Under Development

There are currently 44 new international standards under development. Out of these, 16 standards are completely new, while the remaining are new editions of existing standards. Out of 44 standards under development, the vast majority relate to hydrogen use, with only a few standards covering other stages of the hydrogen life cycle.

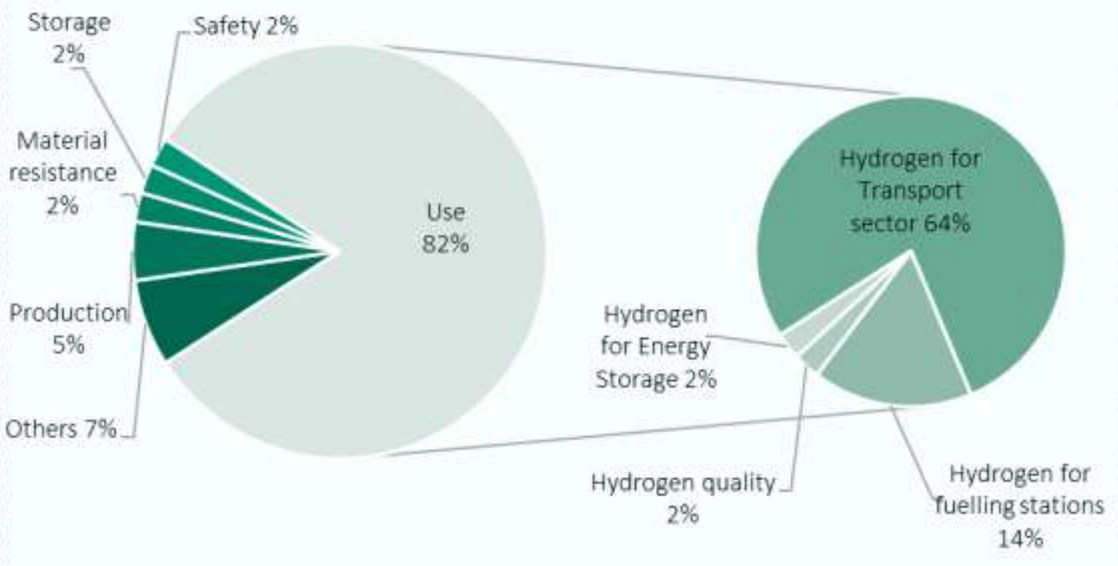
These standards (exception for those in the production of hydrogen) do not differentiate between green, grey, blue and other types of standards. The same trend was seen under the published standards.

Concerning the standard on green hydrogen, ISO 22734 covers its production through water electrolysis. This standard is currently being reviewed and separated into two parts – one covering general requirements and the other covering the testing procedure for performing electricity grid services.

The standards under development on the use of hydrogen cover mostly transport use (64%), followed by hydrogen for fuelling stations (14%). Standards on hydrogen for energy storage and hydrogen quality represent only a small fraction of the standards under development (2% each).

Finally, there are currently seven standards under development at the regional level, all of them being developed by CEN. A breakdown of these standards reveals that the majority (71%) are dedicated to a range of gases, while 29% cover hydrogen use specifically. PrEN 16325 is a revised standard that establishes guarantees of origin of electricity from all sources, including hydrogen.

Breakdown of international standards on hydrogen under development (left), and focus on hydrogen use (right)



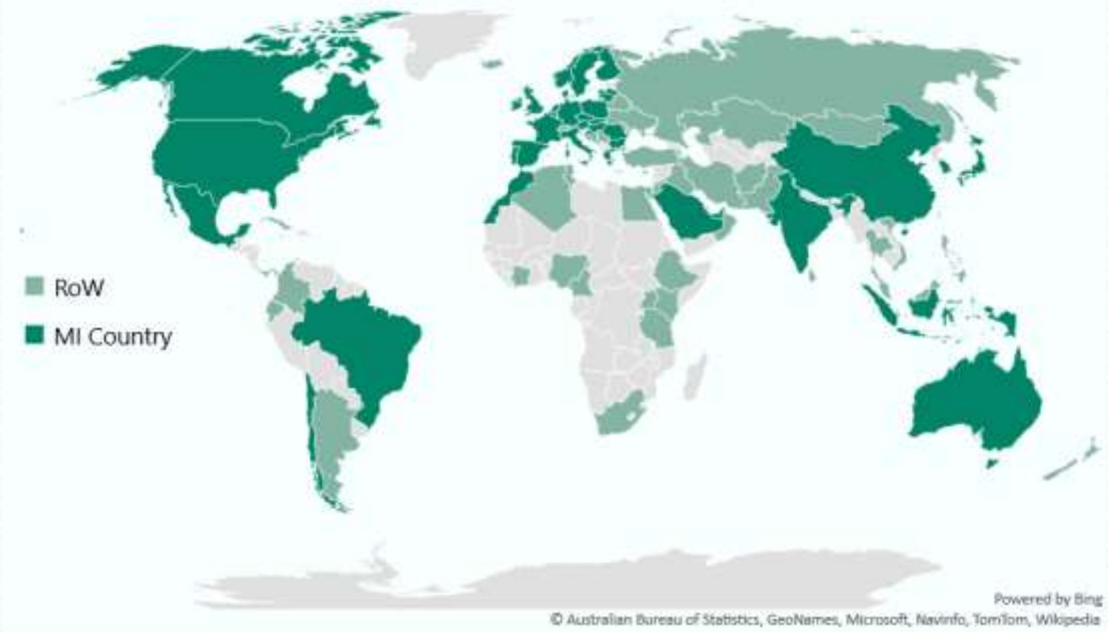
Standards: 3) Countries Developing Standards (1/2)

ISO standards are the most representative of international standards on hydrogen, with this organisation currently including 14 active committees and sub-committees. These standards cover various aspects of hydrogen, including its production, storage, multiple uses, safety, multi-gas, etc. Fuel cell technology as an electrical device is then covered by the IEC, which is represented by 1 technical committee.

The most active committees on hydrogen are Technical Committee 197, which covers hydrogen technologies, and Technical Committee 22, which covers road transport. Two sub-committees are also very active: Sub-committee 37 covers electrically propelled vehicles and Sub-committee 41 covers specific aspects for gaseous fuels. These 3 committees are responsible for 47 standards, amounting to 69% of all standards under ISO and 50% of all standards on hydrogen and fuel cells. The remaining standards are covered by ISO technical committees developing standards on, amongst others, surface coating, space systems and operations, copper and copper alloys, steel, gas cylinders, plastic pipes and fittings for the supply of gaseous fuels, valves, the corrosion of metals and alloys, analysis of gases, and gas turbines.

The ISO's 14 committees and sub-committees engage 92 countries, including all the MI countries. MI countries – namely Canada, China, France, Germany, Italy, the Netherlands, the United Kingdom and the United States – chair one or more technical committees or sub-committees. Out of those 92 countries, 22% participate in 1 technical committee or sub-committee, while 11% participate in all 14 committees or sub-committees.

Geographical distribution of countries participating in ISO standards development in hydrogen in 2021



Standards: 3) Countries Developing Standards (2/2)

ISO TC 197 on hydrogen technologies, chaired by Canada, focuses on systems and devices for the production, storage, transport, and use of hydrogen. Since 1990 its membership has grown from 2 countries to 39 countries, 26 of which are MI countries. Chile, Morocco, the Kingdom of Saudi Arabia and the United Arab Emirates are not members, despite their strong national hydrogen strategy focus.

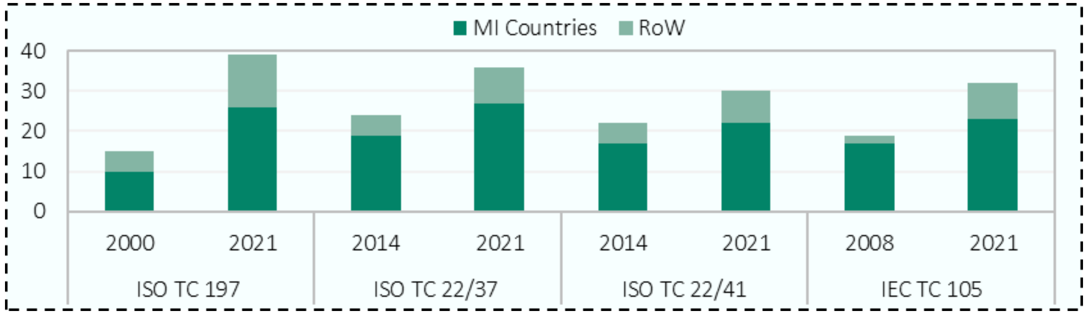
ISO TC 22/37 on electrically propelled vehicles, chaired by Germany, focuses on specific aspects of electrically propelled road vehicles, electric propulsion systems, related components and their vehicle integration. Since 2014, its membership has grown from 24 to 36, 27 of which are MI countries. Brazil, Chile, Morocco, Norway, and the United Arab Emirates are not members.

ISO TC 22/ 41 on the specific aspects for gaseous fuels, chaired by Italy, focuses on the construction, installation and testing of components for vehicles using gaseous fuels, including their assemblies and the interface with refuelling systems. Since 2014, its membership has grown from 22 to 30, out of which 22 are MI countries. Australia, Brazil, Chile, Denmark, Finland, Morocco, the Kingdom of Saudi Arabia, Norway and the United Arab Emirates are not members.

IEC TC 105 on fuel cells, chaired by Germany, focuses on all types of fuel cells and associated applications and co-ordinates its work with ISO TC 22. Since 2008, its membership has grown from 19 to 32 members, 23 of which are MI countries. Chile, India, Saudi Arabia, and the United Arab Emirates are not members.

Country (MI highlighted)	ISO TC 197	ISO TC 22/37	ISO TC 22/41	IEC TC 105
Argentina	✓	✓	✓	✗
Australia	✓	✓	✗	✓
Austria	✓	✓	✓	✓
Belgium	✓	✓	✓	✓
Brazil	✓	✗	✗	✓
Canada	✓	✓	✓	✓
China	✓	✓	✓	✓
Croatia	✗	✓	✓	✗
Czech Republic	✓	✓	✓	✓
Denmark	✓	✓	✗	✓
Egypt	✓	✓	✓	✓
Ethiopia	✗	✗	✓	✗
Finland	✓	✓	✗	✓
France	✓	✓	✓	✓
Germany	✓	✓	✓	✓
Hong Kong	✓	✗	✗	✗
Hungary	✓	✓	✓	✗
India	✓	✓	✓	✗
Indonesia	✗	✓	✗	✗
Iran, Islamic Republic of	✓	✗	✓	✓
Ireland	✓	✓	✗	✗
Israel	✓	✓	✗	✓
Italy	✓	✓	✓	✓

Country (MI highlighted)	ISO TC 197	ISO TC 22/37	ISO TC 22/41	IEC TC 105
Japan	✓	✓	✓	✓
Korea, Republic of	✓	✓	✓	✓
Netherlands	✓	✓	✓	✓
New Zealand	✓	✗	✓	✗
Norway	✓	✗	✗	✓
Poland	✓	✓	✓	✓
Portugal	✓	✓	✓	✓
Romania	✓	✓	✓	✓
Russian Federation	✓	✓	✗	✓
Saudi Arabia	✗	✓	✗	✗
Serbia	✓	✗	✗	✓
Singapore	✗	✓	✗	✗
Slovakia	✗	✓	✓	✗
South Africa	✗	✓	✓	✓
Spain	✓	✓	✓	✓
Sri Lanka	✓	✗	✗	✗
Sweden	✓	✓	✓	✓
Switzerland	✓	✓	✗	✓
Thailand	✓	✗	✗	✓
Turkey	✓	✗	✓	✓
Ukraine	✓	✓	✓	✗
United Kingdom	✓	✓	✓	✓
United States	✓	✓	✓	✓

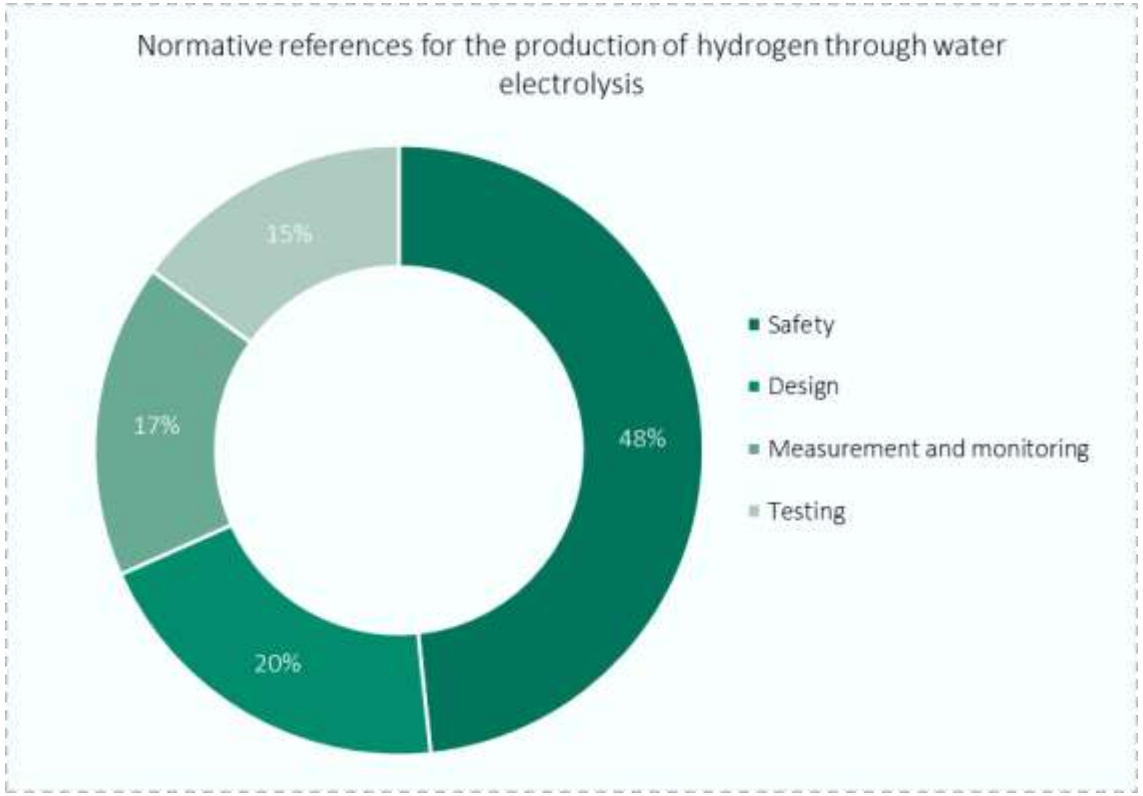


Standards: 5) Normative References

International technical standards under ISO or IEC on hydrogen have relied upon international standards developed for other technologies and appliances, across different sectors.

Normative references for the production of hydrogen through water electrolysis relate to safety measures for around 48% of the total. These are followed by design requirements (20%), measurement and monitoring (17%), and testing (15%).

Safety measures look at safety during installation, and the avoidance of explosions, fires and electrical shocks, in particular; references to design category mostly covered gas cylinders made from various materials, while measurement and monitoring is mostly related to gas and fluid flows in close conduits and testing to environmental standards.



Limitations posed by patents and standards indicators

Despite the numerous insights derived from **patent** data and the importance they have in the technology innovation cycle, patent indicators have some limitations.

Patents may not reflect actual innovations, as not all of these are patented and/or patentable, commercialised and used. Therefore, it is necessary to develop different metrics to gather insights from patent data and to look at different aspects of the innovation cycle. Not all patents necessarily reflect innovative inventions, either, and instead, may have been developed only as a defensive market strategy aimed at protecting existing inventions from imitation, with no further interest in their commercialisation.

Countries and regions also vary in their patenting approach and propensity, with the data are in a way biased towards industrialised countries. Furthermore, the use of patents is tracked by licenses, which provide information on the extent to which companies transform RD&D investment into innovative outputs and protect that investment. Licensing creates new business opportunities, facilitates easier entry into foreign markets and offers the freedom to develop a unique marketing approach. This indicator is impossible to track, however, due to their being no obligations for countries to report licensing.

Tracking emerging technologies with patent data is also challenging. For instance, patent activities often cover both onshore and offshore wind, making it difficult to define clear boundaries and distinctions between the two. Such lack of distinction also occurs in relation to the development of hydrogen-related components.

At the same time, while international **standards** do provide insights into the status of technologies, they also come with limitations.

Historical data availability hinders the possibility of capturing an actual trend by identifying countries that have taken part in standards development. The same applies to the identification of countries adopting standards, as there is no requirement to disclose such information.

Standards development does not start automatically, either, but is a direct response to a request from the industry and/or consumer organisations, demonstrating the market’s needs. This development is a lengthy process, requiring a considerable amount of time from the start of development to the publishing of a new international standard.

Observation from patent and standard indicators (1/3)

The set of patent and standard indicators analysed gives an insightful picture of the status of two emerging technologies: offshore wind and electrolysers. Great achievements have already been accomplished, but continuous effort is required to further develop these two technologies, which are pivotal in accelerating energy transitions and decarbonising our economies.

By tracking innovation metrics, it is possible to see that the development of offshore wind and electrolysers are at different stages of maturity.

For **offshore wind**, invention activity shows two peaks – one around 2012, followed by a decline, and the second in 2018, which due to data lags, may be continuing. This indicator may need to be contrasted against other policy and industry events that occurred during the periods 2007 to 2012 and 2013 until today in order to understand the causes of these trends. One example is the outcome of climate negotiations, which slowed down development, but which were then followed by new innovations. These have driven cost reduction over the last decades, helping the technology explore alternative offshore installation options (at greater distance from the coast and in deeper water), which then achieved high capacity factors.

Interest in green hydrogen, and in **water electrolysis** in particular, is more recent. The rapid grow of inventions after 2012 is in line with the widespread implementation of national energy plans based on the diffusion of green hydrogen technology. Compared to offshore wind inventions, which still cover a smaller share of the entire wind sector, in which many components are used both onshore and offshore, the development of electrolysers is gaining momentum. This development is emerging as enabling technology for greening the production of hydrogen and, in turn, decarbonising energy intensive industries.

International standards show which countries are interested in leading the global commercialisation of a technology. There is greater participation of countries in technical committees related to hydrogen than for wind. Nonetheless, in both hydrogen and wind technology, the number of countries involved in technical committees, as well as the number of new standards developed, has increased over time. The steep increase of new standards related to hydrogen and wind from 2012 indicates growing attention to these technologies from industry.

The analysis of normative references indicates cross-sectoral links, as in the case of offshore wind that benefits from knowledge related to the offshore oil and gas sector. New standards under development indicate the emerging technology trends in offshore wind that are now focusing on the design of floating foundations.

Observation from patent and standard indicators (2/3)

The use of patents requires a higher degree of analysis, since the single number of patents filed over time, or by particular countries, only offers part of the picture, when it comes to the level of inventive activity in a specific area of technology. For example, when the number of **patent families** is monitored, it emerges that China, Japan and the Republic of Korea are the leading countries for both offshore wind and electrolysers. The picture changes, however, when patent data are used to detect the value of inventions and their degree of **internationalisation**.

For offshore wind, European countries are leading in terms of high-value inventions and have an international approach to patenting. By contrasting these indicators with offshore wind deployment, where the offshore wind market is mainly based in Europe, it is possible to identify countries with inventions that have a real impact on global markets.

Likewise, country rankings change once again when we look at their level of patent **specialisation**. For example, Norway and the Netherlands emerge as the most specialised countries in offshore wind. Knowing the national technology capability of these two countries, we can deduce the positive spill-over effect their specialised knowledge has on onshore wind (the Netherlands) and on the offshore oil and gas industry (Norway).

The specialisation metric also shows the recent development of the offshore wind industry in the Republic of Korea and Spain. In contrast, countries like Germany and Denmark, which lead inventive activity in offshore wind, are not very specialised, since their focus is more on other areas of the wind industry.

For electrolysers, patent data also show a different picture when related indicators are analysed under a different perspective. The case of Japan is highly representative, with it being one of the first countries to define a detailed hydrogen road map – already in place since the beginning of this century. On the one hand, Japan leads both high-value and international patenting activity, but, on the other, Japan's electrolysers specialisation level in the hydrogen area is less than in other top countries.

The **knowledge alliances** metric may give us indications of where the hubs are in a technology's development. In the case of offshore wind, such a hub is clearly located in Europe, where pioneering companies produce new technologies that are also installed in coastal regions. The United States is the most connected country for electrolysers, however, having links to almost all the countries active in developing new inventions in this field.

Observation from patent and standard indicators (3/3)

Both technologies have benefitted from existing **standards** on wind and hydrogen, which may have contributed to their deployment.

For **offshore wind technology**, the first standard, published in 2004, applies to the design of both onshore and offshore wind turbines. Since then, 32 standards have been published. The first standard solely applicable to offshore wind was published in 2012 and there are now 6 standards for offshore or floating wind turbines. As differences between onshore and offshore wind turbines are limited, offshore wind turbines largely benefitted from onshore wind standards, which has helped the market for offshore wind to mature faster.

Hydrogen standards have followed a similar pathway. Currently, 126 standards on hydrogen and fuel cells cover production, transport, storage, and use, along with cross-cutting issues, including safety. But only 4 standards on the production of hydrogen differentiate between green hydrogen from water electrolysis and other types. The only standard for the production of green hydrogen was published in 2019. Following new technological knowledge, this standard is currently being revised and will be separated into several standards covering different aspects in more detail. The remaining 122 standards focus on the other parts of the value chain, with the first standard published in 1999 and covering the transport and storage of hydrogen. These existing standards have paved the way for green hydrogen to scale up, once the production of hydrogen reaches commercialisation.

Development of these standards has been driven by MI countries – the Europeans, Canada, China and the United States. Forty countries are engaged in wind standards development, and 46 in hydrogen. Denmark leads standards development for wind technologies, while hydrogen standardisation work is spread across several committees. It is being led by Canada, China, France, Germany, Italy, the Netherlands, the United Kingdom and the United States. This indicates these countries' leadership in knowledge and technical capabilities. All these countries have also adopted enabling measures, including policies and regulations, support for RD&D and deployment activities. Countries with strong hydrogen strategies, such as Chile, Morocco, the Kingdom of Saudi Arabia, or the United Arab Emirates are frequently not engaged, however.

Normative references shed light on innovations and best practices from the same or different technologies and industries, allowing spill-over of knowledge to enhance broader deployment of the technology. For wind energy technologies, almost half the normative references come from the oil and gas industry, followed by those from environmental standards. For green hydrogen production, normative references exist on safety, design, measurement, monitoring and testing.

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PART III
Offshore wind as a case study

This part of the work was carried out in concert with the Innovation Impacts Dashboard (IID) project, funded by the government of the United Kingdom, which concluded in April 2021.

The objective was to develop and pilot a methodology that would analyse the progress of innovative energy technologies by bringing a very wide range of indicators together, relying on data gathered in both projects.

The aim was to provide additional qualitative and quantitative insights into ways in which innovative energy technologies were making progress either fully, or in part, due to RD&D activities.

To explore the value of the approach, the methodology was piloted in **offshore wind technology**. The pilot looked at progress globally, with some insights into the Mission Innovation (MI) countries, including European Union (EU) member states, during the period 2010 to 2019.

The choice of offshore wind was based on the technology's rapid maturation, which has undergone **significant developments** in the past decade and is poised to play an important role in future energy systems.

The case study on offshore wind does come with **caveats**. Progress in offshore wind technology is driven by many factors, of which RD&D is only one. Factors that are hard to measure and/or that affect several technologies simultaneously – such as the impacts of wider systemic innovation, dependencies on supply chain and critical materials, and market dynamics – are excluded from this case study.

The approach explored does not currently address RD&D policies or inputs (*e.g.* RD&D funding), nor does it attempt to prove a causal link between progress made and those RD&D inputs or policies. Instead, it highlights where RD&D may have contributed.

Findings are based on the data accessible in the project time frame, with the data gathering approach thorough, but not exhaustive. Follow-on work will focus on exploring and refining some of those factors.

The indicators also come with specific limitations and the pilot does not aim to present the state-of-the-art in offshore wind technology and industry, nor critique it. Rather, it offers an approach to measuring and understanding progress in offshore wind technology and what this means for RD&D, in order to inform policy makers.

The main outputs of the case study giving initial insights are an online dashboard and the case study '[Tracking the impacts of innovation: Offshore wind as a case study]'. The online [dashboard] provides a visual presentation of indicators, showcasing trends and the geographical distribution of activities in offshore wind technology in the period 2010 to 2019, with some exceptions of shorter and longer periods. The case study accompanies the dashboard and presents the results and discusses the insights and perspectives gained.

Indicators and Innovation Impacts

Clean energy technology innovation – particularly RD&D – plays a critical role in accelerating global energy transition. As this transition progresses and ambitions grow, the need for strong government support for innovation grows alongside it.

Government support mechanisms can include RD&D funding, market instruments, and policies that guide and encourage innovation activities. The purpose of these 'inputs' is to lead to 'outputs' (*i.e.* new or improved technologies, processes and systems) and ultimately 'outcomes' (*i.e.* positive changes in energy systems, such as reductions in CO_2 emissions), with both being grouped as 'impacts'.

To avoid using piecemeal indicators and getting only partial views, this approach studies a range of impact indicators to map the progress of technology, in order to bring new perspectives to help stimulate policy debates and uncover new dynamics.

The approach identifies over 50 indicators and groups them under 3 impact categories of outputs and outcomes that innovation support mechanisms seek to deliver: innovation ecosystem, technology progress and market formation.

Some of the indicators are generic and are applicable to the majority of energy technologies, while others are technology-specific and applicable to offshore wind. The latter is particularly so for indicators under the 'technology progress' category.

The indicators are categorised based on their contribution to policy and strategic objectives, and the order of categories follows the innovation lifecycle.

Due to data availability, the pilot study gathered data for 30 indicators. Most of these were collected under the TEIIF project, while some were collected under the IID project, and others were readily available in IRENA databases. The remaining data was provided by external providers free of charge.

Overall, there has been significant progress in all categories, which in turn increases confidence in the market, unlocking further investments. Despite the progress made, however, the sector needs to continue to innovate, collaborate and harmonise to broaden use, harness wind potential in deeper waters farther from the shore and further reduce costs.

The case study also presents several other indicators as a way to further improve the analysis. These indicators were not added to the case study, however, due to lack of availability or difficulties in gathering data, but can be considered for future work.

Innovation Ecosystem Indicators and Gained Insights

This category encompasses eight indicators under two sub-categories: the state of knowledge development, codification and dissemination; and the state of awareness and collaboration among various actors, public and private, national and international. This group of indicators offers insights into the degree and breadth of activity in the innovation ecosystem.

Scientific publications and their citations, various patent indicators and RD&D collaboration are considered core output in RD&D activities, while international events are a less direct indicator. The latter were included, however, as they offer some insights into how the innovation ecosystem is changing. In particular, the analysis focused on the trends and geographical distribution of MI and EU countries across these indicators and their trends, over the years.

KNOWLEDGE	AWARENESS & COLLABORATION
• Scientific publications • Joint scientific publications • Citation of scientific publications • Citation of joint publications • Web 2.0 citation of publications • Web 2.0 citation of joint publications • Patents filed • Patents filed internationally • Patents of high value • Patents specialisation index • Filing patents by companies per country • Citation of patents	• RD&D collaboration • Membership in industry associations • International conference & events • Co-inventions between countries • Data mining on awareness on technology across web

The innovation ecosystem showed healthy, continual progress, allowing innovations to develop and be adopted. It was enabled by the public and private innovation support mechanisms already in place. The growth of the indicators in this category and their broadening was a positive sign of technological progress, whilst stagnation or consistent falls in these indicators would have called for a re-evaluation of policy, including on innovation support mechanisms.

A HEALTHY AND BROADENING INNOVATION ECOSYSTEM

Active and broadening research base	Active private and public sectors seeking commercialisation of their intellectual property	Active and growing RD&D collaboration between private and public sector organisations
• The number of technology related **scientific publications** for offshore wind **increased 2.5 times** between 2010-2019, with **over 88 000 citations** during the same period. • The large global increase was mainly due to a five-fold **increase from China.** Publication rates **plateaued**, but have persisted **in established markets** (the United States of America (USA), the UK, Germany, Denmark, Norway, Japan and the Republic of Korea), while continuing to grow with a **3.5-fold increase in new markets** across countries in Europe, Asia, Latin and North America, **broadening the geographical offshore wind research base.**	• **Patents** for offshore wind **increased by 60%** from 2010 2017. • **China's** inventions (patent families) grew exponentially, **from 2 to 63** during this period. **Japan** and the Republic of **Korea** produced almost **20%** of the inventions in 2017. • Established markets in Asia (China, Japan and the Republic of Korea) and Europe (France and Germany) were **responsible for 90% of patenting activity in 2017.**	• Offshore wind **RD&D collaborations** grew **fourfold** from 2010 to 2019. • **National** collaborations increased between 2015 2019, while **international collaborations** were prevalent between 2010-2015. This suggests **RD&D is moving into higher technology readiness levels (TRLs)** and the market is maturing. • Almost **60 international offshore wind conferences and events** took place between 2010-2019, with over **55% taking place regularly**, either annually or biennially (China, the USA, Poland, Germany, EU level).

Technology Progress Indicators and Insights

This category encompasses 14 indicators under 3 sub-categories. The latter are: cost reduction, diversity of project characteristics, and technology performance improvements.

This group of indicators offers insights into the ways clean energy technology innovation works to reduce costs, improve performance, generate higher energy yields and, in turn, reduce electricity prices from offshore wind.

These early insights show that in offshore wind technology, both breakthrough and incremental innovations could be seen in the past decade. They also show that the decline in the costing metrics and increase in capacity factors could be attributed to the combination of learning-by-RD&D, learning-by-doing, and economies of scale. The relative scale of these factors, however, is harder to calculate.

COST	PROJECT CHARACTERISTICS	PERFORMANCE

• Total installed costs
• O&M
• LCOE
• Cost competitiveness ratio
	• Water depth
	• Distance from the shore
	• Average turbine size
	• Foundation type
	• Installation time of foundations
	• Number of installations vessels
	• Number of HVDC projects
		• Capacity factor:
		  • Nameplate capacity
		  • Hub height
		  • Rotor diameter
		  • Turbine rating
		• Average downtime per turbine per year

RD&D activities included a range of projects, from diversity in foundation designs, to the ability to go further from shore and into deeper waters. They also saw projects looking at tapping higher wind speeds at greater heights and generating more power using larger rotor diameters. These RD&D activities need to continue to ensure broad global deployment.

TECHNOLOGY DEVELOPMENT IN THE FORM OF DECLINING COSTS, IMPROVED TECHNOLOGY PERFORMANCE AND A WIDENING RANGE OF SOLUTIONS.		
Costs continued to decline	Technological performance improved	Innovative solutions brought diversity and continued to reach different geological conditions
• Overall **installed costs declined by 28%** between 2015 and 2019, but cost volatility is still present due to immaturity of the market. • **Levelised cost of electricity (LCOE) dropped by 32%**, from USD 0.169/kilowatt hour (kWh) in 2010 to **USD 0.115/kWh** in 2019. • Cost declines were **driven by learning-by-RD&D, learning-by-doing and economies of scale.**	• The **capacity factor** increased by 18%, **reaching 44%** in 2019. • Capacity factor improvements were in large part **driven by RD&D activities** contributing to **technology improvements**, including the hub height of offshore wind turbines – which grew by 30% – the rotor diameter of offshore wind turbines – which grew by 40% – and by turbines doubling in size.	• Offshore wind projects reached deeper and more **distant waters, with distance from the shore growing almost threefold.** • Over 80% of all offshore wind foundations were monopile, due to their price and ease of use. To address various seabed conditions, water depths, and differences in manufacturing, installations and operation, a wide range **of foundation types were deployed, enabled by RD&D activities.** • Improvements in the efficiency of offshore wind logistics contributed to increased and faster deployment. RD&D activities contributed to this by, for example, enabling more efficient and specialised **installation vessels** for offshore wind. • To tap potential in **water depths beyond 50 metres**, an **increase in RD&D activities** is needed to improve existing solutions and further explore the suitability of foundations, including **floating foundations.**

Market Formation Indicators and Insights

This category contains 8 indicators and 2 sub-categories: the scale of technology deployment; and the commercialisation of the technology.

This group of indicators comes from the premise that innovation only has an impact if it is deployed. The formation and maturation of a market and the associated enabling conditions for the technology are indirect signs of progress and are influenced by innovation support mechanisms.

The analysis showcases a rapidly growing market with installed capacity and electricity generation increasing every year. The global share of electricity generated from offshore wind in the renewable energy mix still remained very low, however, at only around 1%.

DEPLOYMENT	COMMERCIAL
• Total installed capacity • Total electricity generated • Start-ups • Share of electricity generated by technology in the energy mix • Number of international standards • Countries developing international standards • Countries adopting international standards • New international standards under development	• Certification • Jobs • Trade flows • Licenses applications submitted • Registered trademarks

Even if these deployment metrics belong to the final step of the innovation chain, they are crucially linked to learning-by-RD&D, learning-by-doing and economies of scale. This involves testing technologies in new topographies with higher generation potential that can have a multiplying effect on the deployment levels.

RAPIDLY GROWING MARKETS MOVING TOWARDS MATURITY

Deployment continued to increase	Base of international standards for offshore wind continued to grow	Differentiated products and services led to commercialisation	Strong growth of wind energy exports trade flows
• **Installed capacity** for offshore wind grew more than **ninefold** between 2010-2019, when it reached 28 gigawatts (GW). • **Electricity** generated grew exponentially, from 7.3 terawatt hours (TWh) in 2010 to **68 TWh in 2018.** • In 2018, the share of offshore wind power was **1% of the global renewable energy mix,** up from 0.2% in 2010.	• Countries involved in developing international standards for offshore wind grew from **24** in 2010 to **31** in 2019. • The number of international standards increased from **zero to nine** in the same period.	• The number of registered trademarks for offshore wind grew from **73** in 2010 to **193** in 2015 and then **fell by 55%, to 86,** in 2019 – indicating a shift from the development phase to **commercialisation.**	• Global trade flows in wind energy technology as measured by wind energy exports **doubled** between 2005-2019. • China, Germany and the USA were the largest exporters, while countries like Italy also emerged. In the case of Italy – an onshore wind leader – **RD&D activities and innovation** may have allowed an adaptation of onshore wind technology and an increase in manufacturing capacities.

Indicators Linkages

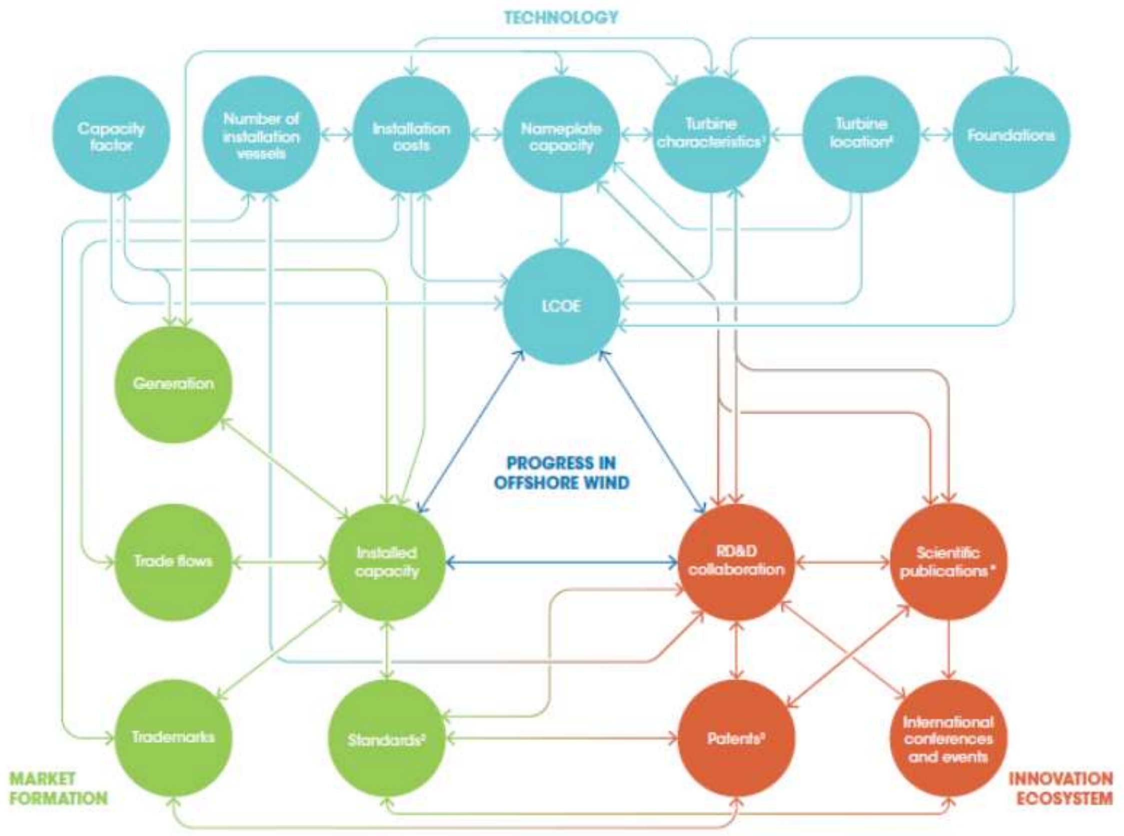
To date, approaches have been largely descriptive and focused on charting the development of technology along the innovation chain by mapping various indicators.

Linkages between indicators, however, help show how interrelated and mutually reinforcing various RD&D activities are in reducing costs and increasing technology deployment.

Linking two or more indicators across the innovation chain could help shed light on the complex picture of innovation performance and related time-lags. It can therefore help identify potential weaknesses and opportunities at different stages.

Linking indicators can also offer insights into which variables may have influenced others and the system's performance as a whole. It can also provide an overview of how technology performance has been influenced and has changed over time at the global and country-level and unveil trends in innovation performance.

Indicator linkages are interesting insights for decision makers, as they help inform the design and formulation of strategies and programmes to better support technology innovation.



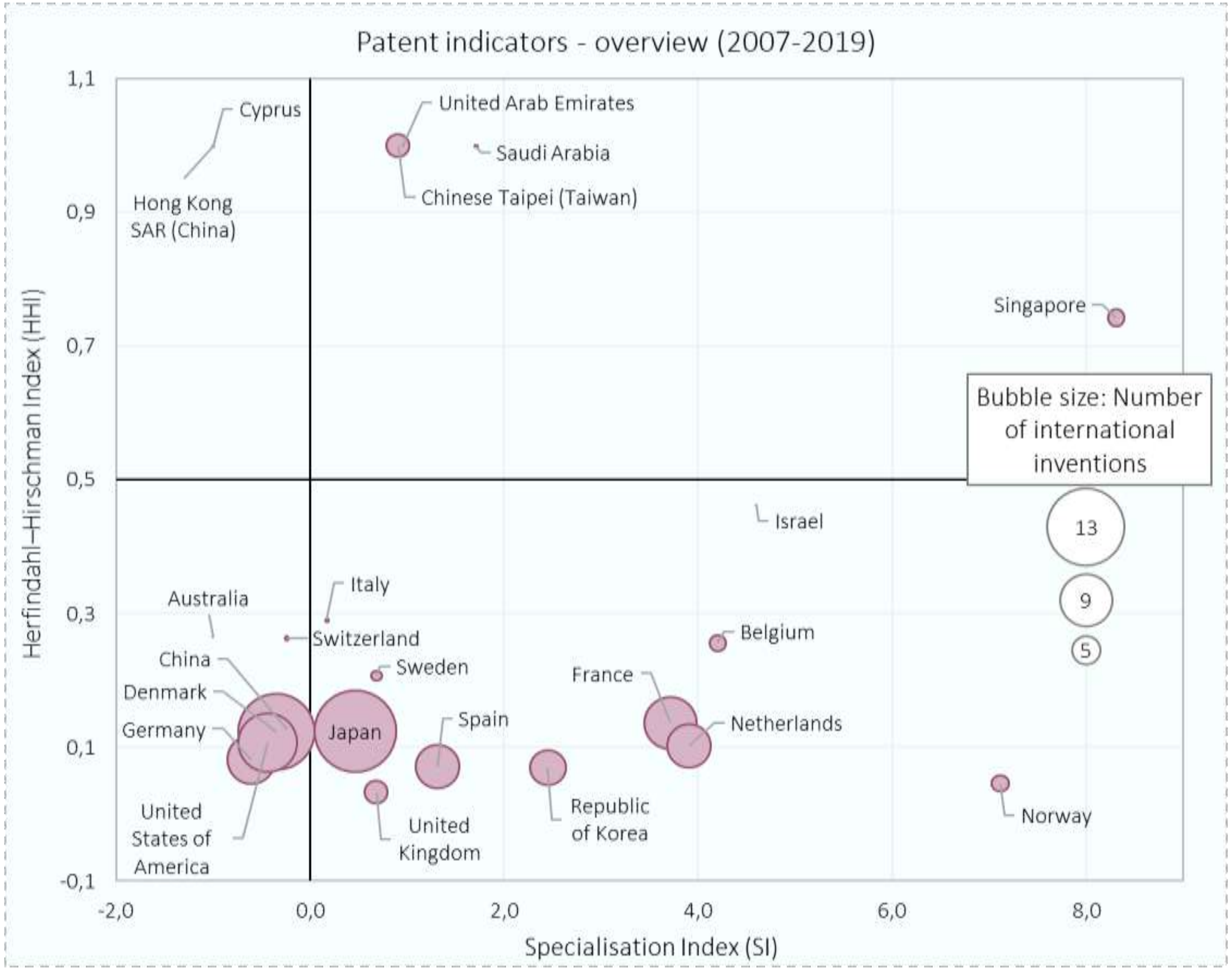
1 Turbine size, hub height, rotar diameter
2 Countries developing and counties adopting standards
3 Patents filed, patents filed internationally, patents of high-value and patents specialization index
4 Distance from shore, water depth

Market and industry

Inventive activity in offshore wind is mostly driven by European countries and their longstanding technology specialisation. Asian countries are catching up quickly, thanks to supportive R&D policies and their knowledge absorptive capacity. Specialised patenting countries also lead technology development.

In the majority of countries, the offshore wind market segment is characterised by low concentration, with a range of actors contributing to the development of innovations. This market condition should be maintained, in order to favour healthy competition and investment to scale-up.

In Europe, the offshore energy industry can be further strengthened in the North Sea. Innovation can drive technology development, enabling installation of large wind farms, built at greater distances from the coast and with bigger and more powerful turbines. Fostering innovation in offshore wind technology is pivotal in meeting the targets for new offshore capacity installed by 2050.



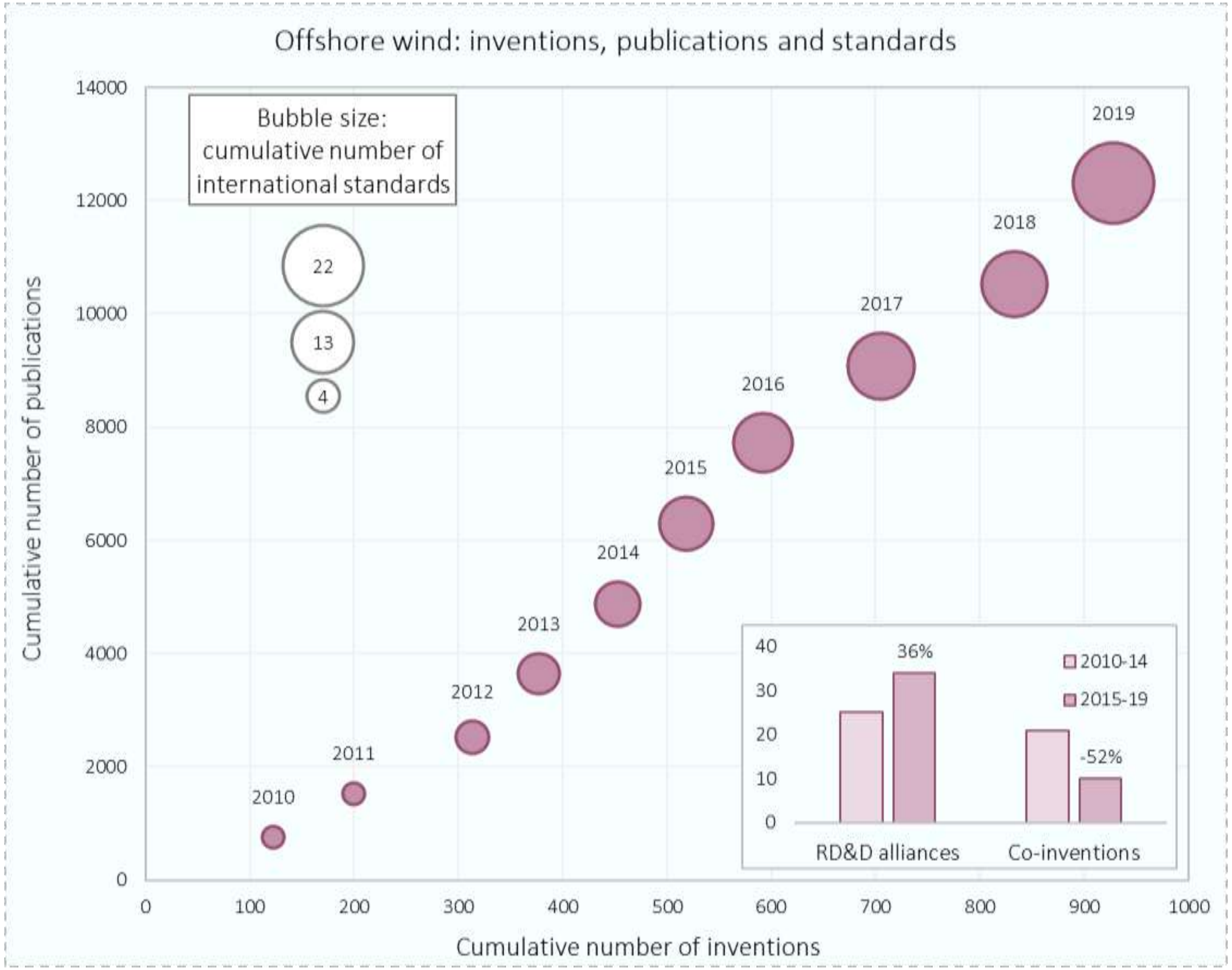
Innovation evolution: inventions, publications and standards

From 2010 to 2019, the ecosystem for research and innovation in offshore wind grew rapidly, across all its main drivers. The metrics show an increase in inventive activity, the production of scientific publications, and the development of international technical standards.

To further boost the effectiveness of the innovation ecosystem, it is necessary to maintain a common ground for actions, where all actors can contribute and dynamically learn from each other via strong, cohesive and continuous co-operation.

The knowledge stock is a key driver in enhancing research and innovation and has to be strengthened. Knowledge transfer is essential to enable entrant actors to participate and contribute to innovation in offshore wind.

This can be done via RD&D and technology collaborations across different countries, involving, to the greatest extent possible, developing and under-developed economies.

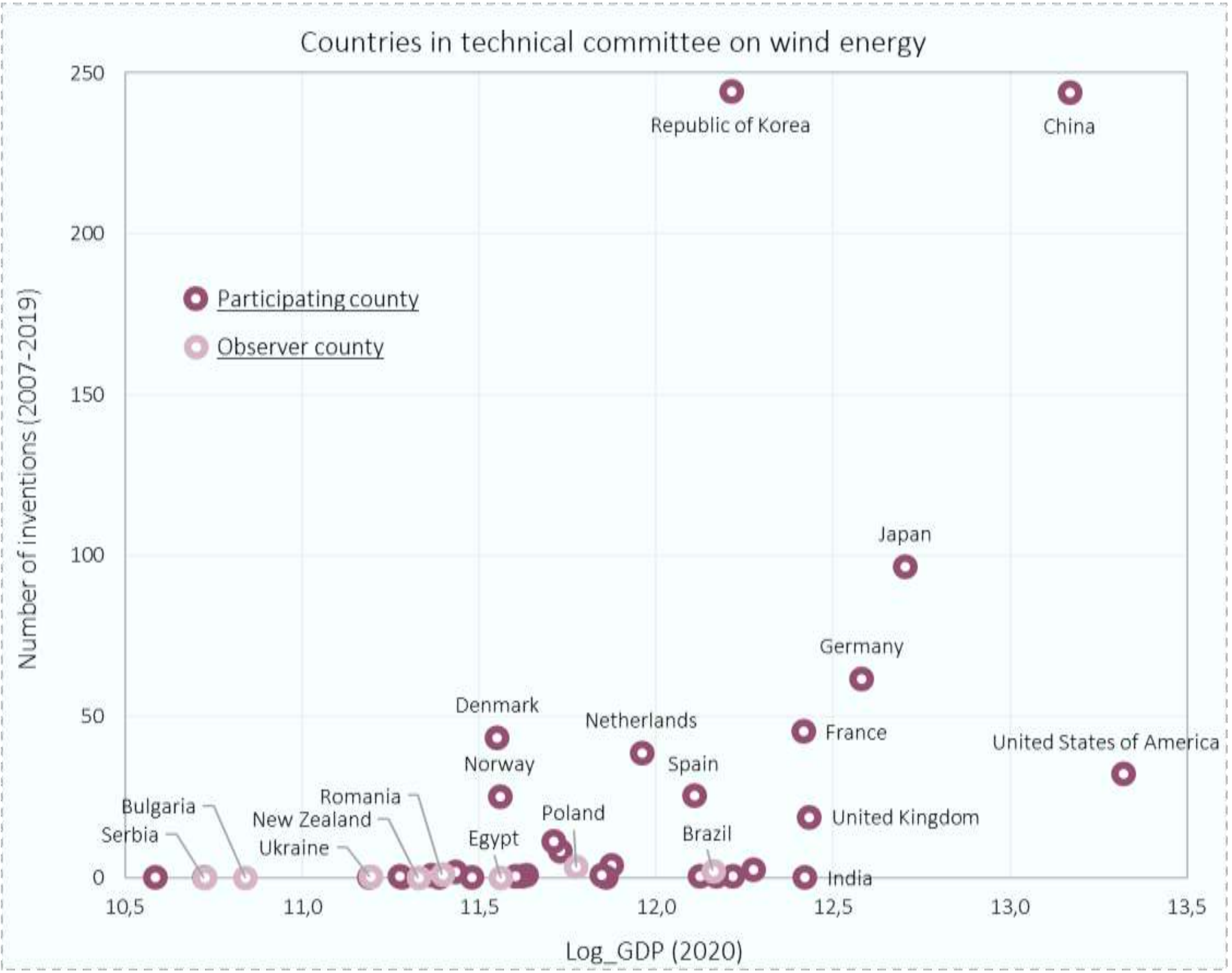


Standards and country participation

Several countries are member of technical committees established to develop technical standards on wind energy. Their participation seems to be linked to country's interest on commercialising wind-related technologies.

Of particular interest is the fact that wealthier economies are more active in this technology area than poorest economies, and that almost all observer countries in the wind technical committee belong to the second group.

Overall, less developed economies must be a part of the standard developing process to ensure the global dissemination of offshore wind technologies. International standardisation bodies should facilitate an increased engagement by representatives from developing countries or professionals from countries with limited technical expertise. If these countries are excluded from the technical standard development process, the chance of giving a holistic and harmonised answer to climate change can be undermined.



Offshore Wind Technology Evolution

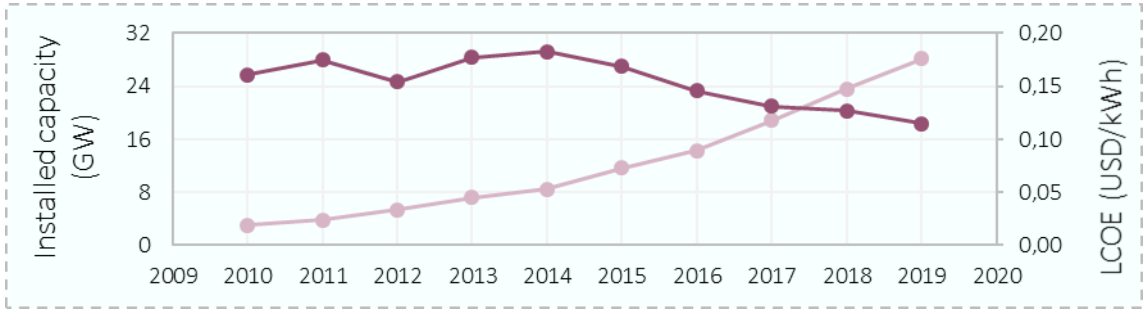
The geographical distribution of offshore wind projects in the 2009 to 2020 period remained constant, with Europe (the United Kingdom, Denmark, and Germany) and Asia (China and Japan) the frontrunners.

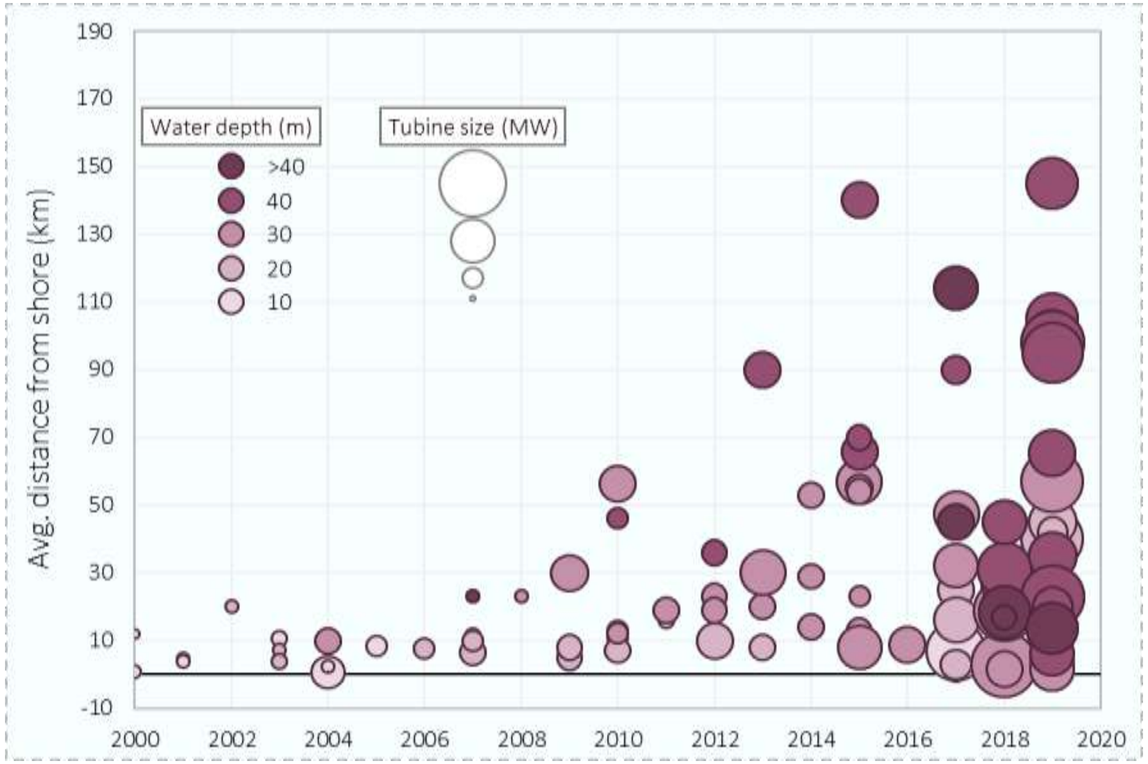
Offshore wind farms were built much closer to the shore and at shallow depths in the early 2010s. To reach the strongest and most consistent wind, RD&D activities have since driven wind farms farther from shore and into deep waters.

A technical potential of over 13 TW can be reached in waters beyond 50 m, with an economically attractive option being floating offshore platforms. This can unlock potential in countries with large seabed drops, allowing wind farms to be located at much greater distance from shore (*e.g.* in Japan, China, the United States and Europe).

In the period examined, total installed costs fell overall from 2015, but were still volatile. The global LCOE also declined from 2014, with an increase in wind turbine capacity. The figures show great potential in learning-by-RD&D through technology improvements.

From 2010 to 2019, the offshore wind market grew significantly, from almost 3 GW of installed capacity in 2010 to 28 GW in 2019. This reflected an average compound annual growth rate (CAGR) of 25%, implying the feasibility and ease of scaling up offshore wind installations. In 2019, Europe and China were the front runners in capacity installed.





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