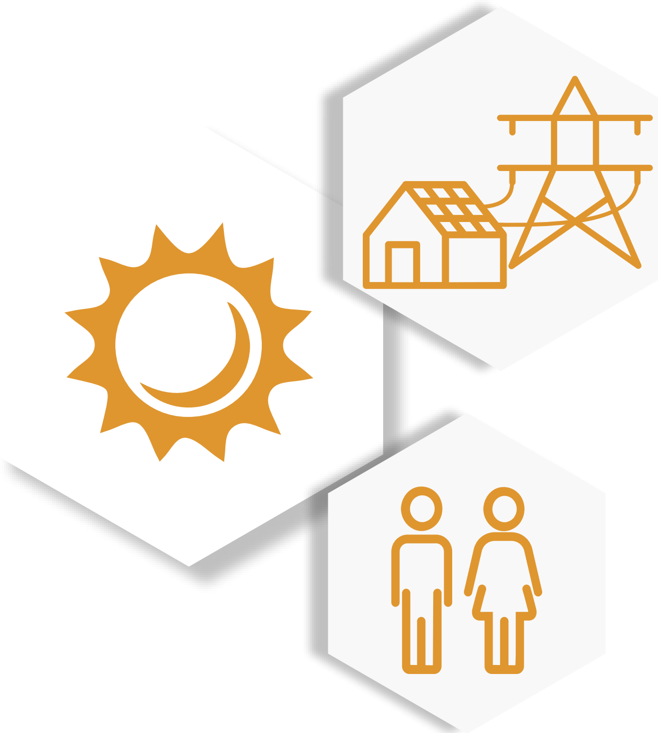

FUTURE OF SOLAR PHOTOVOLTAIC

Deployment, investment, technology, grid integration and socio-economic aspects

A Global Energy Transformation paper

NOVEMBER 2019

ISBN 978-92-9260-156-0

Citation

IRENA (2019), *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper)*, International Renewable Energy Agency, Abu Dhabi.

This document presents additional findings from *Global energy transformation: A roadmap to 2050 (2019 edition)* available for download from **www.irena.org/publications**. For further information or to provide feedback, please contact IRENA at **info@irena.org**.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that serves as the principal platform for co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

Acknowledgements

This report benefited from input and review of experts: Anshu Bhaeadwaj, Jain Pratah, Ghosh Saptak (Centre for Study of Science, Technoogy and Policy), Raed Bkayrat (Clean Tech Advisor & Entrepreneur), Nabih Cherradi (Desert Technologies), Stefan Nowak (International Energy Agency Photovoltaic Power System Programme), Rajeev Gyani, Rakesh Kumar, Remesh Kumar, Arun Misra, Seth Shishir, Upendra Tripathy (International Solar Alliance), Dave Renne (International Solar Energy Society), Christian Thiel and Arnulf Jaeger-Waldau (Joint Research Centre), Kristen Ardani, David Feldman and Robert Margolis (National Renewable Energy Laboratory), Aurelie Beauvais, Bruce Douglas, Raffaele Rossi, Michael Schmela (Solar Power Europe), Frank Haugwitz (Solar Promotion International GmbH), George Kelly (Sunset Technology). Valuable review and feedback were provided by IRENA colleagues: Francisco Boshell, Paul Komor, Neil MacDonald, Pablo Ralon, Michael Taylor and IRENA's Policy Team. The editor of this report was James French-Brooks.

Contributing authors: This report was developed under the guidance of Dolf Gielen and Ricardo Gorini and was authored by Elisa Asmelash and Gayathri Prakash, with additional contributions and support from Rodrigo Leme and Giacomo Gallina.

IRENA is grateful for the generous support of the Federal Ministry for Economic Affairs and Energy of Germany, which made the publication of this report a reality.

Disclaimer

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Annual global temperatures from 1850–2017 Warming Stripes, by **Ed Hawkins**, climate scientist in the National Centre for Atmospheric Science (NCAS) at the University of Reading.

The visualisation ***illustrates the changes witnessed in temperatures*** across the globe over the past century and more. The colour of each stripe represents the temperature of a single year, ordered from the earliest available data at each location to now. The colour scale represents the change in global temperatures covering 1.35 °C.

ABBREVIATIONS

APV	agrophotovoltaic
BoS	balance of system
BNEF	Bloomberg New Energy Finance
BIPV	building-integrated photovoltaic
CAGR	compound annual growth rate
CAPEX	capital expenditure
CdTe	cadmium telluride
CIGS	copper-indium-gallium-diselenide
CO_2	carbon dioxide
C-Si	crystalline silicon
CSP	concentrating solar power
DC	direct current
DER	distributed energy resources
DG	distributed generation
DSO	distribution system operator
EMEA	Europe, the Middle East and Africa
EU	European Union
EV	electric vehicle
FIT	feed-in tariff
G20	Group of Twenty
GBP	British pound
GCC	Gulf Cooperation Council
Gt	gigatonne
GW	gigawatt
GWEC	Global Wind Energy Council
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ITRPV	International Technology Roadmap for Photovoltaic
kW	kilowatt
kWh	kilowatt hour
LCOE	levelised cost of electricity
m2	square metre
MW	megawatt
MWh	megawatt hour
NREL	US National Renewable Energy Laboratory
O&M	operations and maintenance
OPEX	operating expenditure
PERC	passivated emitter and rear cell/contact
PPA	power purchase agreement
PV	photovoltaic
PV-T	photovoltaic-thermal
R&D	research and development
REmap	IRENA's renewable energy roadmap
STEM	science, technology, engineering and mathematics
TW	terawatt
TWh	terawatt hour
VPP	virtual power plant
VRE	variable renewable energy
USD	US dollar
W	watt

EXECUTIVE SUMMARY

THE DECARBONISATION OF THE ENERGY SECTOR AND THE REDUCTION OF CARBON EMISSIONS TO LIMIT CLIMATE CHANGE ARE AT THE HEART OF THE INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA) ENERGY TRANSFORMATION ROADMAPS. These roadmaps examine and provide an ambitious, yet technically and economically feasible, pathway for the deployment of low-carbon technology towards a sustainable and clean energy future.

IRENA HAS EXPLORED TWO ENERGY DEVELOPMENT OPTIONS TO THE YEAR 2050 AS PART OF THE 2019 EDITION OF ITS GLOBAL ENERGY TRANSFORMATION REPORT. The first is an energy pathway set by current and planned policies (Reference Case). The second is a cleaner climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (REmap Case), which limits the rise in global temperature to well below 2 degrees and closer to 1.5 degrees, aligned within the envelope of scenarios presented in the 2018 report of the Intergovernmental Panel on Climate Change (IPCC).

THE PRESENT REPORT OUTLINES THE ROLE OF SOLAR PHOTOVOLTAIC (PV) POWER IN THE TRANSFORMATION OF THE GLOBAL ENERGY SYSTEM BASED ON IRENA'S CLIMATE-RESILIENT PATHWAY (REMAP CASE), specifically the growth in solar PV power deployment that would be needed in the next three decades to achieve the Paris climate goals.

This report's findings are summarised as follows:

- **ACCELERATED DEPLOYMENT OF RENEWABLES, COMBINED WITH DEEP ELECTRIFICATION AND INCREASED ENERGY EFFICIENCY, CAN ACHIEVE OVER 90% OF THE ENERGY-RELATED CARBON DIOXIDE (CO_2) EMISSION REDUCTIONS NEEDED BY 2050 TO SET THE WORLD ON AN ENERGY PATHWAY TOWARDS MEETING THE PARIS CLIMATE TARGETS**. Among all low-carbon technology options, accelerated deployment of solar PV alone can lead to significant emission reductions of 4.9 gigatonnes of carbon dioxide (Gt CO_2) in 2050, representing 21% of the total emission mitigation potential in the energy sector.
- **ACHIEVING THE PARIS CLIMATE GOALS WOULD REQUIRE SIGNIFICANT ACCELERATION ACROSS A RANGE OF SECTORS AND TECHNOLOGIES.** By 2050 solar PV would represent the second-largest power generation source, just behind wind power and lead the way for the transformation of the global electricity sector. Solar PV would generate a quarter (25%) of total electricity needs globally, becoming one of prominent generations source by 2050.

- **SUCH A TRANSFORMATION IS ONLY POSSIBLE BY SIGNIFICANTLY SCALING UP SOLAR PV CAPACITY IN NEXT THREE DECADES.** This entails increasing total solar PV capacity almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels.

- **THE SOLAR PV INDUSTRY WOULD NEED TO BE PREPARED FOR SUCH A SIGNIFICANT GROWTH IN THE MARKET OVER THE NEXT THREE DECADES.** In annual growth terms, an almost threefold rise in yearly solar PV capacity additions is needed by 2030 (to 270 GW per year) and a fourfold rise by 2050 (to 372 GW per year), compared to current levels (94 GW added in 2018).

  Thanks to its modular and distributed nature, solar PV technology is being adapted to a wide range of off-grid applications and to local conditions. In the last decade (2008–18), the globally installed capacity of off-grid solar PV has grown more than tenfold, from roughly 0.25 GW in 2008, to almost 3 GW in 2018. Off-grid solar PV is a key technology for achieving full energy access and achieving the Sustainable Development Goals.

- **AT A REGIONAL LEVEL, ASIA IS EXPECTED TO DRIVE THE WAVE OF SOLAR PV CAPACITY INSTALLATIONS, BEING THE WORLD LEADERS IN SOLAR PV ENERGY.** Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by North America (20%) and Europe (10%).

- **SCALING UP SOLAR PV ENERGY INVESTMENT IS CRITICAL TO ACCELERATING THE GROWTH OF INSTALLATIONS OVER THE COMING DECADES.** Globally this would imply a 68% increase in average annual solar PV investment from now until 2050 (to USD 192 billion/yr). Solar PV investment stood at USD 114 billion/yr in 2018.

- **INCREASING ECONOMIES OF SCALE AND FURTHER TECHNOLOGICAL IMPROVEMENTS WILL CONTINUE TO REDUCE THE COSTS OF SOLAR PV.** Globally, the total installation cost of solar PV projects would continue to decline in the next three decades. This would make solar PV highly competitive in many markets, with the average falling in the range of USD 340 to 834 per kilowatt (kW) by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018.

  The levelised cost of electricity (LCOE) for solar PV is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. Globally, the LCOE for solar PV will continue to fall from an average of USD 0.085 per kilowatt-hour (kWh) in 2018 to between USD 0.02 to 0.08/kWh by 2030 and between USD 0.014 to 0.05/kWh by 2050.

- **THE SOLAR PV INDUSTRY IS A FAST-EVOLVING INDUSTRY, CHANGING RAPIDLY THANKS TO INNOVATIONS ALONG THE ENTIRE VALUE CHAIN AND FURTHER RAPID COSTS REDUCTIONS ARE FORESEEN.** First-generation technologies remain the principal driver of solar industry development and still hold the majority of the market value. Tandem and perovskite technologies also offer interesting perspectives, albeit in the longer term several barriers still need to be overcome. The emergence of new cell architectures has enabled higher efficiency levels. In particular, the most important market shift in cell architecture has resulted from bifacial cells and modules, driven by the increased adoption of advanced cell architecture, such as passive emitter and rear cell (PERC), and by its compatibility with other emerging innovations, such as half-cut cells and others.

- **TAKING ADVANTAGE OF FAST-GROWING SOLAR PV CAPACITY ACROSS THE GLOBE, SEVERAL RESEARCH PROJECTS AND PROTOTYPES ARE ONGOING TO STIMULATE FUTURE MARKET GROWTH BY EXPLORING INNOVATIVE SOLAR TECHNOLOGIES AT THE APPLICATION LEVEL.** One example is building-integrated photovoltaic (BIPV) solar panels. BIPV solutions offer several advantages, such as multifunctionality (they can be adapted to a variety of surfaces), cost-efficiency (savings on roofing material, labour/construction, refurbishment and renovation costs), versatility and design flexibility in size, shape and colour.

Solar panels have improved substantially in their efficiency and power output over the last few decades. In 2018, the efficiency of multi-crystalline PV reached 17%, while that of mono-crystalline reached 18%. This positive trend is expected to continue through to 2030. Yet, as the global PV market increases, so will the need to prevent the degradation of panels and manage the volume of decommissioned PV panels leading to circular economy practises. This includes innovative and alternative ways to reduce material use and module degradation, and opportunities to reuse and recycle PV panels at the end of their lifetime.

- **TECHNOLOGICAL SOLUTIONS AS WELL AS ENABLING MARKET CONDITIONS ARE ESSENTIAL TO PREPARE FUTURE POWER GRIDS TO INTEGRATE RISING SHARES OF SOLAR PV.** To effectively manage large-scale variable renewable energy sources, flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (demand-side management and sector coupling). Some countries, particularly in Europe, have achieved much higher shares in 2017: the VRE share in Denmark reached 53%, in South Australia 48%, and in Lithuania, Ireland, Spain and Germany over 20%. Globally, to integrate 60% variable renewable generation (of which 25% from solar PV) by 2050, average annual investments in grids, generation adequacy and some flexibility measures (storage) would need to rise by more than one-quarter to USD 374 billion/year, compared to investments made in electricity networks and battery storage in 2018 (USD 297 billion/year).

- **INNOVATIVE BUSINESS MODELS AND COST COMPETITIVENESS OF SOLAR PV ARE DRIVING THE REDUCTIONS IN SYSTEM PRICES.** The deployment of rooftop solar PV systems has increased significantly in recent years, in great measure thanks to supporting policies, such as net metering and fiscal incentives- which in some markets make PV more attractive from an economic point of view than buying electricity from the grid- PV-hybrid minigrid, virtual power plants and utility PPA. The competitiveness of distributed solar power is clearly evident amid rising deployment in large markets, such as Brazil, China, Germany and Mexico, however important differences remain between countries, which highlight the further improvement potential.

- **IF ACCOMPANIED BY SOUND POLICIES, THE TRANSFORMATION CAN BRING SOCIO-ECONOMIC BENEFITS.** The solar PV industry would employ more than 18 million people by 2050, five times more than the 2018 jobs total of 3.6 million. To maximise outcomes of the energy transition, however, a holistic policy framework is needed. Deployment policies will need to co-ordinate and harmonise with integration and enabling policies. Under the enabling policy umbrella, particular focus is needed on industrial, financial, education and skills policies to maximise the transition benefits. Education and skills policies can help equip the workforce with adequate skills and would increase opportunities for local employment. Similarly, sound industrial policies that build upon domestic supply chains can enable income and employment growth by leveraging existing economic activities in support of solar PV industry development.

- **UNLEASHING THE MASSIVE POTENTIAL OF SOLAR PV IS CRUCIAL TO ACHIEVE CLIMATE TARGETS.** This is only possible by mitigating the current barriers at different scales (policy; market and economic; technology; regulatory, political and social). Grid integration and grid flexibility, economies of scale, access to finance, lack of standards and quality measures, consumer awareness are among the key barriers that could hinder the deployment of solar PV capacities in the next three decades. Mitigating the existing barriers immediately, through a range of supportive policies and implementation measures including innovative business models, financial instruments is vital to boost future deployment of solar PV capacities to enable the transition to a low-carbon, sustainable energy future.

Figure ES 1. Status and future of solar photovoltaics (PV) - Tracking progress to accelerate solar PV deployment to achieve Paris Climate targets

CO$_2$ EMISSIONS (ENERGY-RELATED) AND REDUCTION POTENTIAL BY SOLAR PV POWER

	2010	2018	2030	2050	ON/OFF TRACK
Energy-related CO$_2$ emissions under current plans and planned policies (Reference Case) (Gt CO$_2$/yr)	29.7	34.5	35	33.1	
Energy-related CO$_2$ emissions under IRENA's climate resilient pathway (REmap Case) (Gt CO$_2$/yr)	29.7	34.5	24.9	9.8	Off track
Avoided emissions due to accelerated deployment of solar PV coupled with deep electrification (Gt CO$_2$/yr) (REmap Case)				4.9	

	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
SOLAR PV POWER IN TOTAL GENERATION MIX					
Solar PV generation share (%)	0.2%	2%	13%	25%	Progress
TOTAL INSTALLED CAPACITY					
Solar PV (GW)	39	480	2 840	8 519	Off track
ANNUAL DEPLOYMENT					
Solar PV (GW/yr)	17	94	270	372	Progress

TOTAL INSTALLATION COST

	2010	2018	2030	2050	ON/OFF TRACK
Solar PV (USD/kW)	4 621	1 210	834 – 340	481 – 165	Progress
LEVELIZED COST OF ELECTRICITY (LCOE)					
Solar PV (USD/kWh)	0.37	0.085	0.08 – 0.02	0.05 – 0.01	On track
AVERAGE ANNUAL INVESTMENT					
Solar PV (USD billion/yr)	77	114	165	192	Progress
EMPLOYMENT					
Solar PV (million)	1.36*	3.6	11.7	18.7	Progress

* The data denoted solar PV sector jobs by 201

1. ENERGY TRANSFORMATION PATHWAYS AND SOLAR PV

1.1 PATHWAYS FOR THE GLOBAL ENERGY TRANSFORMATION

The International Renewable Energy Agency (IRENA) has explored global energy development options from two main perspectives to the year 2050 as part of the 2019 edition of its Global Energy Transformation report (IRENA, 2019a). The first is an energy pathway set by current and planned policies (the Reference Case), and the second is a cleaner, climate-resilient pathway based largely on a more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (the REmap Case).[1]

Box 1. PRACTICAL OPTIONS FOR GLOBAL ENERGY DECARBONISATION

IRENA's renewable energy roadmap, or REmap approach[1] and analysis, includes several key steps (IRENA, 2019a):

- Identifying the current plans for global energy development as a baseline scenario (or Reference Case) as far as 2050. This presents a scenario based on governments' current energy plans and other planned targets and policies, including climate commitments made since 2015 in Nationally Determined Contributions under the Paris Agreement.
- Assessing the additional potential for scaling up or optimising low-carbon technologies and approaches, including renewable energy, energy efficiency and electrification, while also considering the role of other technologies.
- Developing a realistic, practical energy transformation scenario, referred to as the "REmap Case". This calls for considerably faster deployment of low-carbon technologies, based largely on renewable energy and energy efficiency, resulting in a transformation in energy use to keep the rise in global temperatures this century well below 2 °C and closer to 1.5 °C compared to pre-industrial levels. The scenario focuses primarily on cutting energy-related carbon-dioxide (CO_2) emissions, which make up around two-thirds of global greenhouse gas emissions.
- Analysing the costs, benefits and investment needs of low-carbon technologies worldwide to achieve the envisaged energy transformation.

Note: The findings in this report consider policy targets and developments until April 2019. Any new policy changes and targets announced since then are not considered in the analysis and therefore could influence the findings presented in this report.

The findings in this report are based on IRENA's climate-resilient pathway (REmap Case), which is well below 2 °C and closer to the 1.5 °C carbon budget levels provided in the IPCC Special Report on Global Warming of 1.5 °C (SR1.5).

REmap
A Renewable Energy Roadmap

1 For more on the global roadmap and its underlying analysis, see www.irena.org/remap.

1.2 THE ENERGY TRANSFORMATION RATIONALE

Reducing energy-related CO_2 emissions is at the heart of the energy transformation. Rapidly shifting the world away from the consumption of fossil fuels that cause climate change and towards cleaner renewable forms of energy is critical if the world is to reach the climate goals agreed in Paris. There are many drivers behind this transformation (Figure 1).

First, the **rapid decline in renewable energy costs**. The global weighted average cost of electricity from all commercially available renewable power generation technologies continued to fall in 2018. For example, the fall in the cost of electricity from utility-scale solar photovoltaic (PV) projects since 2010 has been remarkable – between 2010 and 2018 the global weighted average levelised cost of electricity (LCOE) from solar PV declined by 77%. Recent record low auction outcomes for solar PV in Abu Dhabi, Chile, Dubai, Mexico, Peru and Saudi Arabia have shown that an LCOE of USD 0.03 per kilowatt hour (kWh) is possible in a wide variety of national contexts (IRENA, 2018). Similarly, in Europe offshore wind projects are now increasingly competing with fossil-fired sources on a subsidy-free basis in wholesale electricity markets (*e.g.* subsidy-free bids in Germany and the Netherlands), while in the United States non-hydropower renewable energy resources such as solar PV and wind are expected to be the fastest-growing source of electricity generation in the next two years.

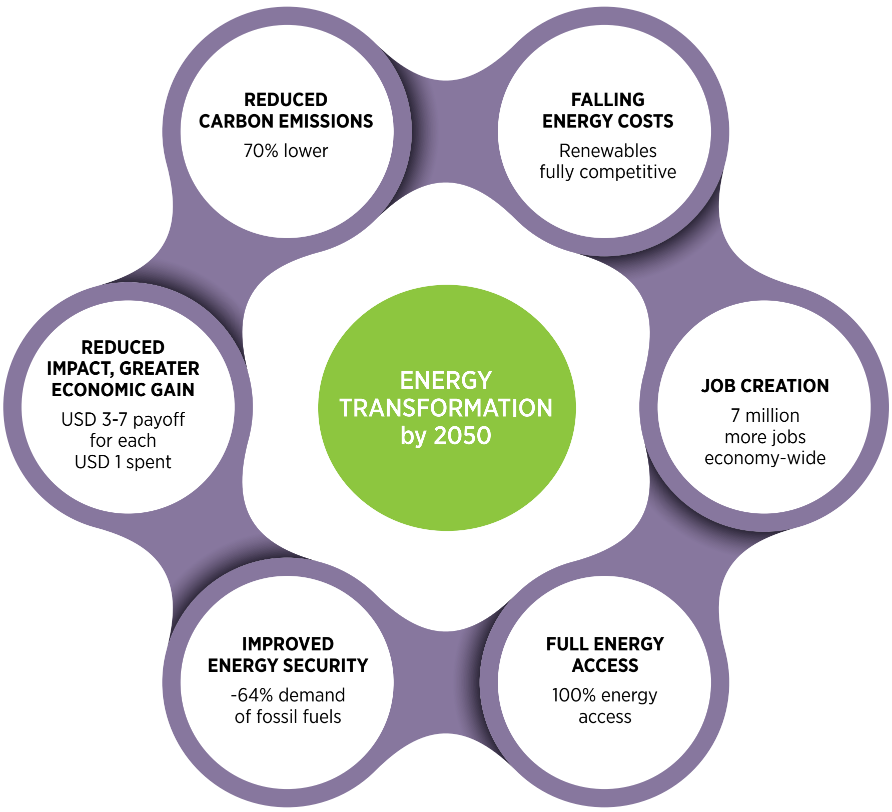
Second, **air quality improvements.** Air pollution is a major public health crisis, mainly caused by unregulated, inefficient and polluting energy sources, (*e.g.* fossil fuel combustion, chemical-related emissions). The switch to clean renewable energy sources would improve the air quality in cities and bring greater prosperity by reducing ill health and increasing productivity. With the rise in usage of renewables, drop in net energy subsidies, would potentially lead to decline in health costs from air pollution and climate effects. The savings from reduced externalities with respect to air pollution and climate change along with avoided subsidies outweigh the additional energy system. For every dollar invested in transforming the global energy system over the period to 2050, there is a payoff of at least USD 3 and potentially more than USD 7, depending on how externalities are valued (IRENA, 2019a).

Thirdly, **reduction of carbon emissions**. The gap between observed emissions and the reductions that are needed to meet internationally agreed climate objectives is widening. The transformation of the global energy system needs to accelerate substantially to meet the objectives of the Paris Agreement, which aim to keep the rise in average global temperatures to closer to 1.5 degrees Celsius (°C) in the present century, compared to pre-industrial levels. A 70% reduction in energy-related emissions would needed by 2050 compared to current levels (IRENA, 2019a).

Then, transforming the global energy system would also **improve energy security and enhance affordable and universal energy access.** For countries heavily dependent on imported fossil fuels, energy security is a significant issue. Renewables can provide an alternative by increasing the diversity of energy sources through local generation, thus contributing to the flexibility of the system and resistance to shocks. Similarly, energy access is an area of great inequality and renewable energy technologies can be applied in rural areas where the grid has yet to reach, harnessing rural electrification, community energy initiatives and distributed energy resources (DER).

Finally, transforming the global energy system would also **bring significant socio-economic benefits**, which are crucial to influencing any political decision. The development of a local renewable energy industry has the potential to create jobs that can accommodate men and women from all disciplines and backgrounds. Should local industries not be developed, countries with energy security problems would just move from importing fossil fuels to importing renewable energy equipment (IRENA, 2019a; IRENA, 2019b).

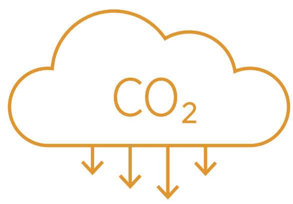
Figure 1: Pressing needs and attractive opportunities are driving the ongoing energy transformation



Note: The key drivers for energy transformation presented in this figure is based on IRENA's REmap Case by 2050 compared to current levels.
Source: (IRENA, 2019b)

CO_2 EMISSION REDUCTIONS AS A MAJOR GOAL

Decarbonising the energy sector and reducing carbon emissions to limit climate change are at the heart of IRENA's energy transformation roadmaps, which examine and provide an ambitious, yet technically and economically feasible, pathway for the deployment of low-carbon technology towards a sustainable and clean energy future.



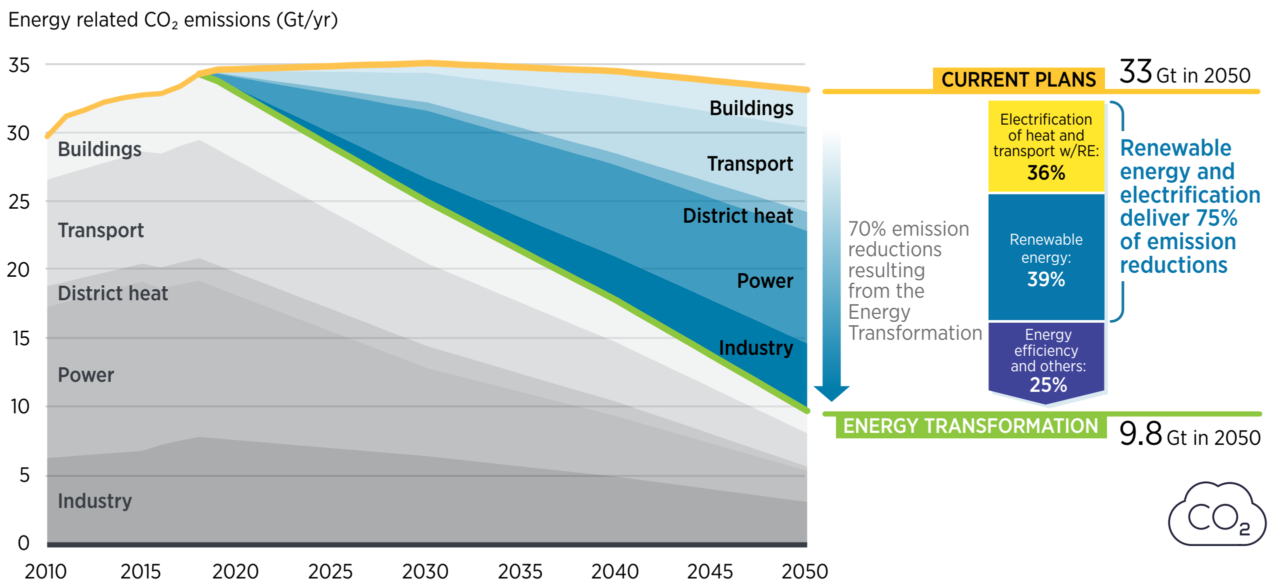
1.3 GLOBAL ENERGY TRANSFORMATION: THE ROLE OF SOLAR PV

Climate change has become a major concern of this century. The Paris Agreement establishes a mechanism to limit global temperature rise to "well below 2°C", and ideally to 1.5°C, compared to pre-industrial levels. The profound transformation of the global energy landscape is essential to realise the agreement's climate targets. Such a transformation is possible with the rapid deployment of low-carbon technologies in place of conventional fossil fuel generation and uses.

To set the world on a pathway towards meeting the aims of the Paris Agreement, energy-related CO_2 emissions need to be reduced by around 3.5% per year from now until 2050, with continued reductions thereafter. The transition to increasingly electrified forms of transport and heat, when combined with increases in renewable power generation, would deliver around 60% of the energy-related CO_2 emission reductions needed by 2050. If additional reductions from direct use of renewables are considered, the share increases to 75%. When adding energy efficiency, the share increases to over 90% of the energy-related CO_2 emission reductions needed to set the world on a pathway to meeting the Paris Agreement targets (Figure 2) (IRENA, 2019a).

The energy transformation would also boost gross domestic product by 2.5% and total employment by 0.2% globally by 2050. In addition, it would bring broader social and environmental benefits. Health, subsidy and climate-related savings would be worth as much as USD 160 trillion cumulatively over a 30-year period. Thus, every dollar spent in transforming the global energy system provides a payoff of at least USD 3 and potentially more than USD 7, depending on how externalities are valued (IRENA, 2019a).

Figure 2: Renewables and efficiency measures, boosted by substantial electrification, can provide over 90% of the necessary CO_2 emission reductions by 2050



Note: "Renewables" implies deployment of renewable technologies in the power sector (wind, solar PV, etc.) and direct end-use applications (solar thermal, geothermal, biomass). "Energy efficiency" includes efficiency measures deployed in end-use applications in the industrial, buildings and transport sectors (*e.g.* improving insulation of buildings or installing more efficient appliances and equipment). "Electrification" denotes electrification of heat and transport applications, such as deploying heat pumps and electric vehicles (EVs); Gt = gigatonne; w/RE = with renewable energy.

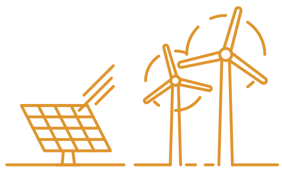
Source: (IRENA, 2019a)

Scaling up electricity from renewables is crucial for the decarbonisation of the world's energy system. The most important synergy of the global energy transformation comes from the combination of increasing low-cost renewable power technologies and the wider adoption of electricity for end-use applications in transport and heat. To deliver the energy transition at the pace and scale needed would require almost complete decarbonisation of the electricity sector by 2050. The REmap Case sets a pathway to achieve a share of 86% for renewables in the power generation mix by 2050 (Figure 3). On the end use side, the share of electricity in final energy consumption would increase from just 20% today to almost 50% by 2050. The share of electricity consumed in industry and buildings would double. In transport, it would increase from just 1% today to over 40% by 2050 (IRENA, 2019a).

Solar, along with wind energy, would lead the way in the transformation of the global electricity sector. Wind power would be one of the major electricity generation sources, supplying more than one-third of total electricity demand. Solar PV power would follow, supplying 25% of total electricity demand, which would represent over a tenfold rise in the solar PV share of the generation mix by 2050 compared to 2016 levels. In the context of total installed capacity by 2050, much greater capacity expansion would be needed for solar PV (8 519 gigawatts [GW]) as compared to wind (6 044 GW).[2]

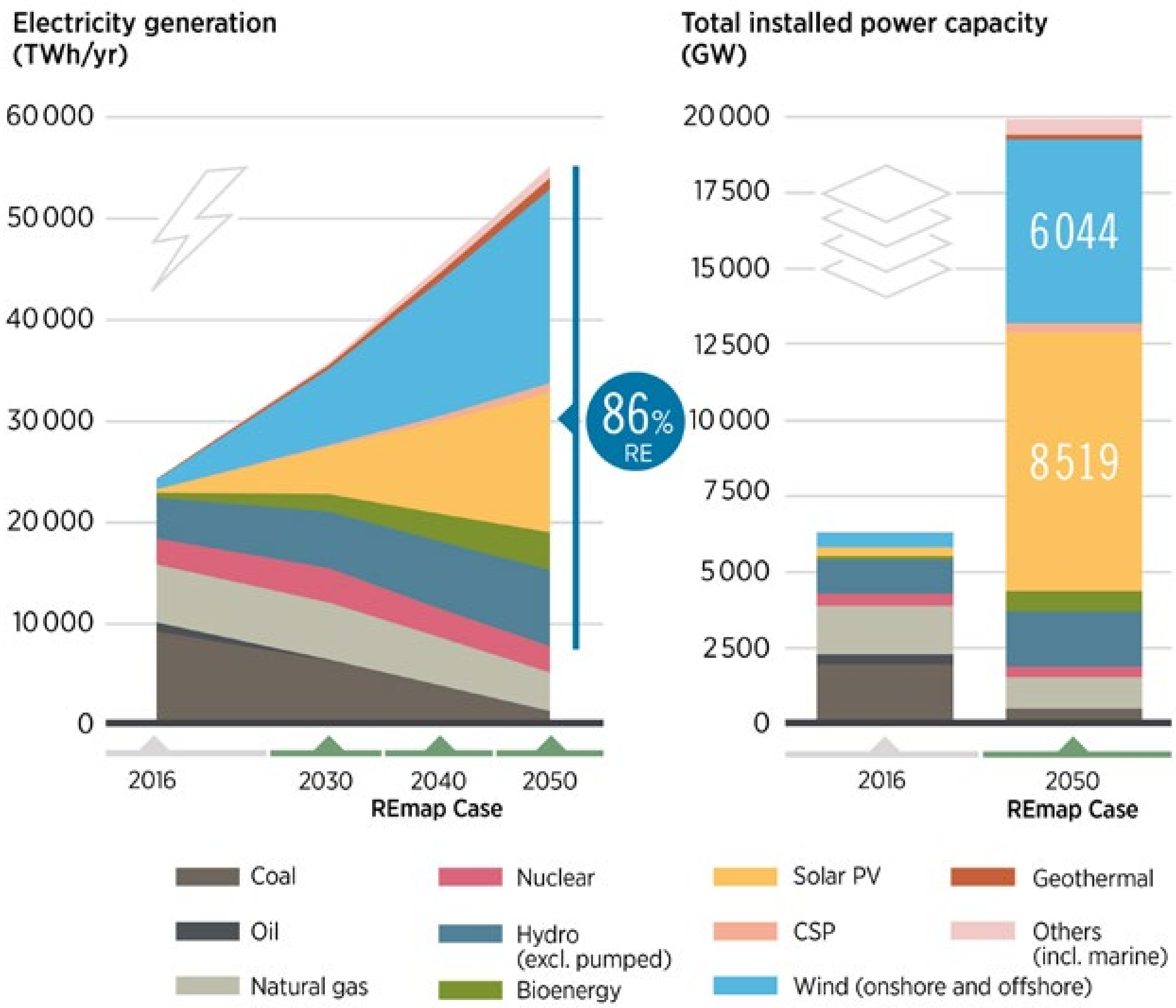
SOLAR PV- A PROMIENT GENERATION SOURCE BY 2050

Alongside wind energy, solar PV would lead the way in the transformation of the global electricity sector. Cumulative installed capacity of solar PV would rise to 8 519 GW by 2050 becoming the second prominent source (after wind) by 2050.



2 A similar forthcoming IRENA working paper on wind explores the role of wind in the context of the global energy transformation to 2050 and will available to download: www.irena.org/publications.

Figure 3: Solar PV would have the largest installed capacity expansion by 2050



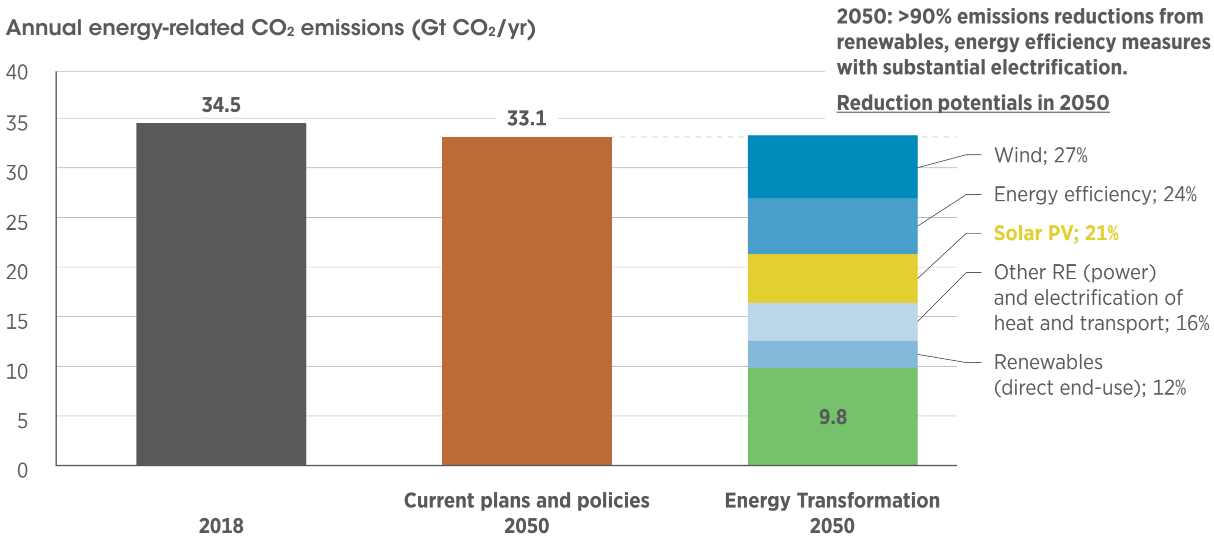
Notes: CSP = concentrating solar power; TWh = terawatt hour.

Source: IRENA (2019a).

SOLAR PV: ITS POTENTIAL TO MITIGATE ENERGY-RELATED CARBON EMISSIONS

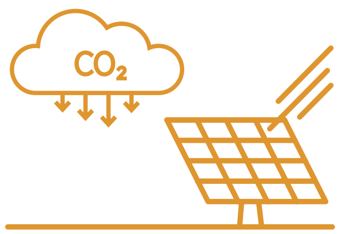
Deploying more than 8 500 GW of solar power – capable of generating more than 25% of total electricity needs in 2050 – can potentially mitigate a significant amount of emissions (4.9 Gt CO_2). This represents 21% of the total emission reduction potential from renewables and energy efficiency measures (Figure 4). Among all low-carbon technology options, solar PV contributes to major emissions reduction potential by 2050. This is mainly due to the significant deployment of solar power replacing conventional power generation sources by utilising the ample resource availability with the best technological solutions at better resource locations across various regions and benefiting from drastic cost reductions, significant end-use electrification of transport and heat applications, shifting energy demand to electricity that can then be supplied by wind (either directly or indirectly, for example power-to-hydrogen) and rising socio-economic benefits.

Figure 4: Solar pv would contribute to 4.9 Gt of CO_2 emissions reductions in 2050, representing 21% of the overall energy-sector emissions reductions needed to meet paris climate goals



ACCELERATED SOLAR PV DEPLOYMENTS CONTRIBUTES TO CO_2 EMISSIONS REDUCTIONS

Among all low-carbon technology options, accelerated deployment of solar PV when coupled with deep electrification would contribute to almost one-fifth of the total emissions reductions needed (nearly 4.9 Gt CO_2) in 2050



2. THE EVOLUTION AND FUTURE OF SOLAR PV MARKETS

2.1 EVOLUTION OF THE SOLAR PV INDUSTRY

Rising concerns about climate change, the health effects of air pollution, energy security and energy access, along with volatile oil prices in recent decades, have led to the need to produce and use alternative, low-carbon technology options such as renewables. Solar PV has been one of the pioneering renewable technologies over the decades. The total installed capacity of solar PV reached 480 GW globally (excluding CSP) by the end of 2018, representing the second-largest renewable electricity source after wind. Last year, solar PV again dominated total renewable and power capacity additions, adding twice as much capacity as wind and more than all fossil fuels and nuclear together, solar PV additions reaching around 94 GW (IRENA, 2019c).

The evolution of the solar PV industry so far has been remarkable, with several milestones achieved in recent years in terms of installations (including off-grid), cost reductions and technological advancements, as well as establishment of key solar energy associations (Figure 5).

Solar power will clearly continue to be an essential renewables option in the coming decades. This working paper sheds light on the prominent role of solar PV in transforming the global energy landscape by 2050. The following sections present an accelerated deployment pathway for solar PV until 2050 under the REmap Case from IRENA's global energy transformation roadmap, together with perspectives on cost reductions, technology trends and the need to prepare future grids for rising shares of solar PV.

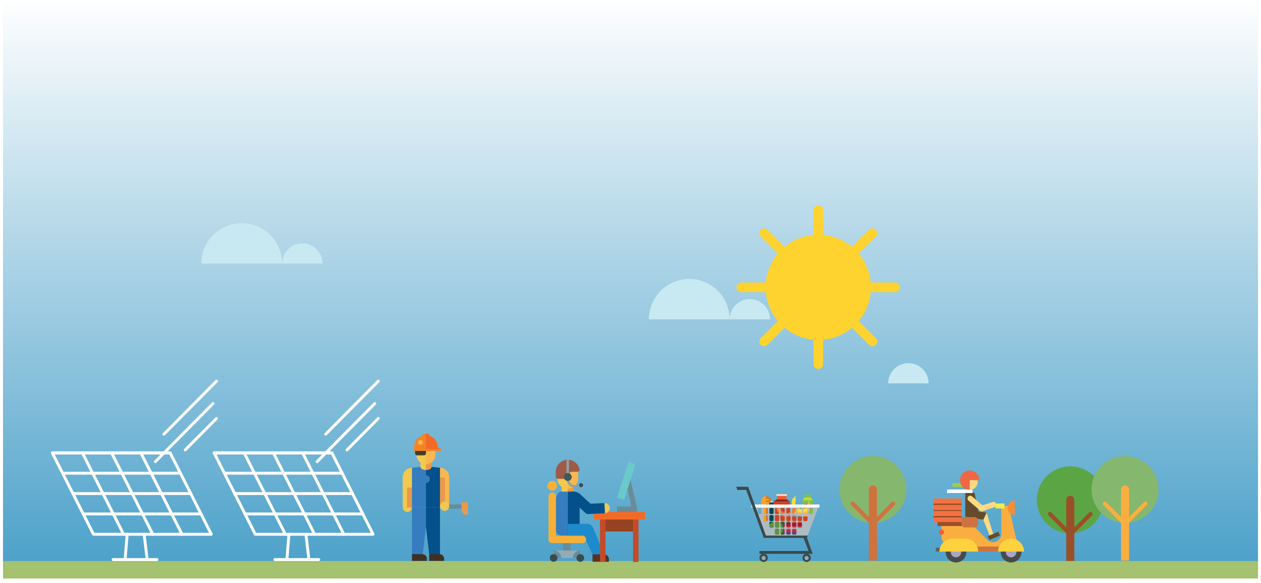
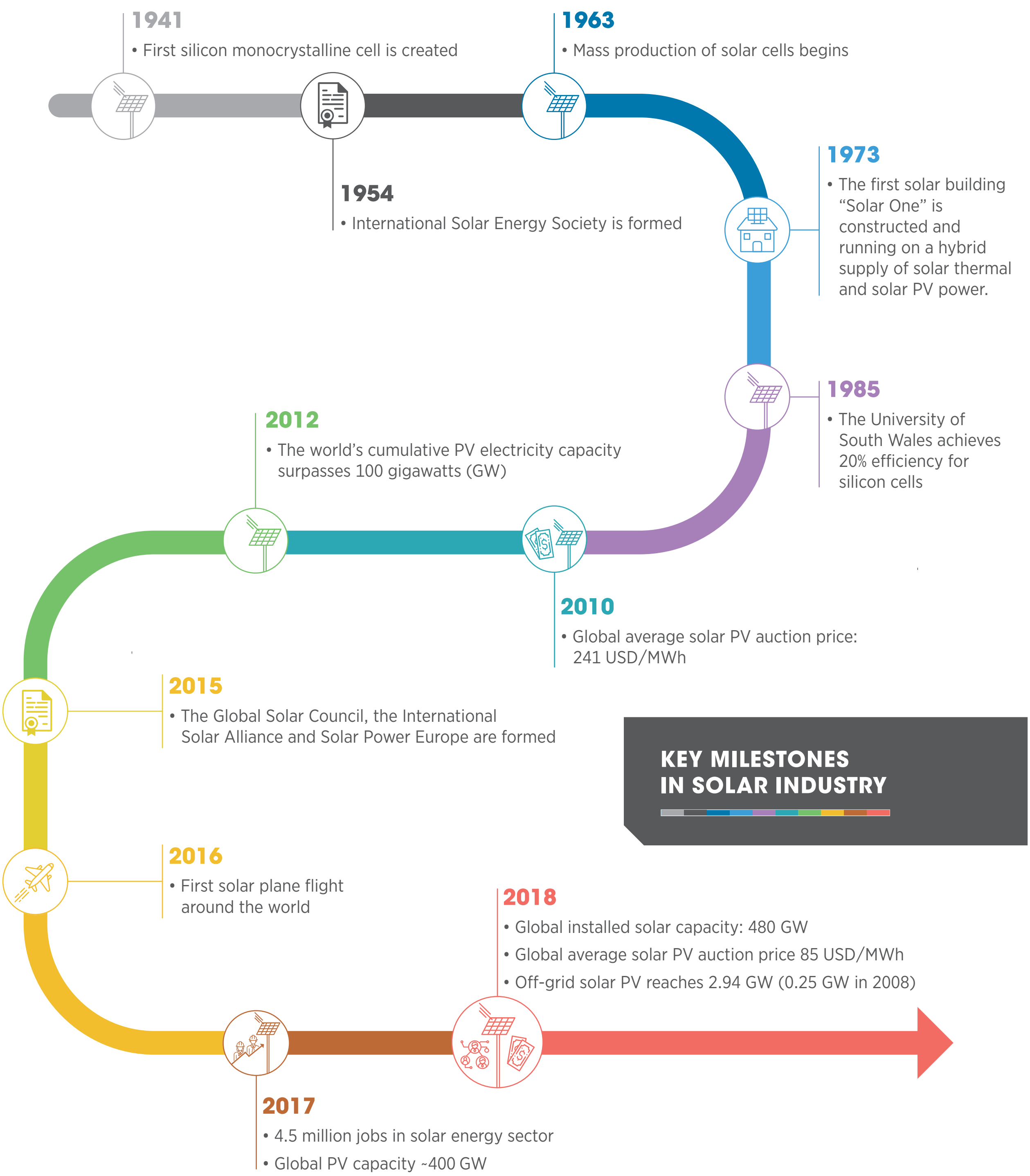


Figure 5: Major milestones achieved by the solar industry



SOLAR PV: A FAST-GROWING AND MATURE RENEWABLE ENERGY TECHNOLOGY

Solar PV is one of the fastest-growing, most mature and cost-competitive renewable energy technologies.

2.2 SOLAR PV OUTLOOK TO 2050

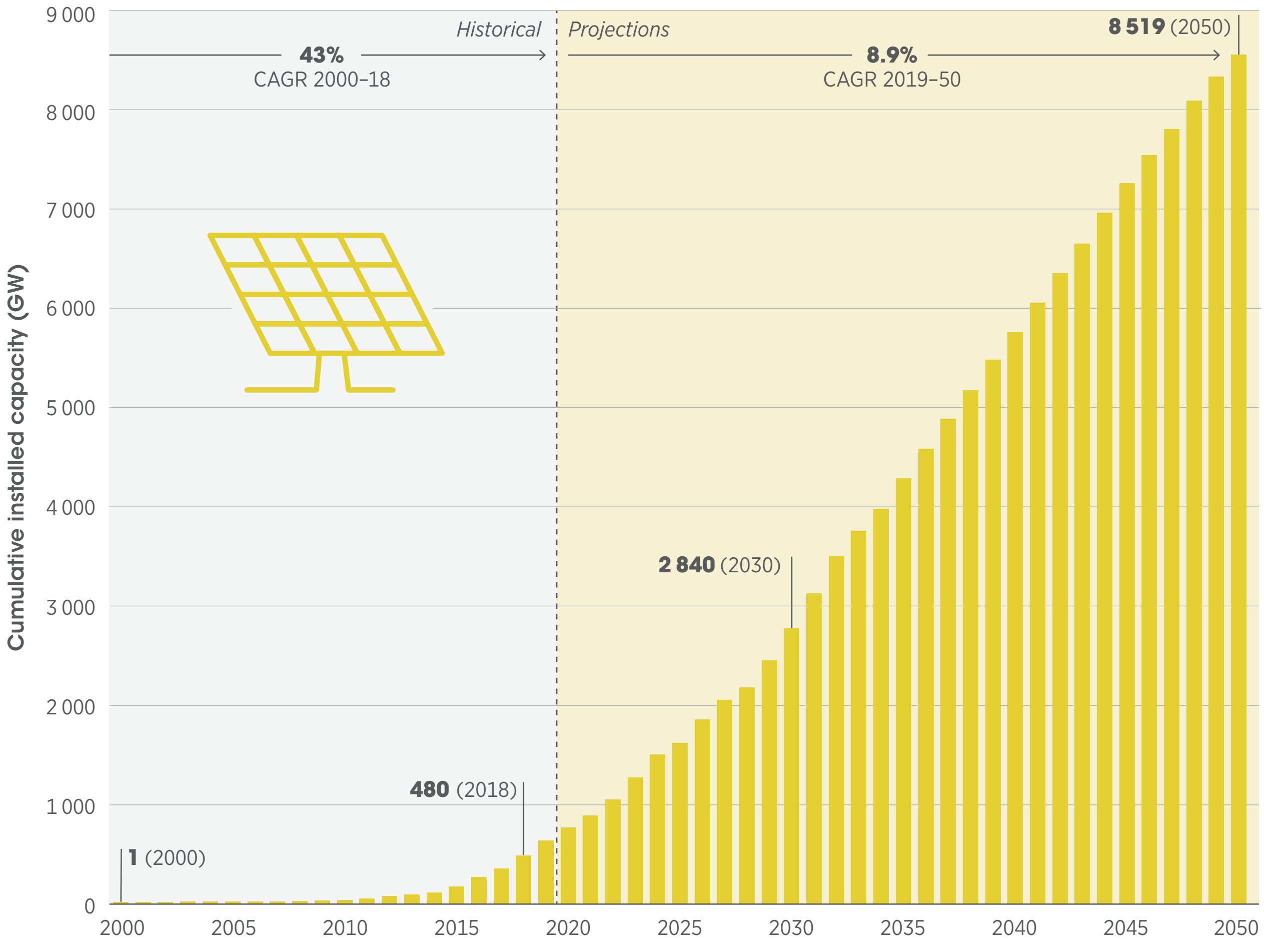
ACCELERATED UPTAKE AND EMERGING MARKETS

The deployment of renewables has been growing at a rapid pace in recent years, reaching record levels and outpacing annual conventional power capacity additions in many regions. Among all renewable technologies, solar PV power installations have been dominating the renewables industry for many years. As of the end of 2018, the global capacity of installed and grid-connected solar PV power reached 480 GW (Figure 6), representing 20% year-on-year growth compared to 2017 (386 GW) and a compound annual growth rate (CAGR) of nearly 43% since 2000 (IRENA, 2019c).

Considering ample resource availability, significant market potential and cost competitiveness, solar PV is expected to continue driving overall renewables growth in several regions over the next decade. From today's levels, IRENA's REmap analysis shows that solar PV power installations could grow almost six fold over the next ten years, reaching a cumulative capacity of 2 840 GW globally by 2030 and rising to 8 519 GW by 2050.[3] This implies total installed capacity in 2050 almost eighteen times higher than in 2018 (Figure 6). At a global level, around 60% of total solar PV capacity in 2050 would be utility scale, with the remaining 40% distributed (rooftop). While utility-scale projects still predominate in 2050, the REmap analysis expects distributed solar PV installations to grow more rapidly, driven by policies and supportive measures, as well as consumer engagement in the clean energy transformation. Recent trends in distributed solar PV and its benefits are explored in Box 1 below.

3 In the REmap analysis, installed solar PV capacity includes utility-scale (60–80%), distributed rooftop (40–20%) and increased electricity access.

Figure 6: Compared to 2018 levels, cumulative solar PV capacity is expected to grow sixfold by 2030, with a CAGR of nearly 9% up to 2050



Sources: Historical values based on IRENA's renewable energy statistics (IRENA, 2019c) and future projections based on IRENA's analysis (2019a).

RAPID GROWTH IN SOLAR PV INSTALLATIONS TO 2050

The global installed capacity of solar PV would rise six-fold by 2030 (2 840 GW) and reach 8 519 GW by 2050 compared to installations in 2018 (480 GW).

Box 2. DEPLOYMENT OF ROOFTOP SOLAR PV SYSTEMS FOR DISTRIBUTED GENERATION

Distributed energy resources (DER) are small or medium-sized power sources that are mainly connected to the lower voltage levels of the system (distribution grid), near the end users. They can potentially provide services to the power system (European Commission, 2015). In the context of solar PV, distributed generation comes from plants connected at low and medium voltages, such as solar PV panels on rooftops.

The deployment of rooftop solar PV systems has increased significantly in recent years, as has distributed storage, in great measure thanks to supporting policies, mainly net metering and fiscal incentives, and falling costs. For example, behind-the-meter storage business models allow consumers to store the electricity generated by rooftop solar PV and consume it later when needed or sell it to the grid.

In 2018 distributed-scale solar PV capacity additions amounted to approximately 43 GW (IEA, 2018a). China represents the leading solar market not only in Asia, but also in the world, with distributed plants contributing 47% of the capacity installed in 2018. Distributed solar has been growing in India as well, where installed rooftop capacity reached 6 GW in 2018, representing the addition of over 2.5 GW over the previous year (SolarPower Europe, 2019a). This increase, however, is marginal when compared to utility-scale installations in India, which represented 82% of cumulative installed capacity, while distributed represented just 10%. As such, policy support is required to intensify off-grid and rooftop installations across the country.

Another player in the region is the Republic of Korea, which has made the expansion of distributed power production a policy goal for its energy planning. This is to overcome issues related to its mountainous terrain, which makes the development of large utility-scale PV plants difficult. The national energy plan aims to increase distributed power generation to reach 18.4% of total generation by 2030, compared to the current 11.2% (SolarPower Europe, 2019a).

In Latin America, Mexico has witnessed strong growth in installed solar capacity, also thanks to a boom in distributed solar – it currently has more than 100 000 solar roofs on homes and on industrial and commercial buildings. The competitiveness of distributed solar is supported by its low installation costs and savings of up to 95% per month on the electricity rates paid by users (SolarPower Europe, 2019a). Distributed solar PV has grown significantly in Brazil as well, where newly added capacity amounted to 390 MW in 2018, mainly due to the increasing competitiveness of the net-metering regulation throughout the country. According to the Brazilian Solar Energy Association (ABSOLAR), this growth is expected to more than double in 2019 (SolarPower Europe, 2019a)

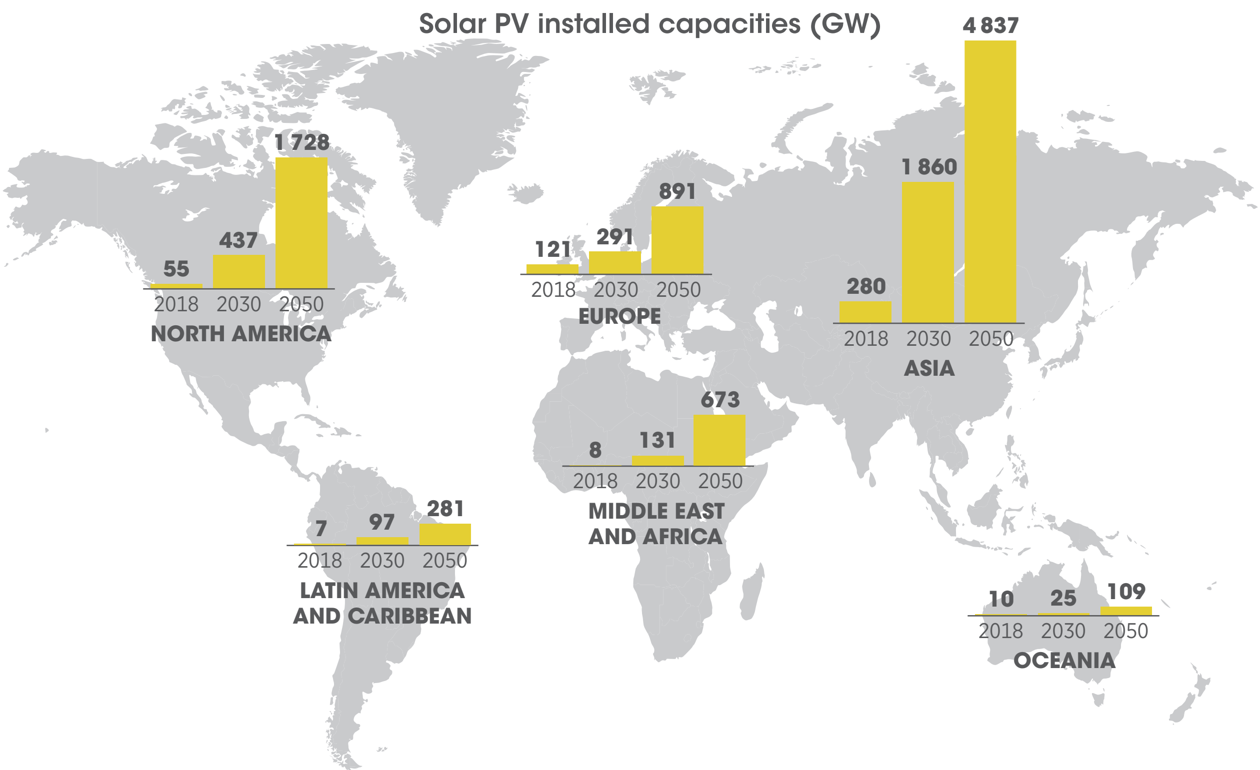
Globally investment in small-scale distributed solar PV systems (smaller than 1 megawatt [MW]) amounted to USD 36.3 billion in 2018, a decrease of 15% from 2017 levels. Whilst Germany, Australia, India, Japan and the Netherlands remained significant markets at over USD 1 billion each, the United States, which is the biggest market for small-scale solar, witnessed a decrease of 15% year on year to USD 8.9 billion (REN21, 2019).

There are several examples of DER increasingly being deployed globally. For instance, the sonnenCommunity is an aggregator in Germany consisting of about 10 000 customers with solar PV generation, battery storage, or both. The aggregator was launched in 2015 mostly for peer-to-peer trading as a virtual power plant (VPP), but as of 2017 the VPP became available to the power grid to provide grid services such as frequency regulation. Compared to alternatives, such as pumped hydro storage, this distributed "virtual" storage resource can react very quickly (in sub-seconds), making it a great provider of primary frequency services to grid operators. A small part of this storage is made available to the German power grid. This reduces both variability in renewable generation and expensive grid expansion requirements (IRENA, 2019d).

The global solar market in 2018 was dominated by Asia, accounting for over half of the world's addition of solar capacity. The region's installed solar capacity reached 280 GW by the end of 2018, dominated by China with 175 GW. The European Union represented the world's second-largest solar PV market, mainly driven by Germany with 45 GW cumulative installed capacity by the end of 2018, followed by North America with 55 GW (Figure 7), of which the United States accounted for 90% (IRENA, 2019a).

Under the REmap scenario Asia would continue to lead global solar PV installations, with 65% of the total capacity installed by 2030 (Figure 7). Within Asia significant deployment would be seen in China, where installed capacity is projected to reach around 1 412 GW by 2030. North America would have the second-highest installed solar PV capacity, reaching 437 GW by 2030, with more than 90% of these installations in the United States. Europe would represent the third-highest region by 2030, with 291 GW of solar PV capacity installed. A similar picture is expected on a 2050 horizon, when Asia would still dominate the scene at almost half of the cumulative global capacity installed (4 837 GW). Within Asia, China would dominate the scene, with a CAGR of 9% after 2018 leading to projected capacity of around 2 803 GW by 2050. North America would still have the second-largest installed capacity, reaching 1 728 GW by 2050, with the United States still dominating the region. Europe could still hold the third place among regions in 2050, with 891 GW of total solar PV capacity installed. More than 22% of these installations would be in Germany, where the installed capacity is projected to reach around 200 GW by 2050. Even though installed capacity may remain highest in Asia, North America and Europe, market growth seems likely to shift to other regions, with large markets also expected to emerge in South America and Africa.

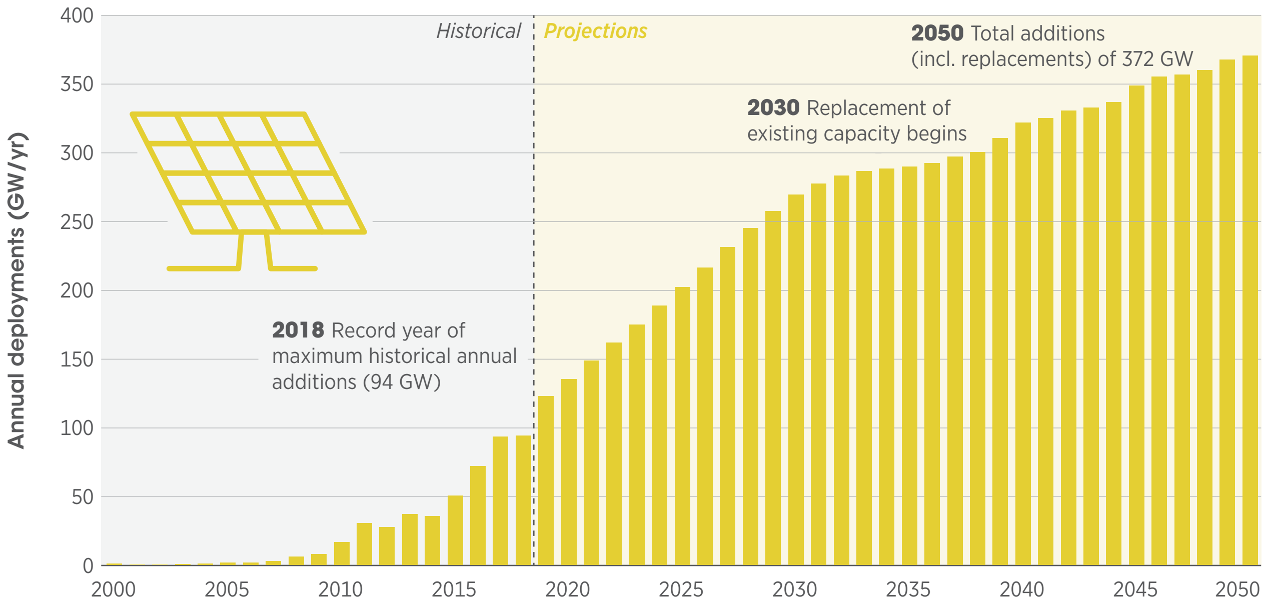
Figure 7: Among the world's regions, Asia is poised to dominate global solar PV installations in the REmap scenario, followed by North America and Europe



Disclaimer: *The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries*

Sources: Historical values based on IRENA's renewable energy statistics (IRENA,2019c) and future projections based on IRENA's analysis (2019a).

Figure 8: Annual Global solar PV additions are expected to reach to 270 GW in 2030 and 372 GW in 2050 under the REmap scenario, compared with 94 GW in 2018



Source: Historical values based on IRENA (2019b) and future projections based on IRENA (2019a).

Annual solar PV capacity gradually increased until 2011, with a drop observed in 2012 (Figure 8). Then annual capacity growth rose and fell until the end of 2014. 2018 marked a record year, when 94 GW of solar PV were added to the global power capacity mix, driven by tremendous cost reductions due to technological enhancements, and policy and supportive measures.

With continuous technological advancement and cost reductions, IRENA foresees the solar PV market growing rapidly over the next three decades. Along with capacity additions, replacement of solar panels at the end of their lifetime is also essential and plays a key role, especially with the benefit of old panels giving way to advanced technologies. Annual capacity additions would more than double by 2030 (270 GW) compared to current levels, and by 2050 are fourfold higher than additions in 2018 (372 GW vs 94 GW per year) (Figure 8).

Currently, annual additions are largely driven by utility-scale projects, reflecting the policies and financial support in various countries. Whilst distributed solar is picking up pace in a few countries, such as Germany, at a global scale distributed levels are still much lower. Mitigating existing barriers and promoting DER are important to scale up solar PV deployment in coming decades. On a positive note, the REmap analysis shows that after 2030, with right market conditions for DER, distributed PV's share of annual additions could start rising and even dominate total PV additions in some countries (see Box 3 above).

SIGNIFICANT GROWTH IN ANNUAL SOLAR PV ADDITIONS TO 2050

Annual capacity additions for solar PV would more than double to 270 GW in 2030, and reach more than 350 GW in the next 30 years, compared to 94 GW added in 2018.

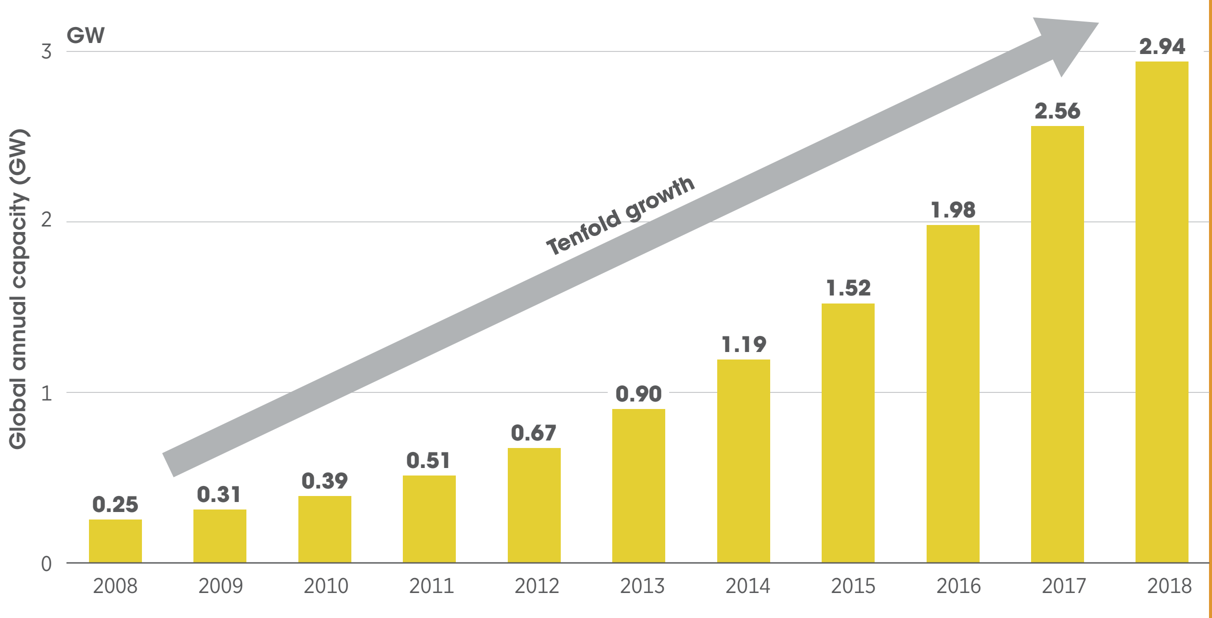
Box 3. SOLAR PV FOR OFF-GRID SOLUTIONS

Off-grid (or stand-alone) applications are typically used where there is no electric grid or when the cost of connecting to the grid is high. Applications are normally smaller than other system types and are often used for small-scale projects in rural areas, as a solution in developing countries, as well as for residential households willing to disconnect from the grid (typically not the most economic or efficient option) (IRENA, 2017a).

A key feature of off-grid renewable energy solutions is that they offer rapidly deployable, reliable and, in many cases, the most economically sustainable option to address the need for energy access (IRENA, 2018b). They can efficiently increase the resilience of energy systems, improve energy security, empower communities, reduce local and regional CO_2 emissions and, depending on which systems are adopted, foster energy price decreases (IRENA, 2019e).

Thanks to its modular and distributed nature, solar PV can be adapted to a wide range of off-grid applications and to local conditions, ranging from lanterns to household systems to village-powering mini-grids. In the last decade (2008–18), the global installed capacity of off-grid solar PV has grown more than ten times, from roughly 0.25 GW in 2008, to 2.94 GW in 2018 (Figure 9). Currently, off-grid solar solutions constitute about 85% of all off-grid energy installations, comprising of solar home systems (about 50%) and solar lanterns/solar lighting systems (about 35%). This is followed by rechargeable batteries (10%) and mini-grids (2%) (IEA et al., 2019).

Figure 9: Global power capacity, off-grid solar PV, 2008–18



Source: IRENA (2019a).

The convergence of several factors has enabled such rapid growth. Firstly, the rapid decrease of PV module costs has meant that off-grid solar PV solutions are now a cost-competitive choice for expanding energy access. Since 2009 such costs have fallen by more than 80%, while globally the cost of solar PV power declined by 73% from 2010 to 2017 (IRENA, 2018b). Secondly, the decrease in technology costs has unlocked innovation in the delivery models and financing models to make technologies and energy services accessible and affordable over the long term. This is the case in East Africa (especially Kenya), which has devised different delivery models to reach unelectrified communities. Smaller systems, such as solar lights, are predominantly based on direct cash sales, while larger systems have been deployed through lease-to-own or fee-for-service approaches (IRENA, 2018b). Thirdly, because of accelerated deployment, investment in the off-grid renewables sector has also grown strongly. Since 2014 annual investment in the stand-alone sector increased to reach USD 284 million by 2017, and investment in the mini-grid sector grew from USD 16 million in 2015 to USD 81 million in 2018 (IRENA, 2018b).

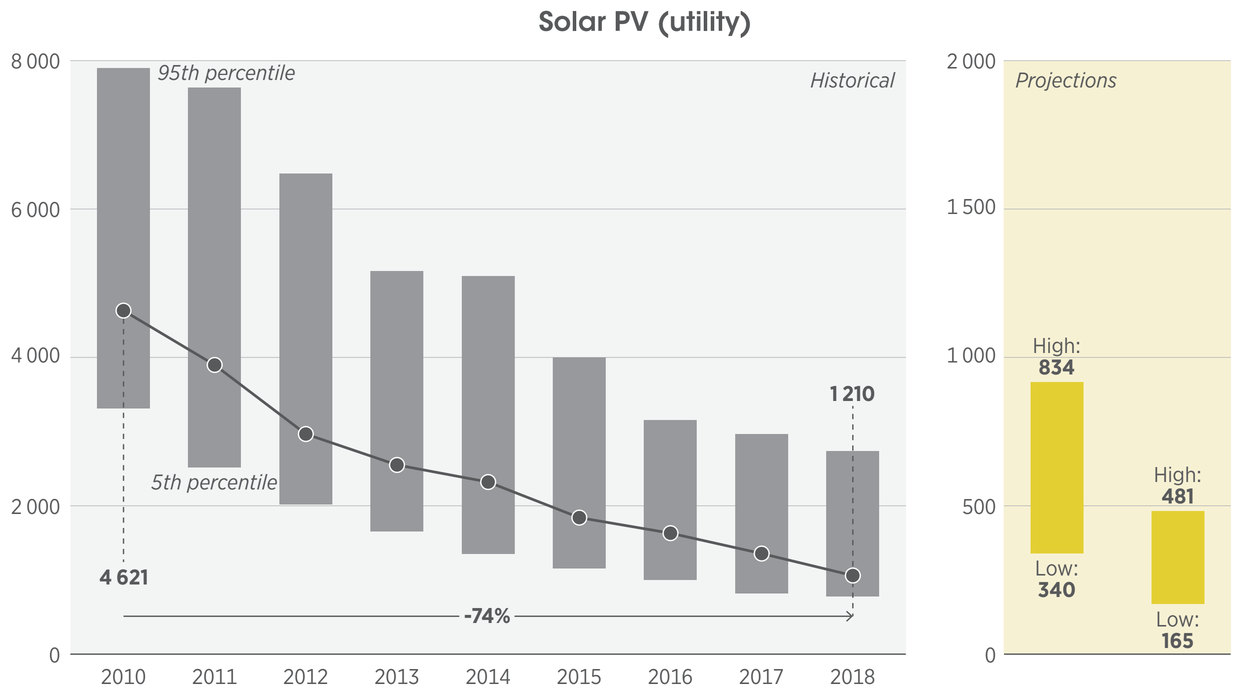
In the REmap analysis 100% electricity access is foreseen by 2030, in line with the Sustainable Development Goals, and solar PV would be the major contributor to this achievement.

STRONG BUSINESS CASE FOR A SIGNIFICANT FUTURE SOLAR PV MARKET

The breakthrough in renewables capacity additions over past few years has largely been achieved due to significant cost reductions driven by enabling government policies, including deployment policies, research and development (R&D) funding, and other policies that have supported the development of the industry in leading countries. Key renewable technologies, such as solar PV, wind, CSP and bioenergy, are already cost competitive and costs are expected to reduce further, outpacing fossil fuels by 2020 (IRENA, 2019f).

Solar PV is emerging as one of the most competitive sources of new power generation capacity after a decade of dramatic cost declines. A decline of 74% in total installed costs was observed between 2010 and 2018 (Figure 10). Lower solar PV module prices and ongoing reductions in balance-of-system costs remain the main drivers of reductions in the cost of electricity from solar PV (IRENA, 2019f).

Figure 10: There has been a rapid decline in total installed costs of solar PV, with costs expected to further decline by 2050



Note: *Future projected value denotes the range in which the global weighted average installed cost of utility scale solar PV projects can fall by 2050. The costs in the figure above represents the total project costs including cost of non-module hardware (i.e. cabling, racking and mounting, safety and security, grid connection, monitoring and control), of installation (i.e. mechanical and electrical installation, inspection), soft costs (i.e. incentive application, system design, permitting, customer acquisition, financing costs and margin)*

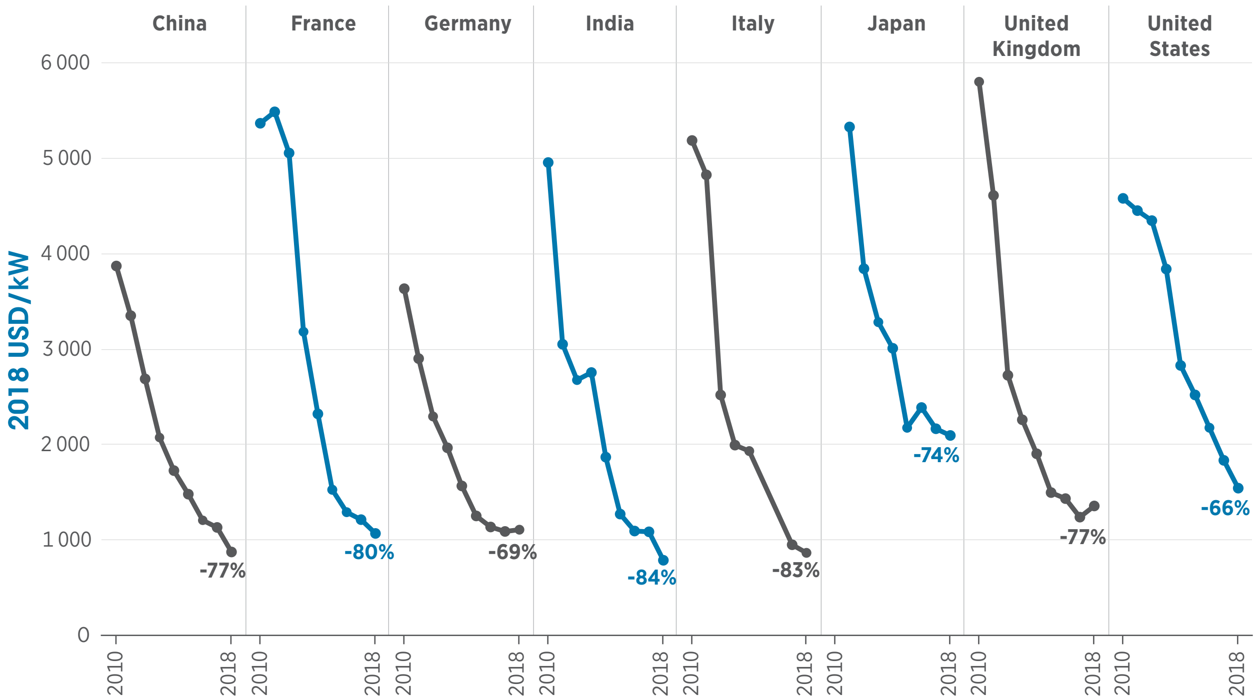
Sources: Historical data based on (IRENA,2019c) and future projections based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, forthcoming a)

SOLAR PV INSTALLATION COSTS WOULD DECLINE DRAMATICALLY FROM NOW TO 2050

Globally, the total installation cost of solar PV projects would continue to decline dramatically in the next three decades, averaging in the range of USD 340 to USD 834/kW by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018.

At a country level, the average total installed cost of utility-scale solar PV projects has declined by between 66% and 84% in major markets during the period 2010–18 (Figure 11). Germany and France witnessed a reduction of 71%, while others have experienced reductions closer to 80%, such as China and Italy (77% and 78% respectively). India was estimated to have the greatest reduction, estimated at 80% (IRENA, 2019e).

Figure 11: Total installed cost of utility-scale solar PV, selected countries, 2010–18

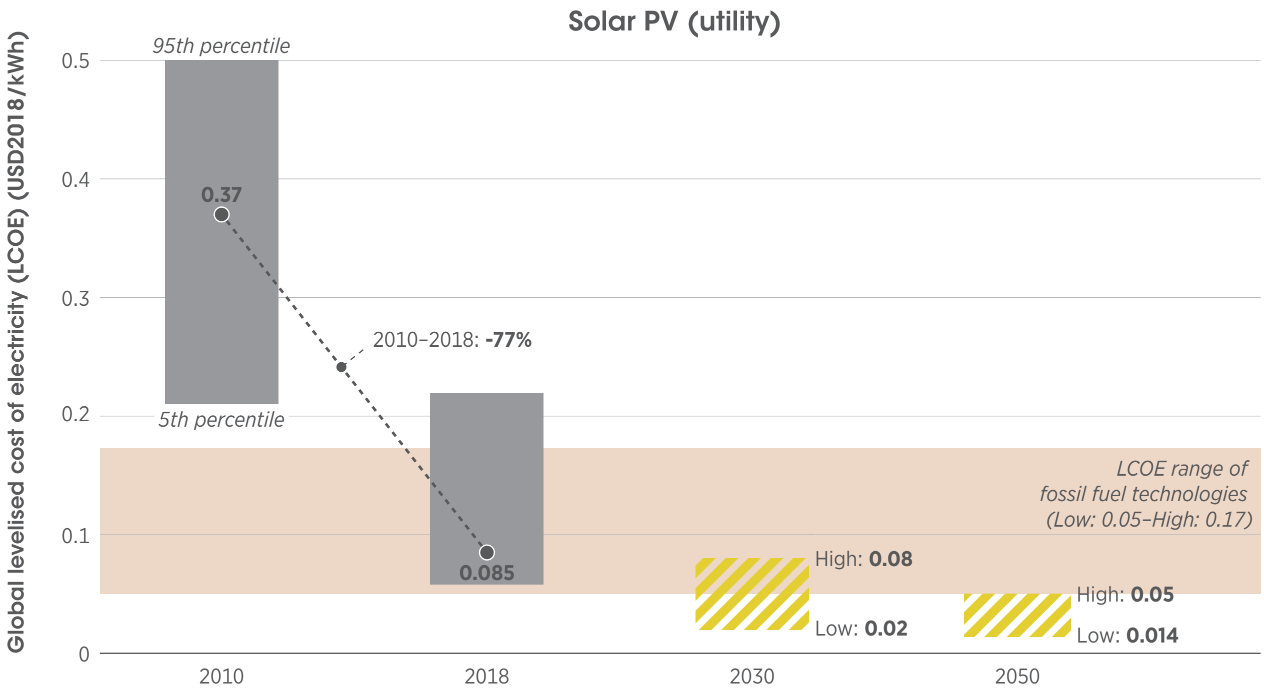


Source: IRENA (2019f).

Alongside the decrease in installed costs, the global weighted average capacity factor of utility-scale PV systems has been increasing. Between 2010 and 2018 capacity factors increased from an average of 14% to 18%. There are three major drivers for these increases: 1) the trend towards greater deployment in regions with higher irradiation levels, 2) the increased use of tracking systems, and 3) improvements in the performance of systems as losses have been reduced, for instance though improvements in inverter efficiency (IRENA, 2019f).

Rapid declines in installed costs and increased capacity factors have improved the economic competitiveness of solar PV around the world (IRENA, 2019f). The global weighted average LCOE of utility-scale PV plants is estimated to have fallen by 77% between 2010 and 2018, from around USD 0.37/kWh to USD 0.085/kWh, while auction and tender results suggest they will fall to between USD 0.08/kWh and 0.02/kWh in 2030. **By 2050, solar PV is expected to be among the cheapest sources of power available, particularly in areas with excellent solar irradiation, with 2050 costs in the range USD 0.014–0.05/kWh** (Figure 12).

Figure 12: The levelized cost of electricity (LCOE) for solar PV is already competitive now compared to all fossil fuel generation sources and would be fully competitive in a few years.



Note: Historical data represent cost of new installations in a specific year and future projected value denotes the range in which the global weighted average LCOE of utility-scale solar PV projects fall by 2050; the capacity factor is assigned to projects that come into operation in a specific year and remains same through the life cycle of a project; LCOE for fossil fuel technologies refers to new capacity/new deployment.

Sources: Historical data based on (IRENA,2019c) and future projections based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, forthcoming a)

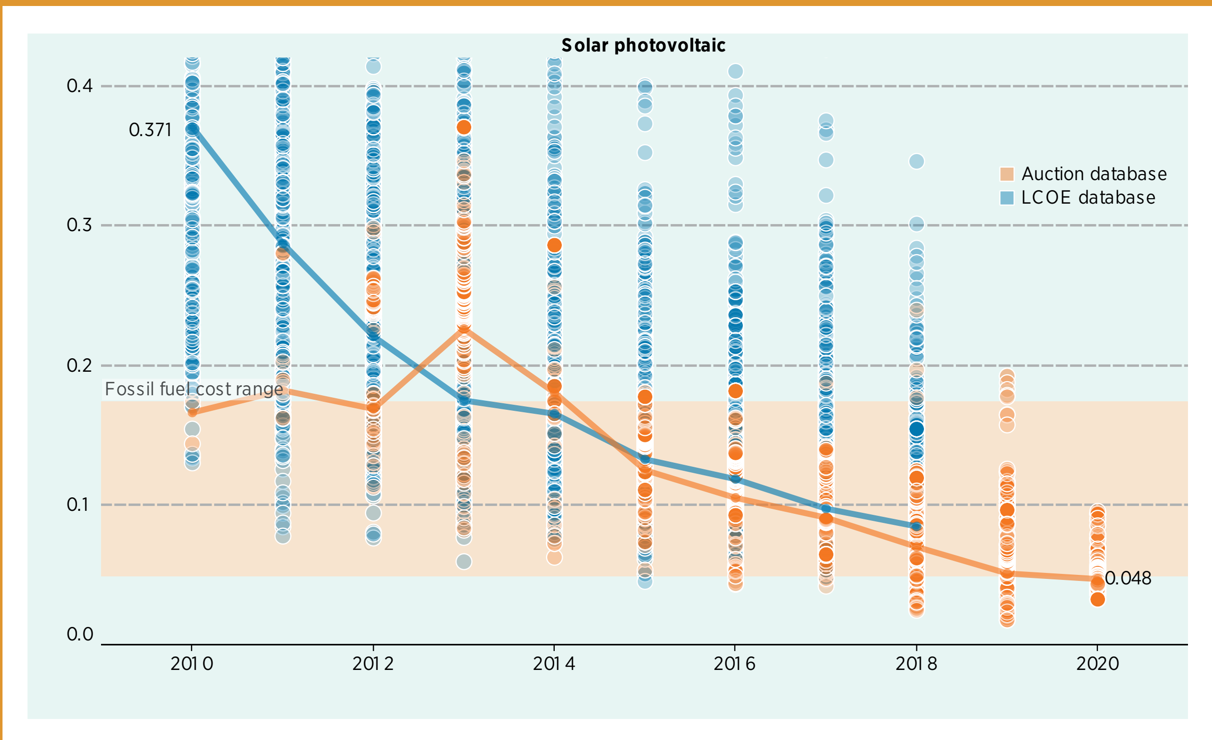
SOLAR PV WOULD BE ONE OF THE CHEAPEST GENERATING SOURCES

The levelized cost of electricity for solar PV is already competitive now compared to all generation sources (including fossil fuels) and is expected to decline further in the coming decades, falling within the range of USD 0.02 and 0.08/kWh by 2030 and USD 0.014 0.05/kWh.

Box 4. CURRENT AUCTION AND PPA DATA FOR SOLAR PV AND THE IMPACT ON DRIVING DOWN LCOES

IRENA'S database of power purchase agreement (PPA) and auction results suggests that the cost of solar PV generation will continue to fall out to 2020. Although care must be taken in comparing PPA and auction results with LCOE calculations, for utility-scale solar PV the auction data suggest that the average price of electricity could fall to USD 0.048/kWh in 2020, a reduction of 44% compared to the global weighted average LCOE of projects commissioned in 2018. This would mean a cost decline rate of 25% per year (an acceleration over recent cost reduction trends).

Figure 13: The LCOE for projects and global weighted average values for solar PV, 2010–20



Source: IRENA Renewable Cost Database 2019

Various aspects play a role in driving down generation costs for the technology. Markets with higher-than-benchmark total installed costs are likely to experience cost reductions as they benefit from competitive procurement. As new markets emerge and mature in regions with plentiful solar resources, higher capacity factors can be expected for projects commissioned there compared to less sunny regions in classic historical markets. Finally, as the bankability of solar PV projects has increased with time, so has the access to lower-cost financing.

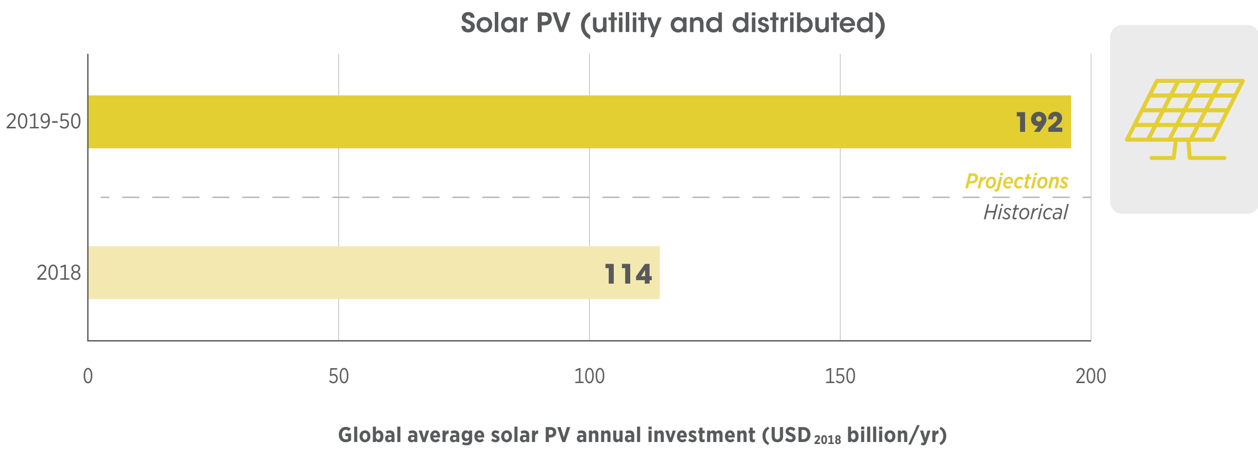
Note: For a detailed discussion of the challenges of comparing PPA and auction data to LCOE calculations, and how IRENA corrects or excludes data for the comparison in Figure 13, see IRENA (2019f).

INVESTMENT NEEDS

The total volume of investment in solar PV is being heavily influenced by the technology's falling costs. It rose steadily from USD 120 billion in 2013 to reach record high levels of USD 179 billion in 2015 as deployment accelerated faster than falling costs. Since then the balance between these two factors has oscillated: in 2016 total investment fell to USD 141 billion, before rising in 2017 to USD 171 billion on the back of a significant increase in capacity additions, before falling again to USD 131 billion in 2018 as new additions remained more or less the same as in 2018, while costs continued to fall (BNEF, 2019). China saw a gradual increase in solar PV investment between 2005 and 2015, reaching record high levels of USD 89 billion in 2017 before dropping to USD 40 billion in 2018. In North America, investment increased steadily between 2012 and 2015, when they reached USD 34 billion, before dropping again between 2016 and 2018, when they amounted to USD 25 billion (BNEF, 2019). **In 2018, investments made in deploying solar PV capacities accounted to nearly USD 114 billion.**

Deploying a total installed capacity of more than 8 000 GW of solar PV by 2050 would necessitate cumulative investment of nearly USD 6.4 trillion from now until 2050. This would translate into annual average investment of USD 192 billion per year over the period to 2050. That represents scaling up annual investment by around 68% from now until 2050 compared to solar PV investment in 2018 (Figure 14).

Figure 14: Scaling up solar PV energy investment is key to accelerate the pace of global solar PV installations over the coming decades.



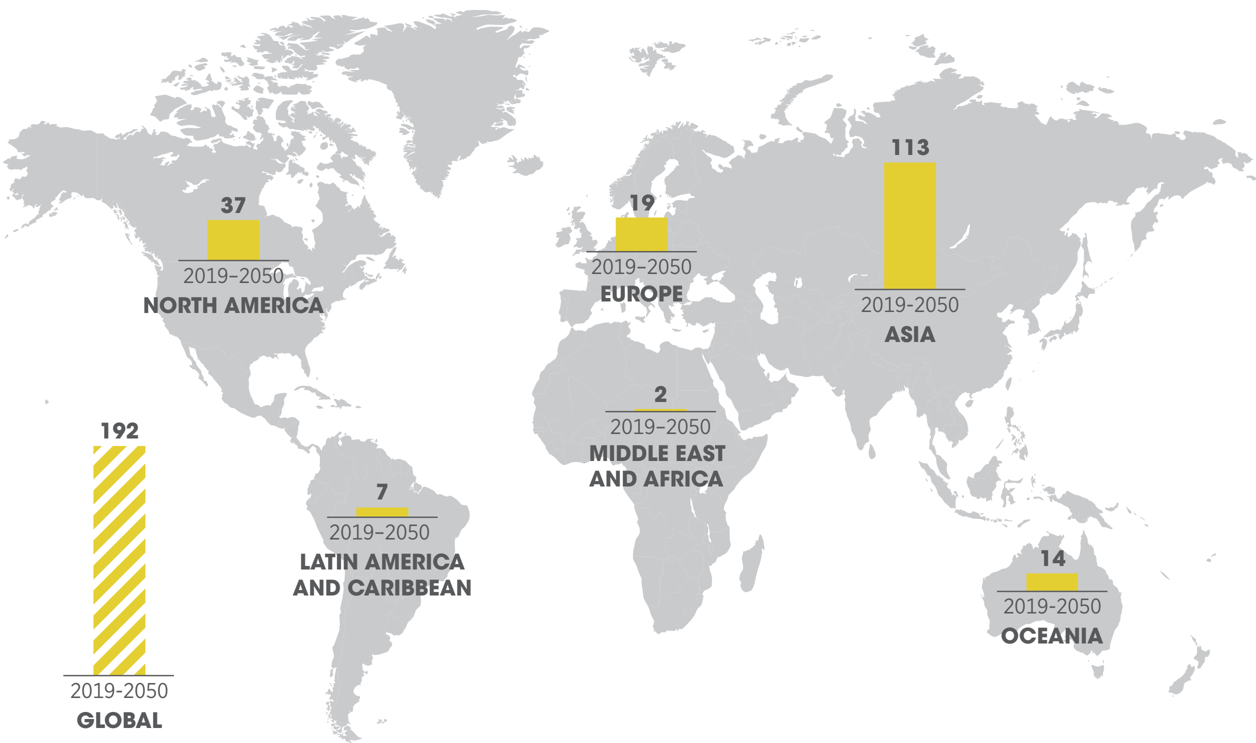
Source: based on IRENA's analysis

SCALING UP SOLAR PV INVESTMENT IS KEY TO FACILITATE THE UPTAKE OF THE SOLAR PV MARKET

Global average annual solar PV investment needs to scale up by 68% until 2050 (USD 192billion/year) compared to 2018 investment (USD 114 billion/year).

At the regional level the major share of global investment would shift to Asia, with USD 113 billion per year from now until 2050, and China and India at the forefront accounting for approximately 57% and 18% of total annual investment respectively. Asia is followed by North America at USD 37 billion per year and then Europe at USD 19 billion per year (Figure 15).

Figure 15: Regional annual investment in solar PV capacity (new and replacement), 2019–50 (USD billion/yr)



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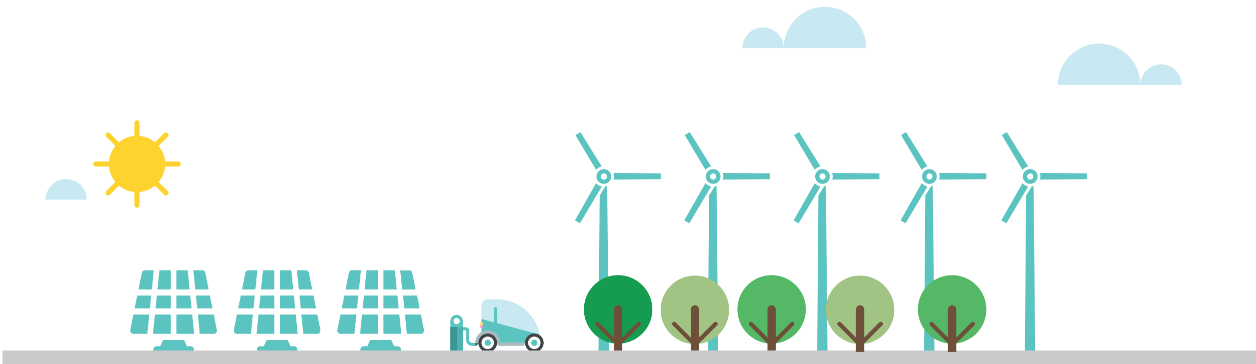
Source: IRENA's analysis.

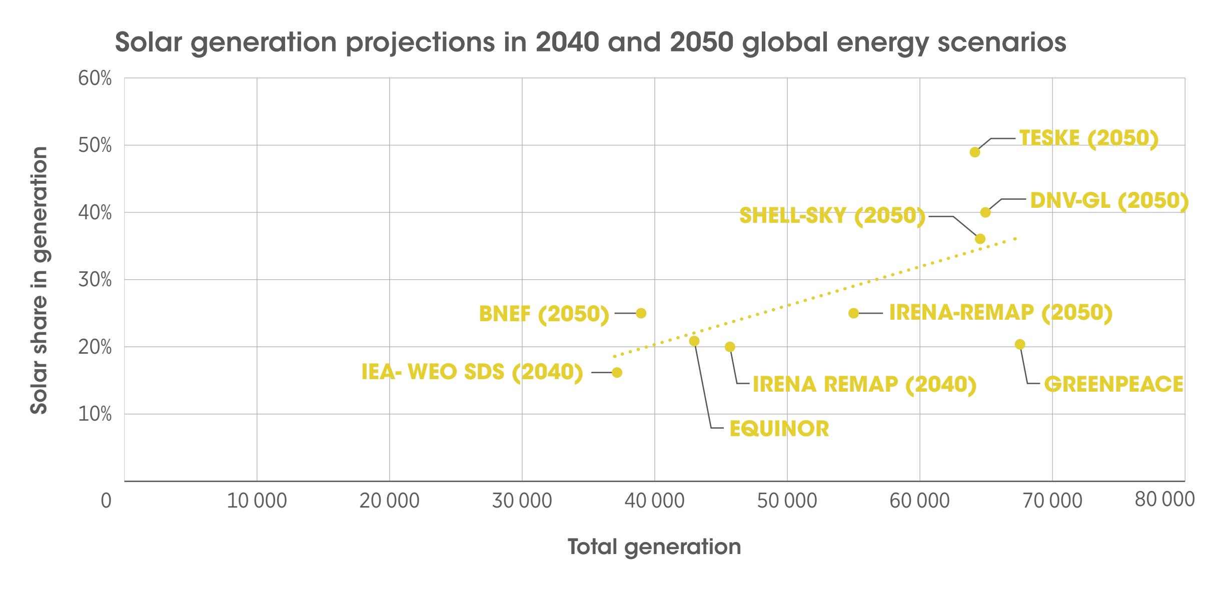


Box 5. THE FUTURE POTENTIAL OF SOLAR: COMPARISON WITH OTHER ENERGY SCENARIOS

Analysis of energy scenarios shows an increasing consensus on the important role that solar power will play in the energy mix in the coming decades.

A comparison analysis also shows a correlation between total power generation and the share of solar power generation in the total generation mix – the scenarios with high solar power generation shares are also the ones with high total power generation. In IRENA's REmap Case solar is foreseen to represent only 25% of total generation, because a stronger emphasis is given to other renewable sources, notably wind, which represents 35% of total generation by 2050. A high solar share can be found in the Teske scenario at 49%, followed by DNV-GL at 40%, and the Shell-Sky scenario at 36% (Figure 16).

Figure 16: Solar generation projections in 2040 and 2050 global energy scenarios



The comparison also suggests that the goal of the limiting temperature increase to well below 2°C would be most achievable with lower overall energy demand, while achieving the 1.5°C target would also require significant structural and lifestyle changes.

Despite the similarities, differences can also be found between the scenarios in aspects such as the level of electrification in end-use sectors and reductions in CO_2 emissions. The divergence in results can mainly be explained by the different objectives behind the scenarios. For many, the analysis is defined by the need to reduce energy-related CO_2 emissions to limit temperature increase to between 2°C and 1.5°C. Others have modelled the energy system in a more conservative (business-as-usual) way.

3. TECHNOLOGICAL SOLUTIONS AND INNOVATIONS TO INTEGRATE RISING SHARES OF SOLAR PV POWER GENERATION

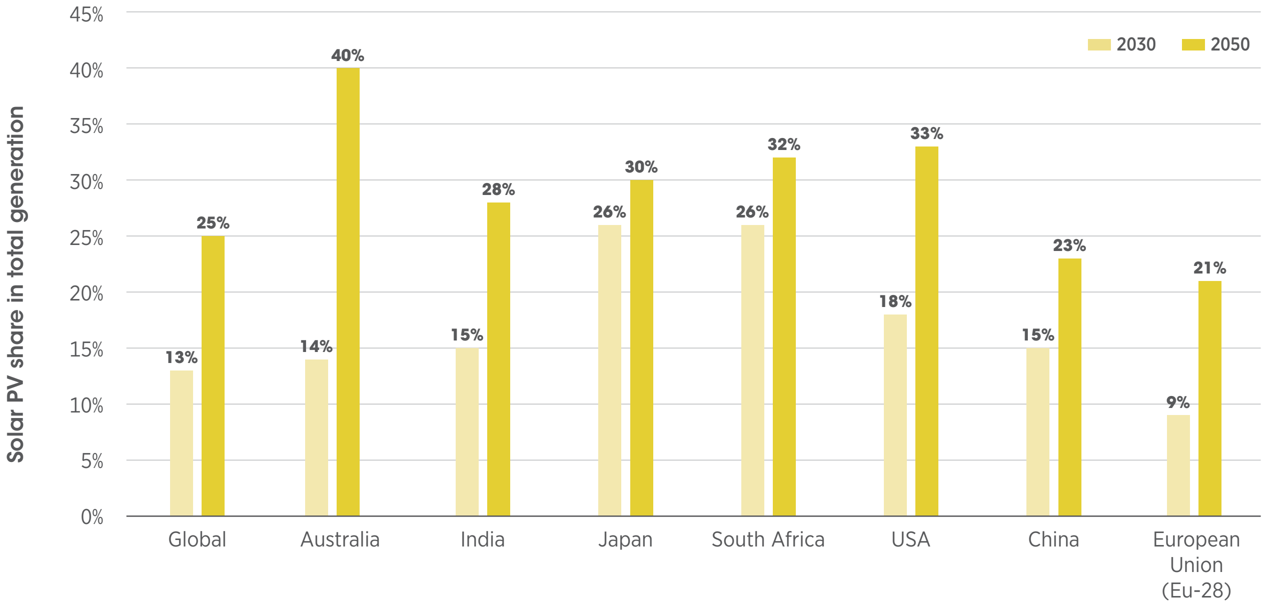
The variable nature of the solar and wind resources will require significant changes to the way the power system operates as the share of variable renewable energy (VRE) reaches high levels in different markets. This will, in particular, require adequate measures to maintain grid stability and reliability. Changes will be needed to the operation and management of the grid on a minute-by-minute basis, while also taking into consideration seasonal variations in solar and wind output.

In an age of low-cost renewable power generation, the success of the energy transition will be underpinned by strategies to integrate high shares of VRE into power systems at the lowest possible cost. At present the share of VRE in the generation mix of the G20 countries is about 10%. Some countries, particularly in Europe, have achieved much higher shares: in 2017 the VRE share in Denmark reached 53%, in South Australia 48%, and in Lithuania, Ireland, Spain and Germany over 20% (IRENA, 2019b).The three largest power systems in the world – China, India and the United States – are expected to double their VRE shares to more than 10% of annual generation by 2022 (IRENA, IEA and REN21, 2018). India met 7.7% of its load with VRE generation between 2017 and 2018 and was on track to reach 9% by 2019. In the United States 7.6% of its electricity came from wind and solar in 2017 (IRENA, IEA, REN21, 2018).

Under the REmap Case, the global share of wind and solar generation increases to 34% by 2030 and to 60% by 2050. This growth in VRE power requires new power market rules and procedures, markets for short-term balancing and flexibility needs, and adequate firm capacity to manage periods of low solar and wind output. It will also require new business models and technical solutions for both the supply and demand sides, such as through the use of aggregators and the deployment of new technologies, including behind-the-meter batteries and demand response (IRENA, 2019d). Deployment of adequate system flexibility measures (Box 6) together with the extension and reinforcement of power grids will be essential to managing the higher shares of VRE generation projected in the REmap Case by 2050.

Based on IRENA's REmap Case, the solar PV share of global power generation would reach 13% by 2030 and 25% by 2050. At the country level, in 2030 Japan and South Africa would both have the highest share of solar power in their electricity mix at 26%, followed by the United States at 18% and India and China both at 15%. In the 2050 horizon, the picture would change significantly: Australia would have the highest solar power share at nearly 40%, followed by the United States at a 33% solar share, South Africa at 32% and Japan at 30% (Figure 17).

Figure 17: A higher penetration of solar power in electricity grids is foreseen in various countries by 2030 and 2050



Source: IRENA (2019a)

IRENA estimates that investment in grids, generation adequacy and some flexibility measures (such as storage) across the entire electricity system would total USD 13 trillion for the period 2016–50 (USD 3 trillion higher than in the Reference Case) to integrate 60% variable renewables (25% solar generation) by 2050 (Figure 19). Nearly two-thirds of the incremental investment in the REmap Case over the Reference Case is needed to extend or enhance transmission and distribution grids, while the remaining investment is needed for power system adequacy and flexibility measures (including storage) along with subsequent investment in smart meter deployment (IRENA, 2019a; IRENA,2019b). In annual terms, more than one-quarter increase in average annual investments would be needed to USD 374 billion/year over the period to 2050 (IRENA, 2019b), compared to investments made in electricity networks and battery storage in 2018 (USD 297 billion/year) (IEA, 2018b).

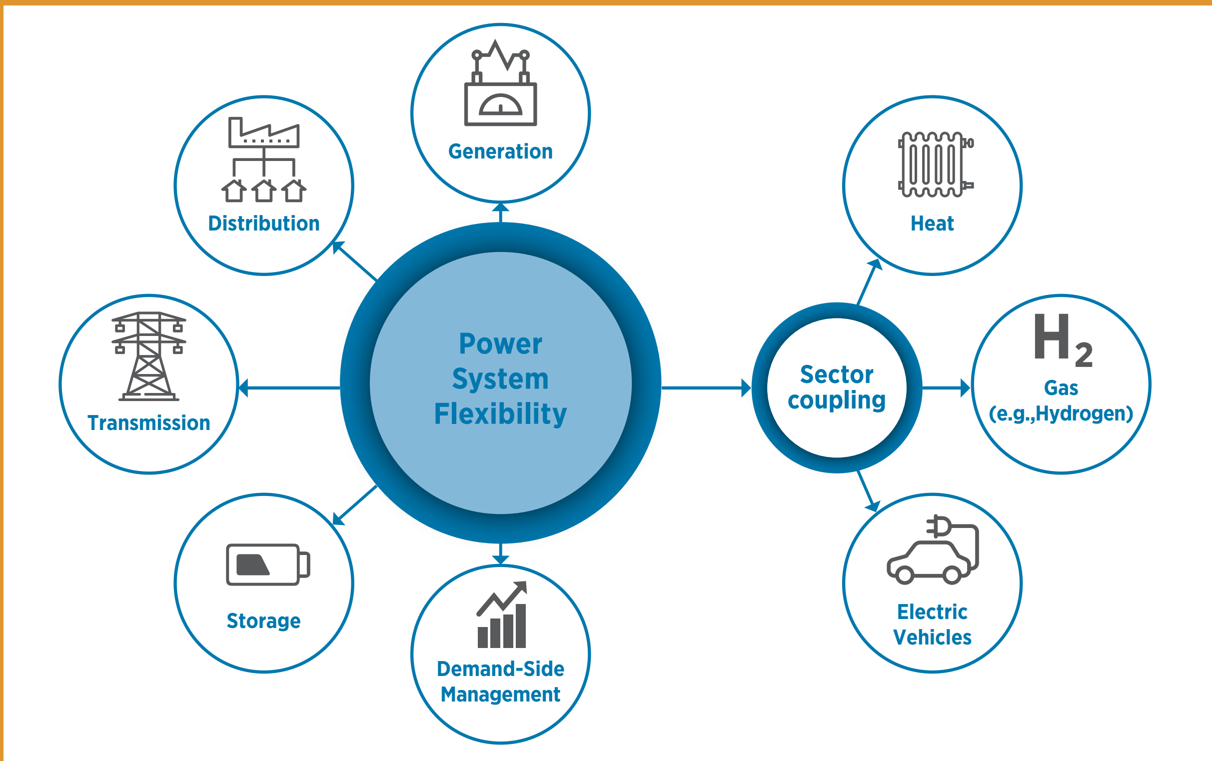
Given the complexity of developing a global model that addresses medium- and long-term planning for VRE and overall power system development, a high-level approach has been applied to identify potential power systems issues in the REmap Case in 2050. Additional investment required to address these issues has been estimated at the global level, based on a bottom-up analysis of the G20 countries. Reinforcement, replacement and expansion of grids are considered to supply projected electricity demand towards 2050 (IRENA, 2019a).

Storage contributes to adequacy and flexibility and is assumed to be widely deployed. This includes some additional pumped hydropower capacity and battery storage as part of decentralised power generation, dedicated utility-scale batteries and also the use of some electric vehicle (EV) battery capacity to support the grid through vehicle-to-grid (V2G) services. By 2050, around 14 TWh of EV batteries could be available to provide grid services, compared to just 9 TWh of stationary batteries (IRENA, 2019g). Hydrogen is certainly one of the emerging technologies that could potentially contribute to the flexibility of power system, acting as “seasonal storage” thereby aiding in integrating high shares of variable renewables. IRENA sees a global economic potential for 19 EJ of hydrogen from renewable electricity in total final energy consumption by 2050. This would translate into 5% of total final energy consumption and 16% of all electricity generation being dedicated to hydrogen production in 2050 (IRENA, 2019h).

Box 6. POWER SYSTEM FLEXIBILITY TO INTEGRATE A RISING SHARE OF VRE

To effectively manage large-scale VRE deployment, flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (demand-side management and sector coupling).

Figure 18: Power system flexibility enablers in the energy sector

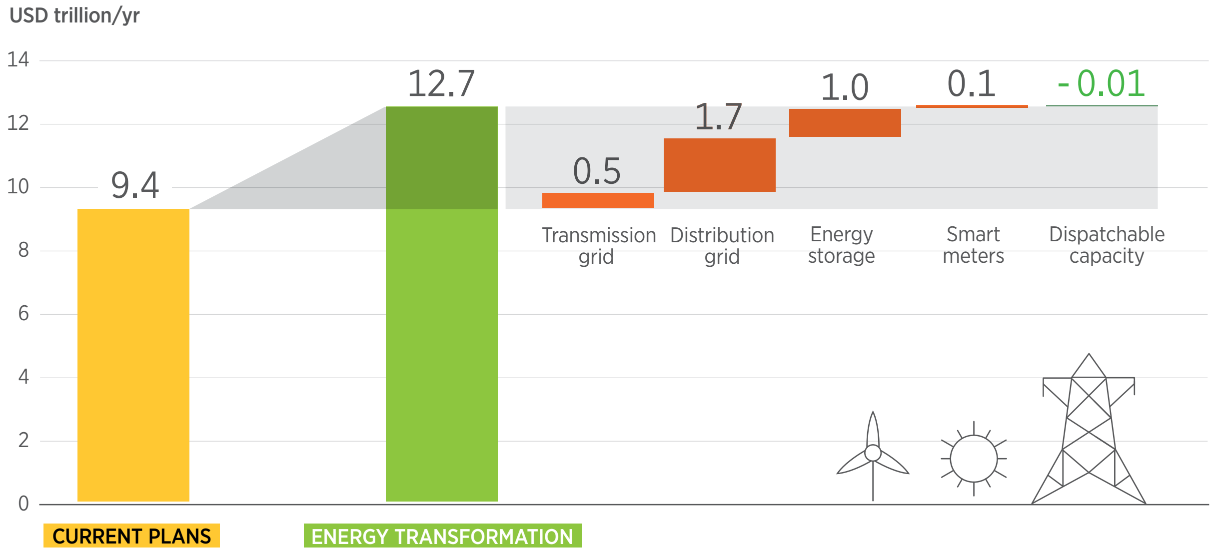


In conventional power systems, flexibility has mainly been provided by generation, with dispatchable generators adjusting their output to follow demand and, if available, pumped hydro dealing with inflexible baseload and reducing the need for power plants to cover peak demand. Important progress has been made in recent years towards increasing the flexibility of conventional power plants, as the demand side was largely unresponsive and provided very little flexibility. Emerging innovations are not only further increasing flexibility on the supply side but are now also widening the availability of flexibility to all segments of the power system, including grids and the demand side (IRENA, 2019d).

Electric Vehicles (EVs) leads way to unleash synergies between low carbon transport mode and renewable electricity generation contributing to “Sector Coupling”. EV fleet could be used as electricity storage option contributing to improved flexibility of power systems with raising shares of variable renewable sources. If unleashed starting today, the use of EVs as a flexibility resource especially via smart charging approaches would reduce the need for additional investment in flexible, but carbon-intensive, fossil-fuel power plants to balance system with renewables (IRENA, 2019g).

Hydrogen contributes to “sector coupling” between the electricity system and industry, buildings and transport, increasing the level of flexibility while facilitating the integration of VRE into the power system. The gas grid can also be decarbonised via renewable hydrogen by taking advantage of low electricity prices, providing seasonal storage for solar and wind, and providing grid services from electrolysers (IRENA, 2019h).

Figure 19: Additional investments are required in grids, generation adequacy and some flexibility measures (such as storage) across the entire electricity system to integrate raising shares of variable renewable sources.



Note: Investment needs for other flexibility resources, including power-to-heat, power-to-hydrogen, demand-side management and thermal storage, are not considered in this estimation.

Source: (IRENA, 2019m)

The optimal strategy for integrating even higher shares of VRE is country- and context-specific. Solutions emerging from the synergies among innovations across all dimensions of the system would make it possible to create reliable and affordable power systems that are based predominantly on renewable energy (Box 7). These innovations offer a broader portfolio of solutions that can be combined and optimised to reduce costs and maximise system benefits (IRENA, 2019d).

Box 7. INNOVATION LANDSCAPE TO INTEGRATE HIGH SHARES OF VRE

IRENA's work confirms that there is no single game-changing innovation for integrating large amounts of VRE into the power system. Innovations in all the segments of the power sector are needed. IRENA has investigated the innovation landscape, identifying and clustering 30 transformative innovations across four dimensions: enabling technologies, business models, market design and system operation (see Figure 20).

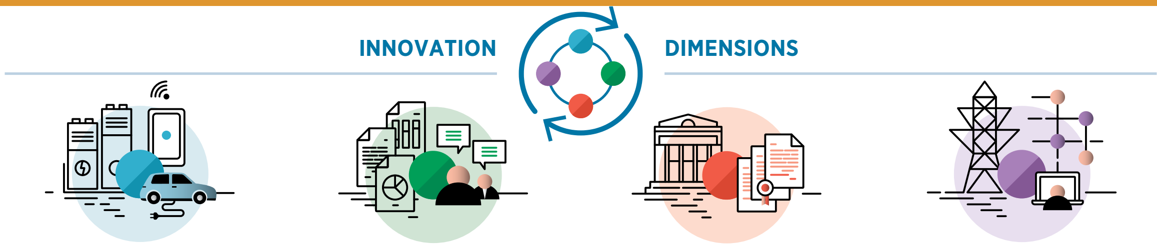
Enabling technologies: battery storage, demand-side management and digital technologies are changing the power sector, opening doors to new applications that unlock system flexibility. Electrification of end-use sectors is emerging as a new market for renewables, which could also provide additional ways of flexing demand if applied in a smart way.

Business models: innovative business models are key to monetising the new value created by these technologies and therefore enable their uptake. At the consumer end, numerous innovative business models are emerging, alongside innovative schemes that enable renewable electricity supply in places with limited options, such as off-grid or densely populated areas.

Market design: adapting market design to the changing paradigm – towards low-carbon power systems with high shares of VRE – is crucial for enabling value creation and adequate revenue streams.

System operation: with new technologies and sound market design in place, innovations in system operation are also needed and are emerging in response to the integration of higher shares of VRE in the grid. These include innovations that accommodate uncertainty and the innovative operation of the system to integrate DER.

Figure 20: The four dimensions of innovation



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Source: (IRENA, 2019d)

4. SUPPLY-SIDE AND MARKET EXPANSION

4.1 TECHNOLOGY EXPANSION

Solar PV power is one of the fastest-growing energy resources in the world and is now the second most-deployed renewable energy technology in the world by installed capacity, after wind. Despite the unprecedented demand growth in recent years, solar PV modules and inverters have fallen in price, benefiting project developers and disadvantaging manufacturers, who have struggled to sustain margins.

The main components of a solar plant that decision makers may consider manufacturing domestically are the solar cells, solar modules, inverters, trackers, mounting structures and general electrical components (IRENA, 2017b). To avoid skills gaps, however, education and training must be attuned to the emerging needs of the industry. This is crucial, as training and skill building form an important part of efforts to generate capable local supply chains. Variables such as government policies incentivising local value creation, the availability of raw materials and the presence of related industries are important drivers for the local manufacturing of PV components. However, the development of a domestic manufacturing industry for solar PV modules may not be optimal in instances of strong competition, especially when neighbouring countries may be large producers with low prices and overcapacity.

The expansion of solar PV markets, combined with falling prices, has contributed to the emergence of new players in the industry, such as Apple and Tesla (mainly in the manufacturing of modules), while some of the top wind turbine companies, such as Gamesa, Goldwind and Mingyang, have also entered the solar industry.

SOLAR MODULES

The global market for solar module production is highly diversified, although some consolidation among manufacturers is taking place. The majority of the market is held by crystalline silicon (c-Si) module manufacturers, thanks to the maturity of the technology and the lower investment costs due to the fall in the price of polysilicon – its raw material (GlobalData, 2018). The thin-film market, by comparison, has fewer manufacturers and relatively few players have been able to consistently commercialise these products.

In 2017 the Asia-Pacific region dominated the market for solar modules, accounting for the majority of the solar PV modules installed globally (76%). This is followed by the Americas and Europe with a share of 14% and 9.5%, respectively. In 2012 specifically, Europe, the Middle East and Africa all together had a higher rate of installation compared to the Asia-Pacific region due to significant solar module installation in Germany, Italy and Spain. However, following subsidy cuts the annual installation rate fell sharply in Europe and paved the way for the Asia-Pacific region to become the global leader in solar PV installations.

SOLAR INVERTERS

The market for solar inverters is currently in a growth phase, the rising demand for power together and various global initiatives to encourage the implementation of renewable smart grids being the main drivers behind this development.

In 2018 the Asia-Pacific region dominated the market for solar inverters, accounting for 71% of new installations globally. It is expected to continue dominating the market in the next decade thanks to the rising number of installations in China, India and Japan. The Americas were the next largest regions in the global solar PV inverter market, with a market share of approximately 24% and reported solar installations of approximately 15 gigawatts (GW). The solar PV markets in the United States and in Canada continued to grow, and in South and Central America, the focus was Chile. The EMEA solar inverter market was the third-largest globally by value in 2018, accounting for 13%. Germany, France and Italy were the top markets in Europe, and the Gulf Cooperation Council (GCC) countries such as Kuwait, Qatar, Saudi Arabia and the United Arab Emirates were the major markets in the Middle East.

At a country level, China, the United States and India were the top countries, collectively accounting for approximately 70% of global PV inverter installations in 2018. With 44.4 GW of annual installations and 48.7% of the global market, China was the most prominent country in the global solar PV inverter market in 2018. After China, the United States registered annual installation of 10.9 GW, representing 12% of global solar PV inverters installed in 2018. The third-largest market was India, recording annual installation of 8.68 GW in 2018 and accounting for nearly 9.5% of the global market. In all three countries, solar PV and inverter installations have been driven by government support policies and schemes such as net metering and feed-in-tariffs (GlobalData, 2019).

5. FUTURE SOLAR PV TRENDS

This section is designed to highlight the technologies that are driving the solar PV industry, its further development and its potential to significantly impact the energy system. It also explores its challenges as the market growths and diversifies.

The solar PV industry is changing rapidly, with innovations occurring along the entire value chain. In recent years, a major driver for innovation has been the push for higher efficiency (Green, 2019). This is reflected by the expansion of passivated emitter and rear cell/contact (PERC) technology, which offers more efficient solar cells and as such increases the performance of solar panels. Increasing cell efficiency is key for competitive module manufacturing, as it directly decreases cell processing costs by reducing quantities required for a given output.

Efficiency is also very important at the system level, with several factors explaining the push for higher-efficiency technologies. From the technical perspective, higher levels of efficiency reduce the number of modules that need to be transported to the installation site, the necessary land area and the length of wires and cables required. From a marketing perspective, companies able to offer the highest-efficiency modules are also generally perceived as having the highest level of technical expertise (Green, 2019).

The next section explores the innovation progress in the solar PV industry in materials, module manufacturing, applications, operation and maintenance, and in ways of decommissioning panels and managing their end-of-life stage (Figure 20).

Figure 21: Solar PV value chain

5.1 MATERIALS AND MODULE MANUFACTURING

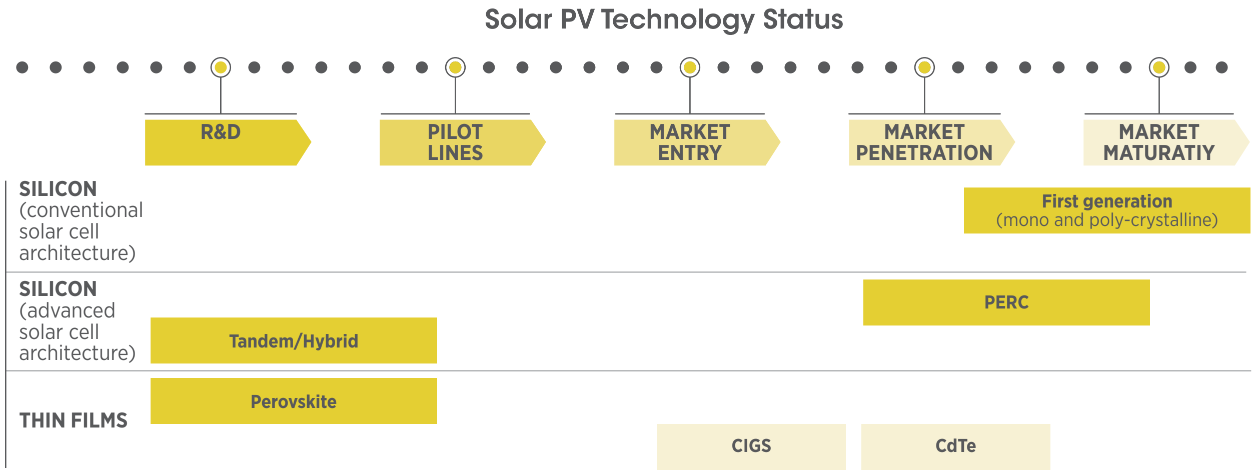
The further growth of the solar PV industry largely depends on reducing the balance of system (BoS), which makes up most of the total installed system costs and has the greatest potential for cost reduction. Ways of achieving this include using cheaper cell materials (and material use reduction), reducing cell manufacturing costs and increasing cell efficiency levels. The following sections highlight major trends in technology improvement.

MATERIALS

Progress in R&D is continuously being made in both existing and emerging technologies, with the aim of achieving further significant cost reductions and performance improvements. A variety of technologies is expected to continue to characterise the PV technology portfolio. First-generation technologies, which have been evolving along the whole PV value chain, still account for the majority of global annual production (Fraunhofer ISE, 2019). Tandem and perovskite technologies also offer interesting perspectives, but in the longer term due to barriers that still need to be addressed and overcome (durability, price).

The Figure 22 gives an overview of the PV technologies and concepts under development that are important in the context of this roadmap.

Figure 22: Solar PV technology status



Notes: CIGS = copper-indium-gallium-diselenide; CdTe = cadmium telluride. PERC = passivated emitter and rear cell/contact

Silicon – conventional solar architecture

Crystalline silicon (c-Si) panels belong to the first-generation solar PV panels and they hold 95% share of worldwide PV production (Fraunhofer ISE, 2019). The economies of scale of its main material, silicon, make c-Si more affordable and highly efficient compared to other materials. Solar panels have improved substantially in terms of their efficiency and power output over the last few decades. The average module efficiency in 2006 was 13.2% for multi crystalline PV panels and 14.7% for mono crystalline PV panels and since then has increased steadily, reaching 17% and 18% respectively. This positive trend is expected to continue through 2030 (Fraunhofer ISE, 2019). The strong competitive position of c-Si in the market thanks to its continually falling cost has made it difficult for other technologies to compete.

However, despite the high-efficiency level of this first-generation PV technology, there remains a lot of scope for improvement, including: 1) lowering the cost of c-Si modules for better profit margins; 2) reducing metallic impurities, grain boundaries, and dislocations; 3) mitigating environmental effects by reducing waste; and 4) yielding thinner wafers through improved material properties (GlobalData, 2019).

SILICON – ADVANCED SOLAR ARCHITECTURE

PERC

A PERC cell uses advanced silicon cell architecture. PERC cells are not much different in construction from a typical monocrystalline PV cell; however, the key improvement is the integration of a back-surface passivation layer, which is a layer of material on the back of the cells that is able to improve the cell's efficiency (Shravan, K. and Chunduri, K., 2018). In fact, the passivation layer increases the overall cell efficiency in three key ways: 1) it reduces electron recombination; 2) it increases absorption of light; and 3) it enables higher internal reflectivity (Marsh, J., 2018). The efficiency gain of implementing PERC architecture for monocrystalline cells is about 0.8% to 1% absolute, while the boost for multicrystalline cells is a little lower, at 0.4% to 0.8% (Shravan, K. and Chunduri, K., 2018).

PERC has started only recently to enter the commercial arena but has quickly become the new industry standard for monocrystalline cells. Several factors have facilitated this remarkable progress, including the major shift of the market towards monocrystalline cells, the improvement in reliability and throughput of production tools, which has consequently improved the passivation quality of the films, and the real momentum in R&D created by the large number of manufacturers now active in PERC production (Shravan, K. and Chunduri, K., 2018).

Tandem/hybrid cells

Tandem solar cells are stacks of individual cells, one on top of the other, that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. Emerging PV technologies comprise several types of tandem cells that can be grouped mainly depending on materials used (*e.g.* organic, inorganic, hybrid) as well as on the kind of connection used. The tandem cell approach has been used to fabricate the world's most efficient solar cells that can convert 46% of sunlight into electricity. Unfortunately, these devices use very expensive materials and fabrication processes, and still cannot break through the market (Cherradi, 2019).

THIN-FILM

Thin film technologies are often referred to as second-generation solar PV. The semiconducting materials used to produce thin-film cells are only a few micrometres thick (IRENA, 2016). These technologies generally include two main families: 1) silicon-based thin film (amorphous [a-Si] and micromorph silicon [a-Si/c-Si]; and 2) non-silicon based (perovskites, cadmium telluride [CdTe] and copper-indium-gallium-diselenide [CIGS]). These technologies can be cheaper to produce, as such they are being deployed on a commercial scale, but they have historically had lower efficiency levels.

Thin-film technology for large-scale power generation gained prominence around 2006, when the cost of silicon rose due to increased demand. Thin-film modules, therefore, made more economic sense despite their low efficiency. However, by 2012 the falling silicon prices, combined with the falling price of highly efficient c-Si modules, have shifted production towards c-Si technology. Whilst first-generation crystalline silicon-based PV has therefore consolidated its commercial status following performance improvements and cost reductions in recent years, the overall market share of thin-film technologies has been constantly decreasing since 2012. Currently, thin-film technology accounts for only 5% of the global solar PV market, while silicon-based solar modules still hold approximately 95% of the global PV module market (GlobalData, 2018).

Non-silicon based thin-film technologies

Perovskites

Currently most solar cells are made from silicon; however, an area to watch is the development of new materials for solar cells. In particular, one of the most promising material is perovskites, a type of mineral very good at absorbing light. The first perovskite PV devices in 2009 converted just 3.8% of the energy contained in sunlight into electricity. However, because crystals are very easy to make in the lab, their performance was quickly improved and by 2018 their efficiency had soared to 24.2%, set by researchers in the United States and the Republic of Korea — close to silicon's lab record of 26.7% (Extance, 2019). However, perovskite efficiency records have only been set on tiny samples (Extance, 2019).

Perovskites still face some significant challenges before achieving market maturity. One of the main ones is durability. Because the crystals dissolve easily, they are not able to handle humid conditions and need to be protected by moisture through encapsulation, for instance through an aluminium oxide layer or sealed glass plates. Another challenge for scientists is that, whist they have been able to achieve high efficiency levels with small perovskites, they have not been able to replicate such effect with larger cell areas.

If these barriers can be overcome, perovskites cells have the potential to change the dynamics and economics of solar power because they are cheaper to produce than solar cells and can be produced at relatively low temperatures, unlike silicon.

Copper indium gallium selenide cells (CIGS)

CIGS cells have achieved high efficiency levels (22.9%) comparable to commercial crystalline silicon (Fraunhofer ISE, 2019). However, manufacturing CIGS cells can be difficult due to the rarity of indium, as well as to the complex stoichiometry and multiple phases to produce them, restricting large-scale production in the near term (Cherradi, 2019).

Cadmium telluride (CdTe)

Cadmium telluride cells have achieved an efficiency of 21%, very similar to CIGS, and are characterised by good absorption and low energy losses (Fraunhofer ISE, 2019). CdTe solar cells are made through low-temperature processes, which makes their production very flexible and affordable. CdTe currently has the largest market share of all thin-film technologies (Cherradi, 2019).

ADVANCED MODULE TECHNOLOGIES

The emergence of new cell architectures has enabled higher efficiency levels. A major driver of this shift has been the emergence of the PERC cells and their compatibility with other emerging innovations, such as half-cut cells. Looking ahead, the most important technological shift in the market relates to bifacial cells and modules, driven by the increased adoption of advanced cell architecture and a focus on system output levels.

Bifacial solar cells

Bifacial solar cells have been under development for decades and their manufacturing process can be considered one of the most advanced for solar modules today (Shravan, K., Chunduri, K., 2019). Bifacial cells are capable of generating electricity not only from sunlight received on their front, but also from reflected sunlight received on the reverse side of the cell. At the time of writing China retains its status as the largest manufacturer of, and end market for, bifacial modules. Worldwide demand has also increased, with countries such as the United States, Brazil and the United Kingdom increasing their use of bifacial modules for utility-scale PV plants. Based on the current market trend, bifacials are extending their geographical reach from Europe and Japan to emerging markets and across the globe (Roselund, C., 2019).

Bifacial operation, facilitated by the uptake of PERC (which is driving the bifacial boom), offers a near-term effective efficiency increase of 5–20% relative by increasing the energy output from a given module area. According to the Fraunhofer ISE's module technology division, nearly every cell producer that has upgraded to PERC is also working on bifacial technology, and the greater that PERC expands, the greater that bifacial modules will too (Shravan, K., Chunduri, K., 2019). Despite the growth and advantages of bifacial cells, the technology still has some obstacles to overcome, such as the lack of an international testing standard, no common ground for power labelling or pricing, and yield simulation and bankability issues.

One type of bifacial module is the *glass-glass module*. These are solar panels with solar cells arranged between two glass panes. They are typically applied to utility-scale systems and provide a heavy-duty solution for harsh environments (*e.g.* high temperatures, high humidity) because they are less sensitive to penetration of moisture. The technology has already been under development for decades, but their high costs and heavy weight has been a barrier to their development. According to the International Technology Roadmap for Photovoltaic (ITRPV), in 2018 the share of glass-glass modules was only 5% and is expected to just double by 2020. However, despite the limited growth foreseen in the short term, the ITRPV expects the technology to pick up within the next 10 years and reach a 40% share.

In a PV module, solar cells are electrically connected to strings. This interconnection, however, can cause optical losses in the module, which affects the reliability of the product. To overcome this limitation, various industrial stringing equipment and soldering technologies are being developed, such as half-cells, solar shingles and multi-busbars.

Half-cells

Half cells involve deliberately cutting a fully processed cell into half with very advanced laser machines. Half-cells are being adopted quickly, thanks to the fact that from a manufacturing point of view only minor changes are needed to include laser machines. Half-cells improve module performance and durability, and can provide an instant power boost of 5–6 watts (W) (Shravan, K., Chunduri, K., 2019).

Thanks to the integration of PERC, half-cut technology has seen achieved efficiencies of up to 18% and power ratings of up to 300 W (Roselund, C., 2019).

Multi-busbars

Silicon solar cells are metallised with thin strips printed on the front and rear of a solar cell; these are called busbars and have the purpose of conducting the electric direct current (DC) power generated by the cell. Older solar cells typically had two busbars; however, the industry has moved towards higher efficiencies and busbars have increased to three (or more) in most solar cells. The increased number of busbars has several advantages: first is the high potential for cost saving due to a reduction in metal consumption for front-facing metallisation (Braun,S., 2013); second, series resistance losses are reduced by employing thin wires instead of regular ribbon (Shravan, K., Chunduri, K., 2019); and third, optimising the width of the busbars leads to an additional rise in efficiency. A higher number of busbars leads to higher module efficiencies because of reduced internal resistance losses; this is due to the lower distance between the busbars. Finally, multi-busbar design is highly beneficial for bifacial technology, especially for improving the bifaciality for PERC cells of 90% (Shravan, K., Chunduri, K., 2019).

Solar shingles

Solar shingles are a type of solar energy solution where solar panels are designed to look like conventional roofing materials, while also producing electricity. Solar shingles have several advantages. First, a key advantage is that they eliminate the need for ribbon, connecting cells like roof tiles. Second and related to the removal of the ribbon, module aesthetics are improved, as the panels are homogeneously coloured. Third, unlike a standard cell, cells for shingle modules have busbars at opposite ends and cells are sliced into several strips, which reduces the current and consequently the load on fingers (metallic super-thin grid fingers, perpendicular to the busbar, collecting the generated DC current and delivering it to the busbars). This also enables a reduction in the number of fingers as well as their thickness, which decreases shading and improves output power of the cell (Shravan, K., Chunduri, K., 2019).

LEVEL OF MATURITY AND PROSPECTS	
Half-cut	According to the ITRPV, a significant uptick is foreseen in the near future – from less than 3% market share in 2017 to 5% in 2018 and 10% by 2020.
Shingles	Although several companies are displaying prototype shingle modules, the Fraunhofer ISE believes that the technology is not yet mature enough, especially due to the fact the manufacturing machinery is not completely optimised.
Bifacial	From almost negligible presence in 2017, the ITRPV anticipates the bifacial concept to gain close to 10% market share in 2018, 15% in 2020 and 40% within the next 10 years.
Glass-glass modules	Despite the small growth foreseen in the short term, the ITRPV expects the technology to pick-up within the next 10 years and reach a 40% share.
Multi-busbars	The ITRPV expects the three-busbar layout to be phased out progressively and be replaced by layouts with 4, 5, 6 and more busbars (Shravan, K., Chunduri, K., 2019).

Source: (Shravan, K., Chunduri, K., 2019).

5.2 APPLICATIONS: BEYOND FIELDS AND ROOFTOPS

Taking advantage of the rapidly growing solar PV capacity across the globe, several research projects or prototypes are underway to stimulate future market growth, exploring innovating solar technologies at the application level. The major developments are as follows.

FLOATING PV

Floating PV is an exciting emerging market, with the potential for rapid growth. According to a World Bank report, as of the end of September 2018 the global cumulative installed capacity of floating PV plants was 1.1 GW (World Bank, 2018).

Demand for floating PV is expanding, especially on islands (and other land-constrained countries), because the cost of water surface is generally lower than the cost of land (GlobalData, 2018). Floating solar is particularly well suited to Asia, where land is scarce but there are many hydroelectric dams with existing transmission infrastructure. Unsurprisingly, the world's top ten plants are located in Asia, namely China, Japan and the Republic of Korea. In particular, Korea has announced the completion next year of what will then become the world's largest floating solar plant, with a capacity of 102.5 MW. Other Asian countries, namely Singapore, Thailand, Viet Nam and India, are also actively pursuing floating solar project development.

Europe has huge potential and demand for floating PV – especially in the Netherlands and France. Large-scale potential can also be found in opencast lignite coal pits. For instance, today the largest floating solar project is in China, with a capacity of 70 MW, and is located in a former coal-mining area of Anhui Province. Meanwhile, another plant in eastern China (in Panji District, Huainan City) has just been connected, becoming the world's largest floating solar plant, which will generate almost 78 000 megawatt hours (MWh) in its first year. Hydropower reservoirs and other artificial bodies of water also have enormous potential. With utility-scale power electronics and grid-connection already established, coupling PV with hydropower offers significant added value (Willuhn, M., 2019a). For instance, the Norway-based independent power producer Statkraft announced the construction of a 2 MW floating PV plant in Albania. The company is using an innovative technology consisting of a membrane-type flotation device, 72 metres in diameter, accommodating 500 kilowatts (kW) of PV. Glass-glass modules are mounted onto special rails, in a way that the modules will be in permanent contact with a thermal membrane (designed to withstand stress and sun exposure) that sits on the water's surface. The water cools the membrane, which in turn cools the modules and enables them to produce more energy (Willuhn, M., 2019a). In addition, by covering the surface of the water reservoir, floating solar plants can also reduce evaporation and protect water quality from excessive algae growth (Thoubborn, K., 2018).

As with any new technology, however, several engineering challenges need to be overcome. For instance, mooring (or anchoring) systems must be designed to withstand the dynamic forces of waves and strong winds and, due to the novelty of the technology, mooring specialists have limited experience in applying such systems to floating PV plants. As a result, floating PV installations are always moving to some extent, which increases with wind load.

BUILDING-INTEGRATED PV PANELS

Building-integrated PV (BIPV) solar panels are an application also known as solar shingles (see above). BIPV solutions have several advantages. First, they are multifunctional as they can be adapted to a variety of surfaces (*e.g.* roofs, windows, walls) as an integrated solution, providing both passive and active functions. A key passive function is thermal and acoustic insulation, as with any other construction material, which is complemented by a unique active function – the PV component – which generates renewable electricity that can be directly used in the building. Other functions, also unique to BIPV systems, include the possibility of real-time thermal or lighting regulation (SolarPower Europe, 2019b).

Second, they provide a cost-efficient solution. They offer potential cost-reduction benefits related to the savings on roofing material, as well as potential efficiencies and time saving in labour/construction (i.e. with roofing and panel installation done simultaneously). Moreover, BIPV can reduce the cost of refurbishment and renovation of existing buildings and create a business case for efficient strategies. When compared to classic roofing materials, BIPV cladding is somewhat more expensive. However, when the additional revenue generated from the electricity produced is taken in to consideration, this higher cost is more than offset (SolarPower Europe, 2019b). Finally, other advantages include versatility and design flexibility in size, shape and colour.

An EU-funded project, PVSITES, is currently developing a new generation of solar panels that can be part of traditional house elements like roofs, windows and glass façades. The project is creating BIPV solar panels alongside building energy management systems and architectural design tools. The aim is to demonstrate the integration of effective energy production with good design to create cost-effective buildings. The project is also developing design software tools for architects to help them better integrate these novel PV products in their designs.

SOLAR TREES

Solar trees work very much like real ones, as they have leaf-like solar panels connected through metal branches using sunlight to make energy. Solar trees can be seen as complementary to rooftop solar systems. They are more ergonomic than solar panels, taking nearly 100 times less space to produce the same amount of electricity as a horizontal solar plant and, as such, constitute a solution for land- and space-scarce economies.

SOLAR-POWERED DESALINATION

Most desalination plants today are powered by fossil fuels, which makes them unsustainable in the long term. The two techniques mostly used by the desalination industry to produce potable water are membrane-based (i.e. reverse osmosis, nanofiltration and electrodialysis) and thermal (i.e. multi-stage flash distillation, multi-effect distillation). Because membrane-based desalination techniques do not require heat, they can be coupled with wind and solar power generation. With the fall in the cost of PV equipment and the increasing demand for desalination, more PV-powered membrane desalination plants can be expected in the coming years.

However, besides membrane-based desalination technologies based on PV only, there is also the possibility of having thermal and membrane-based desalination. Thermal desalination technologies require heat and electricity to operate. Solar energy technologies, such as concentrating solar power (CSP) and photovoltaic-thermal (PV-T), have the benefit of delivering the required thermal energy as a by-product while generating electricity (Cen, J., 2019). Currently, the first demonstration pilot project using PV-T to power a thermal desalination plant based on multi-effect distillation is being built at Jebel Ali (United Arab Emirates). The solar farm is designed in such a way that it produces sufficient thermal – as well as electrical – energy to run the desalination plant off-grid 24/7. During the day, excess solar energy is stored in a hot water tank and batteries power the plant at night (Cen, J., 2019).

SOLAR CARPORTS

Solar carports are ground-mounted solar panels that are installed so that parking lots and home driveways can be laid underneath to form a carport. They have been a very popular alternative or supplement to the classic rooftop systems, with the advantage that they can be installed entirely independently of the roof angle, shape and orientation of the house. Besides providing shade to the vehicles parked underneath, they can efficiently produce electricity and thus offer a number of benefits. First, if coupled with a well-designed charging system, the electricity produced can be used for EV charging and thus reduce the costs of running the vehicle (Thurstom, C.,W.,2019). Second, they can provide energy storage enhancements by having battery storage integrated and available in the system, making the solution independent of sunshine hours. Third, unlike ground-level systems, they are easy to customise and can save space as they do not require an additional structure or land to install them on.

The installation of solar carports is increasing steadily and several factors are driving the growth. Cost is indeed an important factor, as the application is moving out of the niche and into the mainstream, and EV adoption is playing a pivotal role. The price difference between rooftop PV and solar carports continues to narrow, and they are becoming a strong and attractive economic proposition in a growing number of markets. Increased commercial-scale application is also driven by utilities, which are embracing distributed generation as a way to improve grid reliability. Finally, space saving is another important aspect, as carports make better use of land that is already developed, instead of using open land. One study by Callum Watts at the University of California, Davis, showed that the 30 largest commercial buildings in the United States possess a total parking lot area of more than eight million square metres, which, if all covered with solar canopies, would generate an annual total of 15 000 MWh (Thurstom, C.,W.,2019).

SOLAR PV-THERMAL SYSTEMS

Solar PV-T systems combine the production of both kinds of solar energy in one collector. It consists of a solar PV panel combined with a cooling system where cooling agent (water or air) is circulated around the PV panels to cool the solar cells, such that the warm water or air leaving the panels may be used for domestic applications such as domestic heating (Moharram et al., 2013). This cooling system for PV panels has a twofold benefit: it significantly increases the efficiency of PV systems in the electricity sector, and it also allows for the capture of the heat from the PV system for use in space, water and process heating in a range of industries and applications. In fact, PV modules normally use 15–20% of the incoming solar energy, while the rest is lost in the form of heat. The PV-T technology aims to increase the overall efficiency by using this "lost" energy to heat air or water and at the same time cool the PV cells by taking away the heat from the panel.[4]

AGROPHOTOVOLTAIC

Agrophotovoltaic (APV) combines solar PV and agriculture on the same land and consists of growing crops beneath ground-mounted solar panels. Although the concept was proposed long ago, it has received little attention until recently, when several researchers have confirmed the benefits of growing crops beneath the shade provided by the solar panels. These include higher electricity production, higher crop yields and less water used (Beck, M. et al., 2019). APV is a win-win situation for both crops and the solar panels. Many types of food crops, such as tomatoes, grow better in the shade of solar panels, as they are spared from the direct sun and experience less water loss via transpiration, which also reduces water use while maintaining the same level of food production. A key advantage for solar panels is that their efficiency is increased. Cultivating crops underneath reduces the temperature of the panels, as they are cooled down by the fact that the crops below are emitting water through their natural process of transpiration (Hanley, S., 2019).

The project "Agrophotovoltaics – Resource-Efficient Land Use (APV-RESOLA)" has tested the APV concept, showing a land use efficiency of 160% in 2017 and 186% in 2018 and thus confirming earlier research results. The project is located in Germany, near Lake Constance, and consists of a 194 kW solar system on a 5 metre high structure above land used to grow celery, clover, potatoes and winter wheat (Tsanova, T., 2019). The project results show that in 2018 land use efficiency increased, with yields from three of the four crops grown under the panels achieving above the reference yield thanks to the shade under the solar modules, which helped them to better resist the dry conditions in 2018. In fact, solar irradiation beneath the PV system was approximately 30% less than the reference field, the soil temperature was lower even if the air temperature remained the same and the soil moisture was kept higher than the reference field in summer and lower in winter months. The project confirmed the applicability of APV in arid regions (given the exceptionally hot and dry conditions of 2018), especially in developing countries; it also calls for the exploration of APV's applicability under other climate conditions and with other types of crops (Tsanova, T., 2019).

4 http://solarheateurope.eu/2018/04/30/increasingly-popular-heat-and-power-from-the-same-roof/.

5.3 OPERATION AND MAINTENANCE

An operation and management (O&M) system is a key component of a solar plant, as it ensures that the PV system will be able to maintain high levels of technical and economic performance over its lifetime (SolarPower Europe O&M Task Force, 2018). In addition, the O&M phase is the longest in the lifecycle of a PV project, as it typically lasts 20–35 years. As such, ensuring the quality of O&M services is essential to mitigate potential risks.

Innovations and improvements, including more data-driven solutions, are becoming increasingly important because they help O&M services to keep up with market requirements. Important trends in O&M innovation can be grouped in two main categories: 1) smart PV power plant monitoring; and 2) retrofit coatings for PV modules.

SMART PV POWER PLANT MONITORING

Drones for intelligent monitoring of solar PV

The exponential growth seen in PV markets has led to the development of large-scale power plants, which has increased demands for better tools for inspection and monitoring. Normally, the process of monitoring is done by conducting manual inspections; however, these can be replaced by intelligent systems, such as drones. Drones are becoming highly suited to the solar industry due to a wide range of surveillance and monitoring capabilities, the possibility of long-range inspection and easy control. In recent years they have become popular for their capability to monitor large-scale solar parks in less time than by human inspection. With the help of sensing elements, drones efficiently capture the necessary data and send them to the cloud for analysis in less time and in more accurate form (Kumar et al., 2018).

PV plant power output forecasting

Electricity generation from PV plants is limited by the variable nature of the sun's radiation. The growing penetration of PV into electricity markets creates the need for new regulations to guarantee grid stability and the correct balancing of electricity demand and supply (SolarPower Europe O&M Task Force, 2018). The ability to predict PV production is therefore an essential tool to capture economies in a market with a high penetration of non-predictable energy. Currently simulation models and meteorological forecasting resources for specific PV plants are well proven technologies. Algorithms that are able to match weather forecasts with PV plant characteristics are being used to predict energy production on an hourly basis for at least the next 48 hours.

In this context, short-term data collection represents a valuable opportunity to improve PV plant yield forecasting, and improvements in communication procedures between devices (i.e. modules, inverters, sensors, etc.) would contribute to improving intraday forecasting, calculation of performance expectations, and exchange with the energy grid (SolarPower Europe O&M Task Force, 2018). Solar monitoring is indeed a key component in asset operation; however, the process is often difficult, mainly due to two factors. First are frequent failings in communication between devices and the cloud or data centre infrastructure. To overcome this challenge, the Internet of things (IoT) represents a valid solution for PV systems, as it is an interoperability environment where all devices in the field are connected to each other and spontaneously show themselves as available to be connected to the system (SolarPower Europe O&M Task Force, 2018). Second is the lack of proper standardisation of terminology and languages used by all communicating devices. In this regard, efforts are being made throughout the whole PV market to increase standardisation of communication, which will improve the security level, options for communication, and configuration costs for solar monitoring (SolarPower Europe O&M Task Force, 2018).

Smart PV plant monitoring

Innovations in monitoring systems aim to improve the ability to identify the root causes of performance problems that lead to plant underperformance and unavailability. These innovations include advances in single plant and system portfolio monitoring and management, such as: 1) automated maintenance (preventive and emergency), intervention management and (re)scheduling, based on parameters such as alarms and performance data; and 2) algorithms for equipment or plant behaviour and reliability predictions based on historical failure data and simulation models (KIC InnoEnergy, 2015).

RETROFIT COATINGS FOR PV MODULES

Solar power coolant

While progress is being made on increasing efficiency and maximising power output of solar PV, difficulties remain in addressing the need to keep solar PV modules cool, because their performance and lifetime are reduced by the heat of the sun. In fact, the chemical reactions that cause degradation of solar modules double for every 10°C increase above ambient temperature (around 25°C) causing their lifetime, as well as their voltage output, to shrink (Filatof, N., 2019). PV-T systems are currently one of the most popular methods for cooling PV panels. Other techniques include the use of water, which has been widely researched but less successfully applied as an effective PV coolant around the world, because while water can be extremely effective in maintaining the equilibrium of solar panels, incorporating water-based systems into module manufacturing or installation adds cost and complexity (Filatof, N., 2019).

Other approaches include applying a transparent coating of patterned silica to solar cells to capture and radiate heat from infrared rays back to the atmosphere. This was found to improve absolute cell efficiency by more than 1%. Other researchers have found that greater improvements in efficiency can be obtained through processes including infrared reflation and radiative transfers. The idea is to reflect the wavelengths of light in the infrared that cells cannot use (but simply absorb to heat up the system) before they enter the module. If done perfectly, this would result in a temperature drop of about 3°C. Radiative transfer to the sky or to cooler areas around the panels holds the greatest promise for boosting solar module efficiency (Filatof, N., 2019f).

Anti-soiling solutions

Regular module washing is common practice in PV plants, as soiling can significantly and negatively impact their performance. For instance, in Europe soiling causes an average 2% power loss with significant rain, which can go as high as 11% in non-rainy environments. In this context, several anti-soiling solutions are being implemented.

First, robotic panel cleaning technology consists of robots moving along the array of panels. Robotic cleaning strategies involve substantial CAPEX investment, but are very effective for areas with high soiling rates, insufficient water supplies and high labour costs. They are mostly deployed in the Middle East and North Africa, as they are best suited for frequent washing schedules, such as those that require washing on a weekly basis (Mesbahi, 2018). Second, sprinkler systems consist of a water filtration system and a soap dispensing system, mainly used in very dry areas to keep the panels clean with the same cleaning effect as rain. This is indeed a very good and tested system; however, it has two main disadvantages: 1) the large amounts of water used; and 2) the need to constantly monitor filters and soap levels, which is costly and time consuming. Finally, anti-soiling coatings are used to treat modules so that they get dirty less quickly, while making them easier to clean, and thus maintain higher performance levels for longer (Solar Power Europe O&M Task Force, 2018). Currently various anti-soiling coatings are already commercially available and have been installed, and in parallel new solutions are also being developed, mostly based on spray technologies.

Biotechnology/seed selection for zero vegetation treatment

Ground-mounted PV plants may suffer from shading if vegetation inside and outside the plant is not properly controlled. The main innovations in this area seek to reduce the maintenance required without using pesticides or other dangerous products. In particular, these include:

- Using weed control fabrics inside the plant, under the modules and around the perimeter to help limit weed growth. These fabrics combine soil erosion control and weed control into a single product, thereby minimising maintenance needs for green areas.
- Selecting seeds of plants with slow growth and limited height to avoid the need for frequent maintenance (KIC InnoEnergy, 2015).

5.4 END-OF LIFE MANAGEMENT OF SOLAR PV

Despite the growth of solar PV and its bright future, the sun sets on even the best panels. As the global PV market increases, so will the need to prevent the degradation of panels and manage the volume of decommissioned PV panels. The sections below explore innovative and alternative ways to reduce material use and module degradation, and opportunities to reuse and recycle PV panels at the end of their lifetime.

The framework of a circular economy and the classic waste reduction principles (reduce, reuse and recycle) can also be applied to PV panels.

REDUCE: MATERIAL SAVINGS IN PV PANELS

The best option is to increase the efficiency of panels by **reducing** the amount of material used. Whilst the mix of materials has not changed significantly, efficient mass production, material substitutions and higher-efficiency technologies are already happening thanks to strong market growth, scarcity of raw materials and reduction of PV panel prices. Research is progressing towards reducing the amount of hazardous materials, as well as minimising amount of material per panel to save costs. PV material availability is not a major concern in the near term, although critical materials might impose limitations in the long term. In addition, higher prices will improve the economics of recycling activities and drive investment for more efficient mining processes, such as extraction of metals used in the PV manufacturing process (i.e. silver, aluminium, copper and tin). R&D for PV is focusing on reducing or substituting different components used for solar PV panels, namely: c-Si panels (glass, silicon, etc.), CIGS panels (glass, polymer, aluminium, etc.) and CdTe panels (glass, polymer, nickel, etc.) (IRENA and IEA-PVPS, 2016).

REUSE: REPAIRING PV PANELS

Most PV systems were installed in the last six years. A six-year-old panel today has aged by an equivalent of 20% of its expected average lifetime of 30 years (IRENA and IEA-PVPS, 2016). If flaws and imperfections are discovered during the early phase of a PV panel's life, customers can claim guarantees for repair or replacement and insurance companies may be involved to compensate for some or all of the repair/replacement costs. When replacement happens, quality tests to check electrical safety and power output – such as flash test characterisation and a wet leakage test – can be undertaken to recover some value from a returned panel through resale. Repaired PV panels can also be resold as replacements or as used panels at a reduced market price of approximately 70% of the original sales price, and partly repaired panels or components might be sold on the second-hand market (IRENA and IEA-PVPS, 2016).

RECYCLE: DECOMMISSIONING AND TREATMENT OF PV PANELS

Future waste management of installed PV systems largely depends on their type and size. For example, whilst the small and highly dispersed nature of rooftop PV systems can add significant costs to dismantling, collection and transport of expired PV panels, waste management of large utility-scale PV applications is logistically easier. Currently PV waste quantities are very moderate, which reduces the economic incentive to create dedicated PV panel recycling plants. End-of-life PV panels are therefore typically processed in existing general recycling plants. However, in the long run constructing dedicated PV panel recycling plants could increase treatment capacity and maximise revenues thanks to better output quality, and could also increase the recovery of valuable constituents. Recycling technologies for PV panels have already been researched for the past 15 years and now the main challenge is to keep abreast of ongoing cell and panel innovations to obtain the best possible results at acceptable costs (IRENA and IEA-PVPS, 2016).

Given the estimated growth of PV panel waste volumes, the management of end-of-life PV panels is worth examining, along with the associated **socio-economic and environmental benefits** (IRENA and IEA-PVPS, 2016).

The value creation stemming from end-of-life PV management involves:

- **Unlocking raw materials and their value.** The extraction of secondary raw materials from end-of-life PV panels could create important value for the industry. PV panels have an average lifetime of 30 years, and they build up a large stock of embodied raw materials that will not become available for recovery for some time. As such, recovered raw material can be injected back into the economy and serve to produce new PV panels or other products, thus increasing the security of future PV supply. Rapidly growing panel waste volumes over time will stimulate a market for secondary raw materials originating from end-of-life PV panels.
- **Creating new industries and jobs in the PV sector.** The acceptance of future PV panel waste management systems depends on co-operation among the different players across industry, such as waste management companies, utilities, governments, producers, etc. End-of-life PV panel management holds the potential to develop new pathways for industry growth and offers employment opportunities for different stakeholders. Similarly, the PV recycling industry will necessitate trained staff with specific skills and knowledge, education and training programmes.

Box 8. SOLAR PV PERFORMANCE UNDER EXTREME WEATHER EVENTS

Extreme weather events are clearly affecting the solar industry and are becoming the biggest cause of failure of any PV plant. Solar installations have to cope with different natural disasters and, as the frequency of such extreme events grows, the industry will have to find ways of surviving and adjusting to them. Indeed, design, construction and operational factors greatly influence a PV system's survivability from a severe weather event. As such, the industry's efforts are channelled towards both technical improvements and the development and application of updated codes and standards to keep up with the lessons learned from field experience.

Fire

There have been fire-related incidents involving PV systems in several countries, such as the United States, Germany and Japan. In the very rare cases where the PV system was the main cause and source of the fire, the main causes relate to ground or arc faults. However, regardless of the source of the fire, PV systems can affect the ability of firefighters to extinguish the flames. Common hazards include: electrical shocks, collapse of roof structures due to the additional weight of a PV system, and slippery glass surfaces on an inclined roof. Besides introducing guidelines for firefighters, countries have also produced guidelines on technologies, products and installation to mitigate fire hazards. These include, for instance, guidance on installation to reduce the incidence of fires and shocks (*e.g.* ground-fault circuit interrupters [GFCIs] and arc-fault circuit interrupters [AFCIs]) (IEA-PVPS, 2017).

Hurricanes and tornadoes

Recent storms have not only highlighted factors contributing to PV system survivability, but also those leading to failure (US DOE, 2018). Having good O&M practices is a key factor in survivability and pre- and post-storm measures can be applied to minimise damage and recovery time.

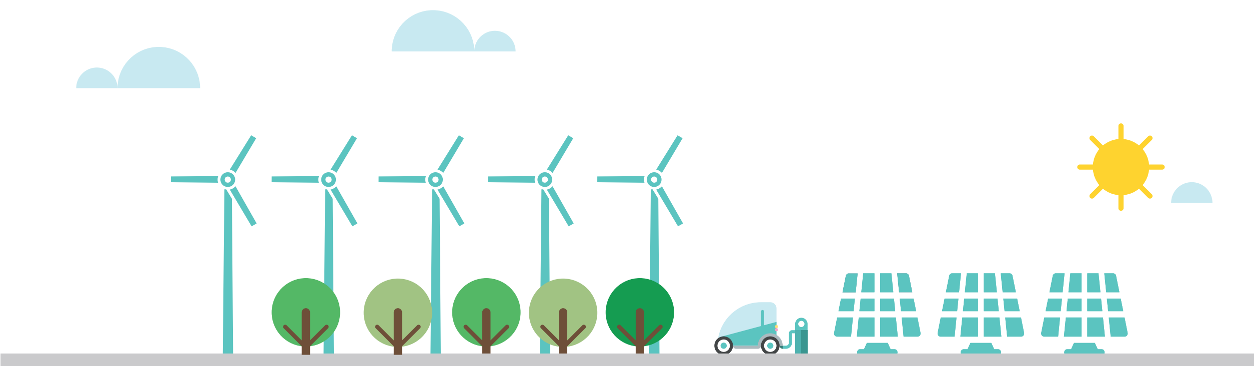
One of the most common causes of equipment loss are solar fasteners. An easy measure to prevent disassembly is to properly use twist fasteners with a true locking capability and highly effective hardware and then proceed to audit the results. Clamping fasteners, which are very practical and fast and easy to assemble, are not adequate for PV systems in extreme weather areas, as they can be easily damaged in high winds. In addition, since one clamping fastener is shared between two modules, the loss of one creates a domino effect and causes the loss of neighbouring modules. A solution to this is to fasten the module to the support structure through mounting holes, using fasteners with specific twist ratings. Module selection is also another important aspect, as preference should be given to modules that have the highest ratings in terms of resistance to pressure. Similarly, modules should be well supported by frame elements to avoid bending and twisting during strong winds. Solar racking with a three-frame rail system for module mounting provides greater rigidity and support than a two-frame rail. Trackers for solar arrays have also improved in design and no longer depend on steel to support them, but rather use control sensors to adjust the angle in relation to wind strength and safely position the panel during storms (US DOE, 2018).

Box 9. THE IMPORTENCE OF STANDARDS IN THE SOLAR PV INDUSTRY

Standards are essential for ensuring safety and quality in the solar PV sector, especially because the reliability, performance and durability of solar equipment is critical to ensuring smooth operation of solar power plants. Moreover, compliance with minimum standards is also often a prerequisite for feed-in-tariffs provided by governments to solar power developers. Currently, almost all modules are certified to meet international standards for design qualification and safety, even if there are still examples of failure in large-scale modules and PV systems, as well as outright fraud.

International efforts are therefore channelled towards strengthening standards for quality management systems for module factories and visual inspection of incoming products. Given the need to improve understanding of product reliability and validation, in 2011 the International PV Quality Assurance Task Force (PVQAT) was formed, initially only comprising US, European and Japanese national laboratories. It has now expanded to include over 700 scientists and engineers working around the globe (Kelly and Mahesh, n.d.). One of the task force's key efforts is to develop scientific methods to predict possible failure by creating new or improved standards. As with many industries, the PV industry has gone through a long history and progression of standards development, which play a central role in supporting technological innovation and the emergence of an industry. The PV industry has achieved a high level of maturity and mass production, meaning that the equipment and raw materials for panel manufacturing need to be standardised. For instance, "ingress protection levels" are used for inverters, cables and modules, and the assigned number tells the customer in a very simple way the degree to which an inverter is protected from rain and dust.

The PV industry is evolving at a fast pace and the process of international standardisation tends to move too slowly to match certain industry developments. For instance, the further development of standardisation, certification, inspection and testing services is clearly necessary, especially regarding: 1) the durability of solar modules, 2) defined quality requirements in national programmes to develop solar PV, 3) certification schemes for PV systems and their installers both in emerging and mature markets,4) public guidelines for the effective design and installation of distributed and off-grid PV systems in developing countries (IRENA, 2017a). Also, in the context of failures relating to wind, which is the most common reason for damage to PV systems, there is a lack of standards to sufficiently inform manufacturers and project developers. There are no wind load standards that take into account static and dynamic loads specific to single-axis solar trackers (Willuhn, M., 2019b)



6. SOCIO-ECONOMIC AND OTHER BENEFITS OF SOLAR PV IN THE CONTEXT OF THE ENERGY TRANSFORMATION

6.1 SOLAR PV SECTOR EMPLOYMENT AND LOCAL VALUE CHAINS

Employment opportunities are a key consideration in planning for low-carbon economic growth. Many governments have prioritised renewable energy development, firstly to reduce emissions and meet international climate goals, but also in pursuit of broader socio-economic benefits.

The solar industry was estimated to employ 3.6 million people worldwide in 2018 (Figure 23). The industry has witnessed the most rapid growth in employment of all renewable energy technologies and is today the jobs leader. Overall, Asia is home to almost 3 million solar PV jobs (85% of the global total), followed by North America's 6.4% share, Africa's 3.9% and Europe's 3.2% (IRENA, 2019i).

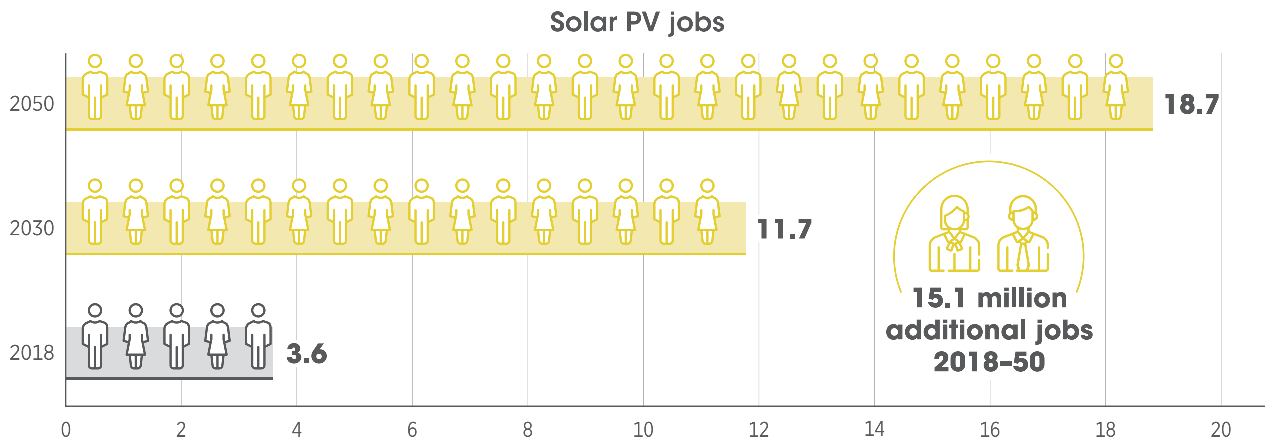
Based on its leading role as a producer and exporter of PV equipment and as the world's largest installation market, China accounted for almost two-thirds of PV employment worldwide, or some 2.2 million jobs. Solar PV employment in the European Union continued its decline and was estimated at 90 800 jobs in 2017 (the most recent year for which data are available). This reflects limited manufacturing activity and reduced domestic installations. In the United States employment fell for a second year in 2018 to an estimated 225 000 jobs.[5] Japan's solar PV industry also continues to face difficulties. Although the country's installation market is still one of the world's largest, annual additions have declined for three year in a row, due to reductions in feed-in tariffs and other policy changes, land shortages and grid constraints (IRENA, 2019i).

These experiences underscore the continuing importance of having appropriate policies both for installations (*e.g.* deployment and integration policies) and for manufacturing (*e.g.* industrial policy and related measures). Despite setbacks, there is reason to believe that the future of solar PV employment is nonetheless bright, given the urgency for more ambitious climate and energy transition policies, as well as the expectation that countries are learning important lessons on the design and coherence of policies.

Arising out of its modelling work that assesses the socio-economic implications of the REmap scenario, IRENA estimates that employment in the solar industry could exceed 11.7 million jobs in 2030 and 18.7 million in 2050 (Figure 23). Another reason for optimism is the growing application of decentralised off-grid solar PV, especially in countries and regions of the world where energy access is still limited. A recent estimate by GOGLA and Vivid Economics (2018) suggests that such applications have already generated some 372 000 jobs in South Asia and parts of sub-Saharan Africa alone. Given continued cost reductions and enforcement of equipment quality standards, employment may be expected to expand significantly in coming years.

5 This figure is an IRENA estimate based on a US Solar Foundation report that puts employment in all solar technologies at about 242 000 jobs, but does not offer a breakdown for solar PV (Solar Foundation, 2019).

Figure 23: The solar PV industry employed 3.6 million people worldwide in 2018 and this number is expected to rise further to 18.7 million people by 2050 in the REmap case



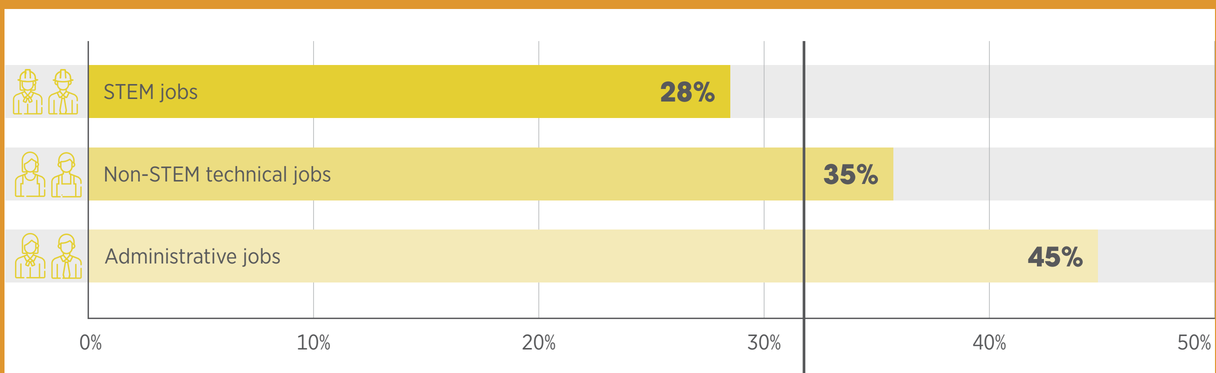
Sources: IRENA (2019a, 2019j).

The rising traction of the solar energy industry demands a growing array of skills, including technical, business, administrative, economic and legal, among others. Widening the talent pool is thus a pragmatic reason for boosting the participation of women in renewable energy, in addition to considerations of greater gender equity and fairness (Box 11) (IRENA, 2019j).

Box 10. IRENA'S WORK ON GENDER BALANCE IN THE ENERGY SECTOR

Recognising a gap in gender-disaggregated data for the renewable energy sector, in 2019 IRENA presented a stand-alone report on gender that integrates up-to-date information from around the world and results from a global survey conducted by IRENA, with support of GWNET and REN21. The survey benefited from the participation of about 1 500 women, men and organisations in 144 countries. Survey results show that the sector employs a larger share of women (35%) compared to the conventional energy field (22%) (IRENA, 2019j).

Figure 24: Women in STEM, NON-STEM technical and administrative jobs in the energy sector.



STEM = science, technology, engineering and mathematics.

Source: IRENA, (2019j).

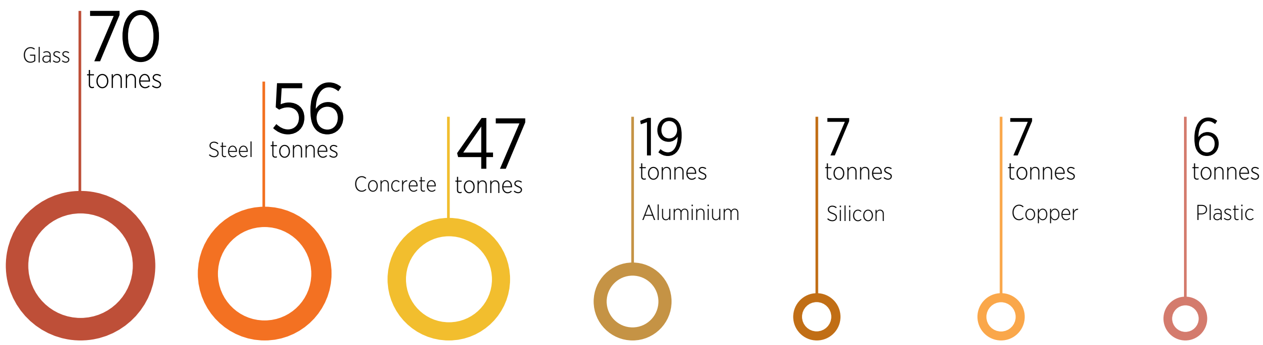
In addition, IRENA is working on a new analysis of the gender dimension of employment impacts among local rural communities affected by large-scale renewable energy project development. The study is gathering primary data from solar and wind projects being developed across sub-Saharan Africa (IRENA, forthcoming b).

5.1.1. DOMESTIC INDUSTRY FOR PANEL MANUFACTURING AND OPPORTUNITIES FOR LOCAL VALUE CREATION

Countries that do not have sufficient capacity to manufacture equipment locally can derive jobs and other benefits in segments of the value chain that are easier to localise. Opportunities for domestic value creation can be created in each segment of the value chain, in the form of jobs and income generation for enterprises operating in the country. Local value chains have the potential to develop local industry and create jobs. However, to identify emerging opportunities and understand the policy measures required to translate socio-economic potential into real gains in the context of solar PV deployment, policy makers need a thorough understanding of the labour, materials and equipment requirements of each segment of the value chain. IRENA's Leveraging Local Capacity report series examines these requirements in various renewable energy industries, including the solar PV industry (IRENA, 2017b). A solar water heating study will be published in 2019 (IRENA, forthcoming c).

Figure 25 shows the main materials needed for plants in these industries, and therefore indicates the kinds of industries most relevant to supply the inputs needed for renewable energy deployment. Maximising value creation from the development of a domestic solar PV industry, for example, requires capacities to be leveraged in industries such as glass, aluminium, silicon and semiconductors. Leveraging this capacity can provide expertise, raw materials and intermediary products for manufacturing PV components such as PV cells and modules, inverters, trackers, mounting structures and electrical equipment.

Figure 25: Materials required for a 1 MW solar PV plant

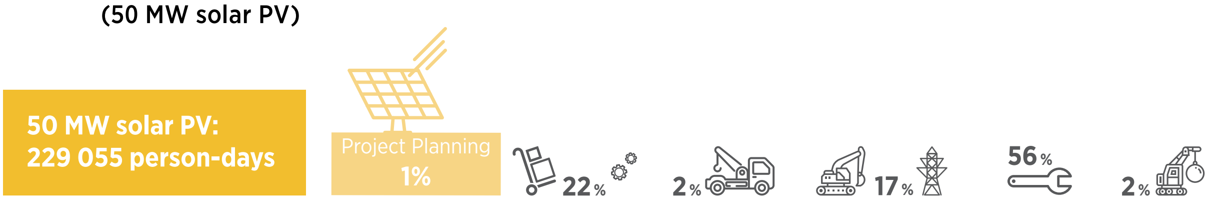


Source: IRENA (2017b).

The Leveraging Local Capacity report series also generates valuable information for policy makers on the occupational and skill structure along the value chain. Figure 25 shows the labour requirement for solar PV farms.

For the development of a typical 50 MW solar PV project, a total of around 230 000 person-days is required from project planning to manufacturing, installation and O&M, as well as decommissioning. The highest labour requirements are in O&M (56%), followed by procurement and manufacturing (22%) and construction and installation (17%). In the procurement and manufacturing segment, factory workers and technicians represent 64% of the labour requirement, followed by engineers (12%). In the O&M segment, construction workers account for 48% of the labour requirement, followed by safety experts (19%) and engineers (15%).

Figure 26: Distribution of human resources and occupational requirements along the value chain (50 MW solar PV)



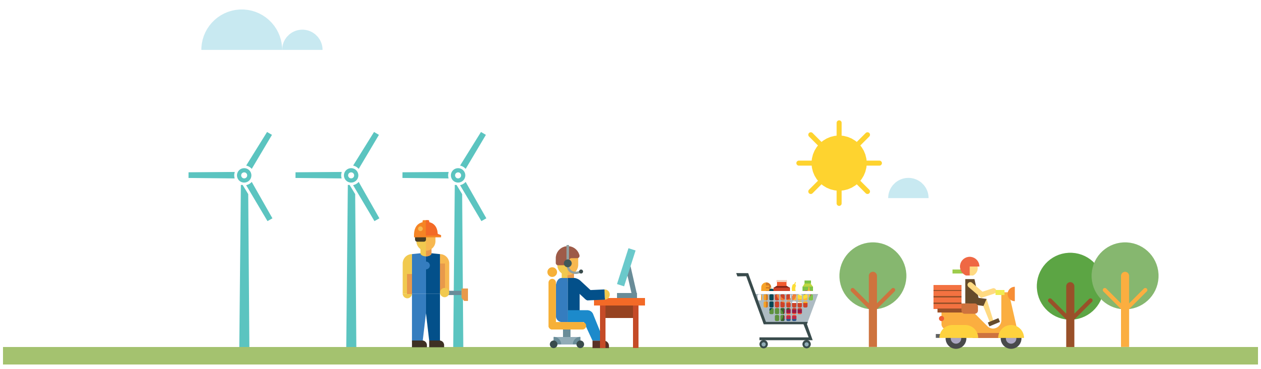
Source: IRENA (2017b).

Construction workers, factory workers, and engineers are the most-needed occupations. But there is also a need for people with a wide range of additional skills, experiences and backgrounds, including in the STEM fields (science, technology, engineering and mathematics), the legal profession, logistics, marketing, land acquisition, permitting and many others.

The main components of a solar plant that decision makers may consider suitable for manufacturing domestically are the solar cells, solar modules, inverters, trackers, mounting structures and general electrical components (IRENA, 2017b). To avoid skills gaps, however, education and training must be attuned to the emerging needs of the industry. This is crucial, as training and skill building form an important part of efforts to generate capable local supply chains. Aspects such as government policies incentivising local value creation, availability of raw materials and the presence of related industries are the main drivers for the local manufacturing of PV components. However, the development of a domestic manufacturing industry for solar PV modules may be difficult where domestic markets are insufficient in volume, where neighbouring or other countries are already large producers, where prices are low or volatile and where overcapacity is already significant.

The creation of domestic manufacturing capacity for solar PV requires access to highly specialised subcomponents, as well as raw materials, and benefits from the existence of industries such as glass, aluminium and silicon that can provide the needed intermediary products for the manufacturing of all PV components (IRENA, 2017b).

The high level of competition in the solar PV panel market, mainly due to the future market demand in and the competitiveness of leading countries, is compounded by the fact that transporting solar energy equipment is less cumbersome than transporting other renewable technologies (such as wind).



6.2 CLUSTERING WITH OTHER LOW-CARBON TECHNOLOGIES: HYBRID SYSTEM

To overcome power supply intermittency arising from the variable resource characteristic of solar energy, and to maintain the reliability and continuous operation of the power system at times of low resource availability, one solution is to combine solar systems with other renewable generation sources such as wind (onshore and offshore), hydro or storage technologies, or emerging technologies such as hydrogen. In 2012, the world's first hybrid project – combining 100 MW of wind and 40 MW of solar PV generation along with a 36 MW lithium-ion energy storage capacity unit – was installed by Build Your Dreams (BYD) and the State Grid Corporation of China in Zhangbei, Hebei Province (JRC, 2014). In 2017, the wind supplier Vestas announced a large-scale hybrid project that combines 43.2 MW of wind and 15 MW of solar generation along with a 2 MW battery storage capacity unit. The global hybrid solar-wind market is expected to grow from more than USD 0.89 billion in 2018 to over USD 1.5 billion by 2025, reflecting a CAGR of nearly 8.5% over the seven-year period (Zion Marker Research, 2019). China was the major market for solar-wind hybrid systems in 2018 and is expected to dominate in coming decades.

Certain countries have already deployed hybrid projects (Box 12) and a steady rise in their number can be expected, especially as a complimentary solution for solving grid integration issues.

Box 11. HYBRID RENEWABLES DEVELOPMENTS

Reflecting the many benefits available from combining renewables power generation sources with storage, projects have been initiated in various countries.

HYBRID RENEWABLES DEVELOPMENTS IN COUNTRIES	
Europe	Vestas and EDP completed Spain's first hybrid 3.3 MW wind-solar project in 2018.
India	In 2016, India introduced a national wind-solar hybrid policy to resolve grid integration issues, with a proposed target of 10 GW of hybrid projects to be installed by 2022 (Zion Market Research, 2019). Just prior to approval of this policy, Hero Future Energies completed India's first hybrid project, combining a 50 MW wind farm with a 28.8 MW solar PV site in Raichur district in April 2018. This project is aimed to be retrofitted with lithium-ion battery storage technology to combat curtailment during times of strong wind resource availability. The Solar Energy Corporation of India recent issued tenders for 2.5 GW of hybrid wind and solar projects to be connected to the country's Interstate Transmission System.
Unites States	GE Renewable Energy aims to develop the country's first commercial integrated 4.6 MW hybrid wind and solar project, in the state of Minnesota. NextEra and the US utility Portland General Electric will build a 380 MW wind-solar plus storage hybrid project in eastern Oregon.

7. STRUCTURING PV BUSINESS MODELS ACCORDING TO HOW THEY COMPETE WITH OTHER GENERATION SOURCES

Thanks to reductions in system prices, PV competitiveness has improved remarkably in the past few years. In many markets self-consuming PV electricity is already more attractive from an economic point of view than buying electricity from the grid. However, under this scenario conventional electricity networks are undermined by customers reducing their energy demand through private generation, mainly rooftop solar PV panels, creating a phenomenon called the "death spiral". As more consumers self-generate electricity, the amount of electricity purchased from the network is reduced, which reduces the revenue the network receives to cover fixed costs (*e.g.* power network maintenance) and necessitates increasing tariff charges. The increase in tariffs simply intensifies the problem, hence the "spiral" reference (Grace, 2018).

In this new context the power industry is being completely transformed, and new and dynamic business models for PV systems can be developed and structured according to how they compete with other generation sources (BSW Solar, 2015).

First, a PV system can **compete at grid parity level** and this implies that competition would take place at or close to the point of grid-supplied consumption, depending on how granular the market is. In this case, PV systems have a natural cost advantage, as they are able to generate electricity at the point of consumption without the need to have transmission and distribution grids to supply an electricity consumer (unlike other sources). Second, a PV system can **compete at generation parity level** with other generation sources. In this case, however, the cost advantage resulting from avoided transmission costs cannot be leveraged by the PV system, either because the grid is needed to supply consumers, or because competition takes place between alternatives that both generate at the point of consumption (*e.g.* diesel generation and PV) (BSW Solar, 2015).

The different PV business models are presented in the box below.

Box 12. PV BUSINESS MODELS

Self-consumption

Self-consumption occurs when the PV system owner and the electricity consumer are the same entity, electricity is consumed on site with no need to use the grid, and excess electricity can be sold to a third party. Self-consumption of PV electricity generated on site can be an opportunity for consumers to reduce electricity costs, grid charges and other fees for electricity supply. At a macro level, grid costs for the transmission of electricity are also saved (for non-grid-connected systems) and CO_2 emissions avoided thanks to the clean electricity generation of PV. Application segments are generally characterised by a high kWh price for grid electricity and include private households and commercial and industrial power consumers. In addition, a PV system owner does not necessarily need to completely cut off from the grid, but can use the grid as a back-up provider, which also entails cost savings. In fact, a system generating 95% of its power from PV enhanced with batteries, while relying on the grid for 5% of power needs, would be more cost-efficient than a power system relying 100% on solar PV.

Two forms of self-consumption are net metering and net billing.

Net metering

Net metering is a measure that promotes the use of distributed generation for local consumption by providing compensation to distributed generators owners (IRENA, 2019d). In practical terms, net metering allows consumers to feed electricity to the grid when they do not need it and consume from the grid when they do.

In the context of solar PV, there are two key advantages of a net metering scheme. First, it incentivises high levels of PV deployment in application segments where the demand curve of individual consumers does not match the solar generation profile and thus represents the best strategy if the goal is to have the highest possible deployment of PV in the electricity system. Second, it allows electricity to be generated and consumed on site and therefore minimises the need for the often-expensive transmission of power across long distances. However, net metering also has several disadvantages. For instance, while avoiding the need for transmission investment, it places a significant amount of pressure on the often inflexible and centralised grid, resulting in distribution problems.

Net billing

Net billing is a market-based compensation mechanism, as prosumer compensation is based on the actual market value of the kWh consumed or injected into the grid. The invoice issued by the retail supplier to the consumer is based on the value of withdrawn electricity after subtracting the value of the injected energy (Energy Community, 2018). Net billing contributes to enhanced grid integration of renewable electricity by: increasing the system's flexibility by engaging the prosumer and by providing electricity bill saving for prosumers. Examples of net billing schemes can be found in the Indonesia, Italy, Mexico, Portugal and the United States (New York and Arizona).

Direct line PPA

A direct line PPA is when the PV system owner sells electricity directly to a nearby consumer who would otherwise have bought it directly from the grid at retail prices. The main advantage for consumers of such a scheme is that it guarantees a fixed cost for electricity over a long period of time, providing a hedge against rising energy prices.

Utility PPA

A utility PPA is when an investor sells the electricity produced to a utility or distribution system operator (DSO), who would otherwise have bought it directly from other generation sources at the cost of generating electricity. The main advantage for generators of such scheme is that it guarantees that all (or almost all) the generated electricity is sold at a fixed price, providing a stable cashflow for the investor. Auctions often rely on utility PPAs for the deployment of renewable energy. While auctions are outstanding instruments for price discovery and have prompted record-low renewable energy prices in recent years, policy makers are increasingly focusing on complementary development objectives such as maximising socio-economic benefits (IRENA, 2019k).

Virtual power plant

In the VPP model, the sale of PV electricity on the electricity exchange is done by pooling several PV plants and other forms of generation (*e.g.* hydro, wind, biogas, fossil-fired). This aims to take advantage of the peak prices of different technologies during certain times of the day to increase profits.

PV-hybrid mini grid

PV-hybrid mini grids are distributed grid-integrated or off-grid systems consisting of distributed generation, multiple energy loads and local grid infrastructure, and are aimed at providing reliable and affordable energy supply at a local level (residential, commercial or industrial). These systems are typically used for remote regions, but can also be applied to industrial parks with an independent grid. There are three main drivers for PV-hybrid mini grids: reliable access to electrification, fuel savings and reduced CO_2 emissions. The wide variety of applications for PV-hybrid mini grids includes: community and utility settings, institutional and campus buildings (*e.g.* government and college/research centres), emergency services (*e.g.* hospitals, police stations, data centres), military operating bases, remote off-grid sites (especially in developing countries and isolated areas) and renewable energy grid integration (if coupled with storage, load management and distributed power, they can manage the variability of renewables entering the grid).

Mini PV

Mini PV systems do not need grid connections; they are used for a single purpose, such as lighting, cellphone charging, water purification, household appliances, and are very flexible as to their location. The main advantages of such a system are electricity savings and easy access to electricity.

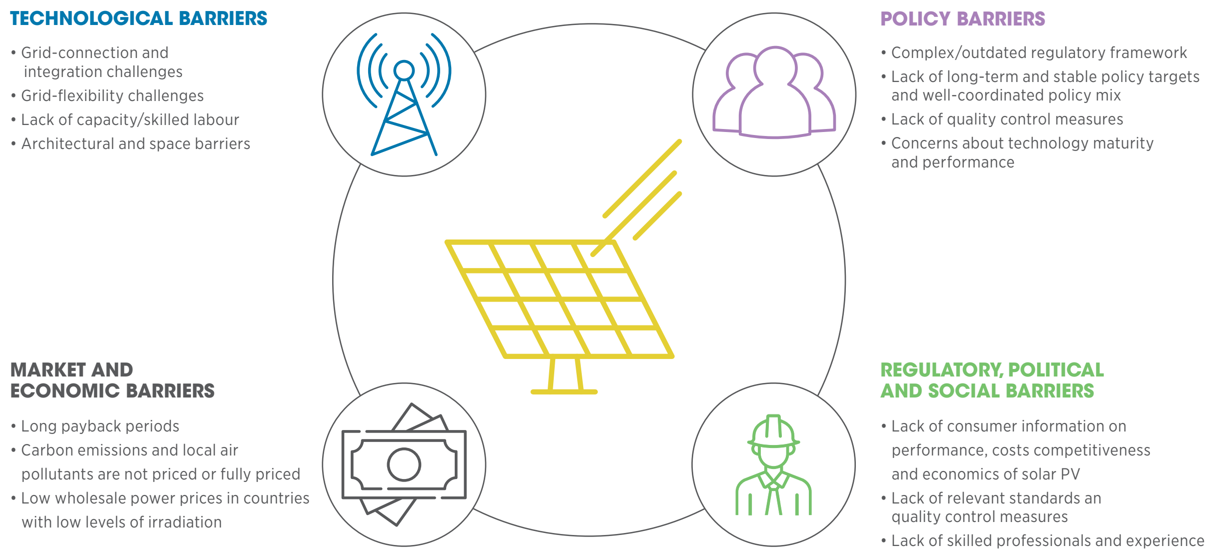
Sources: BSW Solar (2015); IRENA (2019c).

8. ACCELERATING SOLAR PV DEPLOYMENT: BARRIERS AND SOLUTIONS

This report clearly points out that solar PV is one of the strategic renewable technologies needed to realise the global energy transformation in line with the Paris climate goals. The technology is available now, could be deployed quickly at a large scale and is cost-competitive. However, despite the strong momentum, solar PV power projects continue to face serious constraints that could potentially hinder the accelerated growth needed in the coming decades.

In general, renewable energy sources are affected to differing degrees by problems resulting from varying project specifications, geographical contexts and levels of maturity. For solar PV power, existing barriers at different levels (technological, economic, policy, and regulatory and socio-political) could hinder the deployment of solar PV capacity in the next three decades (Figure 27). Mitigating these barriers immediately, through a range of support policies and implementation measures, is vital to boost future deployment.

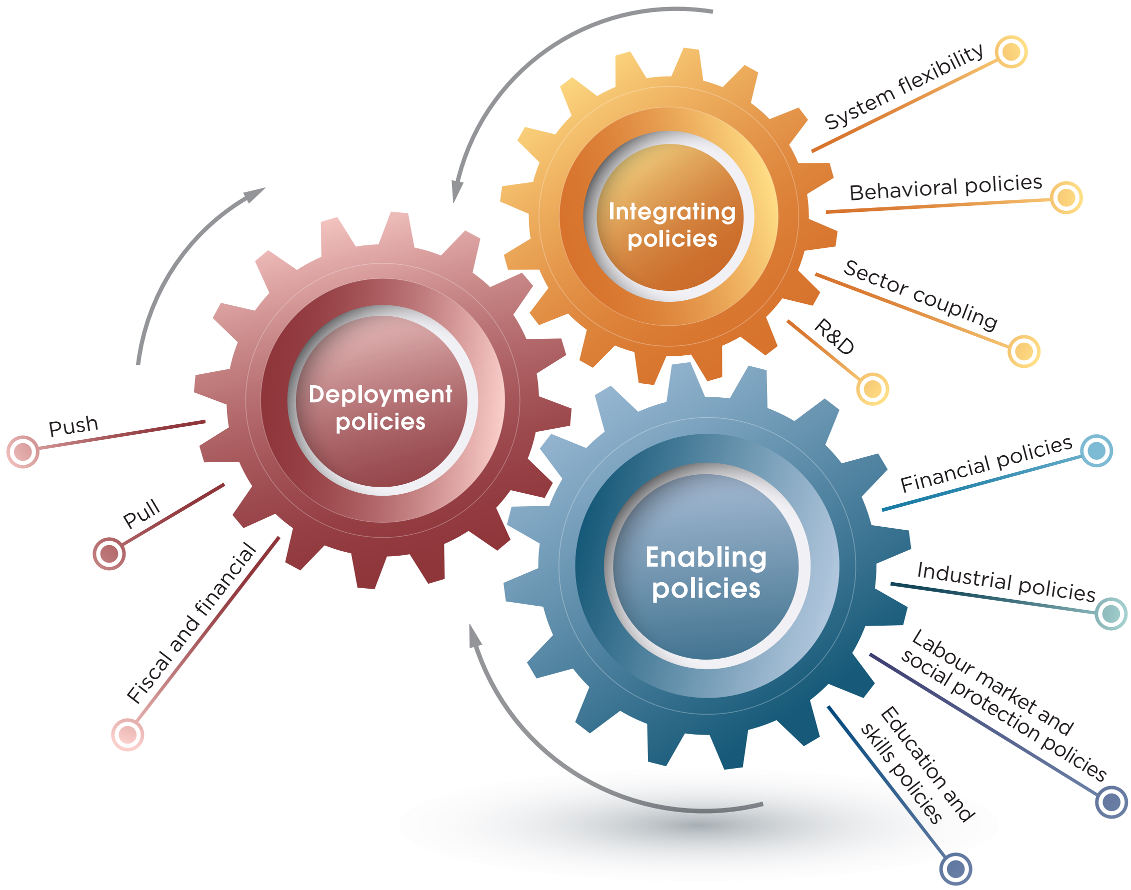
Figure 27: Existing barriers to fostering solar PV deployment



While energy transformation could bring positive overall socio-economic benefits at the global level, a deeper look at the regional level highlights how the benefits (and costs) of the transformation would impact various parts of the world differently. Such differences are due mainly to: 1) countries having different energy transition starting points, 2) the depths, strengths and diversity of supply chains, 3) the degree to which economies depend on fossil fuels, and 4) different levels of national ambition and means of implementation (IRENA, 2019b).

Levelling out the regional and country-level effects of the energy transformation depends on a policy framework that operates on two fronts. The framework should promote the deployment of renewables both to reduce energy consumption and to increase energy access. Simultaneously, the deployment of renewables must be embedded into broader policies that make energy a catalyst of economic, inclusive and sustainable growth. Such a "just transition" policy framework rests on three transformative sets of policies: deployment policies, integrating policies and enabling policies. These sets of policies would need to work together to ensure a just and inclusive energy transition, mainly to overcome all the existing barriers (policy; market and economic; technological; regulatory, political and social) listed in Figure 27 (IRENA, 2019b).

Figure 28: The policy framework for a just transition



The choice of the instrument and its design should be made based on country-specific conditions and objectives. The solutions and measures henceforth are wider and needs a specific study focussing on just addressing the barriers in the industry. This report presents an overview of some of the key aspects to be considered to accelerate solar PV capacity deployments along with some successful examples based on IRENA's comprehensive work on renewables so far along with additional literature review.

8.1 DEPLOYMENT POLICIES

Solar PV has been supported by a range of policy instruments. At a large scale, this support has traditionally been in the form of feed-in-tariffs (*e.g.* in Europe), tax incentives and quotas and obligations (*e.g.* India and the United States), and is now increasingly moving towards auctions. At a small scale, net metering and tax and other fiscal incentives have been the main supporting instruments. In the context of off-grid solar PV solutions, electrification policies and targets, along with innovative business plans, have allowed their increased deployment.

In general, when choosing the right instrument and its design, three key elements should be considered. First, policies should be tailored to country-specific conditions and objectives. Second, deployment policies should offer long-term stability to attract investment. And third, policies should consider all relevant points from the cost trends (IRENA, 2019b).

Deployment policies:

- **Set long-term, well-defined and stable solar PV power targets to attract investment.**

- **Provide long-term stability of policy instruments.**
  - Policy making needs to minimise swings from strong supportive measures to aggressive curbs. Likewise, prolonged periods of policy uncertainty can greatly impact the future of the solar PV industry.
  - Long-term support mechanisms, including capacity or adequacy mechanisms and support schemes for renewables, are widely used to guide generation investment according to national policy priorities and to increase the appetite for investment in renewables from both public and private investors.

- **Adapt policies to changing market conditions.**

- **Deploy renewable energy auctions that achieve policy objectives**, which include ensuring timely project completion, integrating solar and wind power, and supporting a just and inclusive energy transition.

- **Consider financing costs not only for cost-effective deployment strategies for decarbonising power generation but also to explicitly address as part of renewable policies** in order to mitigate the barriers associated with the growth of renewable energy investments.

  - The development of innovative financial schemes could contribute to overcoming financial constraints and allow consumers to invest in solar PV technologies. One key solution is represented by **community-shared and third-party-owned business models**, which create community solar projects. These allow consumers who do not have sufficient solar resource, or who simply cannot afford it, to buy or lease a portion of a shared solar system (Reese, M.O. *et al*, 2018). This model has several benefits, which encourage the development and use of solar PV solutions for the residential market, including: reducing or eliminating of upfront costs (Horath and Szabo, 2018), increasing electricity rate stability and potential bill savings, and helping lower-income consumers to expand their systems, which they would not be able to do due to lack of credit (NREL, 2014).

- **Enable and scale up corporate sourcing of solar PV projects** (IRENA, 2019a).

  - An effective, credible and transparent system for certification and tracking of renewable energy attributes should be supported.
  - Companies should be empowered to engage in direct investments for corporate production of renewable electricity for self-consumption.
  - Companies should be allowed to work with utilities or electricity suppliers to provide corporate renewable procurement options.

SOLUTIONS	SUCCESSFUL EXAMPLES
Stimulate growth of the solar industry and market through clear and well-designed incentive mechanisms	The California Solar Initiative (CSI) was launched in 2006 with the aim of stimulating growth and demand in the solar energy market by providing upfront financial incentives for solar energy installations. The financial incentives provided under the programme were designed to decline over time as experience, innovation and competition in the field continued to lower prices. Thanks to the initiative, California's solar PV capacity has increased more than 16-fold since its enactment, and thousands of jobs and firms throughout the solar energy value chain have been created (Hallock and Kinman, 2015).
Community-shared solar projects	In Brixton, London, three solar rooftop PV projects have been set up under a co-operative structure. The projects have been implemented on council estates and residents of these estates are the members of the co-operative society. Each member earns an equal dividend of about 3–5% of their initial investment per year. Through a dedicated fund, 10–20% of annual revenue is used for energy efficiency improvements, education initiatives and reducing cold draughts (Smedley, 2014).

8.2 INTEGRATING POLICIES

Integrating policies, such as national infrastructure, sector coupling or R&D policies, promote planning and co-ordination. Integrating measures, meanwhile, enhance system flexibility as the share of variable renewables rises (IRENA, IEA, REN21, 2018)

System integration policies:

- **Adopt a systemic approach, drawing together innovations in enabling technologies, market design, business models and system operation.**
  - The implementation of innovations mapped in Box 7 to unlock flexibility across the whole power sector would result in lower costs to integrate VRE and so support the energy transformation. Potential synergies among the different solutions also exist, which can result in lower investments when implementing them together (IRENA, 2019d).
- **Support the deployment of distributed energy resources** (IRENA, 2019d).
  - Emerging distributed energy resources that are connected at the consumer end – such as rooftop solar PV, micro wind turbines, battery energy storage systems, plug-in EVs, demand response and power-to-X solutions (*e.g.*, power-to-hydrogen or power-to-heat) – are decentralising the system and should be supported and deployed.
  - Distributed resources should be enabled to participate in established markets, such as wholesale electricity markets, ancillary service markets and capacity markets (if applicable), so that distributed energy resources are exposed to market price signals. This can be done either via aggregators or by decreasing the minimum capacity requirement for participating in such markets
  - Various emerging digital technologies such as the Internet of Things, artificial Intelligence, and big data and blockchain could support distributed energy resources in responding to system conditions and providing services to the grid, turning them into flexibility providers.
- **Improve existing infrastructure along with building a high-voltage grid, or super grid**, to transport electricity to another region and avoid renewable energy curtailment.
  - The cost of building such a grid is high and must be measured against the economic benefits of both of the systems that the grid is linking. In addition, co-ordination by multiple layers of government (federal, regional and state) is important (IRENA, 2019d).
  - To improve resilience of the grid and the energy access rate with renewable sources, microgrids could be deployed. To strengthen the interconnections among countries within a region, super grids could be a solution.

- **Reduce the uncertainty of solar PV generation through advanced weather forecasting.**
  - Advanced weather forecasting can help reduce the uncertainty of solar generation. Enhancements from the use and management of big data and artificial intelligence can increase the accuracy of the forecast and hence the overall reliability of the system. In turn, better renewable forecasting can help with uncertainty in generation and reserves (Kroposki, 2017).

SOLUTIONS	SUCCESSFUL EXAMPLES
Enable DER to participate in established markets	Some wholesale market operators in the United States have experienced success with this approach. For example, PJM, the largest market operator in the country, has successfully enabled demand response to bid into its ancillary service markets to provide regulation services. In December 2017 the NYISO released a concept proposal for market design that would enable the participation of DER in the wholesale as well as the ancillary service markets. As per this proposal, DER will be treated in the same way as other market resources. They will be able to participate in capacity reserve markets, regulation service markets and other either directly or via the aggregators of small-scale DER (< 100 kW) (IRENA, 2019d).
Digital technologies	PV VPP: The South Australian government and Tesla are developing a network of 50 000 home solar PV units connected to an aggregator. The VPP is expected to meet around 20% of South Australia's average daily power demand (250 MW). Additionally, the new power plant is expected to lower energy bills for participating households by around 30%, and it will benefit all South Australians with lower energy prices and increased energy stability (IRENA, 2019d).
Advanced weather forecasting techniques	PerduS project: Funded by the BMWI, this project in Germany was launched in March 2016. It focuses on Saharan dust outbreaks and on improving weather and PV power forecasts during such weather situations, thereby supporting the incorporation of an increasing share of renewable energy into the German power mix. For example, on 5 April 2014 Germany experienced a large day-ahead PV power forecast error of the order of 10 GW, a result of Saharan dust being transported to Germany during this and preceding days(IRENA, 2019d).

Social integration policies:

- To realise the accelerated growth of solar PV power in coming decades, **the adverse social impacts that may arise during different phases of solar PV projects (planning, construction and O&M) need to be identified and assessed well in advance**, as well as mitigated. In this regard, assuring the quality of solar PV installations is crucial to ensure stability for investors and other stakeholders. This is an essential instrument to protect and accelerate future investment in PV deployment. Quality assurance helps to reduce risk by providing the confidence that a product or service will meet expectations (IRENA, 2017a).

- **Engage local communities from the early stages of solar PV development.** Making the community a fundamental part of a project, throughout all stages of project development and operation, as well as promoting the equitable distribution of economic benefits and costs (*e.g.* through creation of jobs), gives a much better chance of deploying truly community-based sustainable projects.

- **Implement installer certification and licensing/ training programmes to assure the quality of solar PV installations.**

SOLUTIONS	SUCCESSFUL EXAMPLES
Community engagement	United Kingdom: In the case of the construction of the Southwick Solar farm (near the town of Fareham), community relations were of paramount importance. Public communities were involved during construction and operation through regular updates on the project's status and any issues. This was achieved through various community engagement methods, such as educational talks and guided tours through the site, discussion forums and meetings (BRE, 2015)
Quality assurance mechanisms	In Australia, quality mechanisms such as accreditation allow installers (and equipment retailers) to achieve high quality. Once accredited with the Clean Energy Council, solar PV installations are eligible for government rebates such as Small-scale Technology Certificates and feed-in tariffs. To become solar PV accredited, installers must complete training courses and provide evidence of their electrical licence, working at heights certification and public liability insurance. Once approved, the accreditation is valid for two years, after which it is possible to apply for renewal (IRENA, 2017a).

Urban policies:

- For **future urban planning, new buildings** can be designed to integrate PV systems in their structure to maximise the installation space. The lack of adequate installation space for PV panels is a key barrier in the context of cities, as PV panels need to be angled in the right direction to maximise solar exposure. For instance, cities such as Hong Kong, New York, Sydney and London have a cityscape featuring high-rise buildings with major space constraints, as the surface is simply too limited on older high-rise buildings.

- The physical aspect of the city, including the local building stock, also has an impact on how much electricity can be generated from rooftop PV systems (Mah et al., 2018). For instance, houses with limited roof space, such as tenements, a multi-occupancy building typical of Scottish cities, results in less electricity output compared with output from large properties that a typical in other cities.

SOLUTIONS	SUCCESSFUL EXAMPLES
Spatial planning/mapping	Successful work has already been done at the European level, namely through the Coal Regions in Transition initiative in late 2017 by the European Commission. Analysis has been carried out to see the extent to which the use of PV electricity generation systems can help the transition the coal regions of the European Union (Bodis et al., 2019). The analysis used a spatially explicit methodology and considered different types of solar PV systems, such as ground-mounted systems, as well as the installation of rooftop solar PV systems on the existing building stock. Results showed that the available area in those regions is abundant and that solar PV systems could fully substitute the current electricity generation of coal-fired power plants in the analysed regions (Bodis et al., 2019).
Mandating solar installations in new buildings	In 2018 California added new provisions to the state's building code. Among them is the requirement that as of 2020 all new homes be built with solar panels installed. Where solar is not suitable, homeowners must have access to a community solar project or receive efficiency upgrades that compensate (Roberts, D., 2018).

8.3 ENABLING POLICIES

Strengthening policy connectivity and co-ordination between energy and the rest of the economy will draw maximum systemic benefits from the energy transformation. Such policies must focus on building capabilities for renewables production, use and application, as well as on reform of the broader institutional architecture to enable systemic benefits between the energy sector and the wider economy. The enabling framework links four crucial national policies: industrial policy, labour market and social protection policy, education and skills policy, and financial policy.

INDUSTRIAL POLICY

Industrial policies generally are intended to support economic diversification. Mainly, a transition-enabling industrial policy should make the energy sector into a lead sector of the economy. Some recommendations on this aspect are listed below:

- **Promote R&D strategies,** as well as institutions to advance the uptake of R&D results in the public and private sectors.
- **Facilitate competitive environments** in which reduction in the cost of energy is both rewarded through the right to deliver new projects and supported through the provision of targeted public R&D funding.
- **Promote consumer awareness.**
- **Enable targeted public investment to support the uptake of renewables** and to create additional jobs and capabilities.
- **Strengthen and maximise value creation from the development of a domestic solar PV industry**

FINANCIAL POLICY

Mobilising financial investment is crucial for the energy transition to happen.

- **Mobilise significant revenue streams through carbon pricing and other measures**, including green bonds, and devise revenue recycling schemes to achieve a just transition.
- **Use revenues** to support strategic investment in new infrastructure and reallocate and recycle budgets in a way that benefits education, health care and other sectors.
- Carbon taxation revenues can be used to foster new employment creation and to limit the financial burdens of carbon pricing on low-income families and small businesses.

EDUCATION AND SKILLS POLICY

- **Support skills and supply chain development in order to enable the commercialisation of wind technology:**
  - **Technical education and training offered by dedicated institutions** or as part of university curricula can help equip the workforce with adequate skills and would increase opportunities for local employment (IRENA, 2017b).
  - **Facilitate reskilling of the work force from the fossil fuel industry to renewables.** Successful job migration between sectors, however, depends on dedicated retraining policies. Specific policy measures, such as upgrading and supplier development programmes, support for joint ventures, and industrial promotion schemes, may be needed to strengthen the industrial capacity of domestic firms.

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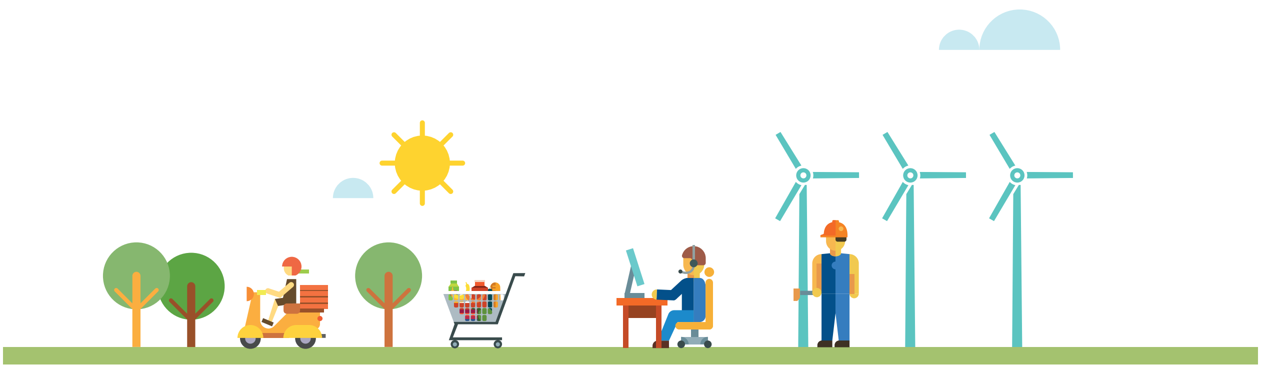

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(ISBN 978-92-9260-156-0)