Solar Energy

Mapping the road ahead

International Energy Agency

October 2019

Abstract

Solar Energy: Mapping the Road Ahead is a collaborative effort of the International Energy Agency (IEA) and the International Solar Alliance (ISA) to provide government, industry and civil society stakeholders with the methodology and tools to plan and implement national and regional solar energy roadmaps. Despite plummeting costs, solar energy expansion still depends largely on policy makers setting ambitious targets and implementing sound policies, market designs and regulatory frameworks, including for technological research, development and deployment. This guide for policy makers addresses all solar technologies – solar photovoltaic (PV) electricity, concentrating solar power (CSP, or solar thermal electricity [STE]), and solar heating and cooling (SHC). As well, it looks at applications such as utility-scale PV and CSP power generation; on- and off-grid distributed electricity generation; solar thermal water/space heating and cooling; solar heat for industry; solar cooking; and solar fuels.

Sound knowledge of solar energy resources, its constituents (direct and diffuse radiation) and variations across time scales is a prerequisite. Solar resources must be analysed together with energy demand, its elements (electricity, heat, transport, fuel) and its variations from one time period to another. Importantly, this guide also addresses resource variability and key energy access concerns.

Designed for decision makers in developing and emerging as well as developed economies, this guide does not cover every aspect of solar energy technology, policy and deployment. Rather, it aims to provide a comprehensive list of steps and issues for each phase of solar energy roadmapping and deployment. Selected case studies encapsulate the wide array of existing applications, and discussions of deployment drivers and barriers are accompanied by realistic recommendations for actions, tools, and useful information.

Acknowledgements

This publication was prepared by the International Energy Agency in co-operation with the International Solar Alliance. Cédric Philibert of the Renewable Energy Division of the IEA oversaw the project and is the principal author. Karolina Daszkiewicz, Simone Landolina and Tobias Rinke, of the IEA, and Mohua Mukherjee, of the ISA, provided key contributions. Paolo Frankl, Head of the Renewable Energy Division, provided strategic guidance. Keisuke Sadamori, Director of Energy Markets and Security reviewed the document and provided expert advice.

Manuel Collares Pereira (Evora University), Luis Crespo (Protermosolar), Edwin Haesen (IEA), Philippe Malbranche (Institut National de l'Energie Solaire), Daniel Mugnier (SHC TCP) and Stefan Nowak (PVPS TCP) provided invaluable insights. Renate Egan (Autralian Photovoltaic Institute), Sarah Grettve (Swedish Energy Agency), , Moira Torres Aguilar, Julien Mas and Cécile Martin-Phipps (ISA), Christoph Richter (SolarPaces TCP), and Mamoru Terakado (NEDO) provided useful comments.

The Communications and Digital Office of the IEA has provided strong support for the publication and distribution of this report, with special thanks to the Acting Director, Jad Mouawad, and to Astrid Dumond, Clara Vallois and Therese Walsh for production and editorial co-ordination. Thanks to Kristine Douaud for editing the report.

This work was made possible by financial support from the French government through ADEME, and from the German government.

Foreword

The potential of solar energy is huge, with enough sunlight striking the earth every two hours to provide the entire planet's energy needs for a whole year. Combined with rapid technological progress and cost declines, solar energy holds the promise to be a very large contributor of clean and affordable energy, in particular for the 7 billion people expected to live in our planet's sunbelt by mid-century.

Technology costs have massively diminished in the past decade, especially for photovoltaic energy. Solar PV is the fastest growing power source around the world, and this will continue. But progress is uneven across countries and related technologies such as solar thermal and concentrating solar are lagging behind. Stronger policies are needed to put solar energy in line with the world's ambitions to achieve energy access for all, tackle climate change and reduce air pollution.

The International Energy Agency (IEA) and the International Solar Alliance (ISA) are working together to accelerate solar deployment in many different areas, thanks to our complementary resources and work programmes. In some countries, policy makers are mainly concerned with smoothly integrating solar into energy systems, including for buildings, industry, and mobility. This is an area where the IEA has considerable experience and is playing a leading role. Other countries are still at an earlier stage and show considerable interest in the ISA programme of work regarding, for example, scaling solar applications for agriculture, solar mini-grids and rooftop solar. For all, affordable finance at scale will prove decisive.

This *Guide for Policymakers* was produced jointly by the IEA and the ISA. Its aim is to inform policy makers, industry, and civil society on how to develop national and regional roadmaps for deploying solar energy at all scales, using all technologies, responding to all sorts of energy needs and taking into account local specific contexts. We trust it provides the necessary information and methodological tools to make solar road mapping a success. We believe it will help all countries reap the magnitude of benefits that would come with an accelerated deployment of solar energy: improved access to energy, increased energy security and affordability, more inclusive and sustainable economic growth, cleaner air in cities and homes, and an invaluable contribution to mitigating climate change.

Dr Fatih Birol, Executive Director

International Energy Agency

Upendra Tripathy, General Director

International Solar Alliance

Highlights

Sound knowledge of solar energy resources, its constituents (direct and diffuse radiation) and variations across time scales is a prerequisite. Solar resources must be analysed together with energy demand, its elements (electricity, heat, transport, fuel) and its variations from one time period to another.

Solar technologies use the radiative energy of sunshine in a wide spectrum of applications to provide electricity, heat and cold, and even fuel. Rather than assessing them separately, photovoltaic (PV) energy, concentrating solar power (CSP) and solar thermal heating and cooling (SHC) should be considered as complementary technologies.

PV technology is unique in its extreme scalability, ranging from watt-scale individual systems to kilowatt- and megawatt-scale distributed domestic and industrial power systems and to power plants of hundreds of megawatts. It can thus provide off-grid electricity access as well as power micro- and mini-grids, strengthen grids at their fringes, and deliver significant power to fully developed existing networks.

PV and CSP are the two main technologies for generating electricity from sunshine. While PV is less expensive, CSP with built-in thermal storage can improve power system flexibility and stability, increase the solar share and integrate more variable renewable energy. Solar power can also be used to produce and export hydrogen-rich chemicals and fuels.

The portfolio of SHC options is even larger, with solar thermal systems offering highly efficient solutions at various temperatures and for different applications (domestic hot water, space heating, district heating, process heat and even thermally driven cooling) in addition to solar electricity-driven heating and cooling devices. While solar thermal energy is currently used primarily for domestic water heating, it has considerable potential to generate process heat in the future.

Elaborating and implementing roadmaps would help ensure successive deployment. The process is as important as the content of the documents, and it should associate all stakeholders, and ensure the collaboration of many ministerial departments at the higher possible level.

Table of contents

Executive summary **7**
Removing barriers to investment 7
A guide for policy makers 8
Findings and recommendations **9**
Policy recommendations 9
Three families of technologies 9
Market and policy trends 13
Enabling technologies and system integration 15
Designing and implementing roadmaps 17
Useful online resources 20
Introduction **21**
About technology roadmaps 21
About this guide 21
Guide structure and roadmapping process 22
About solar energy technologies 23
Enabling technologies and system integration 32
Market overview and trends 36
References **43**
Phase 1: Planning and preparation **45**
Conducting baseline research 46
Technology situation analysis 47
Identifying solar stakeholders 49
Phase 2: Visioning **51**
Drivers of solar energy expansion 52
Deployment targets 54
Phase 3: Roadmap development **55**
Solar technology, project delivery and workforce barriers 56
Barriers to integrating solar projects into the energy system 57
Considerations for the enabling framework 59
Research, development and demonstration support 63
Phase 4: Implementation, monitoring and revision **64**
Setting the timeline and milestones 64
Monitoring roadmap implementation 64
International collaboration 66
References **70**
Annex A. Overview of policy instruments to promote solar uptake **71**
Power sector 71
Price-finding mechanisms 72
References **76**
Annex B. Acronyms and abbreviations **77**
Acronyms and abbreviations 77
Units of measure 78

List of figures

Figure 1. Energy supplies from the three solar technology families (top) and global solar PV annual additions by segment, 2013-24 (bottom) 10
Figure 2. Average auction price by project commissioning date 11
Figure 3. Conceptual daily energy mix with PV and CSP, medium term (left) and long term (right) 12
Figure 4. VRE shares in total electricity generation by selected region, 2018 16

Figure 5. The six phases of VRE integration and the four pillars of flexibility 17
Figure 6. The roadmap development process 18
Figure 7. PV and CSP generation in the Sustainable Development Scenario 19
Figure 8. The roadmap development process 22
Figure 9. Global horizontal irradiation 24
Figure 10. Photovoltaic electricity output 25
Figure 11. Individual solar thermosiphon system (left) and pumped circulation system (right) 27
Figure 12. Direct normal irradiance 30
Figure 13. Main CSP technologies 31
Figure 14. Conceptual daily energy mix with PV and CSP, medium term (left) and long term (right) 32
Figure 15. VRE shares in total electricity generation by region, 2018 32
Figure 16. The six phases of VRE integration and the four pillars of flexibility 33
Figure 17. California's 'duck curve' as PV electricity shares expand 34
Figure 18. Global solar PV annual additions by segment, 2013-24 36
Figure 19. Installed PV capacity in sub-Saharan Africa, 2014-23 38
Figure 20. Gross solar thermal capacity additions, 2008-17 (left), and estimated consumption growth 2018-23 (right) 39
Figure 21. Forecast of CSP capacity by region (left), and of generation by technology (right) 40
Figure 22. Remuneration-setting for utility-scale renewable projects 42
Figure 23. Planning and preparation phase 45
Figure 24. Visioning phase 51
Figure 25. PV and CSP generation in the Sustainable Development Scenario 54
Figure 26. Roadmap development 55
Figure 27. Implementation, monitoring and revision phase 64
Figure 28. Classification of power sector policies 72

List of boxes

Box 1. Solar potential and resources 12
Box 2. Off-grid solar 14
Box 3. The importance of the cost of capital for solar projects 15
Box 4. Solar Cooling 28
Box 5. The importance of the cost of capital for solar projects 35
Box 6. Floating solar PV 36
Box 7. Off-grid solar appliances 39
Box 8. Thought for food: Solar cooling and cooking, a Nigerian example 42
Box 9. Dispersion facilitates variable solar integration 50
Box 10. Leveraging local capacity for solar energy 53
Box 11. When the power sector is not credit-worthy: India's UDAY scheme 58

List of tables

Table 1. Key questions for baseline research 46
Table 2. Key questions for solar technology situation assessment 47
Table 3. Potential stakeholders in solar technology roadmap development 49
Table 4. Typical drivers of solar technology deployment 52
Table 5. Overview of solar technology, project delivery and workforce barriers 56
Table 6. Overview of energy infrastructure barriers and action options 59
Table 7. Overview of policy, regulatory and market framework barriers and action options 60
Table 8. Overview of non-economic barriers 61
Table 9. Overview of financing barriers and action options for solar energy projects 62
Table 10. Quantitative and qualitative indicators for monitoring progress 65

Executive summary

The International Energy Agency and the International Solar Alliance have joined forces to produce this guide providing policy makers, industry, civil society and other stakeholders with the technological information and methodological tools to map a course towards robust, accelerated solar energy deployment. Despite plummeting costs, solar energy expansion still depends largely on policy makers setting ambitious targets and implementing sound policies, market designs and regulatory frameworks, including for technological research, development and deployment. This guide aims to provide a comprehensive list of steps and concerns for each phase of solar energy roadmap design and implementation; an overview of deployment drivers and barriers; realistic recommendations for actions and tools; and useful information sources.

The IEA approach to roadmap development involves two streams of activities (analysis and consensus-building) in four phases (planning and preparation; visioning; roadmap development and implementation; and monitoring and revision).

Unprecedented deployment and cost reductions have taken place in the past ten years: photovoltaics (PV), initially one of the most expensive electricity-generating technologies, has become one of the most affordable. Dispatchable power from hybrid PV-concentrating solar power (CSP) plants was highly competitive in the most recent auctions, and solar thermal technologies are penetrating new markets for industrial processes and district heating networks.

Progress across countries and technologies is uneven, however, and despite plummeting costs and 20 years of uninterrupted global growth, the amount of new solar technology additions in 2018 was similar to the previous year (PV additions remained below 100 gigawatts [GW]). Even worse, the solar heat market has been shrinking continuously since 2013 and is not being counterbalanced by the ongoing renaissance of the much smaller CSP market.

This paradox reveals that numerous barriers – fossil fuel subsidies, administrative obstacles, economic difficulties for grid operators and absent or weak support policies and targets – still impede widespread solar energy deployment. Predictable polices based on clear, long-term targets remain essential to cost-effectively unlock the immense potential of solar energy.

Policy makers in most jurisdictions must therefore set targets consistent with their needs and circumstances, framing policies accordingly and designing regulatory and market frameworks conducive to investment. Together with the energy ministry, the implication at the highest possible level of many other ministerial departments is important to set objectives in their respective sectors, to remove barriers to investment and achieve successful deployment.

Removing barriers to investment

Investment barriers are not the same for all technologies. Although PV efficiency is continuing to improve rapidly, its costs are falling quickly and it is a mature technology, upfront investment costs remain high for many potential solar customers. Money for safe, long-term investments is available, but market and policy risks for solar technologies need to be minimised.

For utility-scale projects, distribution companies' finances are often an issue in developing economies, so decisive policies must be enacted (as in India). Grid integration issues are often feared unnecessarily, so it would help if the experiences of countries that already use significant shares of variable renewables were more widely shared – although it is important to highlight contextual differences. In hot, humid countries, combining solar energy with hydropower can often be a straightforward means of supplying power on demand.

New business models support expanded on- and off-grid PV self-consumption at various scales, for agricultural, extraction, industrial and service sector production to home systems and small appliances. The extreme scalability of solar PV makes it a great asset for achieving universal energy access. Clean cooking, already being experimented with in India, may be the next step.

CSP combines well-proven technologies (commercialised in the 1980s) with more recent concepts. In hot, dry countries, its use is likely to increase as PV electricity saturates daytime demand, initially to respond to demand peaks after sunset (as in Morocco) and then to deliver power around the clock (as in the United Arab Emirates). Lead times for development are long and capital needs are high, and only resolute policies will overcome these obstacles. The involvement of bilateral and multilateral development banks is often necessary.

Solar heating and cooling (SHC) technology success has been mixed. Space heating applications are becoming more common for large-scale district heating systems and are increasingly being integrated into building designs. Industrial heat applications are also expanding, though from a small base. Although solar thermal cooling technology benefits from a good match between demand and resource availability, it is in direct competition with PV systems. Meanwhile, the market for the most mature technology – domestic water heating – is shrinking. Temperate countries should review and strengthen their renewable heat policies (especially for solar heat), as they often lag behind those for electricity.

A guide for policy makers

The process of devising a roadmap is as important as the roadmap itself for ensuring the success of solar energy technologies. The first phase of roadmapping – identifying all stakeholders and engaging in extensive dialogue – is decisive. It leads to the second phase, the building of a common vision.

Elaborating a vision requires that the energy needs of the economy and the population be analysed in their complexity of forms (e.g. electricity vs. heat) and variability, together with solar resources (including temporal and locational variations) and other available energy resources.

Then, the most relevant technology options to harness solar energy for either electricity (PV and CSP) or heat (SHC, or even solar fuels, can be identified. It is crucial to take a holistic approach, and clear, long-term targets must be set. The next step in the process is to identify barriers and ways to overcome them, and to assign responsibilities.

Monitoring implementation is the fourth phase. It may require policy-strengthening, but targets may also be updated and upgraded as problems are solved and costs continue to fall.

Findings and recommendations

Policy recommendations

Governments should develop solar power roadmaps based on analyses of both their energy needs and the heat and electricity opportunities offered by various technologies.

The process of developing and implementing a roadmap is as important as the document itself, and it should associate a wide array of stakeholders and interests. Roadmaps should present a vision, delineate targets and define actions to overcome deployment barriers.

Reducing investment risks appears to be crucial for solar technology deployment now that falling costs offer numerous opportunities for profit. Policy makers and regulators are responsible for defining and implementing regulatory frameworks as well as market designs conducive to investment (and for rapidly connecting solar technologies to the grid when appropriate).

Although financial support for solar technologies may still be needed to jumpstart deployment in new markets, excessive profitability is not a remedy for non-economic barriers, so total support costs should be carefully monitored. At least for large-scale plants, incentives should be rapidly steered towards competitive auctions for long-term power purchase agreements, possibly with some forms of energy management options (curtailment, storage, etc.) and time-based pricing facilitating system integration.

Solar roadmaps should not be undertaken by the energy administration alone. Virtually all other ministerial departments can be interested (if only as energy customers in their day-to-day work) and many would need to be involved as well.

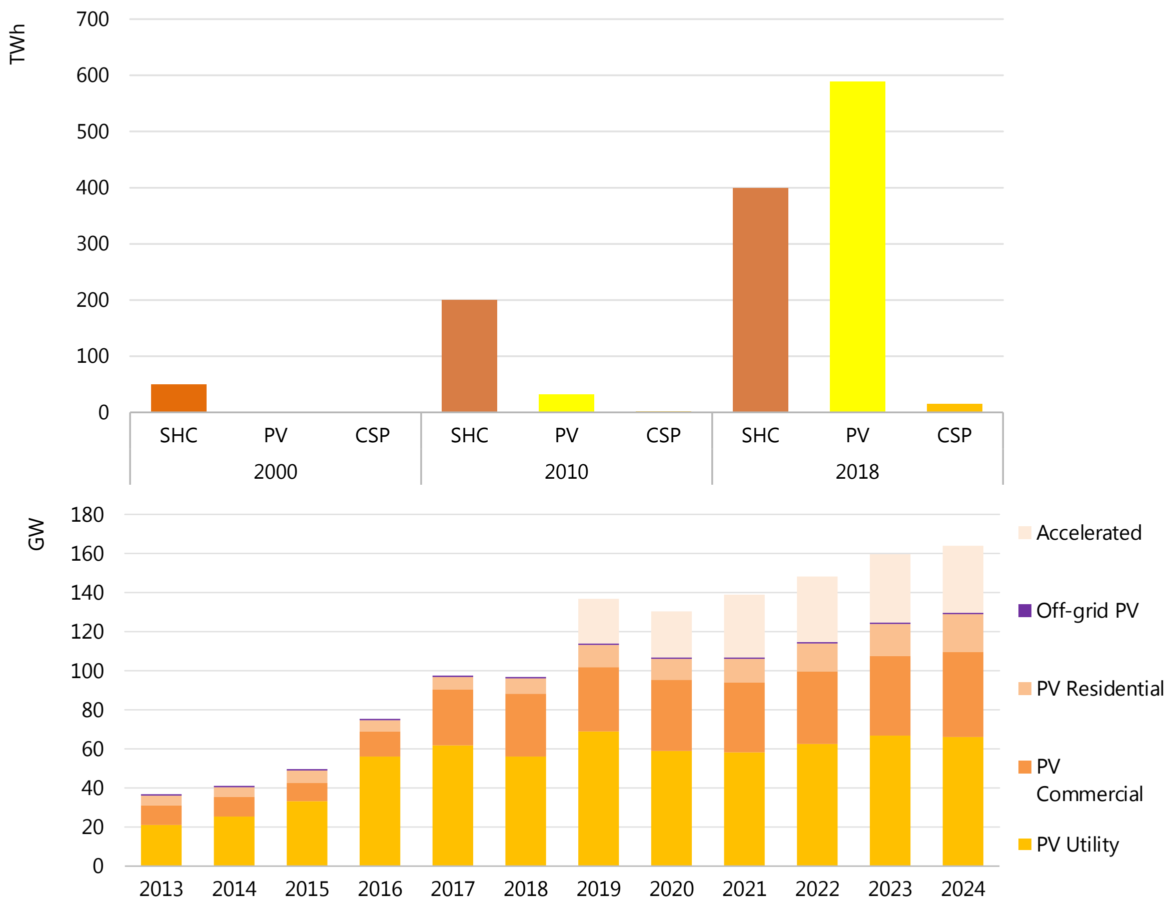
Policy makers are not alone, and can request help from an array of international organisations. The International Solar Alliance, as well as multilateral and bilateral development banks and agencies, offers help and a variety of tools, including financing.

Three families of technologies

Three main technology types are used to harness energy from the sun: **photovoltaic** (**PV**), which directly converts light into electricity; **solar thermal**, or **solar heating and cooling** [**SHC**], which uses using solar radiation to deliver heat; and **concentrating solar power** (**CSP**), which converts concentrated light into heat to drive a heat engine connected to a generator. PV energy, for which cost reductions in the last ten years have been impressive, currently constitutes the most dynamic global market, but the significant possibilities offered by the other technology families must also be considered when laying out a pathway for full-scale solar energy use.

PV cells and modules directly convert solar energy into electricity, using both direct and diffuse radiation. PV technology can be used on the grid or in off-grid applications at capacities ranging from less than 1 watt (W) to gigawatts (GW). On-grid residential systems, often rooftop installations, typically reach the kilowatt (kW) scale; commercial systems, often installed on flat roofs or over parking lots, are in the order of megawatts (MW); and ground-based plants for utilities range from tens to hundreds of megawatts. Grid-connected systems require inverters to transform direct current (DC) power into alternating current (AC). Installations can be fixed or track the sun, usually on one axis only. Off-grid applications range from several watts for initial energy services to mini-grid applications with battery backup, or hybrid designs that complement diesel generators. Although PV was an expensive electricity-generating technology only ten years ago, it is rapidly becoming one of the most affordable. It has overtaken SHC energy supply by 2018 (Figure 1). In the next five years, annual capacity additions will grow from 115 GW to about 130 GW. The total cumulative capacity will reach 1 TW by 2023 at the latest, and 1195 to 1375 GW by end 2024 depending on the case.

Figure 1. Energy supplies from the three solar technology families (top) and global solar PV annual additions by segment, 2013-24 (bottom)



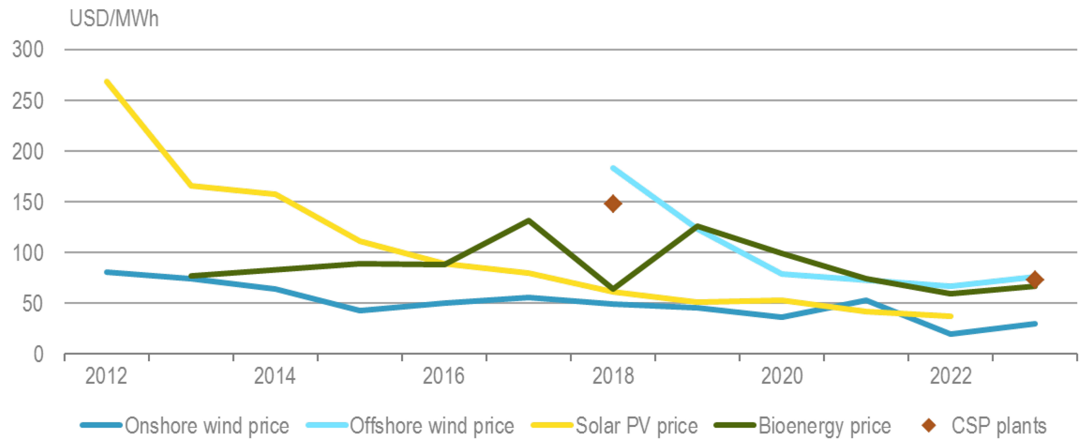
Note: TWh = terawatt hour.

In just ten years, PV has overtaken SHC as the lead solar supplier of energy.

PV modules usually face the equator, with the tilt determined primarily by latitude, but it can also be adjusted to adapt to the ratio of diffuse vs. direct irradiance, or for economic reasons. The tilt tends to equalise electrical outputs despite differing solar resource abundance among regions. A growing proportion of utility-scale plants are also using one-axis trackers to further augment output. The introduction of bifacial technologies may offer additional flexibilities in the overall system design.

Solar light can be captured and transformed by a variety of **solar thermal** technologies and utilised as heat in numerous applications, from domestic hot water to space heating at the individual and collective (district heating) level, as well as for agriculture and industry. Solar air conditioning and industrial cooling can be provided by solar thermal technologies or by PV-run devices. Technologies to store cold can improve the already good match between sunshine and cooling needs, whereas concentration technologies can provide high-grade heat or steam for industrial processes and offer more cost-effective heat storage options. Several large-scale solar concentrating steam plants are under construction in the Middle East and the United States to replace gas-fired ones for enhanced oil recovery operations.

Figure 2. Average auction price by project commissioning date



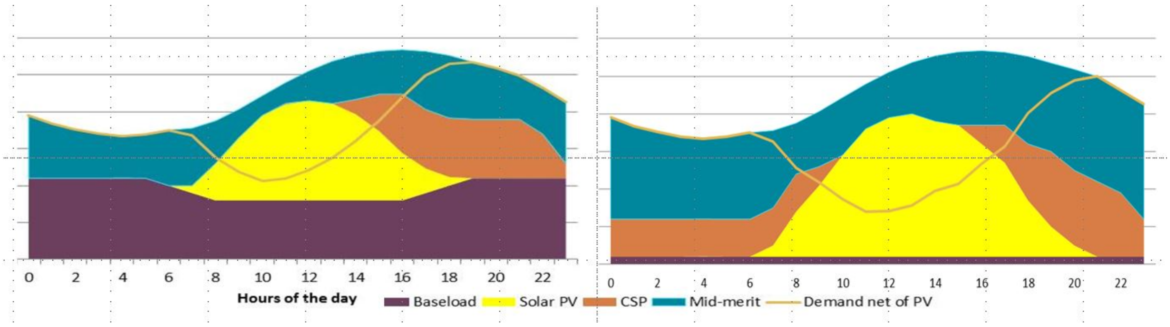
Note: MWh = megawatt hour.
Source: Adapted from IEA (2018b), *Renewables 2018*.

PV electricity cost reductions have been rapid and sharp in a strongly competitive environment.

CSP technology concentrates solar rays to heat a fluid that then directly or indirectly runs a turbine and an electricity generator. The predominant CSP technologies are parabolic troughs (PTs) and solar towers. Unlike PV systems, CSP plants use only direct irradiation and therefore need a daily minimum of sunshine to produce electricity. This limits their use to hot, dry areas with clear skies and reduced dust.

Solar thermal electricity costs more than PV electricity, but it also offers more: CSP plants can integrate thermal storage to deliver electricity on demand, and they contribute to power system stability and flexibility by making it possible to integrate more solar PV and wind power. Different combinations of solar field size, storage tank size and electricity capacities provide great flexibility in CSP plant design. Solar thermal electricity is currently most valuable when generation is shifted to after sunset to complement PV electricity; in the not-too-distant future, all-night generation will be required to further increase the solar share in total electricity generation and reduce the use of fossil fuels (Figure 3).

Figure 3. Conceptual daily energy mix with PV and CSP, medium term (left) and long term (right)

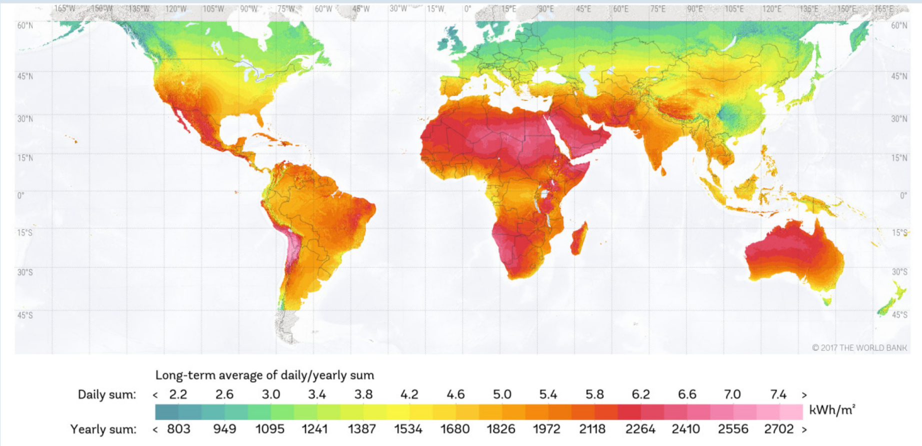


The amount of CSP in the electricity mix will increase as PV saturates daytime production and power systems approach full decarbonisation.

Box 1. Solar potential and resources

Solar irradiation consists of direct and diffuse radiation. Direct (or beam) radiation experienced as 'sunshine' comes directly from the sun's disk, whereas the diffuse radiation experienced as 'daylight' comes from numerous directions. Because solar resources vary daily and seasonally, it is important to consider the extent to which resource availability matches heat and power demand variations, as their correspondence will determine the type of facility required and can signal possible difficulties in deploying solar energy technologies to satisfy energy needs.

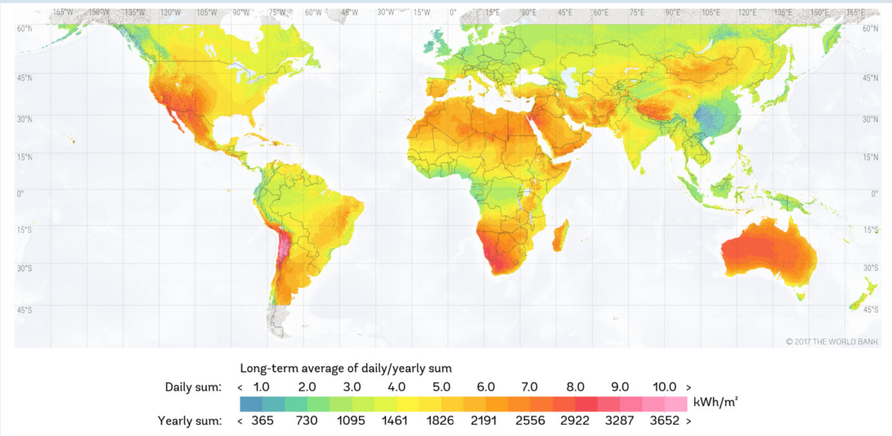
Global horizontal irradiance



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Source: World Bank Group, ESMAP and Solargis (2019), *Global Solar Atlas*, http://globalsolaratlas.info.

Global horizontal irradiance (GHI) measures the density of solar resources available per horizontal surface area, including both direct and diffuse radiations. Other measures of resource availability also need to be considered, depending on the technology to be deployed. For concentrating solar technologies for power or industrial heat particularly, the relevant metric is direct normal irradiance (DNI).

Direct normal irradiance



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: World Bank Group, ESMAP and Solargis, *Global Solar Atlas*, http://globalsolaratlas.info.

Market and policy trends

Record-level PV capacity growth has dominated renewable energy expansion in recent years, and prices have fallen drastically since 2010 – by four-fifths for modules and by almost two-thirds for residential systems. Although growth of PV installation stalled for the first time in 2018, remaining below 100 GW of new PV capacity, growth resumed in 2019 reaching a record 115 GW (estimated) installed in over 110 countries. Cumulative global capacity reaches 609 GW, far surpassing CSP capacity estimated at 6.5 GW by end 2019. In 2018 PV exceeded cumulative solar thermal panel capacity (then 480 gigawatts thermal [GW_{th}]) for the first time.

Owing to significant cost reductions as well as private sector and government initiatives, off-grid solar PV applications have begun to bridge the electrification gap in Asia and sub-Saharan Africa. Mini-grids as well as industrial, agricultural and commercial applications and solar home systems (SHSs) can provide an immediate solution for initial or improved electricity access for households, small businesses and industries.

Box 2. Off-grid solar

The private sector's market-led **solar appliance** revolution of recent years resulted from the ability of a single solar PV panel to supply DC electricity to a distinct solar appliance. Appliances such as portable lanterns, fixed LEDs, phone chargers, fans, TVs, pumps, fridges, vaccine coolers, laptops, rice-cookers, etc., can therefore be operated anywhere on electricity from sunlight.

Solar Home Systems (SHSs) are PV systems that often have a peak capacity in the 100 W range and are installed in off-grid residential dwellings and equipped with a battery for lighting and for powering various appliances for several hours per day. Operated under new business models such as 'pay as you go', SHSs that entered the market just in 2017 gave an estimated 6 million people initial access to electricity. In Bangladesh alone, 12 million people have already gained access to electricity through SHSs.

Larger off-grid solar energy systems are often used for either primary electricity or for backup power during the brownouts and blackouts that frequently occur in developing countries. These systems can generate electricity in an off-grid mode for mines, telecom towers, greenhouses and other agriculture equipment, hotels, hospitals and schools.

For solar heating technologies, even though the Chinese market is shrinking, it is still the world leader by far. After declining since 2009, European markets regained growth in 2018, and some emerging economies have demonstrated market dynamism. While individual solar water heating systems dominate the global market, in several countries (especially Denmark) the installation of large-scale solar thermal plants connected to district heating systems or large buildings has been expanding.

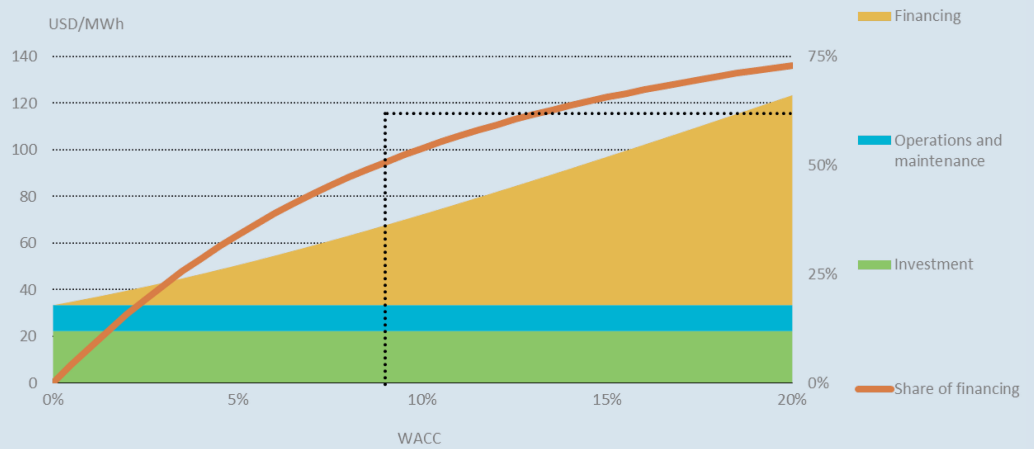
While CSP growth has stalled in the former leading markets of Spain and the United States, a second wave of projects is emerging in the Middle East, Africa and China as market prices fall. The share of projects with built-in thermal storage is increasing, as is storage size.

More than 120 countries now have renewable energy targets for their power sectors – twice as many as in 2010. Support policies in most countries are evolving from open-ended feed-in tariffs to auctions for stable, long-term remuneration mechanisms that may be adapted to delivery times and locations or combined with market prices, to both de-risk investment and offer an incentive to deliver electricity at times and locations that are more beneficial for the power system. For smaller rooftop systems, there is also a shift towards incentivising self-consumption, with various schemes designed to remunerate electricity injected into the grid.

Box 3. The importance of the cost of capital for solar projects

Solar technology costs have dropped drastically in recent years, especially for solar PV. Another factor that has helped reduce the levelised cost of electricity (LCOE) in many countries is the reduction of investment risks. Perceived risk is expressed by the weighted average cost of capital (WACC), composed of interest on bank loans and expected investment returns for equity investors.

Share of financing costs in the LCOE of solar PV



Note: Assumptions are: capex of USD 1/W; annual operational expenditures 2% of capex; 25-year lifetime; 1 800 full-load hours.

This figure reveals the importance of investment risk, depicting the LCOE as the sum of capital expenditures (capex), operations and maintenance (O&M) expenses, and the cost of capital (its share is represented on the right axis). With a WACC higher than 9%, the costs of capital account for over half the kWh cost.

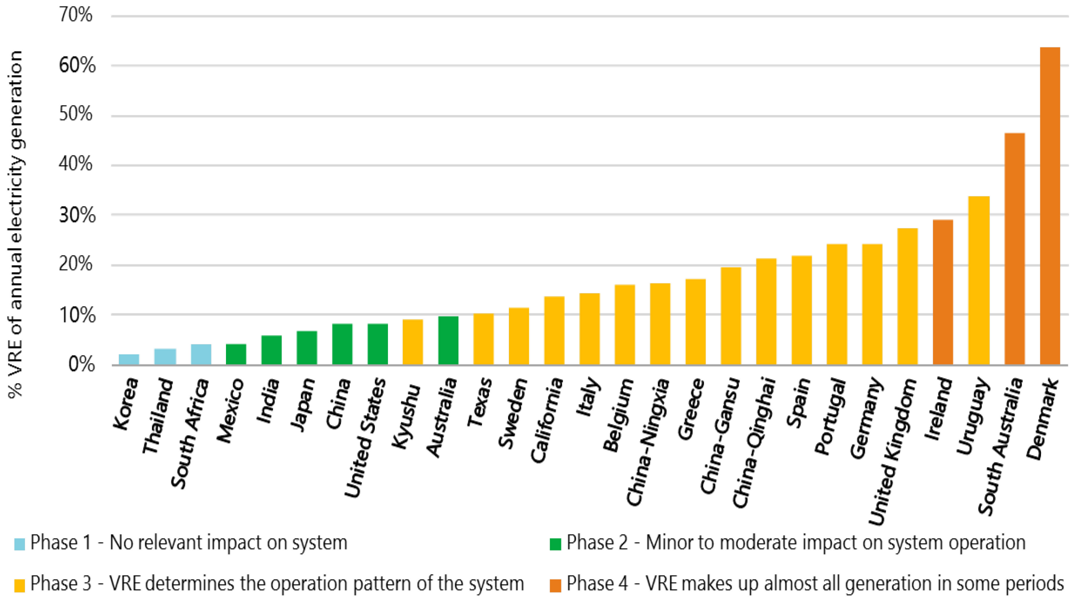
In a comparison of two projects with similar system costs, O&M expenses and solar resources but different WACCs (5% vs. 15%), the second project's LCOE is twice as high. The WACC, which is often overlooked, is important because the bulk of PV plant expenditures occur upfront, before the plant delivers its first kWh.

WACCs can vary considerably depending on the country, policy framework and perception of risk by investors and banks. This is why, even though subsidies are no longer required for solar projects in many cases, governments and regulators have an obligation to establish a risk-mitigating regulatory framework that delivers sufficient certainty relative to returns on investment.

Enabling technologies and system integration

Wind and solar PV capacity have expanded very rapidly in many countries as a result of supportive policies and dramatic drops in technology costs. By the end of 2018, these technologies – collectively referred to as variable renewable energy (VRE) – had attained double-digit shares of annual electricity generation in 20 countries. The IEA classifies VRE integration into six phases as shares increase. While Figure 4 indicates the VRE levels reached in some countries and regions, Figure 5 illustrates these six phases and the four pillars of flexibility: power plants, grids, demand-side response (DSR) and storage.

Figure 4. VRE shares in total electricity generation by selected region, 2018



Source: IEA (2019a), *Status of Power System Transformation 2019: Power System Flexibility.*

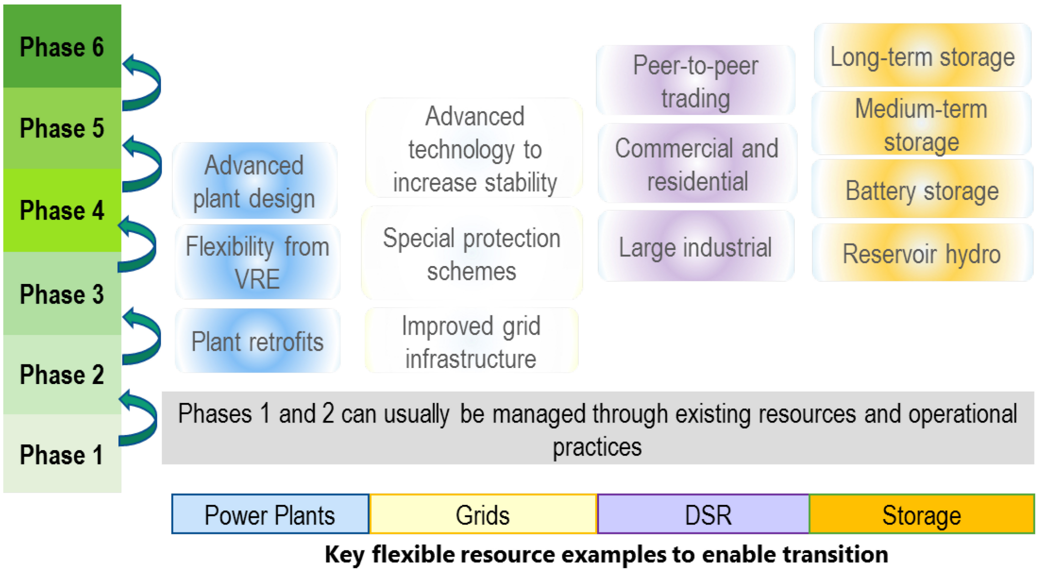
Existing power system flexibility makes it easy to integrate PV electricity initially, but integrating larger shares will require greater flexibility.

The first two phases of integration are easily manageable owing to the flexibility of power systems, but close policy-maker attention is nevertheless very helpful at this stage. Attention should focus on grid connection codes, on adequate forecasting of solar PV (and wind) plant output, and on managing the interface between high- and low-voltage grids. Moreover, steps must be taken to adapt renewable energy deployment to the needs of the wider power system, not only the reverse. This relates especially to the complementarities of technologies with different output profiles (PV, wind, CSP) and to the localisation of new plants, but may also affect plant design and management.

In phases 3 and 4, PV (or wind) accounts for large shares of the power mix. Power system flexibility may need to be increased at this point by implementing DSR, expanding grid interconnections, raising hydropower capacity, using CSP and other thermal plants in a flexible manner, and eventually expanding storage from pumped storage hydropower and batteries.

In the final phases of integration (5 and 6), seasonal imbalances may be the primary impediment to integrating very large shares of solar and wind, with risks of shortages during periods of low sun and wind, and large surpluses at times of high electricity generation and low demand. Flexible electrification of end-use sectors (buildings, industry and transport) and the production of electricity-based hydrogen and hydrogen-rich fuels could provide seasonal renewable energy storage in addition to further decarbonising the overall energy mix. Producing such fuels could also make use of stranded renewable resources in regions with excellent solar and wind potential, launching a novel global energy trade.

Figure 5. The six phases of VRE integration and the four pillars of flexibility



VRE integration requires the use of all flexibility options, of which storage is just one.

Designing and implementing roadmaps

Solar Energy: Mapping the Road Ahead aims to provide government, industry, civil society and community stakeholders with the methodology and tools to successfully plan and implement national and regional solar energy roadmaps. This guide's holistic approach encompasses all solar technologies – solar PV, CSP and SHC.

Figure 6 illustrates the two streams of activities that make up roadmap development: those that focus on analysis (in orange) and those centred on decision-making and consensus-building (in blue).

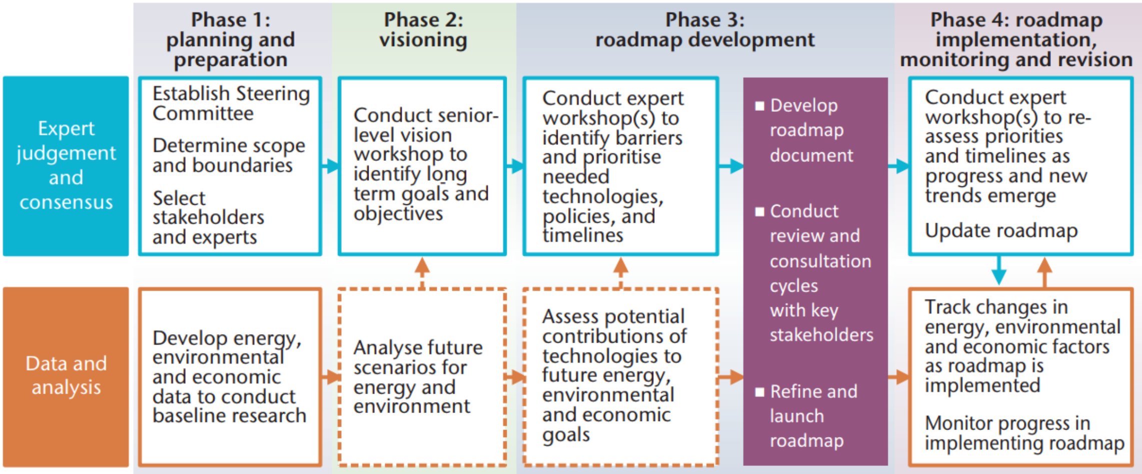
The evolving process by which a roadmap is created, implemented, monitored and updated is crucial to achieve the goals it sets out. Creation of the plan should maximise stakeholder engagement to build consensus and increase the likelihood that those involved will implement the roadmap's priorities and together seek early solutions to anticipated barriers. Ideally, a roadmap is a dynamic document that incorporates metrics to monitor progress in meeting its stated goals, and is flexible enough to be updated as the market, technology and policy context evolves.

The overall process should be overseen by the government, as many ministerial departments could be involved together with the ministry in charge of energy. Virtually all have buildings and services that require energy supply to service the population. Many are also relevant for their action.

For example, the agriculture department is concerned by many applications, from combining PV panels and crops or pasture, running water pumping, transformation processes, etc. The education ministry could help disseminate information to children and through them, families, as well as to older students. The health department is concerned with providing electricity to health services, as well as food preservation, which is also of interest to the ministries of agriculture and economy. The ministry of transportation could help in transitioning from fossil fuels vehicles to solar mobility services. The finance ministry could play an important role in removing subsidies to fossil fuels and introducing some initial support to solar deployment. The ministry in charge of habitat could help link energy efficiency and PV deployment in responding to a growing demand for space cooling… and this list is not exhaustive.

The ISA is available to help countries elaborate their own solar roadmaps, organised around their respective national focal points.

Figure 6. The roadmap development process



Note: Dotted lines indicate optional steps, depending on available capabilities and resources.
Source: Adapted from IEA (2014a), *Energy Technology Roadmaps*.

IEA roadmap development involves two streams of activities (analysis and consensus-building) in four phases: planning, visioning, development and implementation.

The four phases in brief

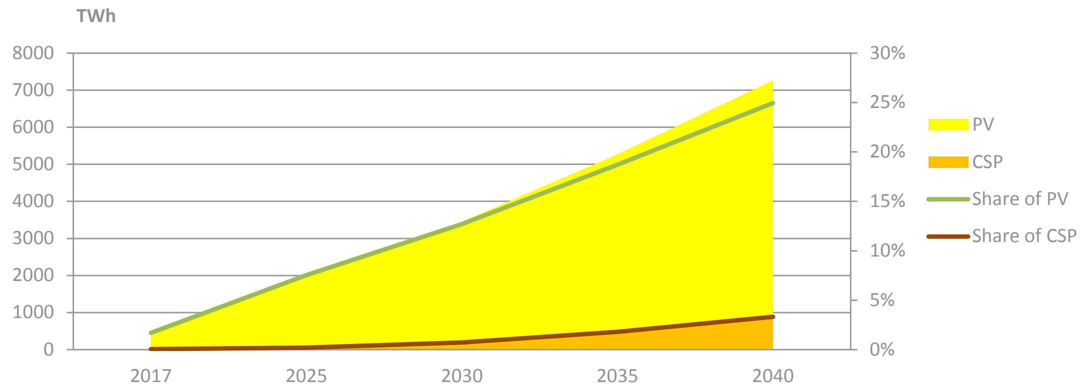
The **planning and preparation phase** involves examining the technological, market and public policy situation specific to the solar technologies covered by the roadmap. In addition to this broad analysis, a comprehensive understanding of solar potential and resources must be developed.

Because the range of essential solar energy stakeholders is wide in most countries, not only is it critical to identify them early in the process, it is also important to consider how they should be involved in roadmapping at the different levels of engagement (Responsible, Authorised, Consulted and Informed).

The second phase of roadmapping involves **developing a vision** for solar technology deployment in the country or region within a specified time frame. A clear statement of the drivers for using solar energy is essential to develop the roadmap's vision and long-term goals.

Clear, realistic targets are an important component of any national or regional roadmap's guiding vision. A precise vision and credible goals make it easier to implement a roadmap effectively, particularly when targets are mandatory rather than aspirational. Although energy infrastructure, energy demand profiles and solar resource accessibility differ from one country to the next, global analyses such as the IEA's Sustainable Development Scenario may nevertheless help guide efforts (Figure 7).

Figure 7. PV and CSP generation in the Sustainable Development Scenario



Source: IEA (2018c), *World Energy Outlook 2018*.

In climate-friendly scenarios, solar technologies provide up to 30% of global electricity.

The next phase, **roadmap development,** is devoted to identifying barriers to solar technology deployment, as well as the actions necessary to overcome them and those responsible for carrying them out. Barriers can be non-economic, such as institutional, administrative, permitting and public acceptance obstacles, among others. Or, they can be economic, often resulting from framework or market design shortcomings that magnify perceived risks for investors and lenders.

The fourth and final phase of roadmap development covers **monitoring** its implementation and establishing a mechanism for regular **updating**. This is an ongoing activity, with tracking and monitoring occurring on a regular basis through a variety of indicators. Support mechanisms and targets should also be revised and adjusted frequently because even proven solar technologies are still evolving quite rapidly and costs are continuing to fall. If support mechanisms take the form of a subsidy, they should not be excessively generous at the expense of taxpayers; meanwhile, targets should be enlarged as costs fall, justifying a greater solar contribution to the country's energy needs and economic development.

Useful online resources

- IEA: *Solar Energy Perspectives* (2011): https://webstore.iea.org/solar-energy-perspectives
- IEA: *Technology Roadmap: Solar heating and cooling* (2012): https://webstore.iea.org/technology-roadmap-solar-heating-and-cooling
- IEA: *Technology Roadmap: Solar Photovoltaic Energy* (2014): https://webstore.iea.org/technology-roadmap-solar-photovoltaic-energy-2014
- IEA: *Technology roadmap: Solar thermal electricity* (2014): https://webstore.iea.org/technology-roadmap-solar-thermal-electricity-2014
- IEA: *Getting Wind and Sun onto the Grid* (2017): https://webstore.iea.org/technology-roadmap-solar-thermal-electricity-2014
- IEA: *Renewable Energy for Industry* (2017): https://webstore.iea.org/insights-series-2017-renewable-energy-for-industry
- IEA: *Renewable Heat Policies* (2018): https://webstore.iea.org/insights-series-2018-renewable-heat-policies
- IEA: "Status of power system transformation 2019" (2019): https://webstore.iea.org/status-of-power-system-transformation-2019-power-system-flexibility
- IEA Energy Technology Network:
  - IEA PVPS TCP publications: http://www.iea-pvps.org/
  - IEA SHC TCP publications: https://www.iea-shc.org/
  - IEA SolarPaces (Solar Power & Chemical Energy Systems programme) publications: https://www.solarpaces.org/
- IRENA, IEA and REN21: *Renewable Energy Policies in a Time of Transition* (2018): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_IEA_REN21_Policies_2018.pdf
- ISA: http://www.isolaralliance.org/
- UNDP, *Derisking Renewable Energy Investment* (2013); *DREI: Off-Grid Electrification* (2018): https://www.undp.org/DREI
- World bank group, ESMAP and Solargis, *Global solar atlas* (2019): https://globalsolaratlas.info/

Introduction

About technology roadmaps

The primary goal of a technology roadmap is to highlight and accelerate deployment of a specific technology or group of technologies. Simply put, a roadmap is a strategy or plan describing the steps to be taken to achieve stated and agreed goals on a defined schedule. It details the technical, policy, legal, financial, market and organisational barriers to these goals, and the range of known solutions to overcome them. Roadmaps can be developed for various levels of deployment – global, national or regional – and can be sector- or technology-specific for different time frames.

The evolving process by which a roadmap is created, implemented, monitored and updated is referred to as roadmapping. The way this process is organised is crucial to achieve the goals it sets out. An effective roadmapping process maximises stakeholder engagement in creating the plan, thereby building consensus and increasing the likelihood that those involved will implement the roadmap's priorities and together seek early solutions to anticipated barriers.

From a geographical prospective, not only the central government should be involved, but also regional authorities and city mayors.

From a sectoral prospective, it is all the more important that many stakeholders beyond energy ministries are involved in this process : agriculture, housing, transportation, health, education and finance among others.

All these stakeholders are critical to a strong roll-out of solar technologies.

Ideally, a roadmap is a dynamic document that incorporates metrics to monitor progress in meeting its stated goals, and is flexible enough to be updated as the market, technology and policy context evolves.

About this guide

Solar Energy: Mapping the Road Ahead aims to provide government, industry, civil society and community stakeholders with the methodology and tools to successfully plan and implement national and regional solar energy roadmaps. This guide's holistic approach encompasses all solar technologies – solar photovoltaic (PV) electricity, concentrating solar power (CSP, or solar thermal electricity [STE]), solar heating and cooling (SHC), and even solar fuels – and addresses synergies and trade-offs to consider when formulating a comprehensive solar strategy. Applications include utility-scale PV and CSP power generation; distributed on- and off-grid electricity generation; solar thermal water/space heating and cooling; solar heat for industry; and solar fuels.

Designed for decision makers in developing and emerging as well as developed economies, this guide does not cover every aspect of solar energy technology, policy or deployment. Rather, it aims to provide a comprehensive list of steps and concerns for each phase of solar energy roadmapping and deployment. Selected case studies encapsulate the wide array of existing applications, and discussions of deployment drivers and barriers are accompanied by realistic recommendations for actions, tools and useful information. Importantly, this guide also addresses resource variability and key energy access concerns.

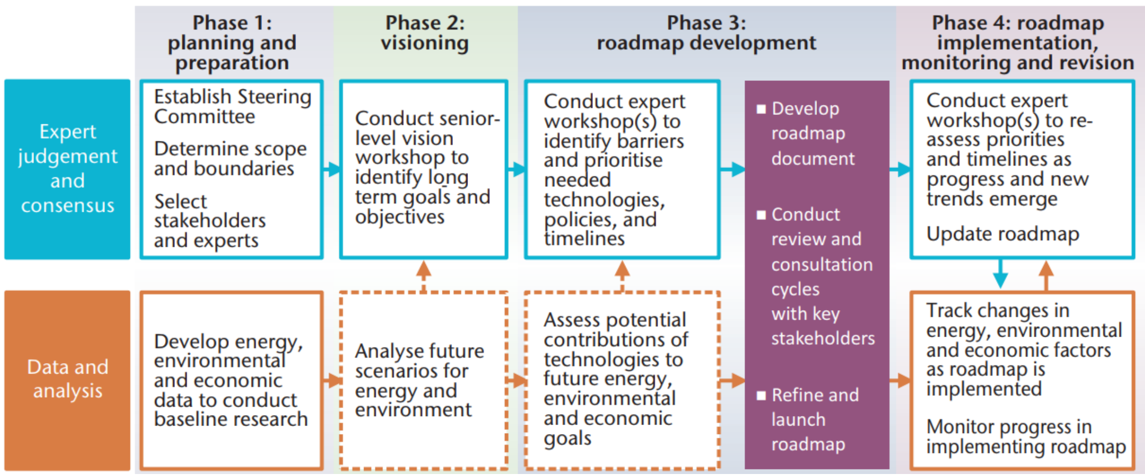
Solar Energy: Mapping the Road Ahead is a collaborative effort of the International Energy Agency (IEA) and the International Solar Alliance (ISA) to build on experience to mobilise investments for extensive solar energy deployment worldwide. While based on new material collected specifically for this guide, it also draws on previous research: i) the IEA's generic roadmap methodology manual, *Energy Technology Roadmaps: A Guide to Development and Implementation* (2014a); ii) IEA (2011), *Solar Energy Perspectives*, which provides insights on solar resources and their uses according to the three types of technologies; iii) the IEA Technology Roadmaps *Solar Heating and Cooling* (2012), *Solar Photovoltaic Energy* (2014b) and *Solar Thermal Electricity* (2014c); and iv) solar technology reports by IEA Technology Collaboration Programmes (TCPs): *Photovoltaic Power Systems* (Photovoltaic Power Systems TCP), *Concentrated Solar Power and Fuels* (SolarPACES) and *Solar Heating and Cooling* (Solar Heating and Cooling TCP).

Guide structure and roadmapping process

This guide is arranged around the four key stages of the roadmapping process (IEA, 2014):

- Phase 1: Planning and preparation
- Phase 2: Visioning
- Phase 3: Roadmap development
- Phase 4: Implementation, monitoring and revision.

Figure 8. The roadmap development process



Note: Dotted lines indicate optional steps, depending on available capabilities and resources.

Source: Adapted from IEA (2014a), *Energy Technology Roadmaps*.

IEA roadmap development involves two streams of activities (analysis and consensus-building) in four phases: planning, visioning, development and implementation.

Figure 8 illustrates the two streams of activities that make up roadmap development: those that focus on analysis (in orange) and those centred on decision-making and consensus-building (in blue). Sound data and analysis should support expert judgments to establish current baseline conditions so that milestones and performance targets can be determined and technology pathways laid out to achieve the roadmap's goals. This process should be followed for effective solar energy roadmap development for any country or region.

About solar energy technologies

Many different technologies with a broad range of applications can be used for solar energy conversion. Although solar technologies can deliver heat and be used for cooling, lighting, electricity generation and fuel production, *Solar Energy: Mapping the Road Ahead* focuses on using solar energy to produce heat (for heating/cooling) and power.

This report therefore covers solar PV, SHC and CSP technologies; applications such as water treatment, seawater desalination and solar fuel production are briefly discussed but are not the focus.

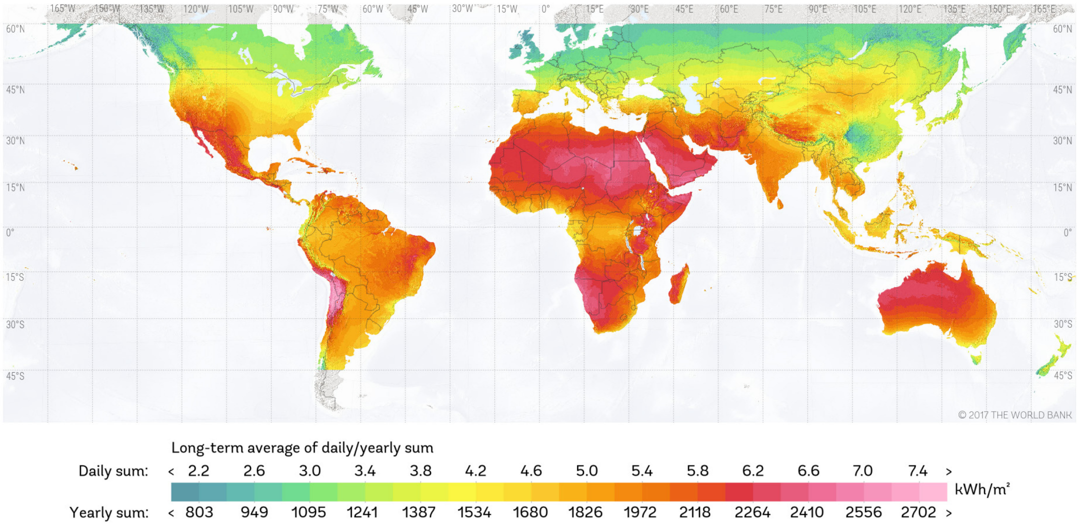
Assessing solar resource potential

Before examining the different technologies, this section details the main characteristics that determine a geographic area's solar energy potential. Some recent initiatives have begun to collect solar resource maps and can be a good starting point for roadmap development.

Solar irradiation consists of direct and diffuse radiation. Direct (or beam) radiation experienced as 'sunshine' comes directly from the sun's disk, whereas the diffuse radiation experienced as 'daylight' comes from numerous directions. Because solar resources vary daily and seasonally, it is important to consider the extent to which resource availability matches heat and power demand variations, as their correspondence will determine the type of facility required and can signal possible difficulties in deploying solar energy technologies to satisfy energy needs.

Global horizontal irradiance (GHI), or global irradiance on horizontal surfaces, measures the density of solar resources available per surface area, but various other measures of the resource also need to be taken into account, depending on the technology to be deployed.

Figure 9. Global horizontal irradiation



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Source: World Bank Group, ESMAP and Solargis (2019), *Global Solar Atlas,* http://globalsolaratlas.info.

Vast regions with rising energy needs receive immense amounts of solar irradiation, but opportunities to use solar energy are increasing even for regions with less solar resources.

Solar resources are highly available in Europe and Russia, but are often even better in the Americas, Africa, the Middle East, Australia, India, and most of China and other Asian countries – the regions where energy demand is expected to rise the most in upcoming decades (Figure 9). Some of these economies could even deploy additional solar energy capacity to export electricity to neighbouring countries, or hydrogen-rich fuels and feedstocks to more remote regions.

Solar photovoltaics

PV systems directly convert solar energy (both direct and indirect) into electricity. The basic building block of a PV system is the PV cell, which is a semiconductor device that converts solar energy into direct-current (DC) electricity. PV cells are interconnected to form a PV module, typically with a capacity of 290 watts (W) to almost 400 W. PV modules and additional application-dependent system components (e.g. inverters, batteries, electrical components and mounting systems) combine to form a PV system. PV systems are highly modular, i.e. modules can be linked together to provide a few watts to hundreds of megawatts (MW) of power (IEA, 2014b).

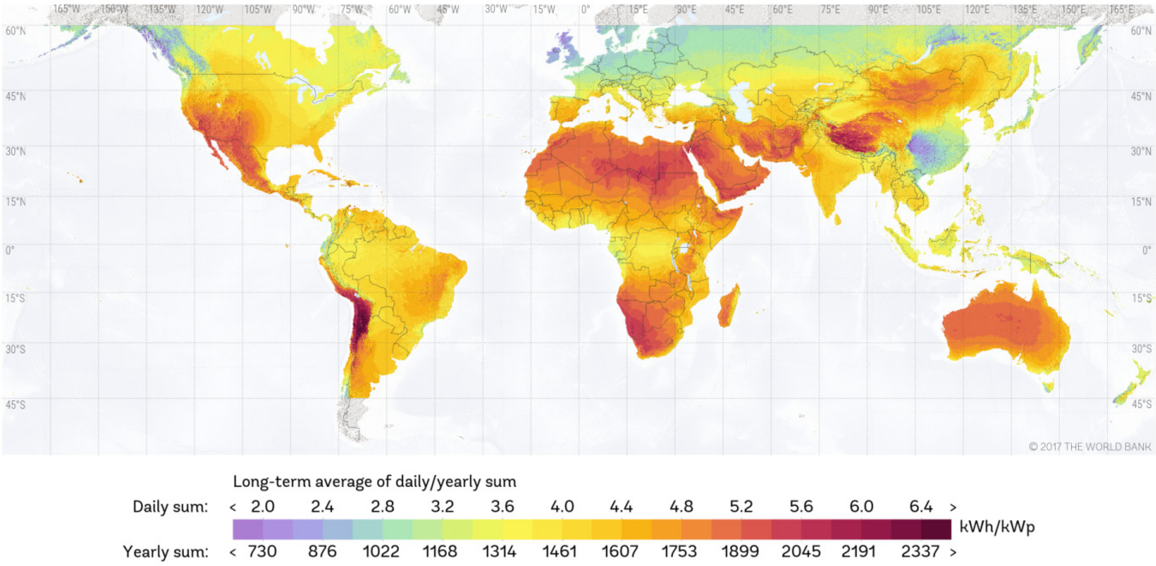
Commercial PV modules are usually divided into two broad categories: wafer-based silicon cells (c-Si) and thin films. The latter, usually based on cadmium telluride (CdTe) or copper-indium-(gallium)-selenide (CIS or CIGS), accounted for 3% of cell production in 2017 (IEA PVPS TCP, 2018).

Silicon cells are usually sliced from ingots or castings of highly purified silicon. The manufacturing process creates a charge-separating junction, deposits passivation layers and an anti-reflective coating, and adds metal contacts. Cells are grouped into modules with transparent glass for the front, a weatherproof material for the back and often a surrounding frame. The modules are then combined to form strings, arrays and systems.

There are two main types of c-Si wafers and cells: multi-silicon and mono-silicon. The first used to be more affordable and the second more efficient, but recently the cost of mono-silicon cells has fallen rapidly and they are expected to dominate the market soon. Whether mono- or multi-silicon, bifacial cells have quickly captured 10% of the overall PV market and may eventually dominate sales. Able to capture light on both front and back sides, they deliver greater output if they are installed in a highly reflective environment. Vertically mounted on a north-south axis, they provide a bit less energy on a daily or yearly basis, but with maximum power during the morning and afternoon and less during noontime, which could be relevant for some applications and complementary to the usual plant installations. This vertical mounting makes also the arrays less sensitive to dust.

PV technology can be used for on- and off-grid applications from less than 1 W to gigawatts. Grid-connected systems require inverters to transform DC power into alternating current (AC). Balance-of-system (BOS) equipment includes inverters, transformers, wiring and monitoring material, and structural components for installing modules on rooftops or building facades, above parking lots or agricultural fields, on the ground or floating on water bodies. Installations can be fixed or track the sun on one axis (for non- or low-concentrating systems). Two-axis systems, necessary for concentrating PV (CPV) systems, have become exceptional together with CPV systems themselves. A tilt, often close to the latitude minus 10 degrees, maximises output, especially for high latitudes (Figure 10).

Figure 10. Photovoltaic electricity output



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Notes: This map illustrates estimated output of fixed-tilt PV panels facing the equator. kWh/kW_p = kilowatt hour per kilowatt peak.
Source: World Bank Group, ESMAP and Solargis, *Global Solar Atlas*, http://globalsolaratlas.info.

PV system capacities range from watts to gigawatts and can be installed for a wide variety of on- and off-grid applications.

PV applications are usually grouped into four segments with distinct markets and drivers:

- residential systems (typically of up to 20 kW on individual buildings/dwellings)
- commercial systems (typically of up to a few MW for commercial and public buildings, schools, hospitals, warehouses and factories, often on rooftops and carpark shades, as well as above crops, greenhouses or pastures)
- utility-scale systems
- off-grid applications of various sizes, from several watts for initial energy services to mini-grid applications with battery backup, or hybrid designs that complement diesel generators.

PV modules usually face the equator, with the tilt determined primarily by latitude, but it can also be adjusted to adapt to the ratio of diffuse vs. direct irradiance, or for economic reasons. The tilt tends to equalise electrical outputs despite differing solar resource abundance among regions. However, a growing proportion of utility-scale plants are using one-axis trackers to augment output, with or without a tilt.

Solar thermal technologies

Solar light can be captured and transformed by a variety of technologies and utilised as heat in many applications. Although the most widespread technologies are non-concentrating ones, concentrating technologies can provide higher-grade heat for many industrial processes and chemical reactions, as well as offer more cost-effective heat storage options. The most mature technology, the solar domestic hot water system, was first deployed on a large scale in the 1960s.

The range of solar thermal collector designs is wide, but they all have a number of components in common: an absorber that collects incoming solar radiation; a circuit through which the heat transfer fluid flows; and housing that reduces heat losses to the environment and protects the collector from degradation.

Collectors are commonly distinguished as either flat-plate or evacuated-tube. Flat-plate collectors have a shallow box housing comprising a casing (aluminium, steel, plastic or sometimes wood), insulation material to reduce thermal losses from the back of the collector, and a transparent solar glass (low-iron type, possibly with anti-reflection features), whereas the housing of an evacuated-tube collector is a glass vacuum tube, so heat losses to the environment are low. In addition, flat-plate evacuated solar thermal collectors have also been commercialised recently. Some collectors incorporate low-level concentration devices called compound parabolic concentrators (CPCs).

Solar air heating systems capture energy from the sun and use it to heat air. More broadly, **passive solar buildings** are designed to maximise free solar irradiation during periods of heat demand and keep it out when the weather is warm; one popular use is home frost protection. Solar air heating systems can also be used for process heat applications (e.g. for crop-drying) and in buildings for space heating and air conditioning.

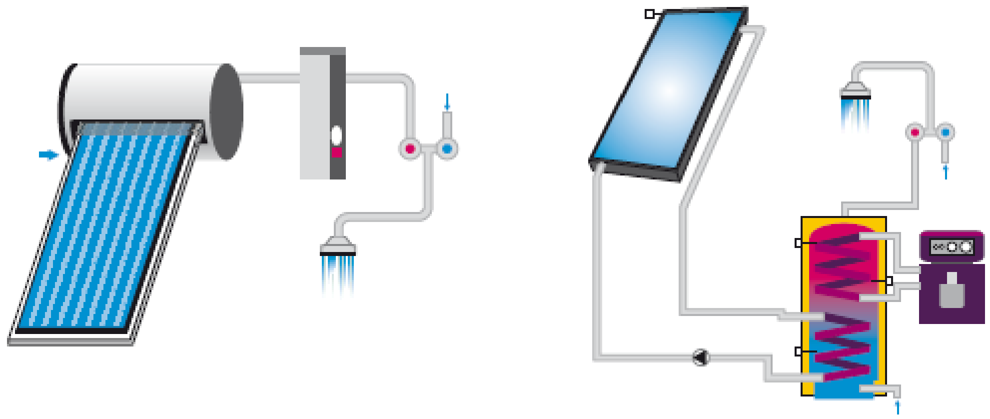
Thermal storage enables the use of solar thermal technologies. It usually takes the form of sensible heat storage, often in water for low-temperature heat but also in molten salts (as in CSP plants) or concrete for higher temperatures (in industrial applications). Latent heat storage uses the phase-change properties of a material, for example using water/ice to store cold in commercial displays and possibly air conditioning systems. Sorption and thermochemical heat storage systems may have higher efficiencies but are not yet widely used.

Concentrating solar technologies focus sunlight from a large aperture onto a small area by means of lenses or mirrors, allowing high-temperature heat to be used effectively with limited losses. Low-concentration collectors can remain stationery and therefore require minimal space, whereas high-concentration collectors or collecting systems (e.g. heliostats and central receiver systems) need to track the sun with precision on one or two axes. So far, high-concentration technologies have been used mainly to produce electricity (see below), but they can also be used in heat applications.

Solar thermal applications for buildings

Solar thermal systems for building applications are of two main types: thermosiphon (natural circulation) and pumped (forced circulation) (Figure 11). Thermosiphon systems, common in frost-free climates, rely on the principle that heated liquids are lighter than cooler ones to circulate heat transfer fluid to heat storage. This avoids the need for pumping and the associated costs, but it means that the heat storage device must be placed on the roof above the collector, so its size is limited by its weight. Although pumped circulation systems allow the collector and heat storage device to be separated (so that storage can be inside the dwelling), they are more complicated because they require pumps and a control system to optimise operations.

Figure 11. Individual solar thermosiphon system (left) and pumped circulation system (right)



Source: Dr. Valentin Energiesoftware GmbH, reprinted in IEA (2012), *Technology Roadmap: Solar Heating and Cooling*.

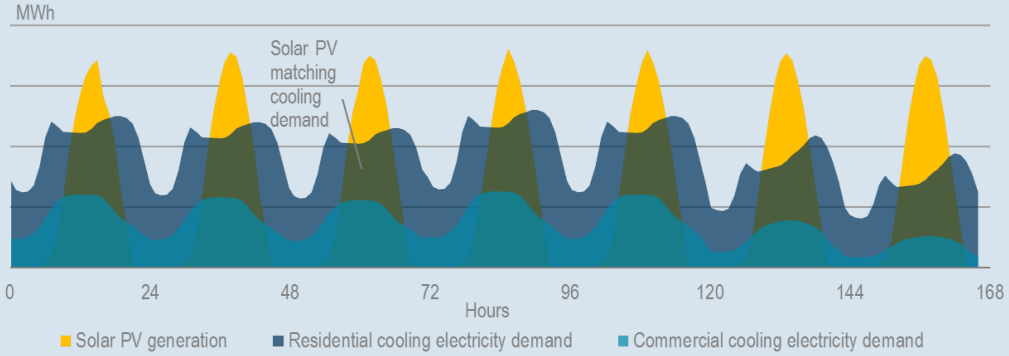
Designs for solar water heating use either natural circulation or a pumping system.

Solar thermal systems in buildings can be used either for domestic hot water production or for a combination of hot water and space heating. They can be part of a more complex heating, ventilation and cooling (HVAC) system, which in turn is part of the larger system of the building itself. Technologies that help integrate solar heating and cooling into HVAC and building systems are essential to the widespread deployment of solar heating and cooling systems.

Box 4. Solar Cooling

Although solar cooling systems have traditionally been thermally driven, sharp drops in the price of PV electricity have made PV-driven air conditioners competitive with conventional solar cooling. This is especially the case for small and medium-sized systems, for which the cost of installing a solar heat-powered system can be high.

Daily space cooling load and solar PV input profile



Note: MWh = megawatt hour.

Source: IEA (2018a), *The Future of Cooling*.

Some solar cooling technologies such as desiccant cooling can maximise comfort by also managing humidity levels (recent research has revealed how humidity aggravates the dangers of heat waves for humans [Russo, Sillmann and Sterl, 2017]). Outside of the summer period, solar thermal systems can be used for purposes other than cooling, such as domestic hot water production and space heating.

Although seasonal and daily solar irradiance largely coincides well with cooling demand in buildings, the thermal inertia of buildings causes cooling demand to remain high long after sunset. While individual solar thermal cooling systems must therefore have some thermal storage (mostly as cold storage) to cover this time period, electric chillers do not. At the system level, however, cold storage in air conditioning systems – a feature that too few companies are marketing – could prompt higher grid penetration of solar PV electricity. As well as their energy efficiency, governments should consider regulating the capacity of these systems to store cold.

As solar thermal cooling is still in the early stages of market development, costs need to be reduced through further development and deployment. A standardised, effective and simplified range of technologies needs to be developed – particularly for single- and multi-family dwellings – to make solar cooling competitive with conventional and supported renewable technologies, enabling widespread deployment. Training, qualification, quality assurance and system certification procedures are also needed to stimulate the market by inspiring consumer confidence.

Source: Mugnier and Jakob (2012), *Keeping cool with the sun*.

Individual domestic hot water systems are generally relatively small, with a collector size of 2 square metres (m^2) to 6 m^2 and storage of 150 litres (L) to 300 L. Domestic solar hot water systems can be designed to cover from 30% of hot water demand to almost 100% , depending on collector area, storage capacity and climate.

Solar heating systems for combined domestic hot water and space heating (called combisystems) use essentially the same collectors as solar water heaters but are mainly pumped (forced circulation) systems. The solar combisystem has a larger collector area and generally larger storage to accommodate space heating needs. In a typical single-family home in a mid-European climate, such a system can reduce fossil fuel consumption by 25% to 30%.

Solar thermal systems are also used for heating and cooling in large-scale applications for district heating, multifamily dwellings and other large buildings (hotels, hospitals, dormitories, etc.), or in block heating plants. These systems, which can have from tens to hundreds of square metres of collectors, are widely used in some European markets (Austria, France and Denmark). Solar energy can be an attractive, low-cost source of heat for district heating systems, for which typical working temperatures range from 30 degrees Celsius (°C) to around 100°C for water storage.

Unglazed water collectors for swimming pool heating are an affordable technology that increases the collector fluid temperature by 10°C to 20°C above ambient temperature. In the United States, Canada and Australia, they are the dominant application of solar thermal technology (IEA SHC TCP, 2019).

Finally, one emerging concept uses solar thermal collectors to support **heat pumps**. Heat pumps can be used for space heating, water heating or both (reversible heat pumps provide heating and cooling). As heat pumps move calories from a cold medium (a building's surroundings) to a warmer one (a building's interior), the useful energy they deliver is several times that of the energy input.

Using a solar collector to moderately raise the temperature from which a heat pump provides a further lift can be very effective: instead of each system working alone, combining them minimises the solar collector's thermal losses and improves the performance of the heat pump (Del Amo et al., 2019)

Solar thermal applications for industry

Solar thermal systems can be used to meet a portion of process heat needs at temperatures below 120°C (such as for washing, leaching, cooking, drying, preheating boiler feed water and space heating in industrial buildings). These processes are common in such industry subsectors as transport equipment, machinery, mining and quarrying, food and tobacco, and textiles and leather. At the end of 2018, at least 741 plants were using solar heat for industrial processes worldwide, with over 100 added in 2017-18 alone.

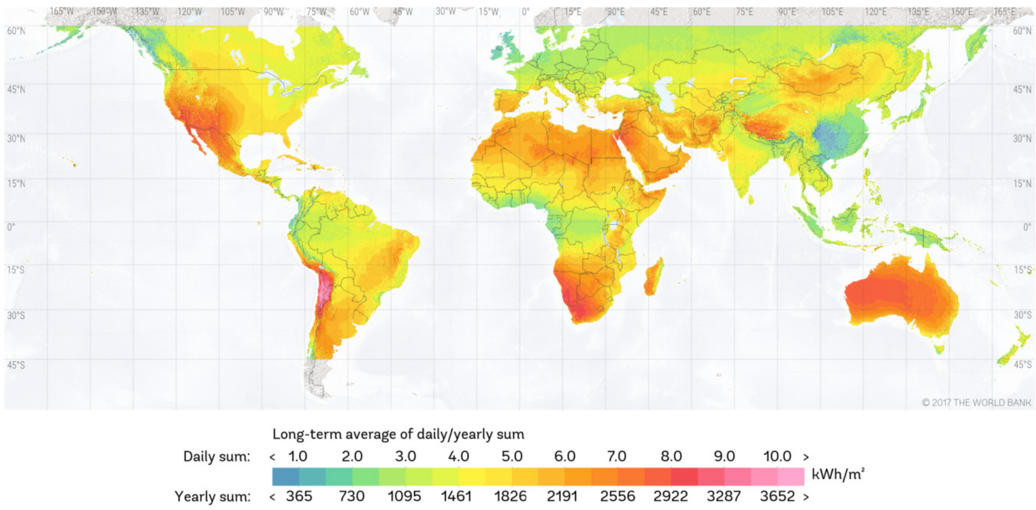
Similar to buildings, the solar thermal technologies used in industry in this temperature range are typically flat-plate or evacuated collectors, although non-tracking CPCs are sometimes used to obtain temperatures of up to 200°C. For solar crop-drying – important in developing countries – much simpler collectors can be used, such as perforated roof panels through which air is drawn via small openings and then ducted to feed the dryers.

For **medium- and high-temperature** applications, sun-tracking concentrating solar technologies are needed, although their use is restricted to areas with good direct normal irradiance (DNI). DNI is much more affected by clouds and aerosols than global irradiance is. In humid equatorial areas, the atmosphere scatters the sun's rays. High DNI is therefore found in hot, dry regions that have reliably clear skies and low aerosol optical depths (a measure of the extinction of solar beams by dust and haze), which are typical in subtropical latitudes from 15° to 40° north or south (Figure 12). (At higher latitudes, weather patterns frequently produce cloudy conditions.) DNI is also significantly higher at higher elevations, where absorption and scattering of sunlight due to aerosols is normally much lower. Thus, the most favourable areas for CSP resources are North Africa, southern Africa, the Middle East, north-western India, the south-western United States, northern Mexico, Peru, Chile, western China and Australia. Other regions, such as southern Europe and central Asia, may also have some CSP plant potential.

Several large-scale concentrating solar thermal plants are being built in Oman, Kuwait and California, entirely enclosed in standard agricultural greenhouses that protect them from dust and wind. Light, concave mirrors rotate around simple, fixed tubes, directly generating steam for enhanced oil recovery (EOR) operations. This technology could also be used to generate medium- and high-temperature heat in refineries and industries. Emerging technologies include solar ovens and solar towers with particle receivers to process non-metallic minerals such as cement materials (IEA, 2017a).

Demand for **water desalination** is expected to continue growing in regions known for water shortages – which often have very good solar resources. Water can be desalinated either through distillation (preferred for highly saline water) or reverse osmosis (IEA, 2011). Distillation usually requires considerable thermal energy, which could be captured using concentrating solar technologies (although another distillation technology, mechanical vapour compression, uses electricity only).

Figure 12. Direct normal irradiance



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

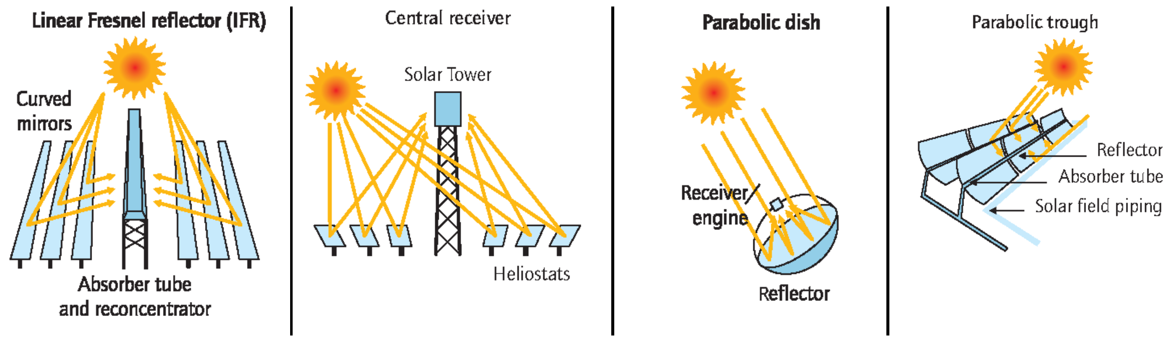
Source: World Bank Group, ESMAP and Solargis, *Global Solar Atlas*, http://globalsolaratlas.info.

DNI is the relevant resource for concentrating technologies, whether for high-grade industrial heat or for electricity generation (CSP).

Concentrating solar power

CSP (or STE) plants concentrate solar rays to heat a fluid, which then directly or indirectly runs a turbine and an electricity generator. Concentrating the sun's rays reduces heat losses in the receiver at working temperatures high enough to ensure fair efficiency in turning the heat into electricity. The predominant CSP technologies are parabolic troughs (PTs) and towers, also known as central receiver systems (CRSs). Other concepts are linear Fresnel collectors, Scheffler dishes and parabolic dishes, which may have engines mounted at their foci (Figure 13). These technologies differ in optical design, receiver shape, nature of the transfer fluid and capacity to store heat before it is turned into electricity.

Figure 13. Main CSP technologies



Source: IEA (2010), *Technology Roadmap: Solar thermal electricity*.

Most existing CSP plants are based on trough technology, but the majority of projects under development now employ tower systems.

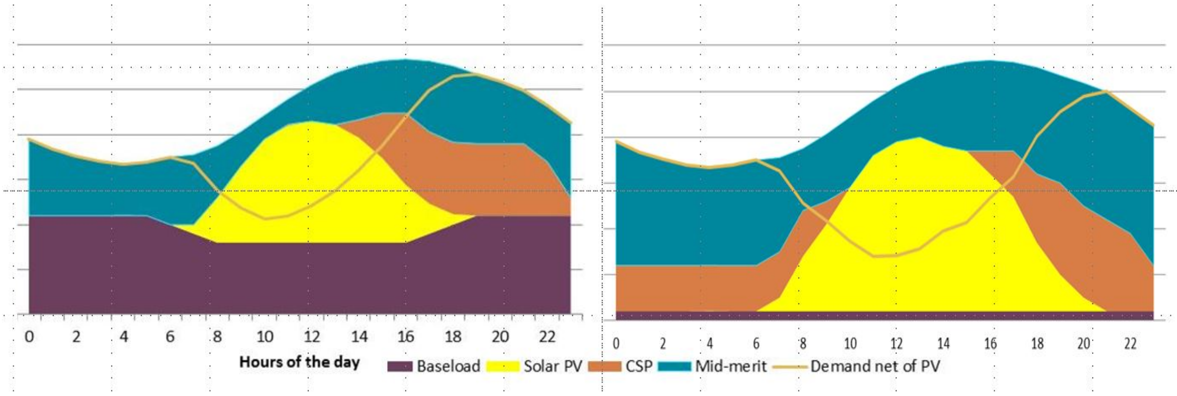
Unlike PV systems that use both direct and diffuse irradiation, CSP plants use only direct. Plus, due to constant heat losses in the solar field, they need a minimum amount of daily direct irradiance to deliver electricity. Their use is therefore limited to geographic areas that have a high DNI rating, and at least one full year of on-the-ground DNI measurement is advised when CSP projects are being considered.

Their capability to integrate thermal storage is an important feature of CSP plants, and some of them also have fuel-power backup capacity. Thus, CSP technology offers dispatchable, flexible electricity production capacity to utilities and grid operators while also enabling effective management of a greater share of variable energy from other renewable sources (e.g. PV and wind power).

CSP electricity costs more than PV electricity – and as costs are expected to continue dropping for both, this relationship is not expected to change. However, CSP generation is in fact competing with PV-plus-storage systems and even with peaking power plants such as gas turbines. The order of preference for these technologies depends on the share of solar electricity in the power mix and the duration of storage required.

Because there are different ways to configure solar fields, thermal storage systems and turbines for CSP plants, electrical capacity is not a good indicator of a plant's importance and annual output. While the highest capacity factor may lead to the lowest levelised cost of electricity (LCOE), this is not necessarily the optimal economic configuration. If the remuneration of the electricity from a CSP plant reflects its value for the power system at all times, it may be beneficial to shift most of the production from midday and the second part of the night to the late-evening and early-morning peak hours (Figure 14).

Figure 14. Conceptual daily energy mix with PV and CSP, medium term (left) and long term (right)

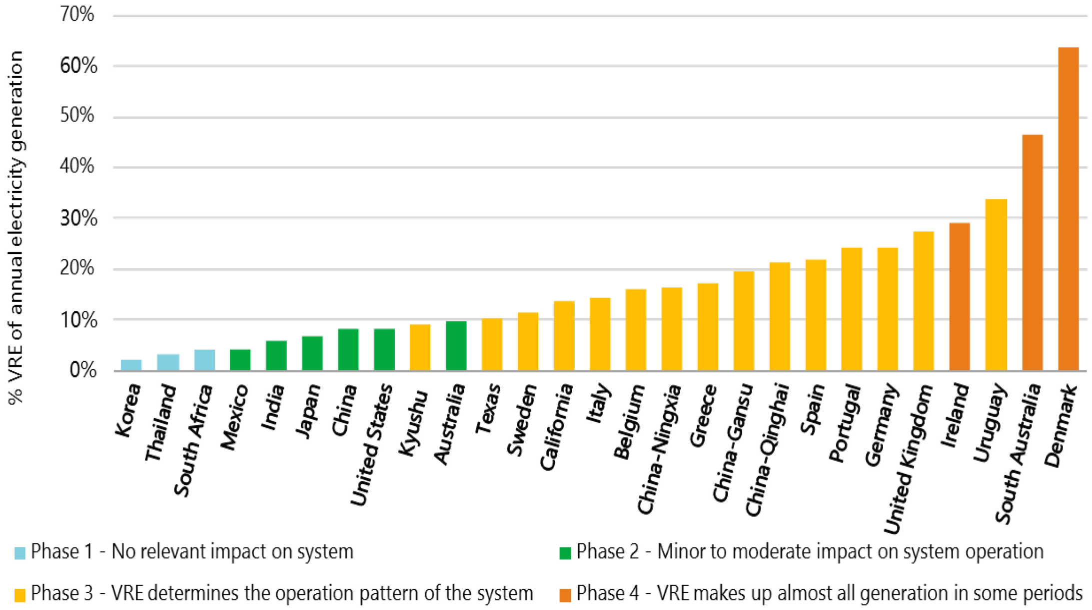


The amount of CSP in the energy mix will increase as PV saturates daytime production and power systems approach full decarbonisation.

Enabling technologies and system integration

Wind and solar PV capacity have increased very rapidly in many countries as a result of supportive policies and dramatic drops in technology costs. By the end of 2017, these technologies – collectively referred to as variable renewable energy (VRE) – had attained double-digit shares of annual electricity generation in 15 countries.

Figure 15. VRE shares in total electricity generation by region, 2018

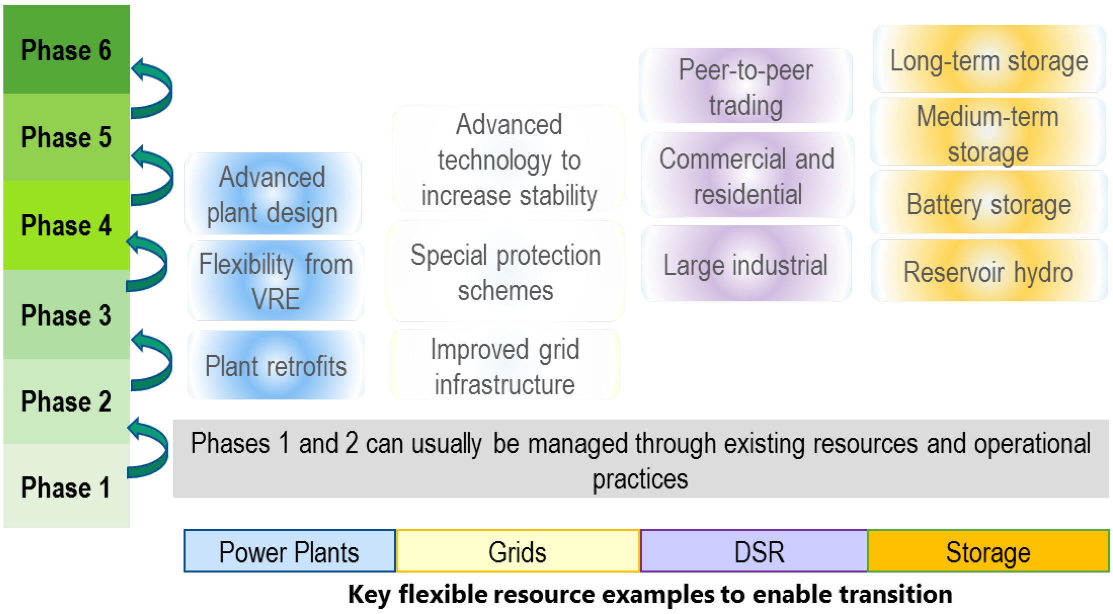


Source: IEA (2019a), *Power System Transformation 2019*.

As most countries are just beginning to deploy solar energy, its variability is fairly easy to accommodate; the majority of suggested measures therefore aim to facilitate further deployment.

System integration challenges emerge gradually as more VRE enters the power system. Figure 15 illustrates current VRE shares in the power mixes of selected countries and regions, while Figure 16 presents the six phases of VRE integration and the four pillars of flexibility: power plants, grids, demand-side response (DSR) and storage. In the first phase of integration, VRE capacity has no noticeable impact on the system, as VRE output variations are insignificant compared with variations in power demand. Some impacts appear in the second phase, but they can be easily managed by upgrades to operational practices.

Figure 16. The six phases of VRE integration and the four pillars of flexibility



VRE integration requires using all dimensions of flexibility, of which storage is only one.

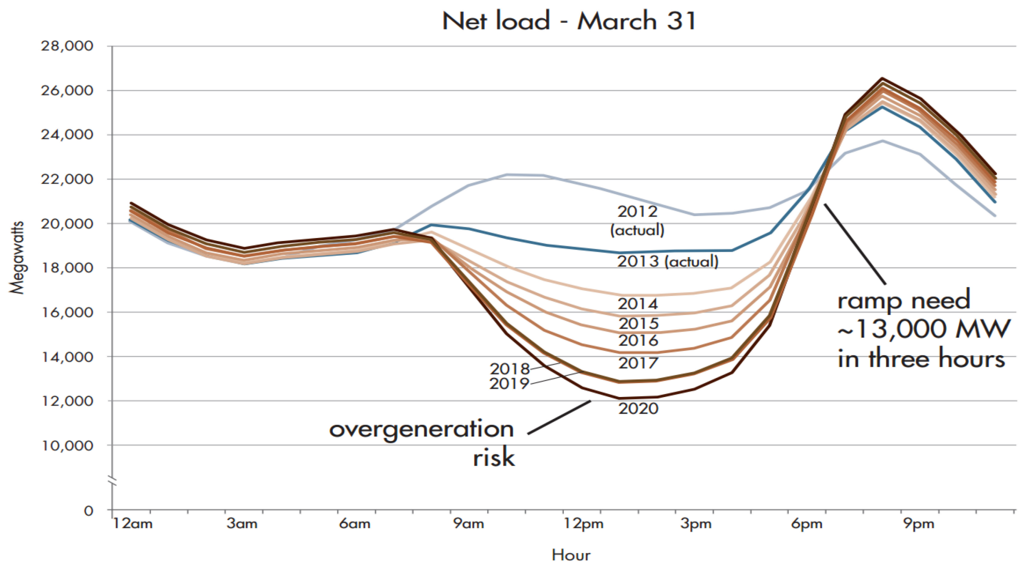
The first significant integration challenges appear in the third phase, in which power systems must become flexible enough to adequately respond to supply-demand balance variability within minutes to hours. Utilities must therefore develop procedures to address these uncertainties: interconnections and DSR (initially involving industries, but eventually residences and electric vehicles) are the primary solutions, as well as maximising the flexibility of existing hydro and thermal power plants. In areas with significant PV penetration, the most challenging time of the day will be late afternoon, when the sun is setting and electricity demand tends to peak. Issues may arise from the minimum running times and rapid ramp-up rates required of thermal power plants, illustrated by the daily demand 'duck curve' of net solar PV production (Figure 17).

Battery storage at various levels of the grid, including behind meters, may become more useful as its costs plummet to the point of making it a competitive solution to meet peak power demand. More transparency and incentives for markets to balance their own profiles would prompt existing assets to maximise their flexibility.

If DNI is high enough, introducing CSP plants is particularly beneficial because they can increase the share of solar energy in the power mix at the same time as raising system flexibility (with thermal storage) and stability (through the rotating inertia of turbines and generators). CSP plants with built-in thermal storage can also provide grid storage and avoid curtailment of PV and wind power generation at relatively low power-to-power efficiency, which is compensated for by low investment costs of additional resistors. Pumped-storage hydropower plants, or higher hydropower plant capacities, may offer similar flexibility and stability. In Africa and elsewhere, hydropower plants along rivers could be divided into twin dams or reservoirs with pumped storage between them (Nombre et al., 2019).

In the fourth phase of VRE integration, power system stability problems may appear. In the few countries already at this stage, system operators are contemplating the use of synthetic inertia (fast frequency response [i.e. very rapid responses to frequency deviations] and/or grid-forming converters) from solar and wind power. Experience has shown that technical grid codes should be updated before phase four is reached to ensure system resilience.

Figure 17. California's 'duck curve' as PV electricity shares expand



Source: California Independent System Operator (2016), *What the Duck Curve Tells Us*.

High PV electricity penetration requires greater power system flexibility.

In the final phases of integration, seasonal imbalances may complicate the integration of very large shares of solar and wind power, with risks of shortages during weeks with low sun and wind and large surpluses at times of high electricity generation and low demand. In addition to further developing the flexible electrification of end-use sectors such as buildings, industry and transport, other options to boost decarbonisation of the overall energy mix and provide seasonal storage of renewable energy are power-to-gas and power-to-liquid technologies (IEA, 2017a; 2019b). Hydrogen and ammonia (which is easier to ship and store) may be particularly useful in the power sector, as their production in regions with excellent solar and wind resources may soon prove cost-effective (Armijo and Philibert, 2019). This could give rise to a novel global energy trade.

Although they are easily manageable, the first phases of integration would strongly benefit from close policy-maker attention, as demonstrated by the positive and less-positive experiences of leading VRE countries. Attention should focus on grid connection codes, adequate forecasting of solar PV and wind plant output, and on managing the interface between high- and low-voltage grids. Moreover, steps must be taken to adapt renewable energy deployment to the needs of the wider power system, not only the reverse. This relates especially to the complementarities of technologies that have different output profiles and to the localisation of new plants, but it may also affect plant design. All these points, further detailed in *Getting Wind and Sun onto the Grid* (IEA, 2017b) should be considered during roadmapping.

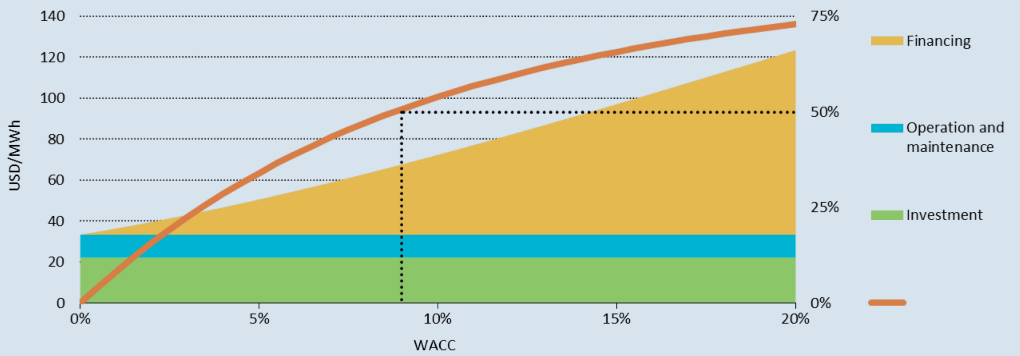
Box 5. The importance of the cost of capital for solar projects

Solar technology costs have dropped drastically in recent years, especially for solar PV. Another factor that has helped reduce the LCOE in many countries is the reduction of investment risk. Perceived risk is expressed by the weighted average cost of capital (WACC), composed of interest on bank loans and expected investment returns for equity investors (who use their own money). The figure below reveals the importance of investment risk, depicting the LCOE as the sum of capital expenditures, operations and maintenance (O&M) costs, and the cost of capital (its share is represented on the right axis). With a WACC higher than 9%, the costs of capital account for over half the kWh cost. This is because the running costs for PV are very low, and up-front investments and financing conditions matter more than for many other electricity-generating technologies, especially fossil fuel-based ones.

In a comparison of two projects with similar system costs, O&M expenses and solar resources but different WACCs (5% vs. 15%), the latter country's solar electricity costs are twice as high. The WACC, which is often overlooked, is important because most of the expenditures for building and operating a PV plant occur upfront, before the plant delivers its first kWh.

WACCs can vary considerably, even for mature, low-risk technologies, depending on the country, policy framework and level of risk perceived by investors and banks. This is why, even though subsidies are no longer required for solar technologies in many cases, governments and regulators have an obligation to establish a risk-mitigating regulatory framework that delivers sufficient certainty relative to returns on investment.

Share of financing costs in the LCOE of solar PV



Note: Assumptions are: capex of USD 1/W; annual operational expenditures 2% of capex; 25-year lifetime; 1 800 full-load hours.

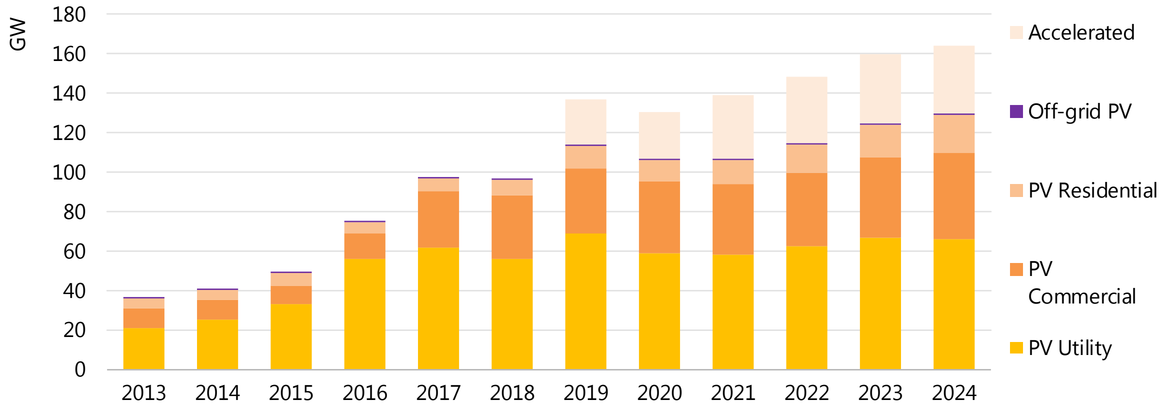
Market overview and trends

Solar PV

Record-level PV capacity growth has been headlining renewable energy news in recent years, as prices have fallen drastically since 2010 – by four-fifths for modules, and by almost two-thirds for residential systems (IEA, 2018c). Cumulative installed capacity increased at an average rate of 47% per year during the past ten years, and in 2017 , almost 100 gigawatts (GW) of new PV capacity was installed in roughly 110 countries. In 2018, new additions remained slightly below 100 GW while it is reaching 115 GW in 2019, raising the total cumulative capacity to 609 GW by year end.

In the IEA's main case forecast, total installed PV capacity reaches almost 1 terawatt (TW), i.e. 1 000 GW, by 2023, or already by 2022 in the accelerated case, which would bring it by 2024 to about 1 375 GW (IEA, 2019c). Distributed applications make up almost half of PV capacity growth until 2024, with commercial and large-scale industrial projects accounting for 70%, residential systems for another 28% and off-grid installations for 2% (Figure 18).

Figure 18. Global solar PV annual additions by segment, 2013-24



Source: IEA (2019c), *Renewables 2019*.

Total installed PV capacity is expected to exceed 1 TW by 2023.

Box 6. Floating solar PV

A floating solar PV system is an array of solar panels on a structure that floats on a body of water, placed most often on artificial lakes and water reservoirs. Projects on open water are more challenging due to greater project design complexity and exposure to rough waters. The combination of hydropower and floating solar PV technologies is important, and several projects are under development, mostly in China.

The first floating solar PV plant was commissioned in 2007 in Japan, and the first commercial site was completed in 2008 in the United States. The plant was deployed on an artificial water reservoir to leave scarce land available for agricultural production. In 2013, the first plant with a capacity greater than 1 megawatt (MW) was completed, and by 2018 several projects in China had reached 100 MW and 150 MW.

The floating solar PV segment grew exponentially from 10 MW in 2014 to 1.1 gigawatts (GW) in 2018, and global potential is estimated at around 400 GW, equivalent to total PV capacity at the end of 2017.

Floating solar PV projects can be particularly suitable in countries with limited land availability and high population density. Placing floating PV plants on water reservoirs limits water evaporation, saving it for drinking, irrigation and/or power generation. As most floating projects are deployed on water reservoirs, irrigation ponds and industrial basins, the technology can benefit from being located close to demand centres.

Moreover, placing floating PV installations on hydropower reservoirs takes direct advantage of the existing electricity infrastructure. Hydropower can smooth out variations in solar output and thus limit PV impacts on the grid.

Floating PV projects usually cost more than ground-mounted installations due to additional expenditures for floaters and more resilient electric components, but the extra cost is made up for by their superior performance (thanks to module cooling), and lower connection costs when installed on hydropower reservoirs.

As floating PV deployment has so far been limited, there are currently no clear, cohesive policies or regulatory approaches for its installation. Each project application is therefore treated on an ad-hoc basis, most often categorised as ground-mounted PV. Because solar PV costs have already dropped significantly and economies of scale will eventually cause the costs of floating installations to fall as well, floating PV is expected to become competitive without the help of major remuneration policies. Immediate policy and regulation focus should therefore be on overcoming barriers to initial deployment; permitting processes must also be developed to address the environmental considerations of placing plants on water reservoirs. Only a handful of countries have clear pricing policies for floating projects, and they are often included in local feed-in tariff policies.

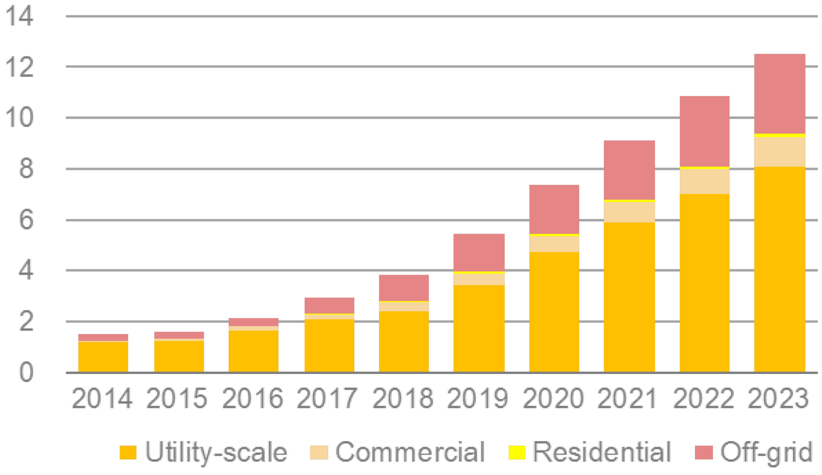
Source: World Bank Group, ESMAP and SERIS (2018), *Where Sun Meets Water*.

Off-grid solar PV applications

Historically, grid electrification has usually been the most cost-effective method to provide reliable electricity services. However, distances between off-grid communities and the nearest network points, the density of the off-grid population, future demographic trends and the financial health of the transmission companies must all be considered and can delay grid strengthening or extension – and may prevent it altogether if costs are prohibitively high.

Owing to significant cost reductions as well as private sector and government initiatives, off-grid solar PV applications have begun to bridge the electrification gap in Asia and sub-Saharan Africa. Mini-grids as well as industrial, agricultural and commercial applications and solar home systems (SHSs) can provide an immediate solution for initial or improved electricity access for households, small businesses, farms and industries (Figure 19).

Figure 19. Installed PV capacity in sub-Saharan Africa, 2014-23



Source: Adapted from IEA (2018b), *Renewables 2018*.

The falling costs of solar applications, new business models and a strong need for electricity services in sub-Saharan Africa are driving on- and off-grid PV growth.

Solar water-pumping, used for irrigating crops and watering livestock, is a particularly important application for farmers in many countries. Among the countries that have deployment programmes, Morocco and India rely on significant government subsidies. In India, 1.75 million stand-alone solar pumps have been planned, as well as the solarisation of 1 million grid-connected pumps.

Solar Home Systems (SHSs) are PV systems that have a capacity in the 100 W range and are installed in off-grid residential dwellings and equipped with a battery for lighting and for powering various appliances for several hours per day. Operated under new business models such as 'pay as you go', SHSs that entered the market just in 2017 initiated electricity access for an estimated 6 million people. In Bangladesh alone, 12 million people have already gained access to electricity through SHSs.

Larger off-grid solar energy systems are often used for either primary electricity or for backup power during the brownouts and blackouts that occur frequently in developing countries. These systems can generate electricity in an off-grid mode for industrial applications such as mining activities and telecom towers, or for commercial purposes such as agriculture, hotels, hospitals and schools.

Mini-grids are stand-alone, off-grid solar PV systems that provide electricity to villages or communities; the number of connected dwellings can vary. Two business cases are usually encountered (or faced ?) : 1) the grid is already existing, supplied by a diesel genset. Adding some PV generation directly spares fossil fuels expenses or helps in increasing the number of operating hours. 2) the grid does not exist yet. Then the total investment cost is much higher and balancing the budget without specific subsidies becomes a real issue.

Box 7. Off-grid solar appliances

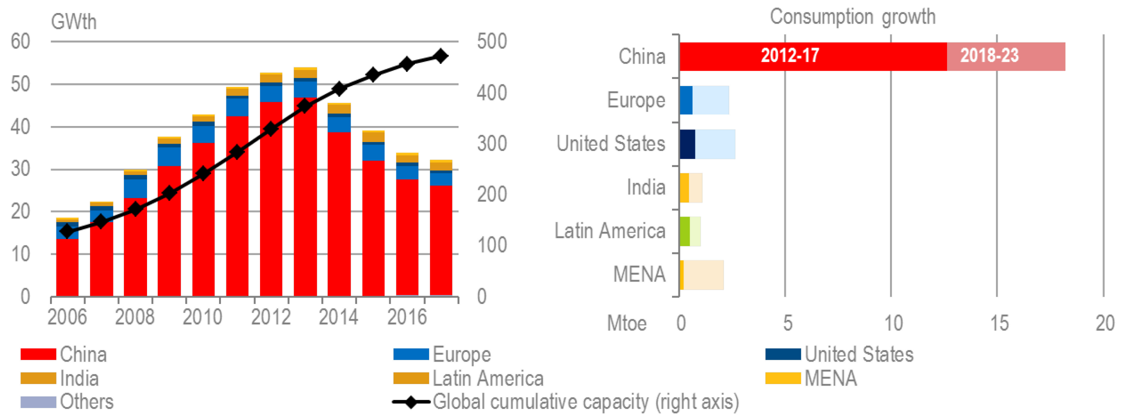
The private sector's market-led solar appliance revolution of recent years resulted from the ability of a single solar PV panel to supply DC electricity to a distinct solar appliance. Appliances such as portable lanterns, fixed LEDs, phone chargers, fans, TVs, pumps, fridges, vaccine coolers, laptops, rice-cookers, etc., can therefore be operated anywhere on electricity from sunlight.

Owing to continuous technological innovation, these appliances require much less electricity than ordinary alternating-current ones. An increasing number of energy-efficient appliances can be powered by small solar panels, which minimises costs, and many also have batteries so that they can be used at night. Panel and battery costs, which currently make up 60% of the total cost of an appliance, are declining quickly.

Solar thermal heating technology

The market for solar heating technologies grew substantially up to 2013, especially in China (Figure 20), and continuous slowdown in the Chinese market is the main reason for declining gross capacity additions globally since 2013. In Europe, market growth has been slower since the 2008 financial crisis and subsequent economic slowdown (particularly in the construction sector), with average annual decreases of 4% between 2009 and 2017; in 2018 however the market grew by 8.4% (Observ'ER, 2019). India and the Middle East as well as some other emerging economies, market growth were more even.

Figure 20. Gross solar thermal capacity additions, 2008-17 (left), and estimated consumption growth 2018-23 (right)



Source: IEA (2018b), *Renewables 2018*.

The shrinking Chinese market is still the world leader for solar thermal heating, but European markets appear to have stabilised and some emerging economies have demonstrated market growth.

Despite the global slowdown in additions, cumulative solar thermal capacity increased 3.5% year-on-year to reach 472 gigawatts thermal (GW_{th}) in 2017, one-fifth more than total installed solar PV capacity. Solar thermal installations – mainly domestic hot water systems for single-family homes and large domestic hot water systems, followed by swimming pool heating – produced an estimated 384 TWh of thermal energy in 2017.

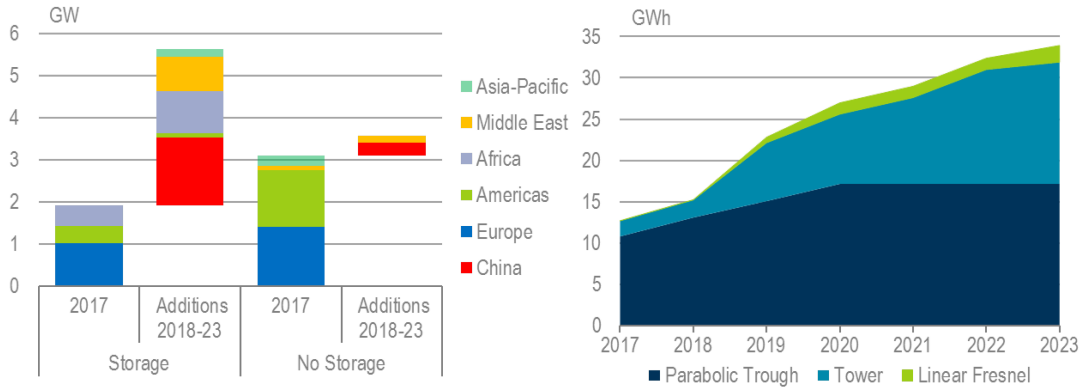
While individual solar water heating systems dominate the global market, in several countries (especially Denmark) the installation of large-scale solar thermal plants connected to district heating systems or large buildings has been expanding. In 2017, 15 large-scale systems (30.4 megawatts thermal [MW_{th}] of capacity) were added worldwide and roughly 300 large-scale (>350 kilowatts thermal [kW_{th}]) solar thermal systems were in operation, with a total capacity of 1 140 MW_{th}.

2017-18 was also a record year for solar heating in industrial processes (SHIP), with 124 projects in 17 countries adding over 130 MW_{th} (a 46% increase), led by the first 100-MW_{th} phase of the Miraah project for EOR in Oman and followed by developments in India, China, Mexico and Afghanistan. This brings cumulative capacity to almost 567 MW_{th} across 741 projects. Nonetheless, SHIP remains only a fragment of the global solar thermal market, accounting for 0.4% of additions in 2017 and 0.1% of cumulative thermal capacity (Weiss and Spörk-Dür, 2019).

Concentrating solar power

Growth in the **CSP industry** has been more modest. Policy changes and PV cost reductions led to complete halts in the former leading markets of Spain (in 2013) and the United States (in 2015). But the geographic distribution of CSP has spread to new countries, including in the Middle East and Africa (Figure 21). Market prices finally seem to be falling, with recent announcements (including the USD 73/MWh for the United Arab Emirates' 700-MW CSP project) indicating significant cost reduction potential. Furthermore, new technologies are reaching commercial maturity and new concepts are emerging.

Figure 21. Forecast of CSP capacity by region (left), and of generation by technology (right)



Source: IEA (2018b), *Renewables 2018*.

As the United States and the European Union have not been deploying CSP since 2015, Morocco, South Africa and China are responsible for recent market growth. Built-in thermal storage has become essential.

CSP capacity had expanded to 5.6 GW by 2018, with the majority installed by Spain and the United States before 2014. From 2018 to 2023, however, global CSP capacity is expected to increase by another 4 GW, mostly in China and the Middle East–North Africa region, almost all with significant thermal storage capabilities.

Recent policy trends

There is a strong link between policy implementation and renewable technology deployment. Policy mechanisms supporting renewables have expanded significantly in recent years in many countries and have also evolved in type and complexity. While this section presents only a short summary, more detailed information is offered below in the sections on roadmapping phases and in the Annex.

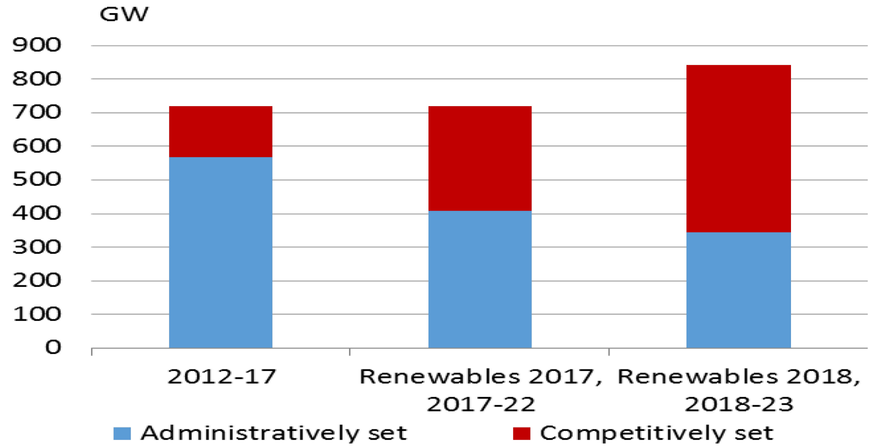
Targets are essential to guide and accelerate a country's renewable energy deployment. They can be adopted at all administrative levels and along various timelines, supporting either total renewable energy production/consumption or just specific technologies and sectors. Although target-setting for renewables has spread rapidly, renewable policies are uneven, with targeted deployment levels for power, transport and heating and cooling varying considerably.

In 2010, 61 countries had some form of support mechanism for renewables in the power sector, while at the same time roughly 30 countries had support policies targeting the transport sector and heating and cooling. Policies for renewable power continued to dominate in 2017 (121 countries) while those for other sectors still lagged behind.

Policies supporting renewables in the power sector are the most evolved because they have been the most applied across countries: substantial policy-making know-how has therefore been acquired and the efficiency of certain policies has been proven. Historically, **feed-in-tariffs and premiums** have been the policies of choice to initiate the deployment of both large- and small-scale renewables, as well as net metering in most of the United States and some other countries for small rooftop projects (under net metering, energy injected into the grid is valued at the same rate as electricity withdrawn from the grid). Feed-in tariff mechanisms proved successful in attracting private investment because they guarantee remuneration, grid access and dispatch priority, and they also provide long-term contracts.

As deployment accelerated, costs fell and technologies matured, governments began to adopt **auctions** to further reduce costs more quickly. Plus, auctions also shift the task of price-finding from governments to market forces when conditions are right, while allowing governments to retain control over capacity volumes coming online (Figure 22). It is therefore expected that fewer and fewer administrations will set remuneration levels for renewables projects in upcoming years. The auction mechanism usually refer to the "least-cost" bid. Some countries (e.g. China, France) have introduced the "best bid", including additional technical and environmental criteria.

Figure 22. Remuneration-setting for utility-scale renewable projects



Source: IEA (2018b), *Renewables 2018*.

Remuneration for small PV projects (with definitions of size differing widely among countries) are, however, still usually set administratively, but the number of projects and cumulative capacities that can benefit are not well defined. Following Germany's example, several countries are progressively reducing remuneration for new-build projects, depending on the pace of deployment. France and India have both instituted auctions for mid-sized projects, such as large rooftop or parking lot PV systems for industrial plants, data centres, warehouses and shopping malls. In addition, numerous countries are now developing specific arrangements to promote self-consumption (or 'prosumption') of PV electricity.

Because the heating and cooling sector is complex and fragmented, effective policy making is challenging. Policies for renewable heat are less widespread than for renewable electricity: while 121 countries had renewable power policies in place in 2017, only 52 had policies for heat. Policy approaches differ depending on whether the policy is aimed at heat demand or supply, buildings or industries, and individual or commercial customers; it also depends whether heating or cooling is targeted. Due to this complexity, a range of policies such as heating and cooling mandates, grants, soft loans and tax incentives is used to target renewables in the heating sector. Energy efficiency policies are also of key importance because they can, for example, make a building or an industrial process more suitable for renewable heat options.

Box 8. Thought for food: Solar cooling and cooking, a Nigerian example

Cooling is also a very important dimension of the agriculture and food and drug delivery chains. A Nigerian start-up is helping farmers and market vendors raise their profits by using 100% solar-powered walk-in cold rooms to eliminate food waste. Its 'ColdHubs' are made of 120-millimetre (mm) insulating panels to retain cold, with energy provided by solar panels mounted on the roof. The energy-efficient mono-block refrigeration units are connected to inverters that enable solar-powered batteries to supply energy for night cooling. Each ColdHub can contain approximately three tonnes of perishable food, arranged in at least 150 units of 20-kilogramme (kg) plastic crates stacked on the floor, and they provide autonomous refrigeration 24 hours a day without grid connection. The temperature can be adjusted to between 5°C and 15°C, extending the shelf life of fruits, vegetables and other food by 2 to 21 days.

Prior to the introduction of ColdHubs, farms and markets lacked cold storage, causing sellable food to often be wasted. ColdHub solutions have been eagerly embraced by farmers and merchants, with those currently in use having reached 100% capacity utilisation. ColdHubs operate on a simple pay-as-you-store model, with farmers and retailers paying NGN 100 (USD 0.50) to store one crate for one day. Each hub is operated by a manager, who monitors the loading and unloading of crates and collects the fees.

There are also numerous solutions that use **solar energy for cooking**, ranging from very rudimentary devices such as simple insulated boxes with a reflective aluminium sheet directing sunlight onto a pot for slow cooking, to large community cooking appliances based on Scheffler dishes, which have had some success in India (IEA, 2011). More recently, solar cooking based on PV electricity or PV-eCook and induction cooktops has stirred interest. The costs of induction cooktops and PV panels have dropped dramatically, but battery systems adapted (or adaptable) to run cooktops are still relatively expensive. Hence, PV-eCook technology hardly seems accessible for the lowest-income households that remain exposed to the problems associated with transitioning to cleaner cooking in developing countries. Whether to give people still relying on traditional biomass access to clean cooking or to facilitate the removal of subsidies for fuels such as liquefied petroleum gas (LPG), governments should be more attentive to developments in solar cooking and consider conducting social and technical experiments before launching large dissemination programmes. India has already completed two small-scale pilots of PV-cooking systems and is contemplating a pilot scheme involving 100 000 households or more.

References

Armijo, J. and C. Philibert (2019), Flexible production of green hydrogen and ammonia from variable solar and wind energy. Case study of Chile and Argentina, *Researchgate*.

California Independent System Operator (2016), What the duck curve tells us about managing a green grid, *Fast Facts,* Folsom, CA.

Del Amo, A., A. Martínez-Gracia, A.A. Bayod-Rújula and M. Cañada (2019), Performance analysis and experimental validation of a solar-assisted heat pump fed by photovoltaic-thermal collector, *Energy*, Vol. 169, pp. 1214-1223.

IEA (International Energy Agency) (2019a), *Status of Power System Transformation 2019: Power System Flexibility*, IEA, Paris.

IEA (2019b), *The Future of Hydrogen: Seizing Today's Opportunit*ies, IEA, Paris.

IEA (2019c), *Renewables 2019: Analysis and Forecasts to 2024* Market Report Series, IEA, Paris.

IEA (2018a), *The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning*, IEA, Paris.

IEA (2018b), *Renewables 2018: Analysis and Forecasts to 2023*, Market Report Series, IEA, Paris.

IEA (2018c), *World Energy Outlook 2018*, IEA, Paris.

IEA (2017a), *Renewable Energy for Industry*, IEA, Paris.

IEA (2017b), *Getting Wind and Sun onto the Grid: A Manual for Policy Makers*, IEA, Paris.

IEA (2014a), *Energy Technology Roadmaps: A Guide to Development and Implementation*, IEA, Paris.

IEA (2014b), *Technology Roadmap: Solar Photovoltaic Energy*, IEA, Paris.

IEA (2014c), *Technology Roadmap: Solar Thermal Electricity*, IEA, Paris.

IEA (2012), *Technology Roadmap: Solar Heating and Cooling*, IEA, Paris.

IEA (2011), *Solar Energy Perspectives*, IEA, Paris.

IEA PVPS TCP (Photovoltaic Power Systems Technology Collaboration Programme) (2018), *Trends 2018 In Photovoltaic Applications*, www.iea-pvps.org

Weiss, W. and M. Spörk-Dür (2019), *Solar Heat Worldwide 2019*, AEE INTEC/ IEA SHC TCP (Solar Heating and Cooling Technology Collaboration Programme)

Mugnier, D. and U. Jakob (2012), Keeping cool with the sun, *International Sustainable Energy Review*, Vol. 6/1, pp. 28-30.

Nombre, A., F. Lempérière, F. Millogo and M. Kaboré (2019), Prospect for African hydropower in 2050, *Hydropower and Dams*, Vol. 2.

Observ'ER (2019), *Solar thermal and concentrated solar power barometer 2019*, Paris.

Russo, S., J. Sillmann and A. Sterl (2017) Humid heat waves at different warming levels, *Nature Scientific Reports*, Vol. 7, Article No. 7477.

World Bank Group, ESMAP and SERIS (2018), *Where Sun Meets Water: Floating Solar Market*, World Bank, Washington, DC.

World Bank Group, ESMAP and Solargis (2019), *Global Solar Atlas*, http://globalsolaratlas.info.

Phase 1: Planning and preparation

Highlights of Phase 1: Planning and preparation

The first phase defines the objectives and scope of the roadmap, establishing clear boundaries (Figure 23). To inform this process, baseline research is conducted characterising solar technologies in the energy system.

At the beginning of the roadmapping process, a steering group is established and the stakeholders are defined.

Baseline research covers information on the overall energy system, including the policy and regulatory environment, as well as the living standard, the capacity to pay and the wider economic framework that will influence the roadmap's scope and coverage.

Information is collected on solar resource availability, the status of the different solar technologies, the existing supply chain and other factors to determine the potential role of each technology.

Duration: 2-6 months.

Resources: research staff, potential travel and infrastructure to conduct interviews.

Meetings: a kick-off meeting of the steering group is recommended.

Figure 23. Planning and preparation phase

During the first phase of development, the roadmap initiative defines the roadmap's boundaries and time frame, collects relevant information on the existing framework to provide an overview and starting point, identifies the range of key stakeholders and establishes the institutional framework for implementing the roadmap. The IEA recommends the following steps during Phase 1:

- **Ensure commitment**: Even the best roadmap needs an audience and committed participants who will be the driving force for implementation.

- **Appoint a steering committee**: Successful roadmapping requires a small, dedicated steering committee with the knowledge and authority to make decisions on goals, scope and boundaries.
- **Develop a statement of purpose and scope:** It is good practice to begin by developing a short document that clearly states the roadmap's purpose, scope and objectives, process and participants.
- **Conduct baseline research:** Baseline data development includes a situational analysis of the key factors affecting the roadmap, such as energy supply and demand, economic growth, purchasing power, technology commercialisation and readiness, infrastructure development and needs, institutional capacities, and energy and environmental policies and regulations.
- **Select stakeholders and experts:** Engaging diverse areas of expertise and involvement early in the process can better inform roadmap development and increase the likelihood of commitment to the resulting document. The participation of network operators is particularly important for successful photovoltaic (PV) deployment.

Further information on each step can be found in IEA (2014).

The remainder of this section covers guiding questions for baseline research, analysing the technological situation for solar technologies, and identifying and selecting stakeholders and experts.

Conducting baseline research

Baseline research should analyse the current situation to identify key factors that may influence the technology roadmap – covering the energy system, the institutional landscape, and the policy and regulatory framework. Table 1 outlines the basic questions that should be answered in baseline research.

Table 1. Key questions for baseline research

Area	Main questions
General	• Energy demand baseline: What is the current overall energy demand and what future developments are expected? • Energy supply baseline: How much energy is produced, imported and exported? • How much solar energy technology has been deployed in the country/region? • Does the country have a long-term energy strategy/plan? • Does the county have carbon pricing in place or, on the contrary, are fossil fuels subsidised?
Institutional context	• Which government institutions deal with energy? • How are state-owned enterprises and private sector companies involved in the energy sector?
Existing energy policy framework	• Does the country/region have specific plans or targets for solar electricity and solar heating and cooling? • Does the country/region have a technology roadmap for any solar technologies or sectors? • Are the rules and regulations for developing energy projects comprehensive and do they create a level-playing field? • Are there regulations in place that may indirectly hinder the deployment of solar technologies? What was the original motivation behind these policies, and is it possible to adapt them?

Area	Main questions
Electricity	• Is information on power system specifics available, e.g. on overall demand and by different consumers? Location of demand? Grid and power capacity? • What is known about sector/customer-specific load profiles? • How is the power sector regulated? • How are generation, system operations, transmission, distribution, retailing/sales and consumption structured? • Is regulation suitable for corporate procurement (bilateral PPAs)? • To what extent do demand variations match those of solar availability (on all time scales)?
Heating and cooling	• What is known about customer-specific demand profiles? • Does the region/country allow energy service companies (ESCOs)? • Do other business models for solar heat exist? • Do policy makers understand specific heat needs at the policy level and do they recognise the lack of renewable heat options for consumers? • Can the infrastructure be adapted to integrate solar heat, e.g. through district heating networks?

A list of the types of data needed for this first phase should be created, including but not limited to statistics, reports and expert knowledge. Preliminary assessments of general data quality and quantification of some metrics can be done through desktop research (of vendor sites, trade associations and ministries) and interviews with industry experts, academics, consultants, industry associations and government officials. However, as even this level of data collection can often be difficult for regions lacking this information, a possible initial activity may be to develop a more robust data collection and assessment system.

Technology situation analysis

The planning and preparation phase involves examining the technological, market and policy situation specific to the solar technologies covered by the roadmap (Table 2). In addition to this broad analysis, a comprehensive understanding of solar potential and resources must be developed.

Table 2. Key questions for solar technology situation assessment

Area	Main questions
Solar resource availability	• Are there significant solar resources that can be exploited? • To what extent have the solar resources already been assessed (e.g. is there high-quality information on the global horizontal, optimally tilted, direct normal and diffuse solar radiation)? • Is available information based on satellite data and also backed up by local measurements? • What information is available regarding the quality of the atmosphere near ground level (i.e. wind, dust, temperature)?

Area	Main questions
Technology	• Does accurate information on technological performance (within or outside the geographic location) already exist? • Based on the resource assessment, which solar technologies may best serve the energy needs of the country? • Are there prospects to export solar electricity or fuels? Is there information on local costs and cost development potential? • Are there environmental concerns to consider in formulating the roadmap? Are accurate life-cycle assessments available? • Which end-of-life factors need to be considered (e.g. operations at end of economic lifetime, repowering, recycling and waste minimisation and elimination)? • What is the potential of the various technologies, and what are the integration issues? • Are there any possible links to other technology areas?
Markets	• Who are the customers and what is the market potential? • Are prices reflective of costs? Is there a time-based tariff structure? • How much experience does the country/region have in developing solar projects? • Is information on the value chain (e.g. manufacturers, suppliers and distributors) available? • Are there any existing studies/forecasts for the market/energy sector? • Does the solar strategy target only the country's own energy needs or is it also export-oriented? • Does the country want to create a local industry? • What are the key socioeconomic priorities that might be supported by the deployment of solar technologies? • What are the strengths of the existing workforce in the country/region? • Is initiating research, development and demonstration (RD&D) capabilities a motivation?
Public policy and regulation	• What is the existing legal and regulatory framework for solar technologies? • Do national/regional policy makers have a comprehensive energy strategy? • Are there policy goals for specific energy technologies and end-use sectors at the national, regional and local levels? • Does the country/region have specific plans or targets for modernising its electricity grids, integrating renewables, decarbonising the power sector, etc.? • What is the current and projected future energy mix? Do national/regional policy makers have renewable energy supply targets? Do they include solar heat and power? • Does the country/region already have a technology roadmap or strategy for bioenergy? What is the time frame? • Are the transport and distribution networks/authorities facilitating the connection of new solar electric capacities at different voltage levels? • Are all the relevant government ministries and agencies involved and co-operating with one another? Is there enough personnel within key bodies to implement national/regional targets? Are responsibilities clearly assigned? • Are there mandates for incorporating solar heat, solar electricity, or limited net energy consumption in new buildings? • Is PV self-consumption supported for households? For businesses? • What is the attitude of the electricity retailers or utilities concerning self-consumption and injection of PV power into distribution networks? Is it allowed? Is it remunerated? • What is the attitude of the banking sector with respect to supporting investment in solar projects at all scales? • Are businesses in various sectors (extractive and manufacturing industries, data centres, retailers, etc.) proactive in securing power purchase agreements for renewable electricity and heat?

Identifying solar stakeholders

Because the range of essential solar energy stakeholders is wide in most countries, not only is it critical to identify them early in the process, it is also important to consider how they should be involved in the roadmapping process (Table 3).

Table 3. Potential stakeholders in solar technology roadmap development

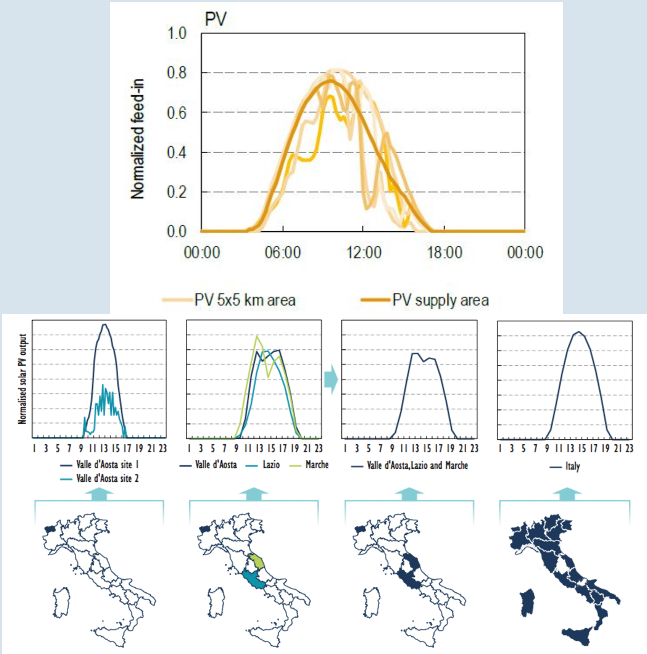
• **Institutional**	• Ministries in charge of energy, finance, environment, industry, etc. • Independent energy market authorities • Land-use planning decision makers • Permitting authorities, courts • Industry groups and associations
• **Industry**	• Network owners and power system operators • Project developers, engineering companies • Installers, operations and maintenance (O&M) companies • Landowners, co-operatives • Others, including providers of enabling technologies, e.g. battery manufacturers, architecture/construction/engineering companies, creators of the built environment for solar technology integration
• **Finance**	• Investors, e.g. development banks, private banks, venture capitalists, pensions funds, hedge funds, insurance companies
• **Consumers and prosumers**	• Interest groups, e.g. environmental non-governmental organisations, consumer organisations, research institutes, universities • Residential electricity consumers • Civil society, community groups and locally affected populations

Once all stakeholders have been identified, a communications and grouping system should be devised according to level of stakeholder involvement. A useful management tool for classifying stakeholders by decreasing level of engagement is the RACI (Responsible, Authorised, Consulted and Informed) scheme. Experience has shown that some stakeholders (e.g. network operators) may need to be persuaded to participate at the highest level of engagement (i.e. Responsible) for successful deployment of distributed PV.

The next phase of roadmap development is to create a common vision.

Box 9. Dispersion facilitates variable solar integration

The aggregated output of dispersed solar and wind plants varies less than that of individual units. For example, a single cloud at midday will cause the output of a solar PV module beneath it to fall from maximum to 20-30% of peak production. If all modules are in the same place, the output of the solar portfolio will drop equivalently. From the system operator's perspective, this is highly undesirable, as a large amount of alternative capacity is needed to manage the loss, with only very short times allowed for ramping/starting up (and for shutting down when the cloud moves). In contrast, if power plants are well dispersed, fluctuations are gentler and slower. The figure on the left illustrates this effect in South Africa: the paler lines show the steeply varying outputs of solar PV plants in 5x5-kilometre (km) clusters, compared with the aggregated output of all solar plants across the country, which smooths into the bell curve expected on a cloudless day. The graphs below show the same result in Italy.



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Phase 2: Visioning

Highlights of Phase 2: Visioning

The goal of the second phase is to define the roadmap's mission statement and time frame, as well as short-, medium- and long-term targets and objectives (Figure 24).

A country/region establishes its vision for solar energy development at this stage, and decides what it wants to achieve by developing solar energy along a specific timeline. It also examines options to meet these goals, based on Phase-1 analyses of energy scenarios.

Conducting a senior-level vision workshop to identify long-term goals and objectives is recommended.

Duration: 1-3 months.

Resources: research staff, infrastructure to conduct interviews.

Meetings: senior-level workshop to establish long-term vision, potential travel or exchange with research organisation developing energy scenarios.

Figure 24. Visioning phase

The second phase of roadmapping involves developing a vision for solar technology deployment in the country or region within a specified timeframe. The vision takes the baseline research into account and builds on stakeholder consultations. The output should be a clear statement of the desired outcome of solar deployment following a predetermined pathway.

The vision should be elaborated based on an assessment of the potential of the different solar technologies and the ambitions of the stakeholders, built on the modelling and scenario analyses of Stage 1.

Other related activities should also be taken into account, such as Nationally Determined Contribution (NDC) pledges submitted to the United Nations' 21st Conference of the Parties (COP21) in line with the Paris Climate Agreement.

As the visioning stage of roadmap development focuses on defining the pathway(s) and milestones for solar technology deployment, the section below discusses the main drivers and target-setting for expanding the use of solar energy.

Drivers of solar energy expansion

A clear statement of the motivations for using solar energy is essential to develop the vision and long-term goals of the roadmap. The drivers and impetus for solar energy development can vary significantly across countries and regions and influence the resulting strategy and portfolio of technologies. Based on research, expert consultations and reviews undertaken for this publication, the major drivers of solar technology deployment can be grouped into four categories (Table 4).

Table 4. Typical drivers of solar technology deployment

Categories	Possible drivers	Expected benefits
Energy access	Universal access to electricity and rural electrification Access to sustainable, reliable and affordable energy	Better health, education, rural development and quality of life. Possibly lower energy service expenditures, development of profitable activities towards economic development
Energy security	Reduced reliance on imported fossil fuels Diversified energy supply mix Greater dispatchable renewable capacity Decarbonised end-use sectors Diversified energy supply for heating	Increased independence/ higher share of energy demand met domestically Improved balance of payments Energy supply diversification, with positive impact on prices and price volatility Relief for constrained infrastructure
Environment	Reduced greenhouse gas (GHG) emissions, particularly CO_2 and methane (CH_4) Improved air quality and less local environmental pollution	Significantly higher indoor air quality through clean cooking Lower combustion of high-emissions fuels
Economic development and employment	Establishment and expansion of local solar energy industry Job creation Potential trade and exports for solar energy carriers Leadership in solar energy research and development	Economic growth associated with new businesses and market for solar energy services (involving planning, installation and maintenance) Possibly lower energy service expenditures Possibly higher disposable income with rural development, which can have positive macroeconomic impacts Possibly greater export-oriented trade involving solar fuels and solar energy carriers Development of a national intellectual property (IP) and patent base

Each jurisdiction will have unique priorities in developing a solar technology roadmap and will need to adapt the approach to its particular national or regional context and resources. While some countries may have assorted drivers for deploying more than one solar technology in several sectors, others may choose to craft their mission statement around just one or two.

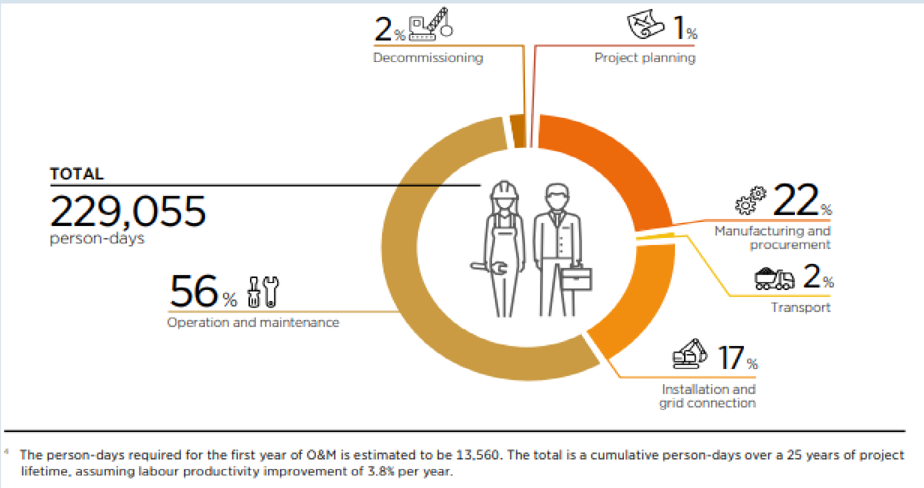
Decision makers should remember that including multiple drivers in the roadmap may influence the targets, data requirements and resource evaluation. Furthermore, a compromise may have to be found among the various drivers to maximise the overall benefits. A well-studied analysis of the value of solar energy for the public and private sectors and civil society at large is instrumental to inform policy and decision makers, especially under tight budgetary constraints.

Also, a study of current and projected energy end uses in the buildings, industry and transport sectors can help narrow down the focus of the roadmap's vision. Solar resource assessments and other baseline and technology research conducted under Phase 1 should not contradict the decisions and outcome of the visioning phase.

Box 10. Leveraging local capacity for solar energy

Countries are putting increasing value on the socioeconomic benefits that can be gained from deploying solar technologies. In fact, these benefits can be a key stimulus, closely linked with the creation of local industry and economic growth. Opportunities for new, local solar technology-related employment exist throughout the value chain, but a careful examination of which parts of the value chain can realistically be created domestically should be part of roadmap development.

Human resources required to develop a 50-MW solar PV plant



Note: The manufacturing of modules and inverters is not included.

Source: IRENA (2017a), *Renewable Energy Benefits: Leveraging Local Capacity for Solar PV*.

In the case of solar PV, creating the capability to produce silicon and PV cells and modules locally and competitively would require significant know-how and economies of scale, which are often difficult to obtain. Fortunately, job creation and local economic development can be achieved in other parts of the value chain more easily. Solar heat and – based on experiences in Morocco and South Africa – concentrating solar power (CSP) are likely more conducive to local employment creation.

Deployment targets

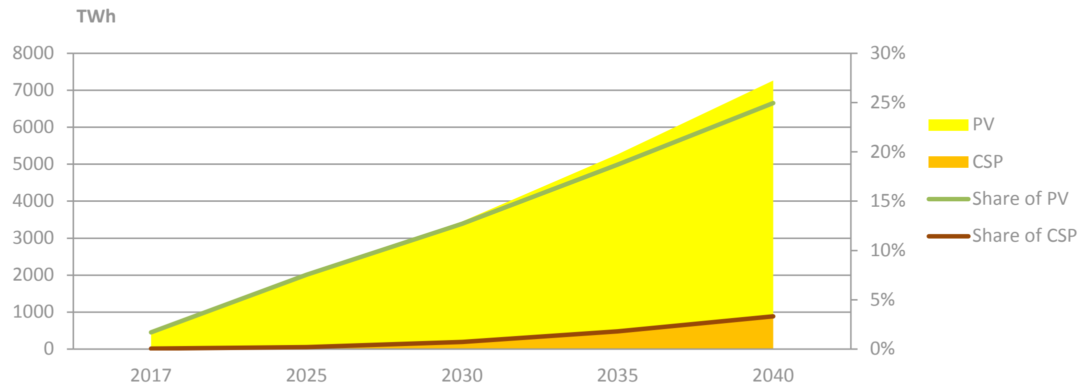
Because countries differ in their energy infrastructures, energy demand profiles and solar resource accessibility and affordability, their different drivers and policy goals will lead to prioritisation of different technology options, pathways and deployment targets. Global analyses such as the IEA's Sustainable Development Scenario may nevertheless help guide efforts (Figure 25). Deployment targets should be based on the assessments carried out in Phase 1, reflecting the viability of the pathways and end uses of the heat, power and (if applicable) solar fuels designated for domestic and/or international markets.

Clear, realistic targets are an important component of any national or regional roadmap's guiding vision. A precise vision and credible goals make it easier to implement a roadmap effectively, particularly when targets are mandatory rather than aspirational.

Although overall targets can be expressed in terms of capacity, generation or consumption, it is recommended that they be further disaggregated by sector (power, heat, transport) and technology or, when applicable, as sub-national targets.

When deployment targets are being formulated, potential synergies or counteractions with energy efficiency effects should be considered. For instance, if targets to expand solar energy use are framed as absolute values rather than as shares of energy demand, energy intensity reductions could actually undermine efforts to cut global energy demand.

Figure 25. PV and CSP generation in the Sustainable Development Scenario



Note: TWh = terawatt hour.

Source: IEA (2018b), *World Energy Outlook 2018*.

In climate-friendly scenarios, solar electricity provides up to 30% of global electricity.

It should be noted, however, that technological advancement also affects the market penetration of solar technologies, and while region-specific factors may influence deployment, technological progress will largely follow global trends. One important aim is to ensure that targets are aligned with a country's strategic objectives, such as for energy supply, job creation and rural development.

Phase 3: Roadmap development

Highlights of Phase 3: Roadmap development

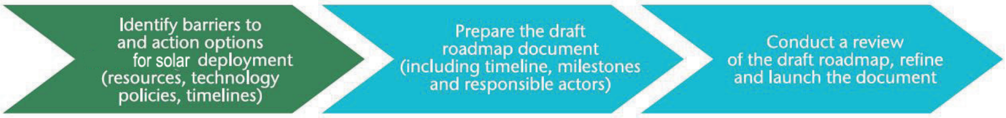
In this phase, implementation barriers are identified, actions to overcome them are determined and assigned to the appropriate participants, and a draft roadmap document is produced (Figure 26).

Duration: 2-6 months.

Resources: research staff, infrastructure to conduct interviews.

Meetings: senior-level workshop to establish long-term vision, potential travel/exchange with research organisation developing energy scenarios.

Figure 26. Roadmap development



Once a vision has been established, the goal of the third phase is to prepare and review a draft roadmap. Its content is usually discussed and determined through a number of expert workshops aimed at identifying barriers to solar deployment within the country or region, and possible actions that decision makers could assign to overcome them. Expert judgement is useful for setting a realistic timeline and roadmap implementation milestones in collaboration with the responsible stakeholders.

This section explores possible barriers that can hinder the deployment of solar technologies and provides an overview of action options and information sources available to policy and decision makers. While many barriers are common across regions, specific ones may apply in particular contexts. Furthermore, many barriers are technology-specific, i.e. different technology options (such as PV, solar heating and cooling [SHC] or CSP) have different solar resource requirements and different implications for connecting to the electricity grid or for system configuration. Decision makers should therefore tailor responses and policy measures to the existing conditions.

While every effort has been made to identify a comprehensive set of potential barriers and responsive actions, no list can be exhaustive. Barrier types and action options fall into several categories:

- Solar technology, project delivery and workforce barriers
- Barriers to integrating solar projects into the energy system
- Considerations for the enabling framework
- The role of international collaboration
- Setting the timeline and milestones.

Each subsection below offers a short introduction to the category and a table listing common barriers and actions to try to overcome them. Although the occurrence of barriers and their associated actions vary for each country, certain recurring elements are identified and summarised in Table 5 through 8. Issues are described, as well as a number of strategies or action options.

Solar technology, project delivery and workforce barriers

This guide outlines the various technologies, and their applications and sizes, available to use solar energy for power, heat and solar fuels. However, market uptake is often restricted by a lack of information about the range of technology options, how they perform under local conditions and how to operate them efficiently within the overall energy system.

Efficiency in project delivery influences project success and the future of the sector. Smooth project execution – from project development and construction right up to commissioning – is therefore a priority. Possible obstacles in this category are also linked with those in most other categories (e.g. integration into the energy system and the enabling framework, including regulatory, administrative, social acceptance and financing barriers).

The high quality of a workforce can enable growth in a sector, but because of the long lead times involved, developing the workforce should be a priority. Participation in regional or international efforts to harmonise standards, certifications and technology development could make quicker development possible (see Phase 4 for further details).

Table 5. Overview of solar technology, project delivery and workforce barriers

Barrier	Instances	Action options
Inadequate resource information	Solar resource information is not available at the quality needed to develop a detailed solar strategy.	Collaborate with international initiatives on solar resource assessment. Initiate public programme for national wind atlas, including long-term solar resource data and time-series data if possible Make all existing meteorological and wind resource assessment data accessible and provide national platform for data sharing.

Barrier	Instances	Action options
Lack of information on technology readiness and applicability	Lack of knowledge about the availability and performance of renewable technologies	Awareness-raising and training programmes for installers, civil engineers and architects
Shortage of qualified workforce	Shortage of local experts in solar technologies for all sectors, which may limit the choice of projects and numbers of installations that can developed High cost of O&M due to local lack of qualified personnel	Develop higher-education curricula and training to meet the whole set of skill requirements and professional profiles of solar energy technologies. Encourage technology and knowledge exchange with mature solar technologies. Support public- and private-sector investment in local capacity-building.
Information asymmetry/ shortage	Technologies and components are not standardised, leading to perceived risks for deployment/ performance. Lack of knowledge about technological options available internationally	Participate in international collaborations on standards. Build capacity through international collaborations for solar energy technologies.

Barriers to integrating solar projects into the energy system

As each individual project is part of the overall energy infrastructure and system, understanding the intersections and addressing integration issues can help make a roadmap a success.

While centralised production remains the core of most energy systems worldwide, the use of distributed, variable renewable energy (VRE) generation systems (including solar PV) is increasing. As greater shares of VRE are integrated into energy systems, the uncertainty of output from these sources means that networks are challenged with effectively balancing supply and demand.

Because CSP plants with thermal storage provide dispatchable electricity, they can adapt to the daily net-load patterns created by higher shares of VRE (especially PV), depending on their operating schedule and storage volume.

In the future, sector-coupling (linking the end-use sectors through electrification) is one of the strategies that may achieve deep decarbonisation of the energy system; this will depend on enabling digitalisation and demand-side management. Also, using solar energy as an energy carrier for the transport sector or as a trade commodity is an important way to introduce very high levels of renewables into the overall energy system.

Box 11. When the power sector is not credit-worthy: India's UDAY scheme

Many developing countries are keen to attract private investment for utility-scale solar energy generation. These are typically large solar farms that are connected to the grid, and the buyer of the electricity needs to be the national electricity company.

Difficulties arise when the distribution company is not credit-worthy, or when it incurs huge losses. When the off-taker is a bankrupt distribution company (or 'discom'), it cannot be counted on for timely payments over a typical contract period of 20 to 25 years. The solar project may therefore never materialise because of a lack of financing and no willing lenders. Even if someone is willing to lend enough for the project to go ahead, the cost of financing will be much higher than if the off-taker were a good credit risk. So, the health of the electricity distribution company is a very important ingredient for the growth of the solar energy sector in that country.

In India in November 2015, the federal government undertook a very bold nationwide reform of state-owned distribution companies that were losing massive amounts of money. The programme was referred to as Ujjwal Discom Assurance Yojana, or UDAY, and it was thought that one of the many benefits of making the distribution companies viable would be provision of a solid platform on which the renewables sector could grow, reinforcing the Power For All initiative.

UDAY had a financial component, to clean up the balance sheets of the over-indebted discoms, and an operational component, to reduce their Aggregate Technical and Commercial (AT&C) losses. The financial component involved a one-time transfer of 75% of each discom's debt onto the books of its respective state, by issuing state government bonds. In exchange for this huge financial benefit, the discoms had to commit to reduce their AT&C losses to a maximum of 15% by 2018-19, raise their power tariffs, reduce their reliance on short-term borrowing, and use operational monitoring indicators. The financial restructuring took place immediately, but studies show that most operational targets have not yet been met.

Most solar investors are still reluctant to sign power purchase agreements with state discoms (unless they are among the handful of very well-managed ones). Instead, they agree to sell their power to federal institutions such as the Solar Energy Corporation of India (SECI) or the National Thermal Power Corporation (NTPC, which is the country's largest public sector power generator). Financiers also prefer this as a payment security mechanism, since the likelihood of being paid is not an issue with these federal agencies. SECI and NTPC then enter into back-to-back contracts with state discoms to off-load the solar energy.

Electricity networks can be underdeveloped or ageing, particularly in rural areas, restricting the population's access to electricity; this lack of infrastructure may also prevent the construction of large-scale power plants. Solar PV and its modular design that makes it well suited to off-grid applications – from watt-scale solar home systems to megawatt- size mini-grids – may provide communities with the energy services that utilities are unable to provide.

In cities or municipalities with existing district heating infrastructure (or in cities being designed from scratch), solar thermal heat has been demonstrating its capabilities, e.g. in Denmark.

Table 6. Overview of energy infrastructure barriers and action options

Barrier	Instances	Action options
Infrastructure obstacles	Insufficient grid capacity; delayed arrival and late connection of new projects to grid	Make grid planning and extension a priority on policy agenda
Grid connection constraints	Transmission and distribution system operator (TSO/DSO) may lack capacity to enable grid connection (or have no interest) Connection fee may be inappropriate Point of connection may be disputed among developers or with transmission owner Long distance between potential site and grid node can be a barrier due to costs or existing rights-of-way	Regulate monopoly control to allow access to independent power producers (IPPs). Regulate system operators to ensure rates reflect costs. Distinguish connection costs from grid reinforcement costs and assign appropriately Ensure transition from legacy vertical utility providers to service providers
Curtailment and other operational constraints	Impact on voltage, frequency and power quality and system stability	Advocate system operators' adoption of state-of-the-art practices, and measures to progressively deal with greater solar energy penetration. Improve policy-maker understanding of issues to better manage operators' concerns. Revise grid code to include voltage control and active power control by solar energy plants
Mismatch with solar availability	Differences between annual solar availability and the load curve may be significant.	Increase power system flexibility and take other measures depending on the phase of VRE penetration.
Solar thermal for district heating	Change in operation due to solar resource variability Inadaptability of network temperature levels for efficient solar production Strong competition from natural gas networks, leading to sub-optimal results	Promote new infrastructure that works at lower temperatures. Adopt international best practices to avoid common mistakes. Integrated urban heating/cooling supply planning.

Considerations for the enabling framework

The enabling framework for solar technologies encompasses policy, regulatory and market structures. While a number of non-economic barriers can be strong determinants of roadmap's success, the enabling framework also has a financial dimension that reflects both the situation of the economy and financial markets as well as investors' perception of risk concerning solar energy projects.

Policy, regulatory and market framework barriers

The policy, regulatory and market framework ensures that energy producers can sell their services and recover their investments. At the same time, these frameworks guarantee the functioning of the energy system overall and create a level playing field for all participants.

Even with costs continuing to fall, government policy remains crucial to attract investment in renewables, as well as to ensure appropriate market design and reliable and cost-effective system integration. With greater deployment, technological maturity and competitiveness, policy instruments and business models are becoming more sophisticated in adapting to renewables, and many policy approaches are also evolving.

An overview of common policy instruments for deploying renewable energy in general and solar energy in particular can be found in *Renewable Energy Policies in a Time of Transition* (IRENA, IEA and REN21, 2018) as well as the Annex.

Table 7. Overview of policy, regulatory and market framework barriers and action options

Barrier	Instances	Action options
Policy and Regulatory framework	'Stop-and go' policy approaches and retroactive changes have undermined investor confidence. Insufficient transparency or excessive complexity of policies and legislations Strong requirement for 'local' procurement	Set up policy frameworks that enable fair sharing of risks and benefits among all stakeholders. Institute predictable, rule-based adjustments of financial incentives, e.g. dependent on deployment.
Land availability/ building access for installation	Statutory restrictions apply to site; site has other economic/landscape value Land may have historic value Lack of clarity for rights of roof access	Reform national planning rules. Assign government to broker planning permissions Establish body to resolve disputes Reform building codes.
Market barriers	Energy pricing that is not cost-reflective Subsidies for fossil fuels Externalities and the failure of costing methods to include social and environmental costs	Consider whether the design of power, heat or transport markets needs to be revised to enhance transparency and foster competition. Phase out fossil fuel subsidies that create inefficiencies and market distortions.
Electricity market design	Ensuring recovery of investment for solar and non-zero marginal cost facilities Curtailment may result from lack of space in the market Large shares of VRE, e.g. from solar PV, may require power market modification	Revisit 'must run' classification of conventional power plants and consider according 'must run'/priority dispatch status for solar electricity At much higher shares and in liberalised markets, encourage market reform of exchanges and futures markets, including design of intraday and balancing markets
Split incentives	Landlords do not invest in solar heat if benefits accrue to tenants	Introduce 'solar obligations' for new-build dwellings

Addressing non-economic barriers

Even when economic barriers have been addressed and resolved, a range of non-economic barriers can disrupt or even prevent the deployment of a specific technology or of renewables completely. Non-economic barriers are usually not isolated and occur in groups from several categories, as barriers are closely related.

Non-economic barriers can be categorised as:

- Institutional and administrative, including permitting
- Public acceptance, including social awareness
- Environmental

Table 8. Overview of non-economic barriers

Barrier	Instances	Action options
Institutional and administrative	Lack of strong, dedicated institutions, lack of clear responsibilities and co-ordination among agencies Slow, opaque permitting procedures, often due to insufficient capacity to manage applications in a timely fashion Developers lack competence in preparing applications Difficulty in getting projects connected to the grid	Rationalise and align policies at all levels of government. Co-ordinate authorities and make sure they all have adequate information for processing applications. Establish one-stop shop to streamline planning processes Offer training for developers in application process Ensure active co-operation from network operators by associating them with the process from the onset.
Public acceptance	Local opposition prevents construction of new grid connections, linked to experience with planning regulations and public acceptance of renewable technologies	Educate local population on benefits of solar electricity (GHG reductions, jobs, etc.) Consider long-distance high-voltage direct-current, and short-distance underground power lines
Environmental	Excessive restrictions on soil artificialisation or visual impacts	Ensure solar energy policy addresses end-of-life issues; limit soil artificialisation and visual impacts of all activities (not singling out solar deployment); deploy solar on contaminated soils.

While the combinations and impacts of these barriers are specific to each market, sector and technology, they are expected to evolve as technologies mature and deployment of renewables expands. Addressing these non-economic obstacles is therefore just as crucial as tackling high upfront costs and market barriers.

Administrative barriers can result in long project lead times. Planning delays and restrictions, a lack of co-ordination among the different authorities, and authorisation delays can all jeopardise the success of a project. Grid connection delays for newly developed large-scale projects undermine the investment value, raise financing costs (due to risk elevation) and make the market uncertain for the future investments. Problems with permitting, land disputes and postponed grid connection occur regularly in developing countries, for example in the sub-Saharan Africa region.

Lack of social acceptance of renewable projects – solar PV or otherwise – can occur in both developing and developed economies, however, and can cause developmental delays that lead to higher project costs or even project cancellations.

Insufficient information-sharing on the availability of policies and measures to support renewable energy projects can also slow down deployment. Well-designed information and education campaigns on the benefits, characteristics and performance of renewable technologies can win social acceptance and unblock deployment.

A lack of effective training and certification programmes for installers and employers working along the supply chain can also impede or interrupt deployment, particularly in the increasing number of countries that have a local content requirement.

Financing and economic considerations

Only ten years ago, solar PV was the most expensive electricity-generating technology, except for certain niche markets (telecom relays, minimum off-grid village electrification), whereas now it is one of the most affordable. Mass production and technology improvements have drastically cut investment costs, while policy frameworks and market designs have reduced market risks so that low-cost financing has been made possible. The cost of solar thermal electricity from CSP plants has dropped sharply, while the price-competitivity of SHC systems varies widely depending on market segment and country.

In the case of solar PV, creating the capability to produce silicon and PV cells and modules locally and competitively would require significant know-how and economies of scale, which are often difficult to obtain. Fortunately, job creation and local economic development can be achieved in other parts of the value chain more easily (and CSP and SHC systems are generally thought to be more conducive to local employment creation).

Access to financing for solar energy technologies is a prerequisite to deployment. Financing costs directly determine a technology's viability due to the high upfront capital costs involved, the long economic lifetimes and the resulting impact of the weighted average cost of capital. Financing renewable energy projects therefore depends on investor confidence and the availability of funds. Table 9 summarises some common barriers and action options, but there is a vast body of research examining how the regional context influences funding availability and specific financing issues.

Table 9. Overview of financing barriers and action options for solar energy projects

Barrier	Instances	Action options
Investment costs and economics	Solar technology's levelised cost of electricity (LCOE) may be uncompetitive relative to other sources of power. The levelised cost of heat (LCOH) of solar thermal may be uncompetitive relative to other sources of heat. Solar technologies can compete on a levelised-cost basis, but up-front capital investment costs are too high.	Reform energy markets to remove inefficient direct and indirect subsidies for conventional sources of energy. Institute government intervention to reduce cost of loans through grant funding, credit guarantees, tax incentives Consider government support for solar energy in the form of tax incentives, credit guarantees or access to affordable financing.

Barrier	Instances	Action options
Investor confidence and perceived risk	Technology risks considered too high by investors Lack of previous investment experience in target countries makes commitments too risky Instability in the policy and/or regulatory framework Mismatch of currencies for revenue and repayment	Establish long-term revenue certainty and/or stable government support mechanisms (e.g. a quota obligation system or tradable certificates). Introduce hedging instruments for overcoming risks. Index revenue to a currency.
Availability of financing	Project promoter or developer unable to provide equity for project Investment banks may be unwilling to offer project financing. In the buildings sector, those who pay for energy services may not make the decisions on new supply-side investments.	Establish or mandate a public bank to support investments when private investors regard the risks as too high. Urge government to support development of domestic or regional bond market in low-carbon goods. Consider strategies to overcome the 'owner-tenant dilemma', including policy measures such as renewable heat obligations.

Research, development and demonstration support

Energy innovation is critical for meeting long-term policy goals. While technological innovation often occurs rather slowly through incremental adjustments, this linear image oversimplifies the relationships among the stages. Innovation in the real world is more complex: for instance, even once a technology has become cost-competitive with relevant alternatives in one country, it may not be attractive in another and may require early-stage support and further innovation.

A number of solar technologies have recently made tremendous progress owing to research, development and demonstration (RD&D) efforts as well as economies of scale. Solar technologies consist of a range of solutions at different stages of market maturity. Direct support for RD&D (e.g. grants, loans, tax credits) and non-RD&D support for business innovation (e.g. support for venture capital and assistance in launching entrepreneurial activities) need to be balanced with targeted policies that foster demand and markets for clean energy (e.g. pricing mechanisms, public procurement, minimum energy performance standards, energy efficiency labels and mandatory targets). All national or regional roadmaps for solar technologies should therefore include opportunities and support for RD&D to further reduce solar technology costs and improve system performance and reliability.

Phase 4: Implementation, monitoring and revision

The fourth and final phase of roadmap development covers monitoring its implementation and establishing a revision mechanism (Figure 27). This is an ongoing activity, with tracking and monitoring occurring on a regular basis.

Figure 27. Implementation, monitoring and revision phase

Setting the timeline and milestones

The stakeholders leading the roadmapping exercise need to consider if and how institutions will be able to adapt to the roadmap's identified actions. For example, requiring planning authorities to accelerate the issuing of permits may take time. The speed with which administrators can assess tariff applications and modify policies depends on resources: acceleration may not be possible without the injection of more human resources, or a fundamental redesign of how to approach the task. Moreover, there may be good reasons for the way the permitting process is designed, and accelerating it to enable solar energy deployment may impact other policy areas. Necessary changes may be brought about more quickly, and be less likely to lead to unintended consequences, if the institutions in question are involved in the roadmapping process from the outset.

Monitoring roadmap implementation

Setting up a monitoring system to track the progress of roadmap implementation should be started in the early stages of the roadmapping process. Monitoring is essential to the IEA's analytical work to inform policy makers whether current policies and settings are effectively driving the desired energy transitions,[1] and the monitoring framework can reveal whether the roadmap needs adjusting in light of experiences gained through its implementation.

Establishing metrics that capture the roadmap's impact (on the energy mix, the economy, technology uptake, etc.) is very important, as they provide governments with information about successes and shortcomings; Table 10 lists potential qualitative and quantitative indicators to

[1] For further information, see www.iea.org/tracking/ and www.iea.org/tcep/.

track and monitor progress. The monitoring system should ensure comprehensive information collection while keeping the reporting burden and costs at an acceptable level.

For each indicator, it is useful to identify the stakeholders responsible for monitoring and reporting, as well for the verification mechanism. Robust data and transparent analysis are important.

Ideally, project owners should be obligated to report available data (including performance data when available), and the privacy and confidentiality of all data should be ensured. There is a vast body of information on data collection – *International Recommendations for Energy Statistics* (UNSD 2018) – and on compiling statistics – the *Energy Statistics Compilers Manual* (UNSD 2016) – from collaboration between the Oslo Group on Energy Statistics and the Intersecretariat Working Group on Energy Statistics (InterEnerStat). These may provide practical guidance for setting up the monitoring framework and data collection.

Table 10. Quantitative and qualitative indicators for monitoring progress

Indicator type	Description
Solar technology deployment	Megawatt hours (MWh) generated per annum by technology and application Share of solar energy (%) in total yearly electricity production by technology and application MW capacity installed by technology and application Share of solar capacity (%) in total installed power capacity by technology and application Capacity factors and full-load hours of solar generation (% and number of hours annually) Solar thermal capacity (m^2 of collector surface and estimated thermal generation or reduced consumption of alternative fuels) Curtailment (electricity only): kWh curtailed, hours of curtailment or % of expected generation Construction lead times (number of months) New patents and technical innovations related to solar energy Public and private R&D expenditures on solar energy
Financial	Total solar energy sector investments per year Value of state-backed investments per year (e.g. via development banks) Annual spending on public financial incentives Ratio of public to private investment Value of certificates traded per year Annual cost of support mechanisms (solar energy and all renewable energy) Domestic investments committed per year Development in cost of solar technologies by application and/or system size
Processes	Number of training workshops organised Number and success rates of research, development and innovation programmes Number of useful new institutions created Number and effectiveness of awareness-raising campaigns organised Reduction in lead times for essential permits and licences Success rates within the permitting processes

Indicator type	Description
Policy	Policies defined and adopted Long-term stability of the policy framework Sectoral strategies developed to implement identified milestones Risk management strategy and implementation
Socioeconomic and environmental impacts	Net jobs created in the domestic solar energy supply chain and annual turnover Social projects supported Contribution of solar energy to the GDP Percentage increase in population connected to electricity grid Percentage increase in population with access to modern energy services Avoided cost of imported fossil fuels Percentage reduction in carbon intensity of electricity generation Percentage reduction in carbon intensity of final energy consumption Avoided GHG emissions per year, particularly CO_2

International collaboration

As highlighted earlier in this report, multilateral collaboration can help accelerate roadmap implementation beyond what would be expected from government and market forces alone, and it can catalyse cost-effective solutions. There are certain barriers that can prove much more costly to overcome, and side-effects that cannot be mitigated well, without strong collaborative approaches, and international partnerships play a key role in facilitating these efforts.

Co-operation and networking can also increase the effectiveness and maximise the impact of RD&D efforts. Energy technology innovation supported by international collaboration can deliver more benefits and bolster effectiveness, priority-setting and industry engagement. There are many models for international collaboration, from bilateral agreements to regional networks and multilateral forums. Some of these international initiatives are outlined below.

International Solar Alliance

The International Solar Alliance (ISA) is a treaty-based intergovernmental organisation established by its parties to collectively address key common challenges to scaling up solar energy in line with their needs. Their goal is to mobilise more than USD 1 trillion for the solar sector and to develop and deploy over 1 terawatt of solar generation capacity by 2030 in ISA member countries.

By May 2019, 75 countries had signed and 53 had ratified the Framework Agreement on the Establishment of the ISA. ISA membership is now open to all UN member countries (ratification procedure in progress). The ISA aims to directly impact the seventh Sustainable Development goal (SDG 7: *Ensure access to affordable, reliable, sustainable and modern energy for all*) and SDG 13 (*Take urgent action to combat climate change*) while striking a balance between the two.

The ISA is founded on a strong governance structure of an Assembly and eight committees: standing; programme; general and legal; finance; and four regional committees. Six task forces, two working groups and a global ecosystem of partners help the ISA maintain its pace.

The ISA has launched five programmes to meet its objectives:

- Scaling Solar Application for Agricultural Use
- Affordable Finance at Scale
- Scaling Solar Mini-grids
- Scaling Solar Rooftop
- Scaling Solar in E-mobility and Storage.

It has also initiated two cross-cutting capacity-building programmes to facilitate massive solar energy deployment in its member countries:

- ISA STAR (on capacity-building, research and entrepreneurship)
- Infopedia (an online solar knowledge repository funded with the support of the European Commission).

The ISA has a unique business model to facilitate implementation of solar projects in its member countries. In its past two years of operations, the ISA has taken on the role of an 'enabler' by institutionalising 30 Fellowships from member countries with a premier institution (IIT Delhi) in its host country, and by training 200 Master Trainers from ISA member countries; of a 'facilitator' by obtaining lines of credit worth USD 2 billion from EXIM Bank of India and USD 1.5 billion from AfD, France, by ensuring MDB investments in solar, and by garnering project preparation support; of an 'incubator' by nurturing initiatives such as Common Risk Mitigation Mechanisms; and of an 'accelerator' by developing tools to aggregate demand for 1 000 MW of solar capacity and 300 000 solar water pumps.

IEA Technology Collaboration Programmes

Nearly half a century ago, the IEA established the Technology Collaboration Programmes (TCPs) as a framework for international collaboration on energy technology RD&D, technology analysis and information sharing. Today, there are three TCPs related to solar technologies:

- the TCP on Photovoltaic Power Systems (PVPS TCP), which conducts a variety of collaborative projects relevant to solar PV technologies and systems, including cost reductions, analysis of barriers and raising awareness of the potential of PV electricity. Further information is available at www.iea-pvps.org
- the TCP on Concentrated Solar Power (SolarPACES TCP), which is a leading international network of researchers engaged in thermal solar for dispatchable power and solar chemistry technologies. Among its key activities, Solar PACES TCP has developed guidelines and supported standards to increase the transparency of the market and reduce risks associated with project development. More information is available at www.solarpaces.org
- the TCP on Solar Heating and Cooling (SHC TCP), which works to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers and by engaging in research and development of components, materials and design as well as raising political and public awareness. More information is available at http://www.iea-shc.org

International Solar Energy Society

The International Solar Energy Society (ISES) is one of the longest-standing international solar organisations, with extensive membership worldwide. ISES provides scientific advice to governments and the public as well as collaborating with the solar industry to inform public opinion through education and outreach activities. Further information is available at www.ises.org

European Technology and Innovation Platform

The European Commission has endorsed a number of European Technology and Innovation Platforms (ETIPs) that bring EU policy makers, industry and research centres together to work on identified priority innovation topics. ETIPs cover a broad scope of energy technologies, with two dedicated to solar:

- the ETIP for Photovoltaics (ETIP PV); further information available at http://www.etip-pv.eu
- the ETIP for Renewable Heating and Cooling (ETIP RHC); further information available at http://www.rhc-platform.org/

CEM Multilateral Solar and Wind Working Group

The Clean Energy Ministerial (CEM) is a high-level global forum where major economies and forward-leaning countries work together to share best practices and promote policies and programmes that encourage and facilitate the transition to a global clean-energy economy. The CEM Multilateral Solar and Wind Working Group strives to promote the accelerated deployment of solar and wind technologies worldwide. It initially focused on developing a global atlas for solar and wind energy; a corresponding long-term strategy on joint capacity building; and a report on economic value-creation effects from renewable energy deployment, including how to measure these effects and policies to facilitate and optimise them. Further information is available at http://www.cleanenergyministerial.org/

MI Converting Sunlight Innovation Challenge

Mission Innovation (MI) is a global initiative focused on scaling up RD&D for clean energy technologies. MI governments have pledged to seek to double their public clean energy RD&D investments over five years. Under the MI framework, the Converting Sunlight Innovation Challenge is bringing together stakeholders to exploit the opportunity of using sunlight to produce carbon-neutral fuels (such as hydrogen) and to develop energy storage chemicals. Further information is available at http://mission-innovation.net.

Multilateral development banks

The solar strategy of the **African Development Bank** (AfDB) – part of its climate change action plan – is explicit in its *Second Climate Change Action Plan 2016-2020.*[2] Pillar 2 of the Plan is

[2] www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/AfricanDevelopmentBankClimate ChangeActionPlan2016-2020.pdf

"Promoting mitigation and low-carbon development in Africa", and the first action item is to scale up renewable energy investment via the AfDB's New Deal on Energy for Africa as well as the African Renewable Energy Initiative (AREI), which is hosted by the AfDB.

One of the items is the USD 10 billion Desert to Power Initiative, for which the AfDB has partnered with the Green Climate Fund to collaborate on an innovative approach to catalyse solar investments from both the public and especially the private sector and institutional investors. This form of blended financing is intended to help fill in shortfalls in capital resources in Africa.

The Initiative aims to develop 10 GW of solar energy across the Sahel region by 2025, which could provide renewable electricity access to over 250 million people, thereby solving many of the region's energy access challenges. By tapping into one of the world's largest sources of solar power, this traditionally underdeveloped region could be dramatically transformed.

The **World Bank Group**'s (WBG's) strategy is laid out in its *Climate Change Action Plan 2016-2020*.[3] Under this plan, the WBG will use multiple instruments to de-risk renewable energy investments with a cumulative target of adding 20 GW of renewable energy generation. Through a combination of policies and power system investments, the World Bank will enable a further 10 GW of renewables to be integrated into grids.

The Scaling Solar programme is one of the initiatives that brings together a suite of WBG services under a single engagement aimed at creating viable markets for large-scale grid-connected solar power in each client country. The 'one-stop-shop' programme aims to make privately funded grid-connected solar projects operational within two years and at competitive tariffs. When implemented across multiple countries, the programme will create a new regional market for solar investment. The package includes: i) *Advice* to assess the right size and location for solar PV power plants in a country's grid; ii) *Simple and rapid tendering* to ensure strong participation and competition from committed industry stakeholders; iii) *Fully developed templates* of bankable project documents that can eliminate negotiation and speed up financing; iv) *Competitive financing and insurance* attached to the tender and available to all bidders, delivering competitive bidding and ensuring rapid financial closing; and v) *Risk management and credit enhancement* to lower financing costs and deliver power at lower tariffs.

The **Asian Development Bank**'s (ADB's) strategy to support the solar sector is called *ADB Strategy 2030*,[4] issued in July 2018. The document identifies seven operational priority areas, one of which is "Tackling climate change, building climate and disaster resilience, and enhancing environmental sustainability". The document states that the ADB will scale up support in these areas and will ensure that 75% of its committed operations (on a 3-year rolling average, including sovereign and non-sovereign operations) will support climate change mitigation and adaptation by 2030. Climate financing from ADB's own resources will reach USD 80 billion cumulatively from 2019 to 2030.

The ADB will also expand its private sector operations to one-third of its total operations by 2024, and will pursue development impact as the key objective of its private sector operations.

In addition, the ADB will catalyse and mobilise financial resources for development. It will strengthen collaboration with multilateral, bilateral and private sector partners and seek financing from commercial and concessional sources. It plans to target a substantial increase in long-term co-financing by 2030, with every USD 1 in financing for its private sector operations

[3] https://openknowledge.worldbank.org/bitstream/handle/10986/24451/K8860.pdf?sequence=2&isAllowed=y
[4] www.adb.org/sites/default/files/institutional-document/435391/strategy-2030-main-document.pdf

matched by USD 2.50 of long-term co-financing. To catalyse investments, it will use public–private partnerships, improve the business environment in developing member countries (DMCs), and enhance DMCs' domestic resource mobilisation.

References

ADB (Asian Development Bank) (2016), *Indonesia: Energy Sector Assessment, Strategy, and Roadmap*, ADB, Mandaluyong City, the Phillipines.

IEA (International Energy Agency) (2018a), *Renewables 2018: Analysis and Forecasts to 2023*, Market Report Series, IEA, Paris.

IEA (2018b), *World Energy Outlook*, IEA, Paris.

IEA (2014), *Energy Technology Roadmaps: A Guide to Development and Implementation*, IEA, Paris.

IEA (2011), *Solar Energy Perspectives*, IEA, Paris.

IEA PVPS TCP (Photovoltaic Power Systems Technology Collaboration Programme) (2018), *Trends 2018 in Photovoltaic Applications*, IEA PVPS, Paris.

IEA SHC TCP (Solar Heating and Cooling Technology Collaboration Programme) (2019), *Solar Heat Worldwide 2019*, IEA SHC, Paris.

IRENA (International Renewable Energy Agency) (2017a), *Renewable Energy Benefits: Leveraging Local Capacity for Solar PV*, IRENA, Abu Dhabi.

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

IRENA, IEA and REN21 (2018), *Renewable Energy Policies in a Time of Transition*, IRENA, IEA and REN21, Abu Dhabi and Paris.

UNSD (United Nations Statistics Division) (2018), *International Recommendations for Energy Statistics.* United Nations, New York.

UNSD (2016), *Energy Statistics Compilers Manual*, United Nations, New York.

World Bank Group, ESMAP and SERIS (2018), *Where Sun Meets Water: Floating Solar Market*, World Bank, Washington, DC.

Annexes

Annex A. Overview of policy instruments to promote solar uptake

Renewable energy policies and programmes are pivotal for successful deployment, as the right policy tool and its correct implementation can often be the key to creating a suitable environment. Efforts to advance the deployment of all types of renewables in the power sector have therefore been led by government targets and policies. Target-setting, which is often the first step in policy- and strategy-making for renewables deployment, determines the deployment objectives for a country, city or region, for specific sectors or for the energy system as a whole.

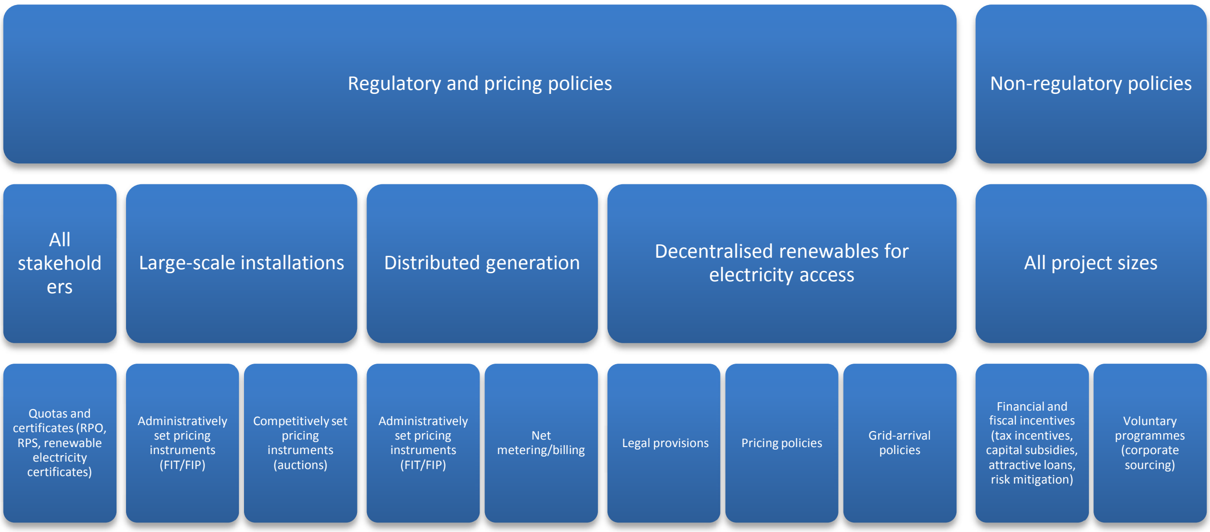
Targets, which can be set at the national, regional or city level, provide a high-level signal to various stakeholders to encourage investment in renewable energy, and they also serve as a foundation for many support policies and measures. Long-term targets that extend several decades into the future must be supported by mid- and near-term goals to keep deployment in check and on track. Overall targets can be expressed in terms of capacity, generation or consumption, and can pertain to all renewable energy resources. However, it is recommended that countries further disaggregate general targets into sectoral (power, heat and transport) and technology-level ones.

Solar deployment targets can express goals either as totals (e.g. X gigawatts [GW] of installed solar capacity by Y year) or in specific terms (a precise amount of utility-scale, distributed PV or off-grid applications added in the country within a defined period of time). Given the variety of solar technologies, solar heating targets should also be adopted.

Power sector

Renewable policies for the power sector are extensive, since this is the sector that has received the most policy-making attention and has had the greatest deployment success thus far. Policies can be differentiated either by type of measure and whether the targeted project will be installed on- or off-grid, or by project size and policy category. They can also be categorised as price-finding mechanisms or net-metering and billing schemes, or as regulatory, fiscal and financial measures (Figure 28).

Figure 28. Classification of power sector policies



Source: IRENA, IEA and REN21 (2018), *Renewable Energy Policies in a Time of Transition*.

Price-finding mechanisms

Quotas and obligations placed on electricity generators or consumers by a central or state government mandate that a certain percentage of power be met with renewable electricity. This mechanism directly translates overall renewable energy targets and shifts the obligation to generators and consumers. Quotas and obligations usually have medium-term targets (e.g. 10 years ahead) as well as annual targets that gradually increase leading up to the end-year. Quotas and obligations, which can be technology-disaggregated into specific technology levels, are most often supported by tradeable certificates.

Tradeable certificates are usually launched to support quotas and obligations and ensure they are met. Market participants, such as suppliers and generators, receive or buy certificates to meet the mandatory quotas established for the year. Certificates can be accumulated to meet obligations and can serve as a trading tool among participants. They are also used in voluntary markets, traded by private companies to meet their corporate renewable goals.

Feed-in tariffs (FITs) are administratively set tariffs for electricity generated by renewable energy technologies. Tariff levels differ according to technology, installation size, mounting system and often location of the installation. Tariffs are assigned in long-term power purchase agreements (PPAs) signed between the generator and responsible energy regulation body or electricity off-taker. PPA durations are usually of 12 to 30 years. Historically used in developed economies to support the deployment of large, medium and small-scale installations, they are now employed for small-scale installations only. They do, however, continue to be used to support all sizes of installations in developing economies where access to financing is limited and investment is riskier overall.

With renewable technology costs falling rapidly, it is challenging for administrators to accurately assign a price to the power generated. Setting tariffs too high (relative to project costs) can lead to overpricing – to the disadvantage of taxpayers or ratepayers – but tariffs that are too low fail to generate investor interest. Furthermore, the volume of new capacity entering the system is difficult for governments to control.

Feed-in premiums (FIPs) are prices added on top of the market price for the electricity produced and sold into the grid from renewable generators. The idea is to use market prices to lead developers and operators of renewable capacities to generate more when prices are high, while still ensuring sufficiently high remuneration to keep financing costs low. FIPs can be either fixed (i.e. remain at the same level regardless of electricity price) or sliding (i.e. differ depending on electricity price evolution). Minimums and maximums are often set on the premium or on total remuneration (electricity price + premium). As with FITs, FIPs are contracted for long periods.

A **renewable auction** is a selection process designed to procure new renewable electricity capacity (or generation volumes) competitively, in which a long-term PPA is granted to a qualified bidder based on a financial offer, and in certain cases, on additional criteria (e.g. the bidder's financial health, bank guarantees received, and previous experience in developing and operating renewable energy plants). Auctions are a price-discovery tool that takes advantage of competitive forces, shifting the burden away from the administrator. Auctions are also an excellent volume-control mechanism, but their design must be carefully tailored to each country's context. Measures to guarantee investor interest must be implemented, but rules for taking part must also be carefully planned to prevent the participation of unsuitable bidders who could later fail to deliver their allotted capacity.

Auctions can be either open to all renewable technologies, wherein all projects compete with one another, or limited to one specific technology, for example solar PV. PPAs can then be structured to incentivise production in some locations more than in others, or at certain times more than others, to reflect the needs of the power system and the economy.

In auctions, bidders are invited to compete for a portion of the capacity up for auction (the minimum capacity size is usually specified in the auction rules), while during **tenders** bidders must bid on the entirety of the sought-after capacity.

Selected bidders are granted long-term PPAs, usually of up to 20 or 25 years depending on the country, project and technology procured. In effect, auctions are a price-finding mechanism for granting contracts similar to the way FITs and FIPs do.

Renewable energy auctions are most suitable for procuring utility-scale projects. Large companies are most likely to participate, be eligible for participation and win the PPA contracts. The auctions environment is difficult for smaller companies to participate in, so there is a risk that competition will, in effect, be limited to several large companies that will dominate the results and cut the smaller entities out of the market.

Upon announcement of the winning bids, developers turn to financial institutions to secure loans, then return to the regulator or the off-taker to sign the PPA. Countries usually set time limits and penalties for late delivery of contracted projects.

Net metering and billing are measures that promote self-consumption of electricity produced from renewable projects, and they are most often used to support the uptake of distributed solar PV installations for either residential or commercial use. This measure allows installation owners to reduce or eliminate the variable-charge portion of their electricity bills. In a net metering scheme, compensation is in energy terms (i.e. credited in kilowatt hours [kWh]), and the credit can be applied to offset electricity consumption within the current billing cycle (e.g. one month), or often in future billing cycles as well. In net billing, the compensation is monetary (i.e. credited in monetary units) (IEA PVPS, 2016). Under a net billing scheme, a distributed generation (DG) system owner can consume electricity generated by the DG system in real time and export any excess to the utility's grid. In this way, net billing is akin to net metering; however, banking kilowatt hours within a billing cycle to offset future consumption is not allowed under net billing. Instead, all net energy exports are metered and credited at a predetermined selling rate the moment they are injected into the grid (IRENA, IEA and REN21, 2018).

Regulatory measures

Contracts for FITs, FIPs and auctions are usually paired with a guaranteed **priority of dispatch**. This rule guarantees the developer the entire generation will be dispatched and generate revenue at the price set in the PPA. Alternatively, curtailment can be compensated at a different remuneration level.

Streamlined permitting processes make it easier to apply for and receive permitting for project installation and grid connection.

Financial and fiscal incentives are made available to reduce upfront capital costs and to improve access to more affordable financing. Financial and fiscal measures such as capital grants, rebates, soft financing and various types of tax discounts or tax waivers can be implemented together and with other measures that support renewables deployment, offering a range of policy support for renewable investment in the country and creating a positive investment environment. These types of measures can be easily amended and applied to non-power sectors, and they are often integrated into energy efficiency policies and programmes.

Capital grants are usually distributed by local governments to assist with the high upfront investment costs of project development. Grants can be used to support a specific technology in a targeted market (e.g. residential or commercial solar PV), and their amounts are based on installation size, type of project owner (individual, private company, community or other) and technology type (e.g. solar PV or bioenergy burner). They and can be set as a share of the initial cost or as a specific amount per installation. Often capped at a certain level (e.g. 40% of the initial cost but no more than USD 2 500 per installation) to limit spending on one particular support policy, grants can also be distributed by utilities or non-profit organisations to fund a portion of feasibility studies, demonstration projects or business development in a niche market.

Soft loans are provided and supported by national and local governments and are distributed by environmental, national or partnered commercial banks to targeted recipients for the development of high-capital-cost projects (such as solar panel installations on top of residential, commercial or agricultural buildings). Loan amounts, which are usually capped for each project based on previously set specifications, are lent at a preferential (i.e. lower) interest rate, and the loan repayment period is often longer than usual to reduce the repayment burden. In some cases, the first repayment instalment can even be postponed (e.g. the borrower may be allowed to begin paying back the loan 12-16 months after the plant has been installed).

Tax discounts, waivers and credits are the most widely used policy instruments globally, as they can be applied to projects and installations of any size, and in areas that are not connected to the grid. In 2017, more than 100 countries offered some form of tax incentive for renewable technology deployment (IRENA, IEA and REN21, 2018). Tax incentives can be adopted alone or in combination with other policy measures such as capital grants and soft loans to help overcome the economic barriers and high initial investment costs of purchasing a renewable energy installation. Support can be given as a waiver or reduction of import tax on equipment, or as a reduction in value-added tax (VAT) or income tax owed on revenue gained from the power or energy generated. Some countries (such as the United States) have also introduced tradeable tax credits: for example, a wind farm operator who generates USD 100 worth of tax deductions can sell these deductions to companies that can then use them to reduce their amount of tax owing (IEA, 2011).

Heating sector

The heating and cooling sector is complex and fragmented, and generally less well understood than the electricity sector. Its complexity makes effective policy making challenging. Demand for thermal energy in buildings varies greatly based on climate, building envelope efficiency, occupancy, occupant behaviour and many other factors. Further, there is a range of heating and cooling requirements for a multitude of industry processes. On the supply side, many different space and water heating options are available, involving many stakeholders – from large, multinational heating equipment manufacturers to small, local installers. Fuels also vary, and the scale of heat production ranges from large combined heat and power plants to small, open fires. Renewables-based heating and cooling technologies face multiple barriers when competing with incumbent (mainly fossil fuel-based) options (IRENA, IEA and REN21, 2018).

Much more effort is needed at the policy level in a larger number of countries. Approaches to renewable heat policies will have to vary among countries to reflect their different circumstances (e.g. in building stock, industrial heat demand and resource potential) and specific barriers. However, while there is no one-size-fits-all solution, all countries should set targets for renewables in the heating and cooling sector and develop strategies to achieve them, coupled with measures for energy efficiency (IRENA, IEA and REN21, 2018).

Various policy tools already employed to support renewables growth in the power sector can also be adjusted and applied to renewables in the heat sector, especially **targets, capital grants, soft loans, tax discounts and waivers**.

Heating mandates and quotas are often implemented through building codes. Mandates are the most common type of policy tool used around the globe to support renewables in heat. Regulator mandates work by specifying that certain types of buildings (newbuild or refurbished; residential or commercial, etc.) meet a certain portion of heating consumption through renewable technologies such as solar water heaters or heat pumps. Mandates therefore provide great deployment certainty. However, while the increase of newbuilds is specific to each country, the refurbishment of existing floor area happens only every several decades, so the pace of expansion for renewable heat in buildings is slow. In 2017, just over 50 countries had some form of policy support in place for renewables in heat, and 22 countries had mandates.

Heat generation-based incentives are similar to FITs in that they provide structured, long-term support, but they do not, however, help diminish the high upfront costs of the investment. Most often used for installing renewable heat generators in district heating infrastructure, heat generation-based incentives are rarely adopted.

Carbon or energy taxes are placed on fossil fuel-based heat generators, which indirectly impacts renewable heat technologies. They provide important price signals and reduce externalities, but design and implementation challenges remain, especially in contexts in which energy-intensive industries are subject to strong international competition and may therefore request exemptions.

Countries also have the option of implementing **bans on fossil fuel heating options**, which can be very effective, provided other suitable heat alternatives are available and accessible for small and large investors alike. The observance of bans and switching to desirable technologies must be strictly enforced by the legislator for this measure to be effective.

References

IEA (International Energy Agency) (2011), *Deploying Renewables 2011: Best and Future Policy Practice*, IEA, Paris.

IEA PVPS TCP (Photovoltaic Power Systems Technology Collaboration Programme) (2016), *Self-Consumption Policies*, www.iea-pvps.org

IRENA (International Renewable Energy Agency), IEA and REN21 (2018), *Renewable Energy Policies in a Time of Transition*, IRENA, IEA and REN21, Abu Dhabi and Paris.

Annex B. Acronyms and abbreviations

Acronyms and abbreviations

AC	alternating current
ADB	Asian Development Bank
AfDB	African Development Bank
AREI	African Renewable Energy Initiative
AT&C	Aggregate Technical and Commercial (losses)
BOS	balance of system
c-Si	crystalline silicon
CAPEX	capital expenditures
CdTe	cadmium telluride
CEM	Clean Energy Ministerial
CH_4	methane
CIGS	copper-indium-gallium-selenide
CIS	copper-indium-selenide
CO_2	carbon dioxide
CPC	compound parabolic concentrator
CPV	concentrating photovoltaic
CRS	central receiver system
CSP	concentrating solar power
DC	direct current
DG	distributed generation
DNI	direct normal irradiance
DSO	distribution system operator
DSR	demand-side response
ESCO	energy service company
EOR	enhanced oil recovery
ETIP	European Technology and Innovation Platform
FIP	feed-in premium
FIT	feed-in tariff
GDP	gross domestic product
GHG	greenhouse gas
GHI	global horizontal irradiation
HVAC	heating, ventilation and cooling
IEA	International Energy Agency
IP	intellectual property
IPP	independent power producer
IRENA	International Renewable Energy Agency
ISA	International Solar Alliance
ISES	International Solar Energy Society
LCOE	levelised cost of electricity
LCOH	levelised cost of heat
LED	light-emitting diode
LPG	liquefied petroleum gas
MI	Mission Innovation
NGN	Nigerian naira
NTPC	National Thermal Power Corporation (India)
O&M	operations and maintenance
OPEX	operating expenses
PPA	power purchase agreement

PT	parabolic trough
PV	photovoltaic
PVPS TCP	Photovoltaic Power Systems Technology Collaboration Programme
RACI	Responsible, Authorised, Consulted and Informed
RD&D	research, development and demonstration
SECI	Solar Energy Corporation of India
SHC	solar heating and cooling
SHC TCP	Solar Heating and Cooling Technology Collaboration Programme
SHIP	solar heating in industrial processes
SHS	solar home system
SolarPACES	Solar Power & Chemical Energy Systems programme
STE	solar thermal electricity
TCP	Technology Collaboration Programme (IEA)
TSO	transmission system operator
VAT	value-added tax
VRE	variable renewable energy
WACC	weighted average cost of capital
WBG	World Bank Group

Units of measure

°C	degrees Celsius
GW	gigawatt
GW_{th}	gigawatt thermal
kg	kilogramme
km	kilometre
kW	kilowatt
kWh	kilowatt hour
kWp	kilowatt peak
kW_{th}	kilowatt thermal
L	litre
m	metre
mm	millimetre
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt hour
MW_{th}	megawatt thermal
TW	terawatt
TWh	terawatt hour
W	watt

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The European Commission also participates in the work of the IEA

IEA association countries:

Brazil
China
India
Indonesia
Morocco
Singapore
South Africa
Thailand

International Energy Agency
Website: www.iea.org

IEA Publications
International Energy Agency
Website: www.iea.org
Contact information: www.iea.org/about/contact

Typeset and Printed in France by IEA - October 2019
Cover design: IEA
Photo credits: © ShutterStock