Technology Roadmap

Solar photovoltaic energy

International
Energy Agency

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- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of CO_2 will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the IEA is developing a series of roadmaps for some of the most important technologies. These roadmaps provide solid analytical footing that enables the international community to move forward on specific technologies. Each roadmap develops a growth path for a particular technology from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential. Roadmaps also include special focus on technology development and diffusion to emerging economies. International collaboration will be critical to achieve these goals.

While its use is small today, solar photovoltaic (PV) power has a particularly promising future. Global PV capacity has been increasing at an average annual growth rate of more than 40% since 2000 and it has significant potential for long-term growth over the next decades. This roadmap envisions that by 2050, PV will provide 11% of global electricity production (4 500 TWh per year), corresponding to 3 000 gigawatts of cumulative installed PV capacity. In addition to contributing to significant greenhouse gas emission reductions, this level of PV will deliver substantial benefits in terms of the security of energy supply and socio-economic development. Achieving this target will require a strong and balanced policy effort in the next decade to allow for optimal technology progress, cost reduction and ramp-up of industrial manufacturing. This roadmap also identifies technology goals and milestones that must be undertaken by different stakeholders to enable the most cost-efficient expansion of PV. As the recommendations of the roadmaps are implemented, and as technology and policy frameworks evolve, the potential for different technologies may increase. In response, the IEA will continue to update its analysis of future potentials, and welcomes stakeholder input as the roadmaps are taken forward.

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This work was guided by the IEA Committee on Energy Research and Technology. Its members provided important review and comments that helped to improve the document. This roadmap would not be effective without all of the comments and support received from the industry, government and non-government experts and the members of the PVPS Implementing Agreement, who attended the meetings, reviewed and commented on the drafts, and provided overall guidance and support for the roadmap. The authors wish to thank all of those who participated in the meetings and commented on the drafts. The resulting roadmap is the IEA's interpretation of the workshops, with additional information incorporated to provide a more complete picture, and does not necessarily fully represent the views of the workshop participants. A full list of workshop participants and reviewers is included in Annex III.

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Key findings

- Solar PV power is a commercially available and reliable technology with a significant potential for long-term growth in nearly all world regions. This roadmap estimates that by 2050, PV will provide around 11% of global electricity production and avoid 2.3 gigatonnes (Gt) of CO_2 emissions per year.
- Achieving this roadmap's vision will require an effective, long-term and balanced policy effort in the next decade to allow for optimal technology progress, cost reduction and ramp-up of industrial manufacturing for mass deployment. Governments will need to provide long-term targets and supporting policies to build confidence for investments in manufacturing capacity and deployment of PV systems.
- PV will achieve competitive parity with the power grid by 2020 in many regions. As grid competitiveness is achieved, the policy framework should evolve towards fostering self-sustained markets, with the progressive phase-out of economic incentives, but maintaining grid access guarantees and sustained R&D support.
- As PV matures into a mainstream technology, grid integration and management and energy storage become key issues. The PV industry, grid operators and utilities will need to develop new technologies and strategies to integrate large amounts of PV into flexible, efficient and smart grids.
- Governments and industry must increase R&D efforts to reduce costs and ensure PV readiness for rapid deployment, while also supporting longer-term technology innovations.
- There is a need to expand international collaboration in PV research, development, capacity building and financing to accelerate learning and avoid duplicating efforts.
- Emerging major economies are already investing substantially in PV research, development and deployment; however, more needs to be done to foster rural electrification and capacity building. Multilateral and bilateral aid organisations should expand their efforts to express the value of PV energy in low-carbon economic development.

Key actions in the next ten years

- Provide long-term targets and supporting policies to build confidence for investments in manufacturing capacity and deployment of PV systems.
- Implement effective and cost-efficient PV incentive schemes that are transitional and decrease over time so as to foster innovation and technological improvement.
- Develop and implement appropriate financing schemes, in particular for rural electrification and other applications in developing countries.
- Increase R&D efforts to reduce costs and ensure PV readiness for rapid deployment, while also supporting longer-term innovations.

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Introduction

There is a pressing need to accelerate the development of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. This challenge was acknowledged by the Ministers from G8 countries, China, India and South Korea, in their meeting in June 2008 in Aomori, Japan where they declared the wish to have IEA prepare roadmaps to advance innovative energy technology.

> *"We will* ***establish an international initiative with the support of the IEA*** *to develop roadmaps for innovative technologies and co-operate upon existing and new partnerships, including CCS and advanced energy technologies. Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognise and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies…."*

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps covering 19 technologies. These technologies are divided among demand side and supply side technologies. Our overall aim is to advance global development and uptake of key technologies to reach a 50% CO_2 emission reduction by 2050 by having the IEA leading the development of energy technology roadmaps under international guidance and in close consultation with industry. The roadmaps will enable governments, industry and financial partners to identify steps needed and implement measures to accelerate required technology development and uptake.

This process starts with providing a clear definition and elements needed for each roadmap. The IEA has defined its global technology roadmap accordingly:

> *"… a dynamic set of technical, policy, legal, financial, market and organisational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific RDD&D information among participants. The goal is to accelerate the overall RDD&D process in order to deliver an earlier uptake of the specific technology into the marketplace."*

Each roadmap identifies major barriers, opportunities, and policy measures for policy makers and industry and financial partners to accelerate RDD&D efforts for specific clean technologies on both a national and international level.

The rationale for PV

Solar energy is the most abundant energy resource on earth. The solar energy that hits the earth's surface in one hour is about the same as the amount consumed by all human activities in a year. Direct conversion of sunlight into electricity in PV cells is one of the three main solar active technologies, the two others being concentrating solar power (CSP) and solar thermal collectors for heating and cooling (SHC). Today, PV provides 0.1% of total global electricity generation. However, PV is expanding very rapidly due to dramatic cost reductions. PV is a commercially available and reliable technology with a significant potential for long-term growth in nearly all world regions. In the IEA solar PV roadmap vision, PV is projected to provide 5% of global electricity consumption in 2030, rising to 11% in 2050.

Achieving this level of PV electricity supply – and the associated, environmental, economic and societal benefits – will require more concerted policy support. Sustained, effective and adaptive incentive schemes are needed to help bridge the gap to PV competitiveness, along with a long-term focus on technology development that advances all types of PV technologies, including commercially available systems and emerging and novel technologies.

Solar energy active conversion technologies

Solar photovoltaics (PV), which generates electricity through the direct conversion of sunlight, is one of the three technologies available to use sunlight as an active source. Concentrating solar power systems (CSP) use concentrated solar radiation as a high temperature energy source to produce electrical power and drive chemical reactions. CSP is typically applied in relatively large scale plants under very clear skies and bright sun. The availability of thermal storage and fuel back-up allows CSP plants to mitigate the effects of sunlight variability. Solar heating and cooling (SHC) uses the thermal energy directly from the sun to heat or cool domestic water or building spaces. These three ways of harnessing the sun are complementary, rather than directly competitive, and developers should carefully assess their needs and environment when choosing which solar technology to use. The IEA is publishing a separate CSP roadmap, while SHC will be incorporated into a Low-Carbon/Energy Efficient Buildings Roadmap, to be published in 2010.

The purpose of the roadmap

This roadmap provides the basis for greater international collaboration and identifies a set of effective technology, economic and policy goals and milestones that will allow solar PV to deliver on its promise and contribute significantly to world power supply. It also identifies the critical window of the next decade, during which PV is expected to achieve competitiveness with the power grid retail prices ("grid parity") in many regions. Achieving grid parity will require a strong and balanced policy effort in the next decade to allow for optimal technology progress, cost reduction and ramp-up of industrial manufacturing for mass deployment.

The actions identified in this roadmap are intended to accelerate PV deployment globally. In some markets certain actions have already been achieved, or are underway; but many countries, particularly those in emerging regions, are only just beginning to develop PV power. Accordingly, milestone dates should be considered as indicative of relative urgency, rather than as absolutes.

The roadmap was compiled using inputs from a wide range of stakeholders from the PV industry, power sector, research and development (R&D) institutions, finance, and governments. Two workshops were held to identify technological and deployment issues, and a draft roadmap was subsequently circulated to participants and a wide range of additional reviewers.

This roadmap is informed by a number of existing regional and national roadmaps, including:[1]

- The European Union's Strategic Energy Technology (SET) Plan and the Solar Europe Industry Initiative
- The European PV Technology Platform's Implementation Plan for Strategic Research Agenda
- The Solar America Initiative (SAI)
- Japan's PV roadmap towards 2030 (PV2030) and the 2009 update PV2030+
- China's solar energy development plans
- India's Solar Initiative
- Australia's Solar Flagship Initiative

This roadmap should be regarded as a work in progress. As IEA analysis moves forward and a new edition of *Energy Technology Perspectives* is published in 2010, new data will come to light that may provide the basis for updated scenarios and assumptions. More importantly, as the technology, market, power sector and regulatory environments continue to evolve, analyses will need to be updated and additional tasks may come to light.

1 See Appendix II for reference/URL links for all of these efforts.

PV status today

Technology performance and cost

PV systems directly convert solar energy 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 up to 50-200 Watts (W). The PV modules combined with a set of additional application-dependent system components (*e.g.* inverters, batteries, electrical components, and mounting systems), form a PV system. PV systems are highly modular, *i.e.* modules can be linked together to provide power ranging from a few watts to tens of megawatts (MW).

R&D and industrialisation have led to a portfolio of available PV technology options at different levels of maturity. Commercial PV modules may be divided into two broad categories: wafer based c-Si and thin films. There are a range of emerging technologies, including concentrating photovoltaics (CPV) and organic solar cells, as well as novel concepts with significant potential for performance increase and cost reduction.

PV technologies: an overview

Crystalline silicon (c-Si) modules represent 85-90% of the global annual market today. C-Si modules are subdivided in two main categories: *i)* single crystalline (sc-Si) and *ii)* multi-crystalline (mc-Si).

Thin films currently account for 10% to 15% of global PV module sales. They are subdivided into three main families: *i)* amorphous (a-Si) and micromorph silicon (a-Si/μc-Si), *ii)* Cadmium-Telluride (CdTe), and *iii)* Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Emerging technologies encompass advanced thin films and organic cells. The latter are about to enter the market via niche applications.

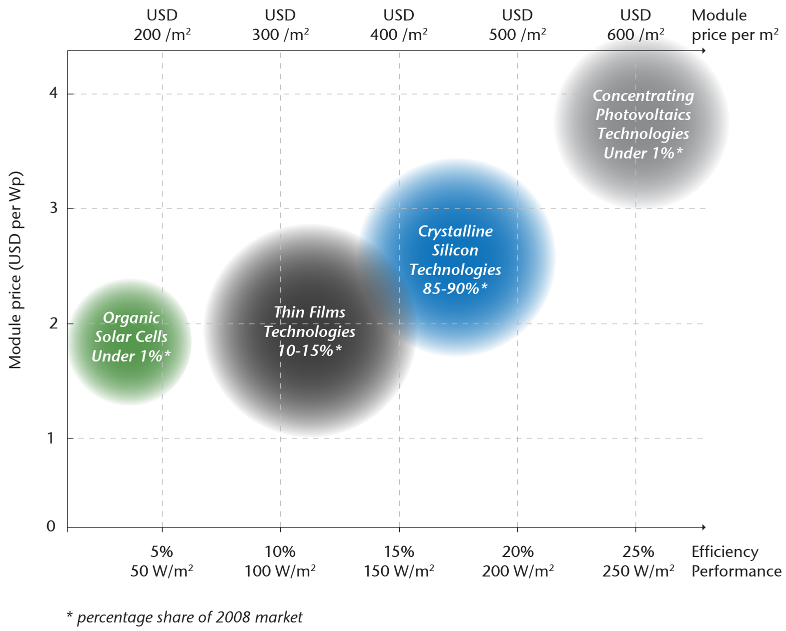
Concentrator technologies (CPV) use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

Novel PV concepts aim at achieving ultra-high efficiency solar cells via advanced materials and photo-chemical processes. They are currently the subject of basic research.

Detailed information on technologies can also be found in the IEA PVPS Implementing Agreement website www.iea-pvps.org

The large variety of PV applications allows for a range of different technologies to be present in the market, from low-cost, lower efficiency technologies to high-efficiency technologies at higher cost. Note that the lower cost (per watt) to manufacture some of the module technologies, namely thin films, is partially offset by the higher area-related system costs (costs for mounting and the required land) due to their lower conversion efficiency. Figure 1 gives an overview of the cost and performance of different PV technologies.

Figure 1: Current performance and price of different PV module technologies*



Note: all values refer to 2008

***KEY POINT**: There is a wide range of PV cost and performance in today's market.*

Conversion efficiency, defined as the ratio between the produced electrical power and the amount of incident solar energy per second, is one of the main performance indicators of PV cells and modules. Table 1 provides the current efficiencies of different commercial PV modules. PV systems can be connected to the utility grid or operated in stand-alone applications. They can also be used in building-integrated systems (BIPV)[2] or be ground-mounted, for example, in large-scale, grid-connected electricity production facilities.

2 In this roadmap, the term building-integrated PV systems is used to indicate *both* retrofit systems mounted on top of the existing building structure and fully integrated systems replacing roof tiles and façade elements.

The investment costs of PV systems are still relatively high, although they are decreasing rapidly as a result of technology improvements and economies of volume and scale. High investment costs, or total system costs, represent the most important barrier to PV deployment today. Total system costs are composed of the sum of module costs plus the expenses for the "balance-of-system", including mounting structures, inverters, cabling and power management devices. While the costs of different technology module types vary on a per watt basis (see Figure 1), these differences are less significant at the system level, which also takes into account the efficiency and land-use needs of the technology. Total system costs are sensitive to economies of scale and can vary substantially depending on the type of application.

Table 1: Current efficiencies of different PV technology commercial modules

Wafer-based c-Si		Thin films		
sc-Si	mc-Si	a-Si; a-Si/µc-Si	CdTe	CIS/CIGS
14-20%	13-15%	6-9%	9-11%	10-12%

Typical turn-key prices in 2008 in leading market countries ranged from USD 4 000 /kW for utility scale, multi-megawatt applications, to USD 6 000 /kW for small-scale applications in the residential sector.[3]

Associated levelised electricity generation costs from PV systems depend heavily on two factors: the amount of yearly sunlight irradiation (and associated capacity factor), and the interest/discount rate. PV systems do not have moving parts, so operating and maintenance (O&M) costs are relatively small, estimated at around 1% of capital investment per year. Assuming an interest rate of 10%,[4] the PV electricity generation costs in 2008 for utility-scale applications ranged from USD 240 /MWh in locations with very high irradiation and capacity factor (2 000 kWh/kW, *i.e.* a 23% capacity factor), to USD 480 /MWh in sites with moderate-low irradiation (1 000 kWh/kW, corresponding to a capacity factor of 11%). The corresponding generation costs for residential PV systems ranged from USD 360-720 /MWh, depending on the relevant incident solar energy. While these residential costs are very high, it should be noted that residential PV systems provide electricity at the distribution grid level. Therefore they compete with electricity grid retail prices, which, in a number of OECD countries, can also be very high.

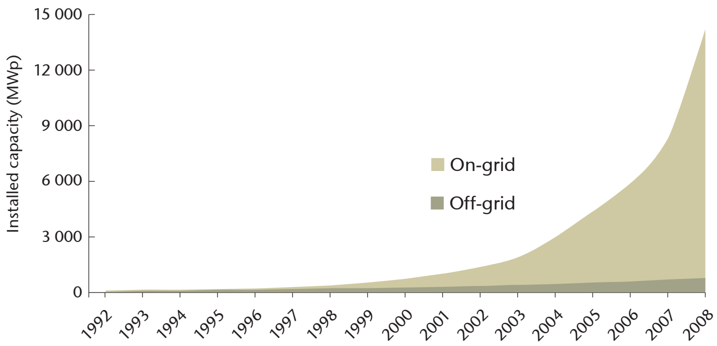
3 The actual range of prices in IEA countries is larger. Best system prices lower than 3 000 USD/kW were reported in 2009. At the same time, according to IEA PVPS 2009, maximum prices for small-scale BIPV systems in 2008 in less mature PV markets could be much higher.

4 This roadmap assumes an interest rate of 10%, in correspondence with the assumption in the IEA *Energy Technology Perspectives* study. However, assuming a lower rate (*e.g.*, 5%) would lead to significantly lower estimates for generation costs.

Market trends

The global PV market has experienced vibrant growth for more than a decade with an average annual growth rate of 40%. The cumulative installed PV power capacity has grown from 0.1 GW in 1992 to 14 GW in 2008. Annual worldwide installed new capacity increased to almost 6 GW in 2008. Figure 2 shows the global cumulative installed capacity of PV for the past two decades.

Figure 2: Cumulative installed global PV capacity

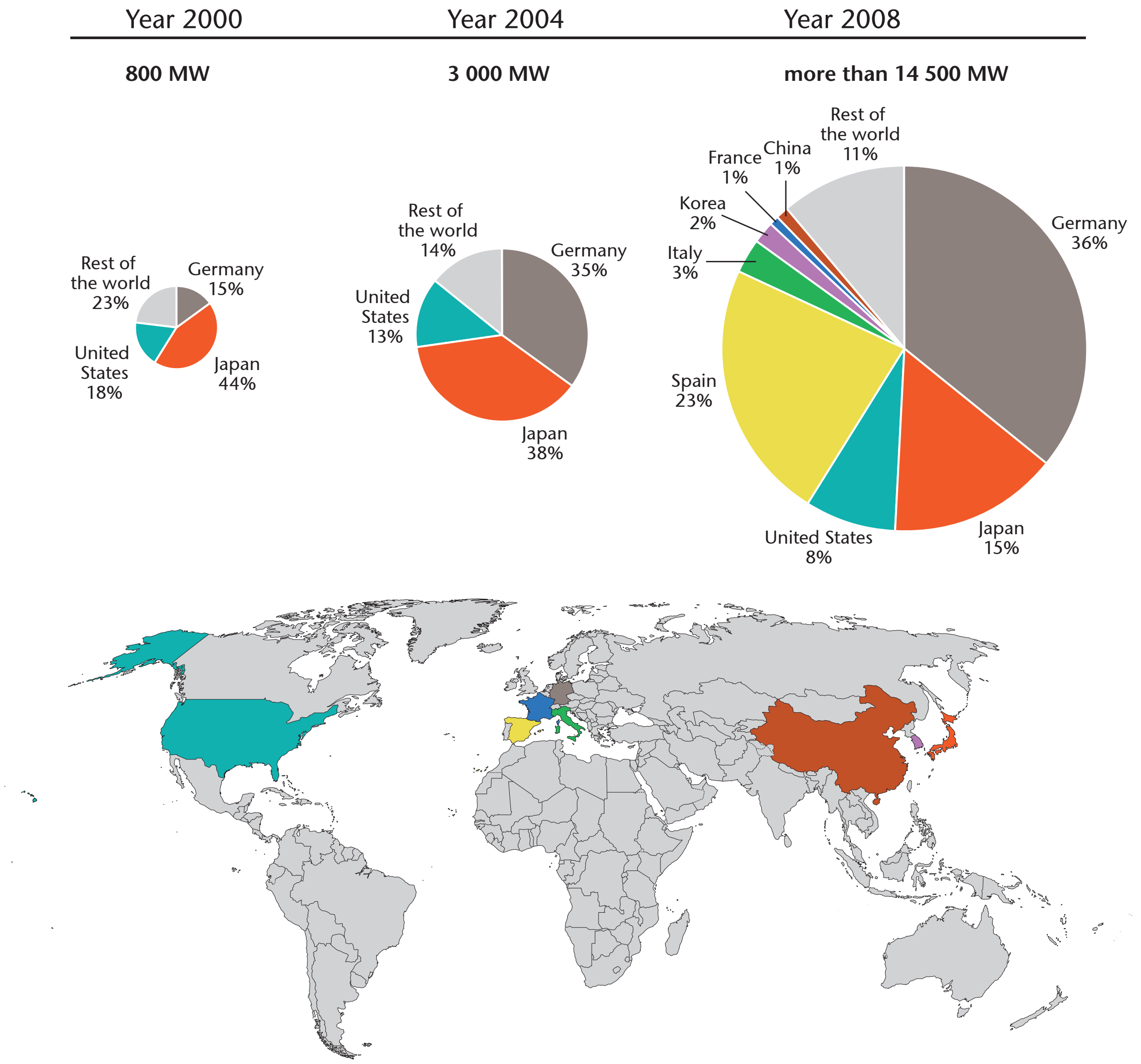


Source: IEA PVPS for those IEA PVPS countries reporting data; estimates for other countries.

***KEY POINT**: The PV market has experienced rapid growth, with an average annual growth rate of 40%.*

Four countries have a cumulative installed PV capacity of one GW or above: Germany (5.3 GW), Spain (3.4 GW), Japan (2.1 GW) and the US (1.2 GW). These countries account for almost 80% of the total global capacity (Figure 3). Other countries (including Australia, China, France, Greece, India, Italy, Korea and Portugal) are gaining momentum due to new policy and economic support schemes.

Figure 3: Solar PV markets in leading countries



KEY POINT: *A handful of countries with strong policy regimes account for 80% of global installed PV capacity; new countries have emerged as important players in the last few years.*

Market end-use sectors

There are four end-use sectors with distinct markets for PV:

- **Residential systems** (typically up to 20 kW systems on individual homes)
- **Commercial systems** (typically up to 1 MW systems for commercial office buildings, schools, hospitals, and retail)
- **Utility scale systems** (starting at 1 MW, mounted on buildings or directly on the ground)
- **Off-grid applications** (varying sizes)

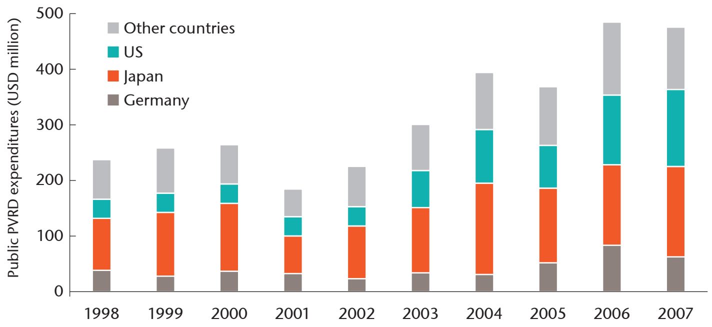
These different applications have different system costs and compete at different price levels. Until the mid-1990s, most systems were stand-alone, off-grid applications such as telecommunications units, remote communities and rural electricity supply. Since then, the number of grid-connected systems has increased at a rapid pace due to incentive schemes introduced in many countries. The majority of grid-connected systems are installed as BIPV systems. However, ground-mounted large-scale installations with a generation capacity in the tens of megawatts have gained a considerable market share in recent years. As a result, off-grid PV systems now constitute less than 10% of the total PV market; however, such applications still remain important in remote areas and in developing countries that lack electricity infrastructure.

Research and development

Worldwide public expenditures for PV research and development (R&D) have substantially increased over the past decade.[5] Public R&D efforts (including pilot and demonstration projects) have doubled in key countries, rising from USD 250 million in 2000 to about USD 500 million in 2007 (Figure 4). Pilot and demonstration projects and programmes account for about 25% (in 2000) to 30% (in 2007) of these expenditures. R&D efforts are important all along the value chain of energy generation; from raw material production to the manufacturing of modules and balance-of-system components. Solar cell and module research constitutes the largest fraction of the R&D portion, typically 75% of total expenditures (*IEA PVPS* 2009).

5 While it is difficult to find detailed data on private sector R&D investment in solar PV, evidence shows that private investment in the early development phase of solar energy systems has expanded rapidly during past few years. Solar energy led all clean energy technology in terms of venture capital investments in 2008, with USD 5.45 billion of investment and 88% growth from 2007 (New Energy Finance [NEF] 2009).

Figure 4: Public PV R&D spending in selected countries



Note: Values in million USD, not corrected for inflation, based on yearly exchange rates.

Source: IEA PVPS.

***KEY POINT**: Government spending on PV R&D has increased in recent years.*

A number of major government and industry R&D efforts aim to make PV a mainstream power source within the next decade, including:[6]

- Within the **European Union's SET Plan**, the Solar Europe Industry Initiative – led by the European Photovoltaic Industry Association (EPIA) – proposes three scenarios resulting in three levels of solar share in the electricity market in Europe: 4% for the *Baseline* scenario, 6% for the *accelerated growth* scenario and 12% for the *paradigm shift* scenario. The EPIA is confident about achieving the *paradigm shift* target, based on the rapid ramp-up of the past decade (average annual growth rate of 40%). The *paradigm shift* scenario requires a rapid, widespread adoption of smart grid technologies and power storage and further improvements in high quality manufacturing and products all along the PV supply chain.

- The **European PV Technology Platform's** Implementation Plan for Strategic Research Agenda includes dedicated R&D efforts along the value chain in order to accelerate technology development and to achieve new levels of cost-effectiveness.

- Through the **Solar America Initiative (SAI)** from 2007-09, the US Department of Energy has launched a plan for integrated research, development and market transformation of solar energy technologies with the mission to make PV-generated electricity cost-competitive with conventional electricity sources by 2015.

- Japan's **PV roadmaps towards 2030 (PV2030)** was developed in 2004 to explore a wide set of R&D options. This effort aims to create viable and sustainable business along the value chain from raw material production to the manufacturing of modules and balance-of-system components. In 2009, the roadmap was **revised to "PV2030+"**; it now aims at achieving technology targets three to five years ahead of the schedule set in PV2030.

- **Australia** has recently announced support for the development of 1 000 MW of utility size solar generation, utilising both solar PV and solar thermal. The goal of Australia's **Solar Flagships** initiative is to demonstrate the integration of utility-scale solar generation into a contemporary energy network.

- **China and India** are each pursuing an aggressive solar PV growth strategy, creating a very important industry and setting up ambitious mid-term targets for the domestic market in the multi-GW scale. **Brazil** is a leading country in the use of PV for rural electrification.

6 *See* Annex II for a list of references and URLs.

Vision for PV deployment and CO_2 abatement potential

Electricity generation and cumulative installed capacity

PV will need to play a significant role in the world's energy mix in 2050 to help achieve global climate change goals at the lowest cost. According to the BLUE Map scenario described in IEA's *Energy Technology Perspectives 2008 (ETP)* publication, by 2050, solar power is expected to provide 11% of annual global electricity production, with roughly half generated from PV (6%) and the remaining from concentrated solar power.[7] This roadmap, however, forecasts a more rapid PV deployment than is estimated in the ETP 2008 study–*i.e.,* PV is projected to reach 11% by 2050, almost the double the level estimated in the BLUE Map scenario.

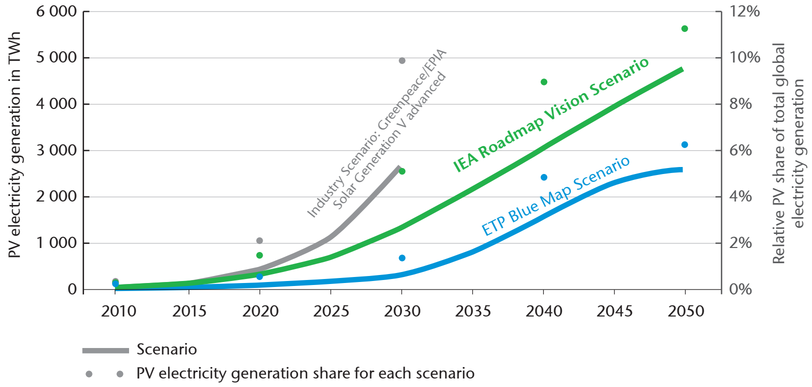
7 Other scenarios in literature indicate contributions well above the ETP 2008 numbers at world or regional level; *see* EREC Greenpeace (2008), EPIA/Greenpeace Solar Generation V (2008), EPIA Set for 2020 (2009), Grand Solar Plan (2008).

Energy Technology Perspectives 2008 BLUE Map Scenario

This roadmap outlines a set of quantitative measures and qualitative actions that represent one global pathway for solar PV deployment to 2050. It builds on the IEA *Energy Technology Perspectives* (ETP) BLUE Map scenario, which describes how energy technologies may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2005 levels. The ETP model is a bottom-up MARKAL model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The ETP model is a global fifteen-region model that permits the analysis of fuel and technology choices throughout the energy system. The model's detailed representation of technology options includes about 1 000 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the ETP model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

An accelerated outlook is justified by the recent PV market growth (Figure 2) and associated cost reductions – the global PV market more than doubled in one year from 2007 to 2008, and system prices fell 40% between 2008 and 2009. This acceleration in the deployment of PV has been triggered by the adoption of PV incentive schemes in an increasing number of countries. As a result of this sort of policy support, this roadmap envisions that PV will achieve grid parity in many countries by 2020. Parity is expected to first be achieved in those countries having a high solar irradiation level and high retail electricity costs. This roadmap also assumes the continuation of an evolving, favourable and balanced policy framework for market deployment and technology development in many countries on the longer term. If such policies are successfully implemented, by 2050 there will be 3 000 GW of installed PV capacity worldwide, generating 4 500 TWh per year, 11% of expected global electricity supply (Figure 5).

Figure 5: Global PV power generation and relative share of total electricity generation



Note: The share of total electricity generation is calculated with the projected world electricity.

Sources: IEA *Energy Technology Perspectives* 2008, EPIA/Greenpeace Solar Generation V generation of the ETP BLUE Map scenario (42 300 TWh).

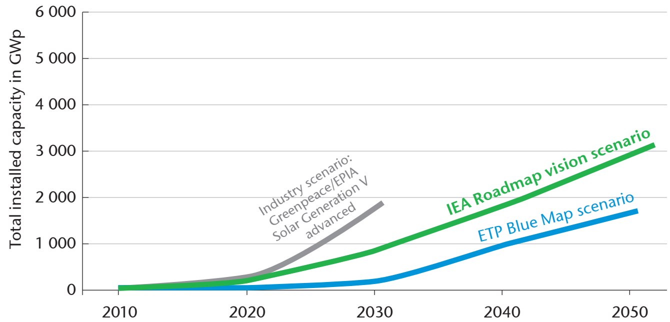
***KEY POINT**: The roadmap envisions PV providing 11% of global electricity generation by 2050.*

The roadmap assumes an average annual market growth rate of 17% in the next decade, leading to a global cumulative installed PV power capacity of 200 GW by 2020.[8] This level of PV market growth is justified by the achievement of grid parity predicted to occur in an increasing number of countries during this time. Achieving grid parity (*i.e.* competitiveness with electricity grid retail prices) will be facilitated in part by policy incentives that support the deployment and decrease overall costs of PV and by measures increasing the cost of other technologies. Accelerated deployment and market growth will in turn bring about further cost reductions from economies of scale, significantly improving the relative competitiveness of PV by 2020 and spurring additional market growth.

From 2020 to 2030, an average annual market growth rate of 11% is assumed, bringing global cumulative installed PV capacity to about 900 GW by 2030. At this time, the annual market volume of new installed capacity would be over 100 GW per year. The total cumulative installed PV capacity is predicted to reach 2 000 GW by 2040 and 3 000 GW by 2050, taking into account the replacement of old PV systems. The forecasted global cumulative installed PV capacity according to this roadmap is presented in Figure 6 and compared with the ETP 2008 BLUE Map scenario and other industry scenarios.

8 Note that this value is significantly higher than the ETP 2008 forecast, but significantly lower than industry's goals. For example, the European SET plan projects 400 GW installed in Europe by 2020, and an indicative target of 700 GW by 2030.

Figure 6: Comparison of IEA roadmap vision of global cumulative installed PV capacity to other scenarios



Note: ETP Blue Scenario's capacity was calculated using 1 500 kWh/kW.

Sources: Outcomes of PV Roadmap workshops 2009, IEA *Energy Technology Perspectives 2008*, EPIA/Greenpeace Solar Generation V.

***KEY POINT**: This roadmap sets an accelerated vision for PV growth; other estimates suggest that PV potential could be higher.*

Emerging economies: rapidly growing PV markets

This roadmap envisions a rapid growth of PV power throughout the world in OECD countries as well as in Asia, and at a later stage in Latin America and Africa. Major economies like China and India have become global solar forces in the past decade, and will remain important market influencers in the decades to come. The potential of PV for distributed generation is very substantial in Latin America and Africa. These world regions may become very important markets in the mid- to long-term. Brazil is a leading country in the use of PV for rural electrification and can play a major role in technology collaboration with developing countries.

Brazil

The main applications of PV technology in Brazil are telecommunications (i.e. microwave repeater stations), rural electrification, water pumping and public lighting in low-income rural communities. Grid-connected PV systems are still in an experimental stage, with a combined power of 22 kWp installed (Varella et al., 2009). In 1995, the Brazilian government launched a programme to promote rural electrification with PV systems, PRODEEM (Programme of Energy Development of States and Municipalities). Approximately 9000 PV systems were installed in the period 1996-2001, with a total of 6 MWp of installed capacity. In 2003, the federal government launched the programme Luz para Todos (Light for All), which aims to supply full electrification in the country by 2010. The programme has an estimated total budget of about USD 2.6 billion funded by the federal government, concessionaires and state governments. A programme for labelling PV equipment and systems was launched in 2003 by INMETRO (Brazilian Institute for Metrology, Standardisation and Industrial Quality) to guarantee the quality of equipment acquired and installed within the Light for All programme. This labelling scheme is currently in force and applies to PV modules, charge controllers, inverters and batteries and is done on a voluntary basis (Varella et al., 2008). The Brazilian PV market is currently dominated by multinationals, and there are no national manufacturers. However, with the support of the government, the Brazilian Centre for Development of Solar PV Energy (CB-Solar), created in 2004, has developed a pilot plant to manufacture cost effective PV modules and silicon solar cells at scale (Moehlecke and Zanesco, 2007).

China

China's solar PV industry has been growing rapidly and the country now ranks first in the world in exports of PV cells. Domestic output of PV cells expanded from less than 100 MW in 2005 to 2 GW in 2008, experiencing a 20-fold increase in just four years (Sicheng Wang, 2008). This is the result of a strong demand from the international PV market, especially from Germany and Japan. However, the PV market demand in China remains small, with more than 95% of the country's PV-cell products exported. In 2008, China's cumulative PV installed capacity was 150 MW (National Energy Administration, 2009). Some 40% of this demand is met by independent PV power systems that supply electricity to remote districts not covered by the national grid. Market shares of solar PV for communications, industrial, and commercial uses have also increased. BIPV systems, as well as large-scale PV installations in desert areas, are being encouraged by the Chinese government, which began providing a subsidy of RMB 20 (USD 2.93) per watt for BIPV projects in early 2009. It is likely that the 2010 and 2020 national targets for solar PV (400 MW and 1 800 MW, respectively) announced in 2007 will be significantly increased. Experts predict that Chinese installed capacity could reach 1 GW in 2010 and 20 GW in 2020 (CREIA, 2009).

India

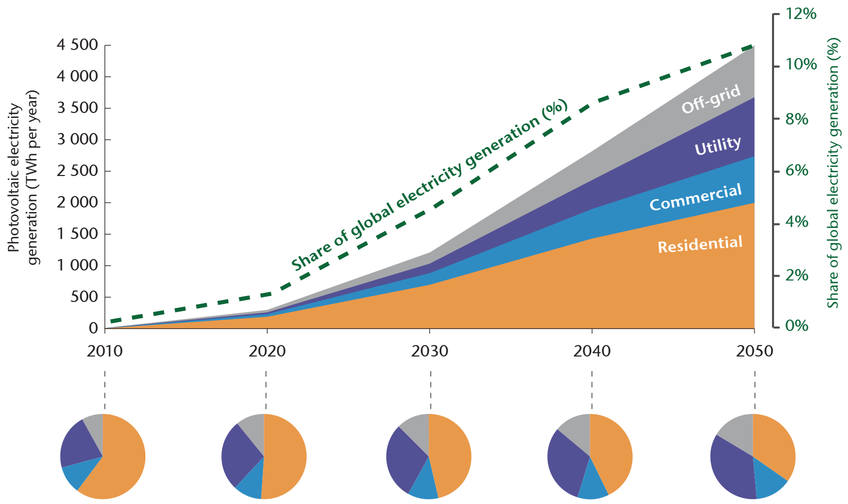
India has a large and diversified PV industry consisting of ten fully vertically integrated manufacturers making solar cells, solar panels and complete PV systems, and around 50 assemblers of various kinds. Together, these companies supply around 200 MW per year of 30 different types of PV systems in three categories – rural, remote area and industrial. However, despite this strong industrial base, PV constitutes a small part of India's installed power generation capacity, with 2.7 MW grid- connected systems and 1.9 MW stand-alone systems in 2008 (Banerjee, 2008). There have been a number of high-level government initiatives that have provided new momentum for PV deployment in India, including:

- *The 2008 Action Plan on Climate Change included a "National Solar Mission" that establishes a target of generating 20 GW of electricity from solar energy by 2020; the programme aims to boost annual PV power generation to 1 000 MW by 2017.*
- *In 2008, the Ministry of New and Renewable Energy (MNRE) established a target of 50 MW of capacity by 2012 to be achieved through its Generation Based Incentives (GBI) programme. The GBI includes production incentives for large solar power plants of INR 12 (USD 0.25) per kWh for PV power for up to 50 MW of capacity, subject to a maximum 10 MW in any one state.*
- *The Eleventh Five-Year Plan (2007-12) proposed solar RD&D funding of INR 4 billion (86.4M USD). The Working Group on R&D for the Energy Sector proposed an additional INR 53 billion (1.15B USD) in RD&D for the Eleventh Five-Year Plan, with the two largest topics being: research on silicon production for PV manufacturing (total investment INR 12 billion [259M USD], including the establishment of a silicon production facility) and research on LEDs (INR 10 billion [216M USD], also including the establishment of a manufacturing facility).*

Applications and market end-use sectors

The relative share of the four market segments (residential, commercial, utility-scale and off-grid) is expected to change significantly over time (Figure 7). In particular, the cumulative installed capacity of residential PV systems is expected to decrease from almost 60% today to less than 40% by 2050. Figure 7 shows a possible development path for electricity generation of PV systems worldwide by end use sector. The relative shares of PV deployment among the different sectors will vary by country according to each country's particular market framework.

Figure 7: Evolution of photovoltaic electricity generation by end-use sector



Source: IEA analysis based on survey reports of selected countries between 1992 and 2008, IEA PVPS, and IEA 2008 (ETP).

***KEY POINT**: There will be a shift from residential to larger-scale PV applications over time.*

Tables 2, 3 and 4 provide more detailed information on the evolution by sector of global electricity generation, cumulative installed power capacity, and annual market, respectively.

Table 2: Annual PV power generation (TWh) by end-use sector

Annual electricity generation (TWh)	2010	2020	2030	2040	2050
Residential	23	153	581	1244	1794
Commercial	4	32	144	353	585
Utility	8	81	368	910	1498
Off-grid	3	32	154	401	695
Total	***37***	***298***	***1247***	***2907***	***4572***

Note that the average electricity generation per kW is 1 300 kWh/kW in the residential sector, 1 450 kWh/kW in the commercial sector, 1650 kWh/kW in the utility sector and 1500 kWh/kW in the off-grid sector.

Table 3: Cumulative installed PV capacity (GW) by end-use sector

PV capacity (GW)	2010	2020	2030	2040	2050
Residential	17	118	447	957	1380
Commercial	3	22	99	243	404
Utility	5	49	223	551	908
Off-grid	2	21	103	267	463
Total	*27*	*210*	*872*	*2019*	*3155*

Table 4: Annual global PV market volume (GW) by end-use sector

PV market (GW)	2010	2020	2030	2040	2050
Residential	4.1	18	50	55	53
Commercial	0.7	4	13	17	20
Utility	1.6	8	28	37	44
Off-grid	0.6	4	14	19	24
Market	*7*	*34*	*105*	*127*	*141*

Cost reduction goals

While the production costs vary among the different PV module technologies, these module-level cost differentials are less significant at the system level, which are expected to converge in the long term. Therefore, this roadmap suggests setting overall cost targets by application (*e.g.*, residential, commercial or utility-scale) rather than for specific PV technologies (*e.g.*, crystalline silicon, thin films, or emerging and novel devices). The roadmap assumes that cost reductions for future PV systems continue along the historic PV experience curve. PV module costs have decreased in the past at a learning rate of 15% to 22%,[9] and have seen a corresponding reduction in total system costs for every doubling of cumulative installed capacity. The roadmap adopts a learning rate of 18% for the whole PV system.

Tables 5, 6 and 7 summarise the cost targets for PV in the residential, commercial, and utility sectors, respectively, in terms of both total turnkey system price (cost per kW installed capacity) and total cost of electricity (cost per MWh energy generated). Such cost targets are the result of the roadmap workshop discussion, based on the Strategic Research Agenda and the Implementation Plan of the *European PV Technology Platform* (2007, 2009), the Solar America Initiative (*DOE* 2007), the Japanese PV roadmap towards 2030 / PV2030+ (*NEDO* 2004, 2009) and the IEA *Energy Technology Perspectives 2008*.

The primary PV economic goal is to reduce turn-key system prices and electricity generation costs by more than two-thirds by 2030. Turn-key system prices are expected to drop by 70% from current USD 4 000 to USD 6 000 per kW down to USD 1 200 to USD 1 800 per kW by 2030, with a major price reduction (over 50%) already achieved by 2020. Large scale utility system prices are expected to drop to USD 1 800 per kW by 2020 and USD 800 per kW by 2050, and in the best case will lead to long-term levelised generation costs lower than USD 50 /MWh.

9 An experience curve describes how unit costs decline with cumulative production. The relevant cost decline measure is given by the progress ratio (P) or the learning rate (L=1-P). A learning rate of 20% corresponds to a cost reduction by 20% for each doubling of cumulative production. Sources: Neji 2007, EPIA; Set for 2020; *A Mainstream Power Source in Europe by 2020*; 2009

Table 5: Cost targets for the residential sector

		2008	2020	2030	2050
Typical turn-key system price (2008 USD/kW)		6000	2700	1800	1200
Typical electricity generation costs (2008 USD/MWh)*	2000 kWh/kW	360	160	100	65
	1500 kWh/kW	480	210	135	90
	1000 kWh/kW	720	315	205	135

Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); operations and maintenance (O&M) costs 1%.

Table 6: Cost targets for the commercial sector

		2008	2020	2030	2050
Typical turn-key system price (2008 USD/kWp)		5000	2250	1500	1000
Typical electricity generation costs (2008 USD/MWh)*	2000 kWh/kWp	300	130	85	55
	1500 kWh/kWp	400	175	115	75
	1000 kWh/kWp	600	260	170	110

Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

Table 7: Cost targets for the utility sector

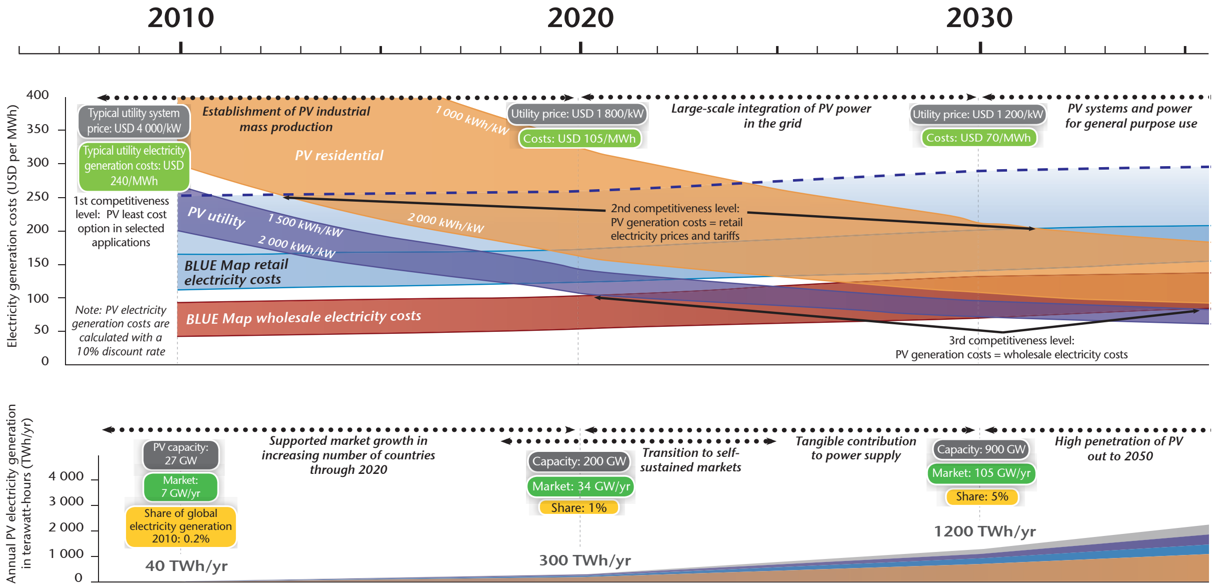
		2008	2020	2030	2050
Typical turn-key system price (2008 USD/kWp)		4000	1800	1200	800
Typical electricity generation costs (2008 USD/MWh)*	2000 kWh/kWp	240	105	70	45
	1500 kWh/kWp	320	140	90	60
	1000 kWh/kWp	480	210	135	90

Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

PV market deployment and competitiveness levels

PV has already achieved competitiveness for a number of products, services and applications. However, the majority of the PV industry output is grid-connected; therefore, the on-grid market will remain the major market segment in the future. Commercial goals for PV are therefore focused on achieving respectively competitiveness with electricity grid retail prices for residential and commercial PV systems, and with electricity generation costs for utility-scale systems. Since electricity prices and solar irradiation vary from one market place to another it is only possible to identify time ranges for PV competitiveness on a global basis. Three main phases have been envisioned for the commercial development of PV (Figure 8).

Figure 8: PV market deployment and competitiveness levels



Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

***KEY POINT**: PV is already competitive today in selected off-grid applications, and will achieve competitiveness in three phases.*

In the first decade, the annual PV market is expected to increase from 6 GW to 34 GW, to ramp-up into mass-scale industrial production, and to reduce system and generation costs by more than 50%. This will allow PV residential and commercial systems to achieve parity with the distribution grid electricity retail prices in a number of countries characterised by a good solar resource and high conventional electricity retail prices. In a few cases, this is likely to occur before 2015. By 2020 PV generation costs are expected to range from USD 13-26 cents/kWh (commercial systems) to USD 16-31 cents/kWh (residential systems), depending on the site-specific solar irradiation level. These costs are expected to be lower than electricity retail prices in several countries. In the same timeframe, utility PV system will achieve USD 10 cents/kWh, arriving at the edge of competitiveness with wholesale electricity costs in some countries. To achieve these goals, PV will require sustained and consistent policy frameworks and support incentives in many countries during this period.

From 2020 to 2030, this roadmap envisions that PV will advance toward large-scale grid integration, and start to become competitive at a much broader scale. Towards the end of the decade, typical utility PV system generation costs are expected to decrease down to USD 7-13 cent/kWh and PV will become competitive at utility-scale with wholesale electricity prices in some world regions. By that time, commercial and residential systems will become cost-competitive in almost all world regions with reasonable solar irradiation. The annual market/shipment volume will have increased by another factor of three over this decade (hitting the benchmark of 100 GW by 2030), leading to a cumulative installed capacity of almost 900 GW worldwide. During this period, economic incentives should begin to gradually be phased-out while maintaining grid access guarantees and sustained R&D support.

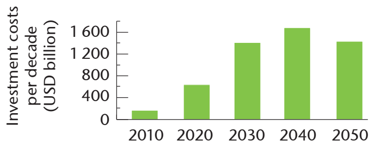
The phase from 2030-2050 will be characterised by the large-scale diffusion of PV systems and power for general purpose uses. System costs will range from USD 800 to USD 1200 /kW depending on the application sector. This will lead to typical generation costs of USD 4.5-9 cent/kWh at the utility scale and of USD 6.5-13.5 cent/kWh at residential level. The annual market will still grow, although at a slower pace than in the two previous decades. The total cumulative installed capacity will increase up to 3 000 GWp. This will generate an electricity production of approximately 4 500 TWh/year, corresponding to a projected share of around 11% of total world electricity generation.

Total investment needs

Achieving this roadmap, based on the assumed evolution of system costs and the need for PV system replacement, will require a total investment on the order of USD 5 trillion (Figure 9).[10]

10 While this figure is large, it is only 6% of the total additional investment needed to achieve the BLUE Map scenario target of reducing energy sector CO_2 emissions 50% by 2050.

Figure 9: PV investments by decade

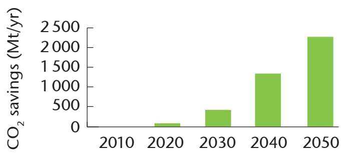


***KEY POINT**: Achieving this roadmap's goals will require an investment of USD 5 trillion.*

CO_2 emissions reduction

The deployment of PV will contribute significantly to the reduced carbon intensity of electricity generation. Taking into account the different average CO_2 emissions of electricity production mixes in different world regions, and using the BLUE Map scenario average long-term emission reduction coefficients for the power sector, the 4 500 TWh generated by PV in 2050 is expected to save 2.3 Gt of CO_2 emissions on an annual basis worldwide, almost twice that predicted in the BLUE Map scenario. This corresponds to approximately 5% of the total avoided CO_2 emissions (48 Gt) from all technology areas projected in the ETP 2008 BLUE Map Scenario with respect to the Baseline Scenario. Over the period 2008-2050, the estimated cumulative savings are around 100 Gt of CO_2 (Figure 10).[11]

Figure 10: Annual CO_2 emissions avoided through PV



11 This takes into account an average operational lifetime of 35 years and the relevant decommissioning and substitution of old plants.

***KEY POINT**: This roadmap's accelerated use of PV results in emissions reductions of more than 2 Gt CO_2 per year by 2050.*

Technology development: Strategic goals and milestones

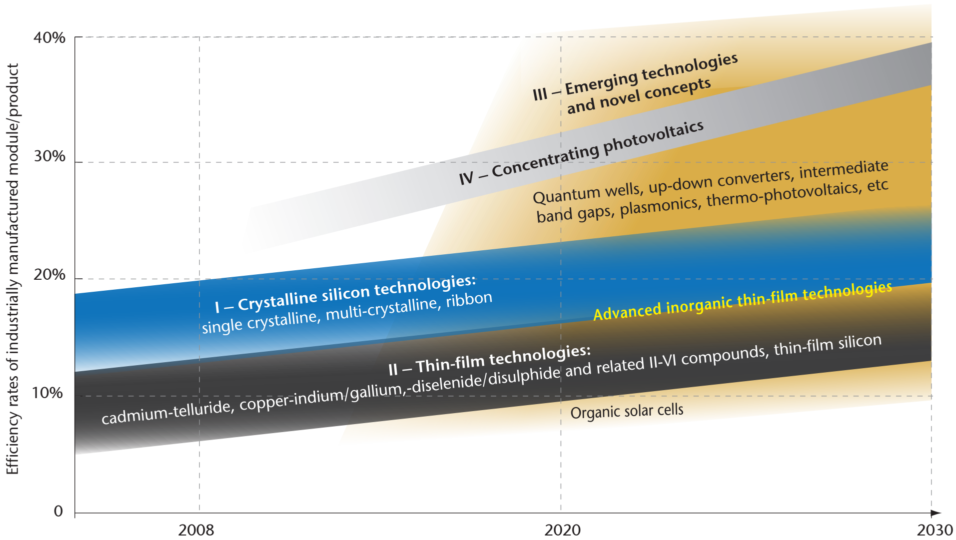
Achieving the deployment path outlined in this roadmap will require a significant investment by government and industry in effective technology development and policy implementation.

This section identifies short-, mid- and long-term technology goals and milestones and related key R&D issues.

Technology trends

With the aim of achieving further significant cost reductions and efficiency improvements, R&D is predicted to continuously progress in improving existing technologies and developing new technologies. It is expected that a broad variety of technologies will continue to characterise the PV technology portfolio, depending on the specific requirements and economics of the various applications. Figure 11 gives an overview of the different PV technologies and concepts under development.

Figure 11: Photovoltaic technology status and prospects



Source: IEA PVPS.

***KEY POINT**: Current technologies will co-exist with emerging technologies and novel concepts.*

Table 8 summarises a set of general technology targets for PV systems, expressed in terms of (maximum) conversion efficiency, energy-payback time, and operational lifetime. Typical commercial flat-plate module efficiencies are expected to increase from 16% in 2010 to 25% in 2030 with the potential of increasing up to 40% in 2050. Concurrently, the use of energy and materials in the manufacturing process will become significantly more efficient, leading to considerably shortened PV system energy pay-back times.[12] The latter is expected to be reduced from two years in 2010 to 0.75 year in 2030 and below 0.5 year in the long-term. Finally, the operational lifetime is expected to increase from 25 to 40 years.

12 The energy pay-back time is defined as the time needed for the PV system to repay the energy spent for its manufacturing.

Table 8: General technology target

Targets (rounded figures)	2008	2020	2030	2050
Typical flat-plate module efficiencies	Up to 16%	Up to 23%	Up to 25%	Up to 40%
Typical maximum system energy pay-back time (in years) in 1500 kWh/kWp regime	2 years	1 year	0.75 year	0.5 year
Operational lifetime	25 years	30 years	35 years	40 years

Specific technology goals and R&D issues

Crystalline silicon

Today, the vast majority of PV modules (85% to 90% of the global annual market) are based on wafer-based c-Si. Crystalline silicon PV modules are expected to remain a dominant PV technology until at least 2020, with a forecasted market share of about 50% by that time *(Energy Technology Perspectives* 2008*)*. This is due to their proven and reliable technology, long lifetimes, and abundant primary resources. The main challenge for c-Si modules is to improve the efficiency and effectiveness of resource consumption through materials reduction, improved cell concepts and automation of manufacturing.

The manufacturing of c-Si modules typically involves growing ingots of silicon, slicing the ingots into wafers to make solar cells, electrically interconnecting the cells, and encapsulating the strings of cells to form a module. Modules currently use silicon in one of two main forms: single- sc-Si or mc-Si.[13] Current commercial single sc-Si modules have a higher conversion efficiency of around 14 to 20%. Their efficiency is expected to increase up to 23% by 2020 and up to 25% in the longer term. Multi-crystalline silicon modules have a more disordered atomic structure leading to lower efficiencies, but they are less expensive (see Table 9 and Figure 1). Their efficiency is expected to increase up to 21% in the long term.

Continuous targeted R&D on sc-Si technologies in public and industrial research with a near-term focus can result in a substantial cost reduction and an associated volume effect, both of which are needed to enhance the competiveness and accelerate the scaling-up of PV in the next decade. The major required R&D efforts for crystalline solar cells are summarised in Table 9.

13 Recently, ribbon technologies have been developed that have potentially similar efficiencies as mc-Si but a much better utilisation rate of silicon feedstock. However, this particular technology has not yet achieved significant market shares.

Table 9: Technology goals and key R&D issues for crystalline silicon technologies

Crystalline silicon technologies	2010 – 2015	2015 – 2020	2020 – 2030 / 2050
Efficiency targets in % (commercial modules)	• Single-crystalline: 21% • Multi-crystalline: 17%	• Single-crystalline: 23% • Multi-crystalline: 19%	• Single-crystalline: 25% • Multi-crystalline: 21%
Industry manufacturing aspects	• Si consumption < 5 grams / Watt (g/W)	• Si consumption < 3 g/W	• Si consumption < 2 g/W
Selected R&D areas	• New silicon materials and processing • Cell contacts, emitters and passivation	• Improved device structures • Productivity and cost optimisation in production	• Wafer equivalent technologies • New device structures with novel concepts

Thin films

Thin films are made by depositing extremely thin layers of photosensitive materials in the micrometre (μm) range on a low-cost backing such as glass, stainless steel or plastic. The first thin film solar cell produced was a-Si. Based on early a-Si single junction cells, amorphous tandem and triple cell configuration have been developed. To reach higher efficiencies, thin amorphous and microcrystalline silicon cells have been combined to form micromorph cells (also called thin hybrid silicon cells).[14] In the area of II-VI semiconductor compounds, other thin film technologies have been developed, including Cadmium Telluride (CdTe) and Copper-Indium-Gallium-Diselenide (CIGS).

The main advantages of thin films are their relatively low consumption of raw materials, high automation and production efficiency, ease of building integration and improved appearance, good performance at high ambient temperature, and reduced sensitivity to overheating. The current drawbacks are lower efficiency and the industry's limited experience with lifetime performances.

Increased R&D is needed to bring thin film technologies to market and to create the necessary experience in industrial manufacturing and long-term reliability. The most promising R&D areas include improved device structures and substrates, large area deposition techniques, interconnection, roll-to-roll manufacturing and packaging. Table 10 summarises the prospects and key R&D issues for thin film technologies until 2030.

14 Another option currently being researched is the combination of single-crystalline and amorphous PV cell technology. The HIT (Heterojunction with Intrinsic Thin layer cells) technology is based on a crystalline silicon cell coated with a supplementary amorphous PV cell to increase the efficiency.

Table 10: Technology goals and key R&D issues for thin film technologies

Thin film technologies	2010 – 2015	2015 – 2020	2020 – 2030
Efficiency targets in % (commercial modules)	• Thin film Si: 10% • Copper indium gallium (di)selenide (CIGS): 14% • Cadmium-telluride (CdTe): 12%	• Thin film Si: 12% • CIGS: 15% • CdTe: 14%	• Thin film Si: 15% • CIGS: 18% • CdTe: 15%
Industry manufacturing aspects	• High rate deposition • Roll-to-roll manufacturing • Packaging	• Simplified production processes • Low cost packaging • Management of toxic materials	• Large high-efficiency production units • Availability of manufacturing materials • Recycling of modules
Selected R&D areas	• Large area deposition processes • Improved substrates and transparent conductive oxides	• Improved cell structures • Improved deposition techniques	• Advanced materials and concepts

Thin film technologies are in the process of rapid growth. In the last years, thin film production units have increased from pilot scale to 50 MW lines, with some manufacturing units in the GW range recently announced. As a result, thin films are expected to increase their market share significantly by 2020.

II-VI semiconductor thin films

CdTe cells are a type of II-VI semiconductor thin film and have a relatively simple production process, allowing for lower production costs. CdTe technology has achieved the highest production level of all the thin film technologies. It also has an energy payback time of eight months, the shortest time among all existing PV technologies. For CIGS cells, the fabrication process is more demanding and results in higher costs and efficiencies compared to CdTe cells. Today, CdTe has achieved a dominant position amongst thin film in terms of market share and has a market-leading cost-per watt. However, it is difficult to predict which of the thin film technologies will reach higher market shares in a mid- and long-term perspectives.

Emerging technologies and novel concepts[15]

Emerging technologies

Emerging PV technologies comprise advanced inorganic thin film technologies (*e.g.* Si, CIS) as well as organic solar cells. Within the organic cells area, there are different technology branches such as the dye sensitised solar cell (a hybrid approach of an organic cell retaining an inorganic component) and fully organic approaches. Organic solar cells are potentially low cost technologies that are about to make their market entrance for niche applications. Their relevance for energy production in power applications, however, remains to be proven. Another emerging PV technology is based on the concept of thermo-photovoltaics whereby a high efficiency PV cell is combined with a thermal radiation source. This concept could also become relevant for concentrating solar technologies in the future.

15 The label "emerging" applies to technologies for which at least one "proof-of-concept" exists or which can be considered longer – term options that will radically improve the development of the two established solar cell technologies – crystalline Si and thin film solar cells. The label "novel" applies to developments and ideas that can potentially lead to new innovative technologies.

Novel PV concepts

Novel PV concepts aim at achieving ultra-high-efficiency solar cells by developing active layers which best match the solar spectrum or which modify the incoming solar spectrum. Both approaches build on progress in nanotechnology and nano-materials. Quantum wells, quantum wires and quantum dots are examples of structures introduced in the active layer. Further approaches deal with the collection of excited charge carriers (hot carrier cells) and the formation of intermediate band gaps. These novel concepts are currently the subject of basic research. Their market relevance will depend on whether they can be combined with existing technologies or whether they lead to entirely new cell structures and processes. Large market deployment of such concepts – if proven successful – is expected in the medium to long term. Considerable basic and applied R&D efforts aimed at the mid- to long-term are required in order to further develop these approaches and to ultimately bring them to market in end use applications.

Concentrator technologies (CPV)

All PV technologies described so far are so-called flat-plate technologies which use the naturally available sunlight. As an alternative, direct solar radiation can be concentrated by optical means and used in concentrator solar cell technologies. Considerable research has been undertaken in this high-efficiency approach because of the attractive feature of the much smaller solar cell area required. Low and medium concentration systems (up to 100 suns) work with high-efficiency silicon solar cells. For the highest concentration levels beyond 500 suns, III-V compound semiconductors are being used for the CPV solar cells and efficiencies beyond 40% have been achieved in the laboratory.

The CPV technology is presently moving from pilot facilities to commercial-scale applications. Further R&D efforts are required in optical systems, module assembly, tracking systems, high-efficiency devices, manufacturing and installation. The prospects and key R&D issues for CPV as well as emerging and novel technologies are summarised in Table 11.

Table 11: Prospects and key R&D issues for concentrating PV, emerging and novel technologies

	Concentrating PV	Emerging technologies	Novel technologies
Type of cell	High cost, super high efficiency	Low cost, moderate performance	Very high efficiency Full spectrum utilisaton
Status and potential	23% alternating-current (AC) system efficiency demonstrated Potential to reach over 30% in the medium-term	Emerging technologies at demonstration level (*e.g.* polymer PV, dye PV, printed CIGS) First applications expected in niche market applications	Wide variety of new conversion principle and device concepts at lab level Family of potential breakthrough technologies
Selected R&D areas	Reach super high efficiency over 45% Achieve low cost, high-performance solutions for optical concentration and tracking	Improvement of efficiency and stability to the level needed for first commercial applications Encapsulation of organic-based concepts	Proof-of-principle of new conversion concepts Processing, characterisation and modelling of especially nano-structured materials and devices

Policy frameworks: Roadmap actions and milestones

Deploying PV according to the vision of this roadmap requires strong, consistent and balanced policy support. The four main areas of policy intervention include:

- Creating a policy framework for market deployment today and the next decade, including tailored incentive schemes to accelerate market competitiveness
- Improving products and components, financing models and training and education to foster market facilitation and transformation
- Supporting continuing technology development and sustained R&D efforts to advance the cost and efficiency improvements outlined above
- Improving international collaboration to allow for accelerated learning and knowledge transfer to emerging and developing countries

Achieving the ambitious deployment goals set and overcoming existing barriers will require targeted action all along the PV value chain (*i.e.* raw materials, module technologies, balance of system components), and throughout the lifecycle of product development from basic research to demonstration and deployment. It will also require measures fostering technologies enabling a large-scale deployment of PV, such as energy storage and grid integration technologies. This section presents a set of key actions intended to create an effective policy framework that will directly or indirectly support successful large-scale PV deployment. More detailed actions can be identified for the coming decade, which is the critical time period for policy action in order for PV to achieve the vision outlined in this roadmap. A number of important issues will remain relevant beyond 2030.

Regulatory framework and support incentives

This roadmap recommends the following actions:	Milestones
Set long-term targets, supported by a transparent and predictable regulatory framework to build confidence for PV investments. The regulatory framework should specifically include financial incentive schemes to bridge the transition phase until PV has reached full competitiveness, and ensure priority access to grids over the longer term.	Begin 2010. Phase-out depends on when PV becomes fully competitive in a specific country; 2020 latest
Design and implement a regulatory framework to facilitate large-scale PV grid integration, including targeted Smart Grid based demonstrations for areas of high PV implementation.	Complete by 2020

Set predictable financial incentive schemes and regulatory frameworks

The high capital requirements for PV installations and manufacturing plants are clear, long-term, effective and predictable financial incentives (*e.g.* feed-in tariffs, feed-in premiums, portfolio standards, fiscal incentives, investment subsidies) and framework conditions (*e.g.* access to grids) for the next decade at least to provide sufficient investor confidence. Governments should establish long-term PV targets that can be implemented by such financial incentive schemes for market introduction and deployment. These schemes must be designed with long-term energy policy objectives in mind and should be steadily reduced over time to foster innovation and the development of the most cost-efficient technologies. As PV reaches grid parity, economic incentive schemes should evolve towards a market-enabling framework based on net metering and priority access to the grid.

Providing economic support alone, however, is not enough. Non-economic barriers can significantly hamper the effectiveness of support policies. Administrative hurdles such as planning delays and restrictions, lack of co-ordination between different authorities, long lead times in obtaining authorisations and connection to the grid, are key barriers for PV deployment. Governments should address administrative barriers by ensuring coherence and co-ordination between different authorities and implementing time-effective and streamlined administrative authorisation procedures for PV systems.

To date, most PV incentive schemes concentrate on grid-connected systems. Stand-alone and rural PV systems are rarely supported, despite the fact that they may offer the most cost-efficient solution (*e.g.*, replacing diesel generation). Dedicated and sustainable strategies to support off-grid PV applications and services, in particular for rural electrification, need to be established. Schemes should take into account non-economic barriers as well as the need for new financing and business models, particularly in developing countries.

Establish regulatory frameworks that facilitate large-scale PV grid integration

Given its variable, non-dispatchable nature in distributed applications, PV presents new challenges for grid integration. In most areas of the world, PV has not yet achieved an electricity generation share larger than 1%, and can currently be absorbed by existing grids without any problems. However, with an increasing number of PV systems in place, interconnection and load management will become important issues. Grid accessibility and integration challenges may prevent PV from achieving this roadmap's vision if not properly addressed in the short term. However, better grid planning and management also bring opportunities. For instance, PV can reduce critical summer load peaks in some regions, reducing the need for high-cost peak generation capacity and new transmission and distribution investments.

In order to accomodate an increasing share of variable PV, a higher degree of system flexibility is required. This will require new ways of thinking about how electricity is generated and distributed and the development of new technologies that make it simple, safe, and reliable for solar electricity to feed into the grid. Flexibility[16] can be increased both through market and transmission optimisation measures. Market measures include expanding markets to smooth overall variability and implementing demand response measures that better match demand with supply. Transmission optimisation measures include improved interconnection and adoption of advanced transmission and management technologies, including smart grids and metering and enhanced energy storage.

Addressing the issue of grid integration will require governments to act in the near-term, given the long lead times between planning and investing in new grid infrastructure and technologies. Regulators should initiate long-term planning aimed at increasing system flexibility and grid management. In areas with strong direct normal irradiation, planning the concurrent development of dispatchable CSP would allow for a larger amount of grid-connected PV.

In areas with a planned high use of PV generation, government should foster and co-finance smart grid demonstration systems, which would enable faster large-scale deployment of PV.

16 Flexibility refers to the amount of quickly dispatchable capacity – generation, interconnection and storage – that is available to respond to fluctuations in supply and demand. Source: *Empowering Renewable Energies – Options for Flexible Electricity Systems, IEA 2008.*

Market facilitation and transformation

This roadmap recommends the following actions:	Timeframe
Establish internationally accepted standards and codes for PV products and components to foster greater consumer adoption.	2010-2020
Identify new financing and business models for end-users and rural electrification to catalyse grid investments and storage solutions for the full-scale integration of PV.	2010-2020
Enhance training, education and awareness for skilled workforce along the PV value chain; expand outreach to residential and commercial customers.	2010-2025

Establish standards and codes

Standards, codes and certificates help create confidence and better handling of PV products. It is not only a question of safety and quality assurance but of improving the competitiveness of the industry by avoiding administrative hurdles and reducing unit costs. Standards, codes and certificates are needed for performance, energy rating and safety standards for PV modules and building elements; for grid interconnection; for quality assurance guidelines all along the value chain; and for the reuse and recycling of PV components. The development of an internationally agreed upon set of codes and standards will permit the increased deployment of a variety of PV technologies.

The IEA PVPS Implementing Agreement identified the following priorities for the development of standard and codes:[17]

i) PV industry internal standards for more efficient manufacturing

ii) PV as power supplier in interconnection issues

iii) PV as "multifunctional" products, *e.g.* BIPV.

17 These topics have been analysed within the IEA Implementing Agreement on Photovoltaic Power Systems; see www.iea-pvps.org

Foster new financing and business models

PV systems need considerable up-front investments, but once installed are low cost to operate. High initial investment costs are an important barrier for residential and small commercial customers and for off-grid applications. Investment barriers require innovative and uncomplicated financing approaches including the development of PV market and business models aimed at end-user service and efficiency. Today, most incentives are provided to PV grid-connected systems; PV systems in high-efficiency isolated homes are often not rewarded. Addressing this gap will require a shift in business models. One option that shows promise is the development of energy service companies (ESCOs) that own the system and provide an energy service to the end-user for a periodic fee. The user is not responsible for the maintenance of the system and never becomes the owner. Governments should explore providing financial incentives to PV ESCOs for on-grid and off-grid applications.

The high cost of capital and limited access to funds exacerbates the investment cost challenge in the developing world. To overcome the barrier of high capital costs and encourage the widespread use of PV in rural and remote communities, new implementation models for financing and operating PV systems are needed. Several financing mechanisms are available (IEA PVPS 2008):

- **Direct (cash) sales**: The end-user immediately becomes owner of the system.
- **Credit sales**: The end-user obtains a credit from the PV dealer or from a third-party institution (possibly through micro-credit initiatives). Depending on arrangements, the end-user

ultimately becomes the owner and the PV system can be used as collateral against the loan**.**

- **Hire (lease) purchase and a fee-for-service model**: The PV supplier/dealer or a financial intermediary leases the PV system to the end-user. At the end of the lease period, ownership may or may not be transferred to the end-user. Alternatively, a fee-for-service model based on an ESCO can also be applied.

Governments can also address the investment cost challenge by creating a market framework and/or mechanisms that foster investments in innovative grid and storage technologies. Time-dependent electricity tariffs (higher at peak load in summer), capacity value markets and ancillary PV markets have all shown promise and merit further exploration and adoption as appropriate.

Create a skilled PV workforce

Efforts are needed to increase the number of qualified workers for a growing solar industry along the value chain and the lifecycle of PV product development, from research to system installation and maintenance. A well-trained workforce is necessary to ensure technology development, quality installations, cost reductions, and consumer confidence in the reliability of solar installations. These activities should focus on building the capacity of educational institutions to respond to the increased demand for high-quality training for solar installers and code officials.[18] Governments are encouraged to provide training and education to create a skilled PV workforce along the full value chain. This involves developing outreach programmes that target specific professional groups (*e.g.*, local government planners, architects, home builders).

18 For an example of a PV workforce training effort, see the US Department of Energy's Programme website at http://www1.eere.energy.gov/solar/education_training.html

Technology development and RD&D

This roadmap recommends the following actions:	Timeframe
Increase public RD&D funding	2010-2020
Ensure sustained RD&D funding in the long-term	2020-2040
Develop and implement smart grids and grid management tools	2010-2030
Develop and implement enhanced storage technologies	From 2030 on

Increase public R&D funding and ensure sustained, long-term RD&D funding

PV comprises a set of technologies at differing levels of maturity. All of them have significant potential for improvement. Increased and sustained RD&D efforts are needed over the long-term in order to accelerate cost reductions and transfer to industry of the current mainstream technologies; develop and improve mid-term cell and system technologies; and design and bring novel concepts to industrialisation. Significant RD&D is also needed at system level, specifically in terms of improving the product requirements for building integration and minimising the environmental impacts related to a very large-scale deployment of PV systems.

The main short-term (S), mid-term (M) and long-term (L) R&D priorities for PV are:

- Improve the technical performance and cost-efficiency of solar cells, modules, and system components, both for existing as well as for new solar cell technologies (S-L)
- Improve manufacturability of components and systems for industry-scale production with

substantial mass production and cost reduction potential (including manufacturing plant demonstration) by utilising economies of scale and scope (S)

- Design PV as a building material and architectural element that meets the technical, functional, and aesthetical requirements and cost targets (S-M)
- Develop emerging technologies and novel concepts with potentially significant performance and/or cost advantages (M-L)
- Apply life-cycle assessments and optimise the environmental impact of PV systems (M-L)
- Develop and implement recycling solutions for the various PV technologies (S-M)

RD&D expenditures for PV have been increasing in recent years. However, they fall short in matching the needs to achieve the vision of this roadmap. Recent IEA analysis[19] suggests that RD&D expenditures in solar energy should increase by a factor of two to four in order to achieve the BLUE Map 2050 goals of reducing CO_2 emissions by 50% at global level.

In the short-term it is crucial to increase public RD&D funding to accelerate the PV deployment process. This is in line with the recognition by the IEA Ministers at their October 2009 meeting that "[…] more effort should be made to increase substantially public-sector investments in research, development and demonstration of these [low-carbon] *technologies, with a view to doubling such investments by 2015*". In the long-term, beyond 2020, an increasing involvement of the private sector, also through the implementation of innovative public-private partnerships, will be key to achieve the required RD&D funding levels.

19 *Global Gaps in Clean Energy Research, Development, and Demonstration, IEA 2009,* prepared in Support of the Major Economies Forum (MEF) Global Partnership by the International Energy Agency.

Develop and implement smart grids and develop and apply enhanced energy storage technologies

Just as the original electricity grid system helped facilitate the industrial innovations of the 20th century, an advanced "smart" grid will be needed to support the low-carbon technologies of this century. The smart grid can provide a range of benefits to both end users and generators, including the ability to monitor and manage the bi-directional transport of electricity in a way that accommodates the non-dispatchable nature of PV generation thus enabling increased PV deployment. As previously noted, this aspect will become increasingly more important as the amount of PV installed in regional electricity grids increases significantly above current levels. As such, the advancement of smart grids will be instrumental to the widespread use of PV envisioned in this roadmap.

By using digital technology, the smart grid will enable the control of conventional generation along with demand-side management that responds to the variable generation of PV. The smart grid will allow for seamless implementation of storage technology that can act as a load in times of excess generation relative to demand and as an electricity generation source when demand is greater. The smart grid can also process real time meteorological data that will allow the prediction of PV system output, enabling it to be managed more like dispatchable generation.

The generation profile of PV can also be combined with system design aspects for smart grids as new electricity grids are built and existing grids are maintained. By its nature, PV produces the majority of its electricity during the summer, reasonably aligning with the seasonal daily peak demand for electricity. The ability of the smart grid to then monitor and manage the electricity flow at nodes will allow for more accurate system sizing and needs assessment. This could reduce system costs in implementation and postpone investment in system upgrades, allowing for better utilisation of current electricity system infrastructure.

An advanced metering infrastructure that is part of smart grid deployment will also allow PV system operators, both small and large scale, to better understand system operational characteristics. This will ensure proper maintenance and provide operators with the ability to optimise electricity production.

After 2030, when PV is expected to reach a share of 5% of global electricity generation, the development and application of enhanced storage technologies will become increasingly important as a strategy to meet the needs for flexibility and to minimise the impacts of the variable PV power integration into electricity grids. Sustained RD&D efforts in enhanced storage technologies such as NaS cells, pumped hydro, redox flow cells, Compressed Air Energy Storage (CAES), electric double-layer capacitors, Li-ion batteries, Superconducting Magnetic Energy Storage (SMES) and flywheel systems will all contribute to achieving these ambitious goals.

International collaboration

This roadmap recommends the following actions:	Milestones
Expand international R&D collaboration, making best use of national competencies.	Begin in 2010 and continue
Develop new mechanisms to support exchange of technology and deployment of best practices with developing economies.	Begin in 2010 and continue
Assess and express the value of PV energy in economic development, particularly with respect to rural electrification.	2010-2020
Encourage multilateral development banks (MDBs) to target clean energy deployment.	2010-2020 and beyond

Expand international RD&D collaboration

Greater co-ordination is needed between national PV energy RD&D actors across the globe. Increased collaboration among nations will ensure that important issues are addressed according to areas of national expertise, taking advantage of existing RD&D activities and infrastructure. Long-term harmonisation of PV energy research agendas is also needed, as is the establishment of international testing facilities for materials and system components. One example of international PV energy technology collaboration is the IEA Photovoltaic Power Systems Programme (PVPS). This Implementing Agreement is one of 42 such initiatives covering the complete spectrum of energy technology development. The PVPS includes technology experts from 23 countries, who together have developed a research programme focused on accelerating the development and deployment of PV energy. Elements of this programme can help lay the foundation for greater collaboration among OECD and non-OECD countries.

Develop mechanisms to support best practices in developing economies

Vast PV resources exist in many countries where deployment has not yet begun to approach its potential. Many emerging economies – notably China and India – are becoming important global players in PV, both in terms of installed capacity and in manufacturing. China has already become a major PV manufacturer, with more than 15% share of global PV cell production. Fast economic growth, limited energy supply, and abundant conventional resources are encouraging countries such as China and India to look first to conventional energy supply. Without sufficient incentives and capacity to do otherwise, these countries are likely to follow a carbon-intensive development path.

OECD governments are encouraged to assist developing economies in the early deployment of renewable energy. The exchange of best practice in terms of PV technology, system integration, support mechanisms, environmental protection, and the dismantling of deployment barriers are important areas. Dynamic mechanisms will be required to achieve successful technology and information transfer.

Assess and express the value of PV energy in economic development

The clear expression of the value of PV energy, in terms of climate protection and other development challenges such as rural electrification is important for accelerated PV deployment. Benefits in terms of innovation, employment and environmental protection should be accurately quantified and shared with developing economy partners, particularly in terms of their ability to contribute towards the fundamental questions of adequate energy provision and poverty alleviation.

Low-carbon rural electrification in developing regions: the role of PV

Approximately 1.6 billion people around the world do not have access to a regular supply of electricity, and as a result are often deprived of electric lighting, adequate clean water supplies, and other basic services (World Bank, 2010). Most of these people live in remote rural areas that are difficult or uneconomical to reach with conventional electricity infrastructure. In many areas without access to an electricity grid, inefficient and high-polluting diesel generators are used for basic power needs.

Deploying PV technology in isolated or under-developed areas can be a cost-effective option for clean electricity production. PV is attractive as a distributed energy source to provide basic power services, and can better the lives of people in many ways, including supplying clean electricity to light homes or schools; running medical refrigerators; powering small businesses; and pumping or purifying water. Further enhancing PV's appeal as a solution for rural electrification is the fact that many developing countries are situated in climates that are extremely well suited for harnessing solar energy throughout the year.

In 2005 the G8 agreed to a Plan of Action for achieving the Millennium Development Goals, with clean energy now playing a more central role. Many multilateral development banks and bilateral agencies have since increased financing for renewable energy projects, including some designed to bring PV technology to rural areas in developing countries.

Though financing for PV programmes at the national level principally comes from international sources, many emerging economies have earmarked their own funds for development, including rural electrification, by levying tariffs on grid electrification or by taxing other energy sources. Market mechanisms like Certified Emissions Reductions produced through the Clean Development Mechanism can further augment project funding. When rural PV projects and programmes fall short of their goals, it has often been due to a lack of skilled personnel at various levels – from government ministry and implementing agency staff to installation and maintenance workers. This lack of local capacity can usually be addressed if appropriate measures are identified during a project's early stages. With effective co-ordination and planning, PV applications in rural areas can improve the lives of hundreds of thousands of people at a reasonable cost. They can be implemented on a local or regional scale, depending on the size of the programme and the resources available to carry it out.

Encourage international aid providers to target clean energy development

Multilateral development banks are an important source of financing for joint development efforts. Financing facilities can be designed on a case-by-case basis to support differing needs. Since 1993, the World Bank (WB) and the Global Environmental Facility (GEF) have supported projects to improve commercial markets and financing for renewable energy technologies in developing countries. In China, from 1999 to 2007, the WB and the GEF provided USD 40 million in grants and loans to fund market surveys, key capital investments, and the development of product standards and certification. This effort played an important role in supporting the sale of PV systems to approximately 400 000 rural households and institutions during the eight-year period, and helped make China the top producer of solar equipment and components in the world today.[20] Bilateral development banks are also an important source of development finance. The German state-owned *Kreditanstalt fuer Wiederaufbau Bank* (KfW), for example, invested USD 340 million (EUR 230 million) in renewable energy projects in developing economies in 2008.

These sorts of targeted solar aid projects should be expanded to cover additional countries and regions with strong solar potential.

20 World Bank (2008), "Solar Systems for 400,000 Rural Households in China," World Bank, Washington, D.C.

Conclusion: Actions for stakeholders and next steps

This roadmap has responded to the G8 and other government leaders' requests for more detailed analysis regarding the growth pathway for PV energy, an important GHG mitigation technology. It describes approaches and specific tasks regarding PV research, development, and deployment; financing mechanisms; grid integration; legal and regulatory frameworks; public engagement; and international collaboration. It provides regional and end-use sector projections for PV deployment from 2010 to 2050. The roadmap identifies the next decade as a critical time window in order to accelerate the development and deployment of PV technologies. Achieving this roadmap's vision will require a strong, long-term and balanced policy effort in the next decade to allow for optimal technology progress, cost reduction and ramp-up of industrial manufacturing for mass deployment. Priority actions for the next ten years include:

- Provide long-term targets and supporting policies to build the needed confidence for investments in manufacturing capacity and deployment of PV systems.
- Implement effective and cost-efficient PV incentive schemes, which will have to be transitional and decrease over time, in order to foster innovation and technological improvement.
- Develop and implement appropriate financing schemes, in particular for rural electrification and other applications in developing countries.
- Increase R&D efforts to reduce costs and ensure PV readiness for rapid deployment, while also supporting longer-term innovations.

The table below details actions and milestones to aid policy makers, industry and power-system actors in their efforts to successfully implement PV energy.

Stakeholder	Action items
National governments	• Establish market support mechanisms to achieve grid competitiveness – to be phased out over time. • Develop regulatory framework preparing large-scale integration of PV into the grid. • Facilitate internalisation of external costs of energy for a more level playing field. • Streamline building codes and standards for PV products and interconnection rules. • Set energy standards that account for solar building regulations and obligations. • Increase R&D funding to accelerate cost reductions and efficiency gains. • Improve educational/outreach programmes on environmental advantages of PV.
Universities and other research institutions	• Identify PV educational development/training needs for important areas like small-scale system installation and grid connection; develop training plans/grants for universities. • Develop national PV technology RD&D roadmap that identifies pathways to achieve critical longer-term technology breakthroughs.
International development ministries	• Provide aid for PV capacity building in developing economies, including distributed electricity planning, site identification and development, etc.
Multilateral development agencies	• Ensure maximum efficacy of international aid for rural electrification in key regions by co-ordinating with other donors (multilateral and bilateral).

Stakeholder	Action items
PV industry	• Support training and education for skilled workforce along the PV value chain; technology outreach to target audiences/stakeholders. • Accelerate technical improvements, industrial processes, standardisation and scaling up of manufacturing. • Pursue increased performance for PV cell/module technologies and Balance-of-System components.
Utilities and other market stakeholders	• Develop business models for end-users and rural electrification. • Streamline building codes and standards for PV products and interconnection rules. • Support training and education for skilled workforce along the PV value chain; technology outreach to target audiences/stakeholders. • Deploy smart grid technologies and grid management tools.
State, provincial and local governments	• Support new national regulatory framework to enable large-scale integration of PV into the grid. • Collaborate across jurisdictions to reform local building codes and standards to facilitate PV implementation and integration.
Non-governmental organisations	• Monitor progress toward PV development and policy milestones and publish results regularly to keep government and industry on track. • Identify and publish information on regulatory and bureaucratic barriers to PV deployment.

The PV roadmap is meant to be a process, one that evolves to take into account new technology developments, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that PV energy development efforts are on track to achieve the GHG emissions reductions that are required by 2050. As such, the IEA, together with government, industry and NGO stakeholders will report regularly on the progress that has been achieved toward this roadmap's vision. For more information about the PV roadmap inputs and implementation, including additional analysis that informed the conclusions in this document, visit **www.iea.org/roadmaps**.

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Appendix II.
List of relevant websites

International Energy Agency	
International Energy Agency (IEA)	www.iea.org
IEA PVPS Implementing Agreement	www.iea-pvps.org
IEA Committee on Energy Research and Technology (CERT)	www.iea.org/about/stancert.htm
IEA Working Party on Renewable Energy Technologies (REWP)	www.iea.org/about/rewp.htm
IEA Renewable Energy Implementing Agreements	www.iea.org/Textbase/techno/technologies/renew.asp
IEA PVPS Links to international organisations	www.iea-pvps.org/links/org_int.htm
IEA PVPS links to web resources	www.iea-pvps.org/links/resource.htm
Other	
Association PV Cycle	www.pvcycle.org
European Photovoltaic Industry Association (EPIA)	www.epia.org
EPIA SET for 2020	www.setfor2020.eu
European PV Sunrise	http://www.pvsunrise.eu
ISET	www.iset.uni-kassel.de
Institute for Energy Diversification and Saving of Spain – IDAE	www.idae.es
PV Accept	www.pvaccept.de/eng/index.htm
PV Upscale – Urban Scale PV Systems	www.pvupscale.org
Solar Energy Industries Association (SEIA)	www.seia.org
Non-European organizations	
Australian PV Association	www.apva.org.au
Japan Photovoltaic Energy Association	www.jpea.gr.jp
American Council on Renewable Energy	www.acore.org
SEMI	www.semi.org
Canadian Solar Industries Association	www.cansia.ca
Chinese Renewable Energy Industries Association	www.creia.net
Taiwan Photovoltaic Industry Association	www.tpvia.org
Malaysian Photovoltaic Industry Association	www.mpia.org.my
nternational Photovoltaic Equipment Association	www.ipvea.org

Appendix III.
List of workshop participants and reviewers

Workshop participants

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Gerardo Montanino	GSE
Stathis Peteves	EC JRC Energy systems evaluation unit
Brian Robertson	Sunworks
Nadine Roemann	SCHOTT Solar AG
Naoki Sakai and Anil Terway	Asian Development Bank
Jigar Shah	Carbon War Room
Jens Widdeleff	Danish Energy agency
Multiple reviewers	US Department of Energy

Appendix IV. Abbreviations, acronyms and units

AC	Alternating-current
a-Si	Amorphous silicon
a-Si/μc-Si	Micromorph silicon
BIPV	Building-integrated systems
CAES	Compressed air energy storage
CCS	Carbon capture and storage
CdTe	Cadmium Telluride
CIGS	Copper-Indium-Gallium-Diselenide
CIS	Copper-Indium-Diselenide
CPV	Concentrating photovoltaics
CPV	Concentrator technologies
c-Si	Crystalline silicon
CSP	Concentrating solar power
DC	Direct-current electricity
EPIA	European Photovoltaic Industry Association
ESCOs	Energy service companies
GBI	Generation Based Incentives
KfW	Kreditanstalt fuer Wiederaufbau Bank
MDBs	Multilateral development banks
PV	Photovoltaic
R&D	Research and development
RD&D	Research, demonstration and development
RED	IEA Renewable Energy Division
SAI	Solar America Initiative
SET	Strategic energy technology
SHC	Solar heating and cooling
SMES	Superconducting magnetic energy storage
USD	United States dollar

Units

Gt	Gigatonnes
g/W	Grams/watt
GW	Gigawatt = 10^9 watts
kWh	kilowatt-hour
kW	Kilowatt
MW	Megawatt
MWh	Megawatt-hour
TWh	Terawatt-hour
W	Watt
µm	Micrometre

NOTES

Technology Roadmap Solar photovoltaic energy

2010

2015

2020

2025

2030