Executive Summary

This publication builds upon past analyses of solar energy deployment contained in the *Word Energy Outlook, Energy Technology Perspectives* and several *IEA Technology Roadmaps*. It aims at offering an updated picture of current technology trends and markets, as well as new analyses on how solar energy technologies for electricity, heat and fuels can be used in the various energy consuming sectors, now and in the future.

If effective support policies are put in place in a wide number of countries during this decade, solar energy in its various forms – solar heat, solar photovoltaics, solar thermal electricity, solar fuels – can make considerable contributions to solving some of the most urgent problems the world now faces: climate change, energy security, and universal access to modern energy services.

Solar energy offers a clean, climate-friendly, very abundant and inexhaustible energy resource to mankind, relatively well-spread over the globe. Its availability is greater in warm and sunny countries – those countries that will experience most of the world's population and economic growth over the next decades. They will likely contain about 7 billion inhabitants by 2050 *versus* 2 billion in cold and temperate countries (including most of Europe, Russia, and parts of China and the United States of America).

The costs of solar energy have been falling rapidly and are entering new areas of competitiveness. Solar thermal electricity (STE) and solar photovoltaic electricity (PV) are competitive against oil-fuelled electricity generation in sunny countries, usually to cover demand peaks, and in many islands. Roof-top PV in sunny countries can compete with high retail electricity prices. In most markets, however, solar electricity is not yet able to compete without specific incentives.

Technology trends

The dynamics of PV deployment have been particularly remarkable, driven mostly by feed-in tariffs. PV is extremely modular, easy and fast to install and accessible to the general public. With suitably established policies and mature markets and finance, PV projects can have short lead times. The rapid cost reductions driven by this deployment have confirmed earlier expectations related to the learning rate of PV. They have also increased confidence that sustained deployment will reduce costs further – if policies and incentives are adjusted to cost reductions, but not discontinued.

Solar thermal electricity (STE) allows shifting the production of solar electricity to peak or mid-peak hours in the evening, or spreading it to base-load hours round the clock, through the use of thermal storage. Fuel back-up and hybridisation with other resources help make it reliable and dispatchable on demand, and offer cheaper options for including solar energy in the electricity mix.

STE today is based on concentrating solar power (CSP) technologies, which can be used where the sun is very bright and the skies clear. Long-range transmission lines can transport clean STE from favourable areas (*e.g.* North Africa) to other large consuming areas (*e.g.* Europe). As such, STE complements PV rather than competing with it. Today, large-scale PV plants emerge, though one important advantage of PV is that is can be built close to consumers (*e.g.* on building roofs). STE lends towards utility-scale plants, but small-scale STE may find niche markets in isolated or weak grids. Firm and flexible STE capacities enable more variable renewable energy (*i.e.* wind power and solar PV) in the electricity mix on grids. While very high penetration of PV requires large-scale investment in electricity storage, such as pumped-hydro plants, high penetration of STE does not.

Off grid in developing countries, solar PV and STE can transform the lives of those 1.4 billion people currently deprived of access to electricity, and those who can barely rely on their grid. Solar cooking and solar water heating can also provide significant contribution to raise the living standards in developing economies. Even in countries with well developed energy systems, solar technologies can help ensure greater energy security and sustainability.

End-use sectors

The largest solar contribution to our energy needs is currently through solar heat technologies. The potential for solar water heating is considerable. Solar energy can provide a significant contribution to space heating needs, both directly and through heat pumps. Direct solar cooling offers additional options but may face tough competition from standard cooling systems run by solar electricity.

Buildings are the largest energy consumers today. Positive-energy building combining excellent thermal insulation, smart design and the exploitation of free solar resources can help change this. Ambient energy, *i.e.* the low-temperature heat of the surrounding air and ground, transferred into buildings with heat pumps, solar water heating, solar space heating, solar cooling and PV can combine to fulfil buildings' energy needs with minimal waste.

Industry requires large amounts of electricity and process heat at various temperature levels. Solar PV, STE and solar heating and cooling (SHC) can combine to address these needs in part, including those of agriculture, craft industry, cooking and desalination. Solar process heat is currently untapped, but offers a significant potential in many sectors of the economy. Concentrating solar technologies can provide high-temperature process heat in clear-sky areas; solar-generated electricity or solar fuels can do the job elsewhere. More efficient end-use technologies would help make electricity a primary carrier of solar energy in industry.

Transportation is the energy consuming sector that is most difficult to decarbonise – and it is the most dependent on highly volatile oil prices. Solar and other renewable electricity can contribute significantly to fuel transport systems when converted to electricity. The contribution from biofuels can be enhanced by using solar as the energy source in processing raw biomass.

In countries with bright sunshine and clear skies, concentrating solar technologies enable the production of gaseous, liquid or solid fuels, as well as new carriers for energy from fossil feedstock, recovered CO_2 streams, biomass or water. Solar-enhanced biofuels would have a smaller carbon footprint than others. Solar fuels could be transported and stored, then used for electricity generation, to provide heat to buildings or industry and energy for transport.

A possible vision

Earlier modelling exercises at the IEA have been seeking for the least-cost energy mix by 2050 compatible with cutting global energy-related CO_2 emissions by half from 2005 levels. The High-Renewable scenario variant showed that PV and STE together could provide up to 25% of global electricity by 2050. In such carbon-constrained scenarios, the levelised cost of solar electricity comes close to those of competitors, including fossil fuels, at about USD 100/MWh by 2030.

This publication elaborates on these findings, looking farther into the second half of this century. It assumes that greenhouse gas emissions will need to be reduced to significantly lower levels. It assumes that electricity-driven technologies will be required to foster energy efficiency improvements and displace fossil fuels in many uses in buildings, industry and transportation. It finally tests the limits of the expansion of solar energy and other renewables, in case other low-carbon energy technologies are themselves limited in their expansion for whatever reason. After 2030, these limits are not mainly determined by the direct generation costs of solar energy, but rather by its variability, footprint (land occupied), and the lower density and transportability of solar compared to fossil fuels.

Under all these strong assumptions, a long-term energy mix dominated by solar energy in various forms may or may not be the cheapest low-carbon energy mix, but it would be affordable. In sunny and dry climates, solar thermal electricity will largely be able to overcome variability issues thanks to thermal storage. In the least sunny countries, as well as in sunny and wet climates, the variability of PV electricity and wind power will need to be addressed through a combination of grid expansion, demand-side management, hydro power, pumped hydro storage and balancing plants. The footprint (land occupied) of solar energy will raise challenges in some densely populated areas when all possibilities offered by buildings are exhausted, but is globally manageable. In these circumstances, and provided all necessary policies are implemented rapidly, solar energy could provide a third of the global final energy demand after 2060, while CO_2 emissions would be reduced to very low levels.

Policy needs

A broad range of policies will be needed to unlock the considerable potential of solar energy. They include establishing incentives for early deployment, removing non-economic barriers, developing public-private partnerships, subsidising research and development, and developing effective encouragement and support for innovation. New business and financing models are required, in particular for up-front financing of off-grid solar electricity and process heat technologies in developing countries.

The number of governments at all levels who consider implementing policies to support the development and deployment of solar energy is growing by the day. However, few so far have elaborated comprehensive policy sets. Public research and development efforts are critically needed, for example, in the area of solar hydrogen and fuels. Policies to favour the use of direct solar heat in industry are still rare. Principal-agent problems continue to prevent solar heating and cooling to develop in buildings, obstacles to grid access and permitting hamper the deployment of solar electricity, financing difficulties loom large. The recent growth in instalment is too concentrated in too few countries.

The early deployment of solar energy technologies entails costs. Support policies include a significant part of subsidies as long as solar technologies are not fully competitive. They must be adjusted to reflect cost reductions, in consultation with industry and in as predictable a manner as possible. Incentive policies must not be abandoned before new electricity market design ensures investments in competitive solar energy technologies, grid upgrades, storage and balancing plants.

The development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise. These advantages are global. Hence the additional costs of the incentives for early deployment should be considered learning investments; they must be wisely spent and need to be widely shared.