European Commission

LOW CARBON ENERGY OBSERVATORY

PHOTOVOLTAICS

Market development report

Joint Research Centre

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Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

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Acronyms and Abbreviations

CAGR	Compound annual growth rate
CAPEX	Capital expenses (ETRI definition)
EC	European Commission
EERA	European Energy Research Alliance
EII	European Industrial Initiative
EPIA	European Photovoltaic Industrial Association (now SolarPower Europe)
EPC	Engineering, Procurement and Construction
EU	European Union
EU PVT(I)P	Photovoltaic Technology (Innovation) Platform
EUPVSEC	European Photovoltaic Solar Energy Conference
FP4/5/6/7	Fourth/Fifth/Sixth/Seventh Framework Programme (EU R&D programmes)
GW	Giga Watt
IEA	International Energy Agency
ITRPV	International Technology Roadmap for Photovoltaics
KPI	Key Performance Indicator
LCA	Life-Cycle Analysis
LCoE	Levelised Cost of Electricity
NREAP	National Renewable Energy Action Plan
O&M	Operation and Maintenance
PPA	power purchase agreement
PV	photovoltaic(s)
R&D	Research and Development
R2R	Roll-to-roll (production process)
SETIS	Strategic Energy Technologies Information System
SET-Plan	European Strategic Energy Technology Plan
Si	Silicon
SPE	SolarPower Europe (formerly EPIA)
SV	System value [of a variable renewable electricity source]
TF	Thin film
VRE	Variable renewable energy
WACC	Weighted Average Cost of Capital

1 INTRODUCTION

1.1 Scope

The photovoltaic industry has grown rapidly from a small group of companies and key players into a global business. It takes in an extensive value chain, from raw materials to device production to system installation and maintenance (Figure 1). This Technology Market Report gives an overview of current trends, taking advantage of information from various data providers, including grey literature and data sources. Where possible, the data coverage is up to the end of 2018.

1.2 PV technology and market readiness

PV boasts a broad range of technologies. These can be broadly classified as either "commercial", i.e. being used in mass production, "emerging" i.e., small production volumes or "novel", i.e. concept or early laboratory stage. In the commercial category, crystalline silicon wafer based photovoltaics are by far the dominant technology, with share of over 95 % in 2018 (corresponding to over 100 GW or 400 million individual modules). Other commercial products include thin-film technologies, in which the active material layers of a few microns thickness are deposited on glass or metal substrates, and concentrating photovoltaics that use lenses to focus light on small cells. Standardised solutions are available for mounting, control and grid integration (in particular DC-AC inverters). The world's largest PV plant is currently the 1 547 MW (43 km^2) Tengger solar park in Zhongwei, Ningxia, PRC, while the EU's largest is 300 MW, located at Cestas in France.

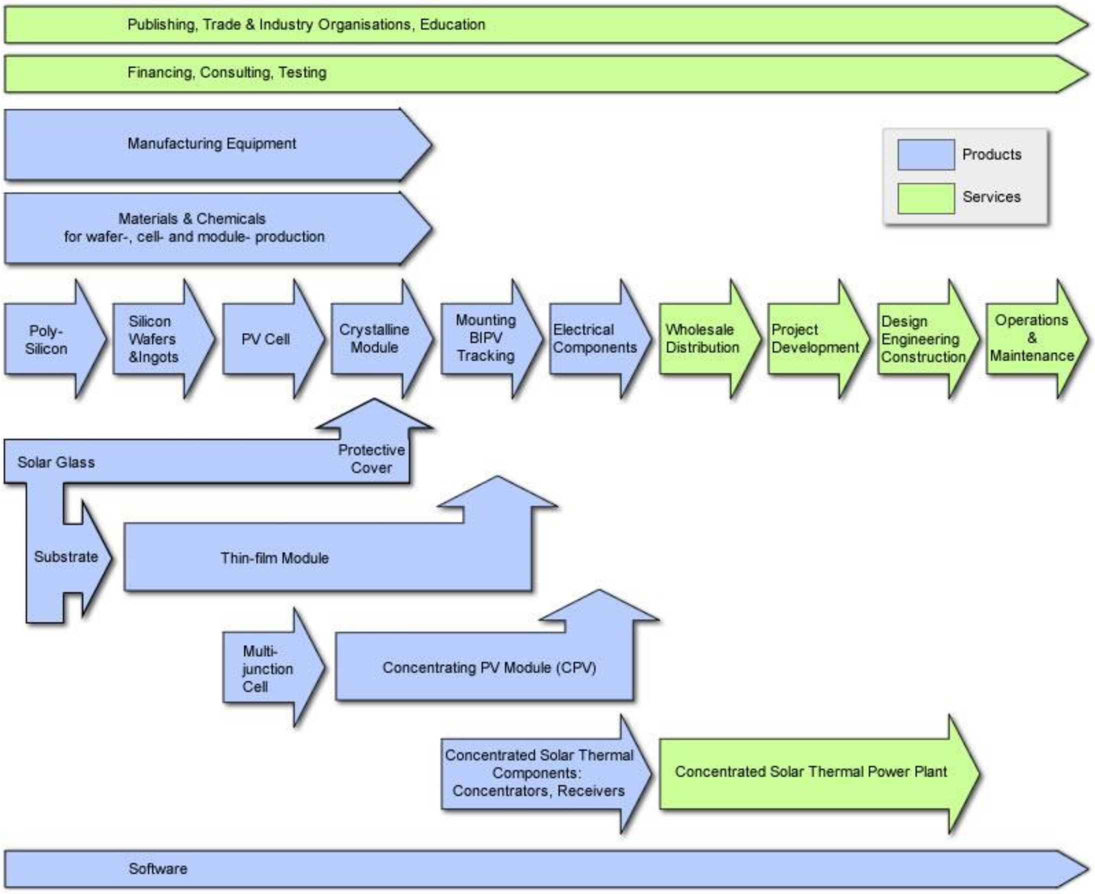
Overall, the existing PV technology mix provides a solid foundation for the future growth of the sector. No single technology can satisfy all the different consumer requirements, ranging from mobile and consumer applications, and the need for a few watts, up to the multi-MW utility-scale power plants. If material limitations or technical obstacles restrict the further growth or development of a single technology pathway, then the variety of technologies will be an insurance against any stumbling blocks towards the emergence of PV as a large-scale electricity source.

Cost-effective large-scale systems can produce electricity at competitive prices in many EU locations: For the second half of 2018, Bloomberg New Energy Finance [1] reports benchmark LCOE between 50 EUR/MWh in Spain and 78 EUR/MWh in the United Kingdom. For comparison, the LCOE benchmark for wind onshore ranges between 35 EUR/MWh in Sweden to

84 EUR/MWh in Croatia, while the cost of producing power through newly built gas- or coal-fired power plants ranges from 71 to 115 EUR/MWh in Germany.

Costs for residential and smaller commercial PV systems are higher (even up to a factor of three in some markets, depending on a variety of factors, many unrelated to the technology). Nonetheless JRC analysis shows that the EU rooftops could potentially produce 680 TWh of solar electricity annually (representing 24.4% of current electricity consumption), two thirds of which at a cost lower than the current residential tariffs [2].

Figure 1: Value Chain of PV Industry (source: GreenRhinoEnergy)



1.3 Current market penetration

Over the last two decades, PV electricity generation has grown from being a tiny niche market to providing about 600 TWh electricity in 2018, roughly 2.5% of the world electricity production. The cumulative power of installed PV plants increased to 518 GW at the end of 2018, of which 117 GW (23%) are in the EU [3]. The terawatt level should be reached in a few years,, indeed already by 2023 according to the IEA Renewable Energy Market Report 2018 [4]. The sector currently involves approximately 48 000 companies worldwide [5] and employs over 3 million people [6].

Honduras is the country with the highest share of solar photovoltaic generated electricity with over 13%. Several EU countries were also leaders in terms of penetration of PV in the electricity market in 2018 (**Figure 2**), notably Italy (8.3%), Greece (7.3%) and Germany (7.2 %) [7]. The US state of Hawaii is experiencing a solar PV boom with penetration heading towards 12% and expects to double this share within five years. The impact of high penetration levels is a subject of much on-going study, where factors such as the distribution of the PV plants is a major consideration i.e. many small units pose different grid management issues to a system dominated by large-scale plants. Integration with storage systems is also a crucial aspect.

The market for PV products can be broken down broadly into 2 main categories:

- Utility-scale or centralised systems: plants typically greater than 1 MW designed purely for supplying the grid.
- Rooftop or decentralised systems: typically installed on or near buildings, which make use of part or all of the electricity generated. This category covers a wide range of sizes, from residential roofs with systems of a few kW to larger commercial roofs or adjacent structures, with system sizes up to 1 MW.

Globally the share of centralised systems has been growing and by the end of 2017 these accounted for 59% of installed capacity [8], up from 36% in 2011. In the current market, the centralised-decentralised split is approximately 70:30. In Europe, decentralised residential and commercial segments continue to play a major role, albeit with large country-to-country differences, as indicated in Figure 3. Overall, utility systems now account for 34% of cumulative capacity. The decentralised sector comprises 19% residential rooftop systems, 30% commercial rooftop systems and a 17% industrial segment [9].

In terms of product types, both the utility and rooftop/commercial segments are currently addressed by the classic "module", with rectangular shape and an area of approximately 1.5 m^2. The power of each design varies somewhat according to the efficiency of the PV technology used (polycrystalline silicon, monocrystalline silicon, bifacial, thin film etc.).

Figure 2 PV penetration in national electricity demand, 2018 (source data [7], graphics JRC). NB The following countries also have PV installations but less than a 1% share: Cyprus, Estonia, Finland, Hungary, Ireland, Latvia, Lithuania, Poland, Slovenia, Sweden, Luxembourg, Malta and Croatia

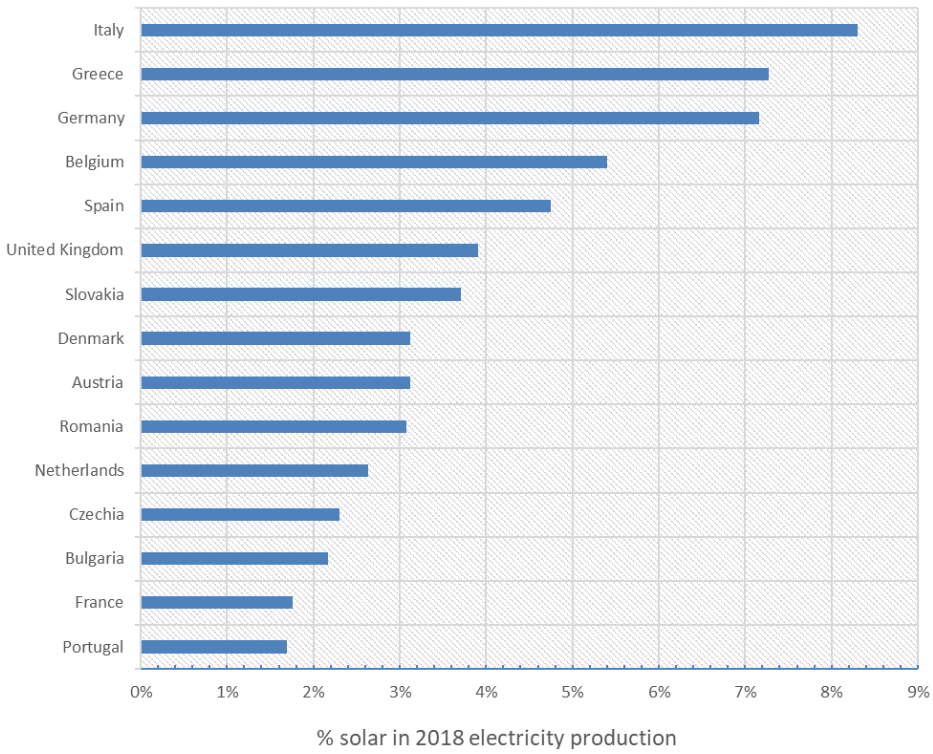
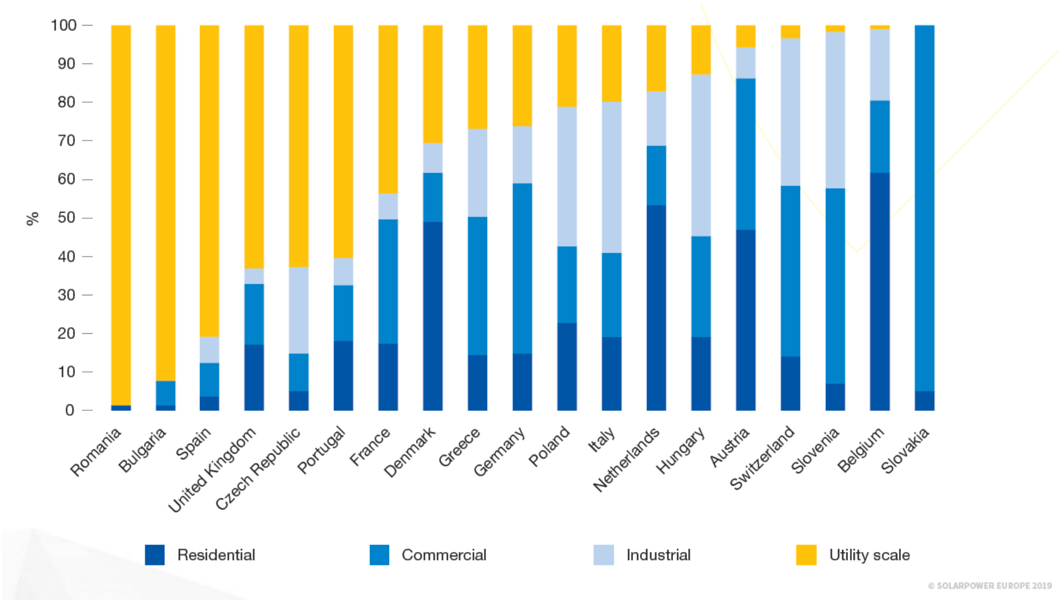


Figure 3 Shares of decentralised and centralised systems in 2018 in European countries with significant PV installations. [9]



The international standards for performance and reliability developed up to now have provided a sound basis for the market, with product differentiation based primarily on price. Moreover, the market for large systems is dominated by a limited number of companies who have developed "bankable" products and strong links to project developers, ensuring competitive project financing. For residential installations a "know-brand" product is of high importance to many local installers. Obtaining a significant market for a new product means also addressing these challenges.

At the utility scale, one route for product form innovation lies in significantly increasing module area and the use of cost-effective, automated mounting systems. Already In 2009 Applied Materials presented prototype 5.7 m^2 modules, but the concept did not develop commercially at the time. In 2018, First Solar started delivery of its Series 6 modules, which have an area of 2.47 m^2 and a power rating between 420 and 445 W. An alternative strategy is to move away from modules to strip-type products e.g. mass-produced on roll-to-roll devices using thin film technology

Regarding deployment and mounting systems, for utility scale plants the use of east-west trackers is becoming of increasing interest, as an additional 10% to the system costs can increase energy yields by up to 30% in high insolation locations and use of bifacial module technologies. Other areas of innovation include floating PV systems (now over 1 GW installed globally) and agro-PV systems to allow dual-use of agricultural land.

For the rooftops category, there is considerable scope for product innovation, particularly if one includes building integrated PV (BIPV). PV-integrated building skins and facades offer additional possibilities. Aesthetics and public acceptance may also become important factors. BIPV has long been tipped as the next big growth sector for PV products (the SUPSI BIPV status report catalogues 95 European products, covering various panel designs for roofs and facades as well as roof tiles and shingles [10]), but a series of factors including costs, lack of standards and a conservative construction sector have hampered progress.

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2 TECHNOLOGY TRENDS AND PROSPECTS

2.1 Technology Deployment and Cost Trends

Wafer-based crystalline silicon continues to be the dominant PV technology, accounting for 96% of the market (117 GW in 2018). About 52% of all silicon solar cells use multi-crystalline silicon, and the remainder mono-crystalline silicon.

So-called "p-type" silicon devices in either multi-crystalline or mono-crystalline have formed the bulk of the installations to now. This sub-sector led the dramatic cost reduction seen over the last 10 years, with the emergence of GW-scale production. n-type cells offer superior performance (for several fundamental physics reasons) but up to now the production cost differential has favoured the p-type. According to the International Technology Roadmap for Photovoltaics, the market share of n-type mono-crystalline silicon is currently about 5 % but expected to grow to 10% by 2020 and around 30% by 2028 [11]. The global average of silicon consumption was about 4.0 g/Wp in Q3 2018, and this should to drop to a value between 2.1 and 3 g/W by 2028 [11].

Thin film technologies emerged some decades ago, taking advantage of then-new large area deposition methods, and have been progressively increasing their efficiencies. The active material is typically only a few micros thick, deposited on glass, metal or plastic substrates. Cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous and other thin-film silicon have been commercially available since the 1980s. Developments over the past 3-4 years have seen the champion efficiencies match those of polycrystalline silicon.

US thin-film manufacturer First Solar dominates CdTe technology and is one of the top module producers. However, due to the migration of their manufacturing platform from a 0.9 m^2 module size to 2.47 m^2 module size, production volume in 2018 was reduced to about 3 GW, but expected to rise again in 2019. CIGS production is dominated by Solar Frontier, Japan. Market figures for 2017 show that these two technologies contributed about 3 % of global production or 3 GWp. Although amorphous silicon (a-Si) was the first commercially successful thin-film solar cell technology, material quality and light-induced degradation effects have so far limited the efficiency to modest values. It is no longer competitive with other thin film technologies or with wafer-based silicon, and the market share was well below 1 % in 2018.

Commercialisation of organic PV devices remains a challenge. Issues include stability, faster power output degradation rates than for other technologies, low module efficiencies and corresponding added balance of systems costs. Dye solar cells (DSCs) exploit light absorption in dye molecules (the “sensitizers”). Despite the continuous improvements since their discovery in 1991, long-term stability and a reasonable efficiency are still the key challenges to commercializing these PV cells. DSCs have however attracted interest for BIPV applications, for instance as semi-transparent coloured glass facades desirable.

Concentrating PV designs are classed according to concentration factors and whether they use a parabolic dish or lenses to focus light. High concentration systems are suitable only for locations with high direct normal irradiance. The modest deployment to date (cumulative power approximately 400 MW) has come with significant improvements in cells, optics, modules and trackers, as well as in system integration. However, the sector has not been able to achieve significant economies of scale in production and sufficient cost reductions to stay competitive. The sector saw severe restructuring and company closures. Low concentration systems have made little progress so far in the market.

The LCEO PV Technology Development Report 2018 provides more details on technology issues [12]. Concerning long-term cost trends, recent studies highlight the large potential for continued reductions. Bloomberg New Energy Finance expects that averaged CAPEX for utility, commercial and residential photovoltaic systems will decrease by over 40% from 2018 to 2030 [13]. Projected utility scale PV system CAPEX in USD 600/kW in 2025 and USD 510/kW in 2030 (2018 USD values). This CAPEX reduction is again higher than forecast by the 2015 KIC InnoEnergy report [14], which looked at the impact of over 30 innovations over the period 2015-2030. Figure 4 shows the CAPEX reductions foreseen for 6 generic technology and system types. Operating and maintenance costs were also analysed. Overall, they anticipate LCOE savings of at least 37% for conventional c-Si technology, 49% for high efficiency c-Si technology and at least 44% for thin film.

The Fraunhofer ISE study for Agora Energiewende [15] takes a longer-term view to 2050, looking at both high-cost and low-cost scenarios for ground-mounted (utility) systems. Figure 5 summarises the approach, which indicates a CAPEX range from 280 €/kWp to 610 €/kWp in 2050 (2014 values). Interestingly the module efficiencies are 24% and 35% respectively, underlining the importance of this parameter in relation to BOS and area-related costs.

NREL [16, 17] has also looked at long-term LCOE values, identifying possible pathways to 3 ¢/kWh (utility-scale), 4 ¢/kWh (commercial), and 5 ¢/kWh (residential). Figure 6 shows the case for residential system costs

Figure 4 KIC InnoEnergy: projected reduction of CAPEX for PV installations to 2030.

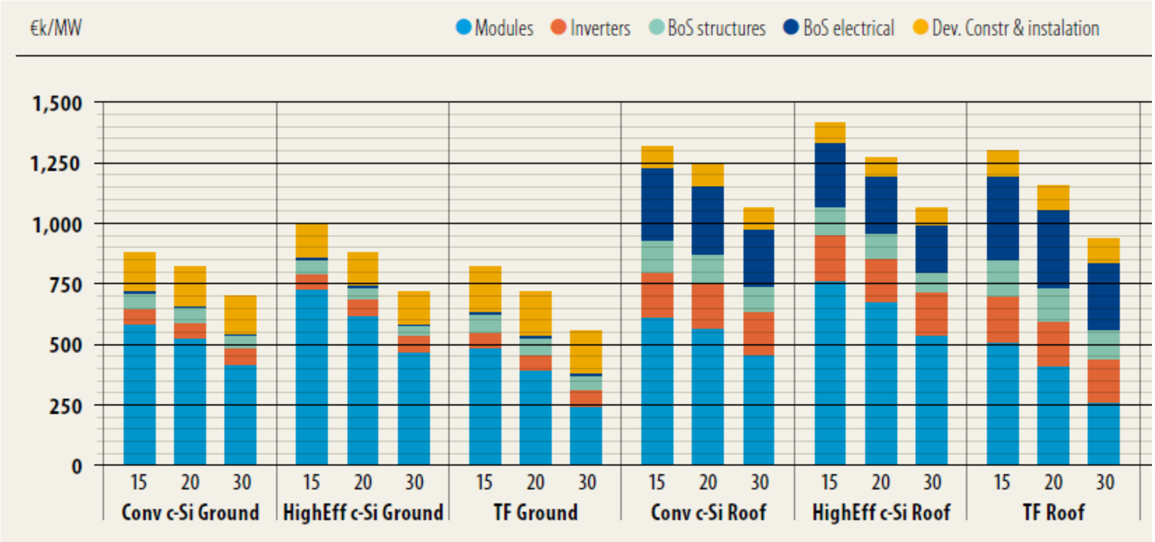
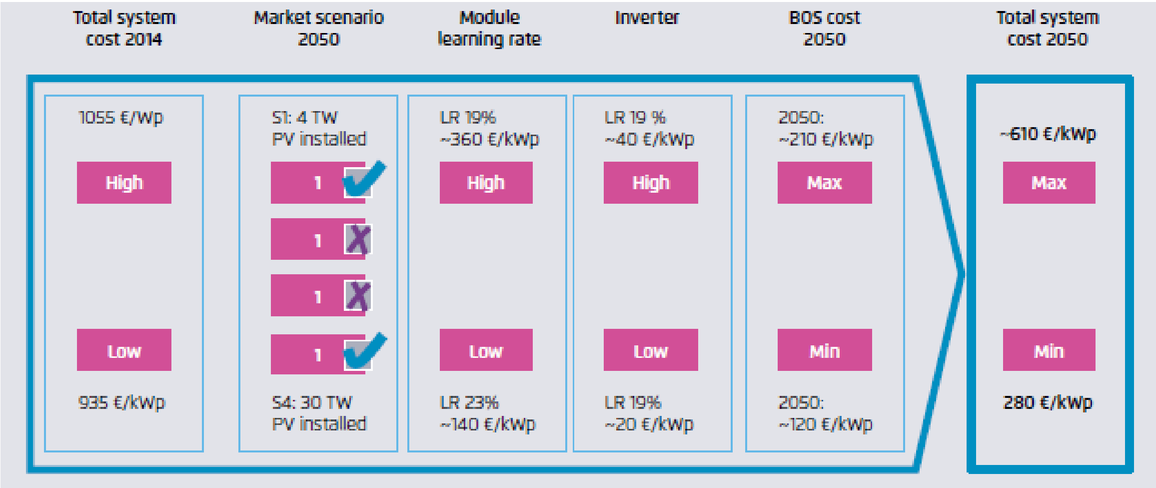
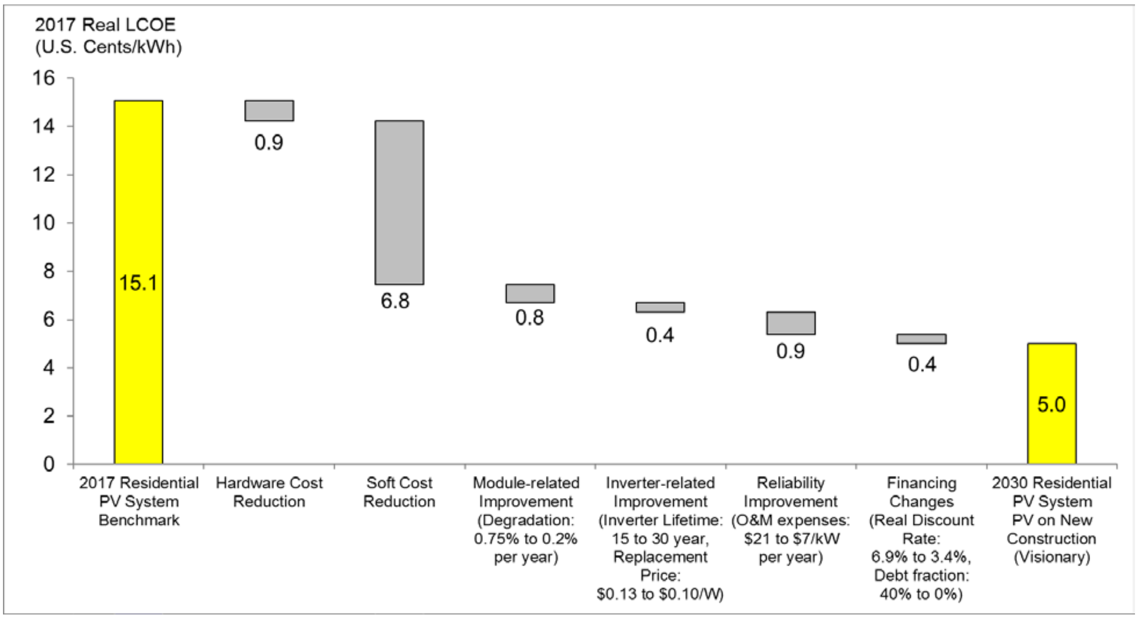


Figure 5 Fraunhofer/Agora Energiewende: a range of PV system costs in 2050 is derived by combining minimum and maximum assumptions



The European PV Technology Innovation Platform [18] has also looked at long-term trends for CAPEX, OPEX and LCEO. They estimate a possible system price of approximately 300 €/kWp for a 1 MW system, with a module efficiency of 30% by 2050. With a 4% real WACC, this leads to LCEO values in Spain of below EUR 20/MWh and around EUR 30/MWh in the UK and Sweden, about 60% less than in 2016. At this point PV will be the cheapest form of electricity generation in most countries (although the cost to the system will be higher once distribution and other integration-related charges are taken into account).

Figure 6 Modeled residential PV LCOE reductions for the US new home construction market visionary pathway in 2030, compared with the Q1 2017 benchmark [17]



2.2 Deployment Targets and Current Status

2.2.1 EU

The legal framework for the overall increase of renewable energy sources was set with the Directive 2009/28/EC, and in their National Renewable Energy Action Plans (NREAPs), the Member States also made estimates for different technologies, including plans for up to 84.5 GW PV by 2020. The EU exceeded this level already in 2014 and should reach well over 130 GW by the end of 2020.

In December 2018 the European Union adopted a recast of the renewables directive (DIR 2018(2001)) which includes a binding renewable energy target for the EU for 2030 of 32%, but with a clause for an upwards revision by 2023. To meet this, Member States are required to submit a National Energy and Climate Plan (NECP) by the end of 2019, including details of renewable energy production capacities.

2.2.2 United States of America

There are no renewable energy targets at federal level. but 29 states plus the District of Columbia, Guam, Puerto Rico, and Virgin Islands, have Renewable Portfolio Standards (RPS[1]) and 22 of these have solar or distributed generation provisions.

At federal level carbon emissions are regulated by the US Environmental Protection Agency (EPA) to assist in cutting GHGs by 17 % by 2020. In 2014 EPA proposed rules for carbon emissions reductions of 30 % (from 2005 levels) by a state-by-state approach to be implemented between 2020 and 2030. In October 2017, EPA proposed to repeal the Clean Power Plan because it exceeded EPA's authority. On December 6, 2018, EPA proposed to revise the New Source Performance Standards (NSPS) for greenhouse gas emissions from new, modified, and reconstructed fossil fuel-fired power plants. After further analysis and review, EPA proposes to determine that the best system of emission reduction (BSER) for newly constructed coal-fired units, is the most efficient demonstrated steam cycle in combination with the best operating practices. This proposed BSER would replace the determination from the 2015 rule, which identified the BSER as partial carbon capture and storage. The primary reason for this proposed revision is the high costs and limited geographic availability of CCS.

The main driver for the installation of photovoltaic power are the different RPSs and the 30% investment tax credit for solar, which was prolonged for a further 5 years in December 2015. In two years, the USA more than doubled their PV power capacity and reached a cumulative PV power capacity of 51.8 GW at the end of 2017.

2.2.3 Japan

Japan has a long history of support for the introduction of renewable energies and photovoltaic power through its sunshine programmes. After the 2011 Great East Japan Earthquake, electricity supply and demand status had become tight in Japan and the efforts to accelerate the use of renewable energy sources were stepped-up. The Feed-in Tariff (FIT) program for renewable energy power generation facilities took effect in July 2012 based on the "Renewable Energy Law".

The 5th Strategic Energy Plan was approved by the Japanese Cabinet in July 2018. The plan aims to increase the self-sufficiency of electricity production from 8% in 2016 to 24% in 2030 and to reduce GHG emissions by 80% until 2050. Despite an increase in the renewable

[1] Regulatory mandate to increase production of energy from renewable sources.

electricity share, the contribution of photovoltaic power with about 75 TWh remained unchanged [21]. At the end of 2018 Japan had installed PV systems with a total of over 55 GW.

2.2.4 China

According to the 13th Five Year Plan (2016-2020) adopted on 16 March 2016, China intends to continue cut its carbon footprint and become more energy efficient. The share of non-fossil energy should increase from 12 % in 2015 to at least 15 % by 2020. Further targets are 18 % fewer carbon dioxide emissions and 15 % less energy consumption per unit of GDP in 2020 compared to 2015. Under this Plan, investment in non-fossil power should be RMB 2.3 trillion (EUR[2] 309 billion) and about RMB 2.6 trillion (EUR 349 billion) are foreseen for the upgrade of the grid infrastructure of which RMB 1.7 trillion are intended for the distribution network [19].

In July 2017, the National Energy Administration (NEA) published the new implementation guide for the 13th Five Year Plan (2016 -2020) [19]. In this guide, 86.5 GW of new PV capacity is foreseen, i.e. 54.5 GW ground mounted systems and 32 GW "Top Runner Programme" installations. Together with the 45 GW of PV capacity foreseen in the Poverty Alleviation Programme of the 13th Five Year Plan and the already connected capacity of over 110 GW at the end of July 2017, this could bring the total capacity to over 240 GW in 2020.

On 31 May 2018, China's National Development and Reform Commission (NDRC), the Ministry of Finance and the National Energy Board issued a common statement were they announced the end of the feed in tariffs for new utility-scale solar projects and the intention to use competitive bidding in the future [20]. The timing of this announcement was a surprise for most in the solar industry. However, the phase out of the feed-in scheme was not completely unexpected after NEA released a draft of the Renewable Portfolio Standard and Assessment Methods, that would create a market for renewable energy certificates (RECs), for comment in March 2018. At the end of September 2018, a second draft was released for comments with an updated target of at least 35% of renewable power by 2030.

During the first six months of 2018, already more than 24 GW were connected to the grid, increasing the total PV power capacity to over 155 GW. It is also worth to mention that the top-runner programme, where module efficiency thresholds are 18% and 18.9% for multi and mono respectively, the poverty alleviation programme and the residential quota are unaffected from the policy change.

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[2] Exchange rate September 2016: EUR 1.0 = CNY 7.45

2.3 Market Mechanisms and Support Policies

There is a wide range of incentive systems across the European Union (see [3] for example), which lead to widely differing incentives and rates of return for a PV investment. The 2009 Renewable Energy Directive stimulated PV deployment throughout the European Union. Many Member States rolled out ambitious incentive policies, providing "feed-in tariffs" for a guaranteed period as the most effective means to ramp-up installed capacity. The resulting increase of the volume of module production led to an enormous cost decrease, nurturing the willingness to install PV systems, even at continuously decreasing feed-in-tariffs. As a result, several Member States found themselves with a huge accumulation of financial commitments, which are being compensated either by a levy on the electricity price or by the taxpayer in general. In consequence, the Member States either throttled back significantly their incentive offerings, or even claimed back retroactively their incentives from PV operators. Moreover, in MS with a relatively high (>20%) share of PV in the overall generation capacity, the take-up and distribution of PV electricity led to an increasing regulatory framework to limit negative repercussions on the national electricity grid.

For centralised systems, many MS now use auctions and tenders that grant the winning bid or bids the price they offered (bidding price) during a certain period. The payment modality is generally similar to the feed-in premium: a payment on top of the price received from selling electricity in the wholesale market to reach the bidding price. They tend to include a "wholesale price balance" mechanism for situations where the wholesale market price exceeds the bidding price, so that the difference is returned to the state or its representative entity.

In consequence, national PV policies are today very diverse across the European Union, distorting positive effects of competition on cost reduction and slowing down progress towards one of the ultimate goals of the Juncker Commission "to become the world number 1 in renewable energies". The following outlines some of the main issues:

<u>Investment Costs</u>

Spot checks in MS show that there are considerable differences in the specific investment costs per unit of capacity installed. They range from below 1000 EUR/ kWp to as much as 2500 EUR / kWp. This is largely due to factors such as a lack of competition between dealers and installers as well as local legislation and regulations, while differences in labour costs and installation requirements have a lower influence. Lack of competition across borders regarding hardware and national differences in installer certification requirements are additional reasons.

Taxation

Across the Member States VAT regimes for renewable energy equipment purchases range from full VAT, reduced VAT to no VAT at all. Moreover, there is a wide range of additional fees for a permit to connect to the grid and other administrative fees. They are applied on a per-installation basis (and can be as high as 1000 EUR), on an installed power basis or a combination of both. Member States also have different approaches to taxation and general permitting conditions, and even to the applicability of income tax and definition of commercial activity. All these factors contribute to quite heterogeneous market conditions, which influence the cost and therefore the investment in PV systems.

Financial Costs

Depending on the local interest rate applied, cost of capital can be a significant part (up to 50%) of LCoE. Across the member states, the rates applied by banks vary according to their own risk assessment, and by the share of debt financing. On top of this, there is credit default insurance, and other property-specific charges such as increased fire insurance.

Operation and Maintenance Costs

There is a lack of robust data available regarding maintenance and repair costs of small PV systems, or that regarding compensation for degradation or failures. As a conservative approach, in JRC analyses both components together are assumed to be about 2% per year of the initial investment, with the caveat that these need to be closely watched in future. Some LCoE studies use lower values and often it is unclear, for instance, to what extent the replacement of inverters or other components is accounted for. This can be a significant factor for long-term economic assessments, as once the initial investment has been amortised and/or the feed-In-tariff scheme ended, O&M will be the only cost.

For utility-scale systems, O&M costs have declined substantially over the last years, reportedly by 50% since 2015. This is welcome but means that quality of the components, the installation and operation need to be tightly controlled to maintain the foreseen financial return. For ground-mounted systems, land rent, if applicable, needs to be included in this cost category.

Permitting

Even though installing PV on, or integrated into buildings is now quite well accepted by local planning authorities, this is not the case for larger (>1 MW) sized, ground-mounted PV arrays. Such systems are the most cost-effective approach for deploying PV electricity. There are many differences across MS regarding eligibility and the possible incentives (usually small or none). Even though today many of the large systems are financed via power purchase agreements, meaning entirely financed by investors, there is no common framework for allowing the construction of such systems.

Grid connection, storage and self-consumption

The development of PV in a post FiT-market is crucially dependent on the possibility to either use or store the electricity generated directly (by simple or collective self-consumption) or to have access to a metering arrangement with the grid operator, for instance with net metering scheme. Up to now the administrative situation for self-consumption has been very heterogeneous across the EU, but the 2018 recast of the renewables directive (RED-II) and the energy market directive (EMD-II) ensure the right to simple self-consumption (by one consumer/generator with to be defined levels of financial support). These directives also establish definitions and basic requirements for collective activities, via renewable energy communities in RED-II and citizen energy communities in EMD-II (Table 1). However, the actual conditions depend on the transpositions into national laws, and this is an on-going process [22].

Table 1 Main characteristics of energy communities in EU directives (after [23])

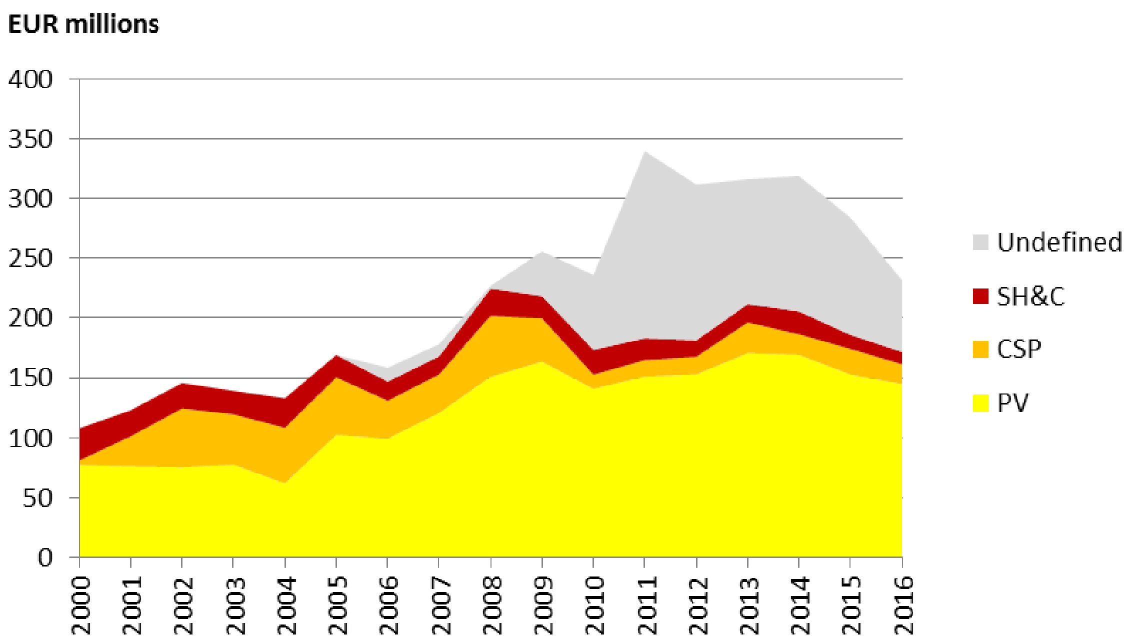
CHARACTERISTIC	RENEWABLE ENERGY COMMUNITY (RED-II)	CITIZEN ENERGY COMMUNITY (EMD-II)
MEMBERSHIP	Natural persons, local authorities, including municipalities, or small enterprises and microenterprises, provided that for private undertakings their participation does not constitute their primary commercial or professional activity	Natural persons, local authorities, including municipalities, or small enterprises and microenterprises
GEOGRAPHIC LIMITATION	The shareholders or members must be located in the proximity of the renewable energy projects that are owned and developed by the Renewable Energy Community	No geographic limitation, MS can choose to allow cross-border Citizen Energy Communities
ALLOWED ACTIVITIES	Can be active in all energy sectors. Production, consumption and selling of renewable energy	Electricity generation, distribution and supply, consumption, aggregation, storage or energy efficiency services, generation of renewable electricity, charging services for electric vehicles or provide other energy services to its shareholders or members
TECHNOLOGIES	Limited to renewable energy technologies	Technology neutral

2.4 R&D investment and patenting activity

FS-UNEP [24] report that globally R&D investments in solar energy reached US$ 6.6 bn in 2018, with US$ 4.4 coming from corporate sources and the remainder from public budgets. The total represents almost a doubling since 2016, largely driven by increased corporate spending. Solar has a 50% share of R&D spending on renewables, underlining the innovation potential in the sector. No regional breakdown is available for 2018, but the EU accounted for 19% of global solar R&D investments in 2017.

To get better picture at EU level and for PV specifically (the above data refer to all solar technologies, even if PV has by far the largest share), the JRC [25] analyses the information collected by the IEA from its member countries. This is subject to several limitations both in terms of coverage (China and India are not in the historical data), disaggregation and completeness Figure 7 shows the data for R&D investment by EU member states in solar technologies from 2000 to up to 2016. If confirmed, the latest value[3] (EUR 235 m) would be a fall from over EUR 300 m in 2014. PV takes the major share compared to concentrating solar power and solar thermal heating. Up the 2010 there is consistent growth, but subsequently the level appears to have plateaued at about EUR 150 m. The reasons for this not fully clear: the downturn in EU-based manufacturing can have played a role in reducing R&D spending.

Figure 7 Public investment by EU member states in solar energy technologies, as reported to the IEA.



[3] This value is below that reported in the BNEF/UN Environment study, which used a wider range of data sources.

Also, its not clear to what extent trends in public spending on R&D for closely related technologies (e.g. for power systems, grid integration and for battery storage) are reflected here. If the EU is to continue its role as a PV technology leader, it will need to maintain or increase the level of R&D investment going forward.

Concerning R&D investments being made by public and private organisations, patent statistics can provide a route to analyse key players and trends (albeit with a 3 to 4 time lag given the process for processing applications). The JRC [26] has analysed data from Patstat (European Patent Office). Figure 8 shows the trend in counts of patent families[4] per year from 2000 to 2014 for three categories: all patent families, so-called "high-value" patent families i.e. application made to two or more patent offices, and granted patent families. Overall filings grew strongly from 2000 up to 2012, but have decreased in 2013 and 2014. In terms of global regional breakdown for 2014, China took the largest share when considering all patent family applications, followed by Japan and Korea. However if just the "high-value" patent families are considered (Figure 9) a different picture emerges, with Japan as leader and the EU in second positon[5].

Figure 10 shows the specialisation index, representing the patenting intensity of selected countries and regions for the period 200 to 2014 [26]. The EU value was consistently below the global average reference level, implying that patenting activity has been less specialised in photovoltaics than in some other regions such as Japan and Korea.

When the patent data is used to generate estimates of R&D investments, a similar time trend emerges, with a peak of approximately EUR 8.6 bn in 2011 and a subsequently fall to EUR 5.9 bn in 2013. For the EU countries in 2014 the highest investments were in Germany, France, UK, the Netherlands and Italy, in that order. The same data is used to map the level of activity of individual companies and organisations filing patent data. Table 2 lists the top 50 globally for 2014. Fourteen EU organisations are represented, of which 5 are research organisations (CEA, ECN/TNO, Fraunhofer and IMEC).

[4] Patent documents are grouped in families, with the assumption that one family equals one invention.

[5] The LCEO Photovoltaics Technology Development Report provides more details on the breakdown in terms of patent classes.

Figure 8 Global trend in patent filings under PV related families (CPC Y02E 10/50 series).

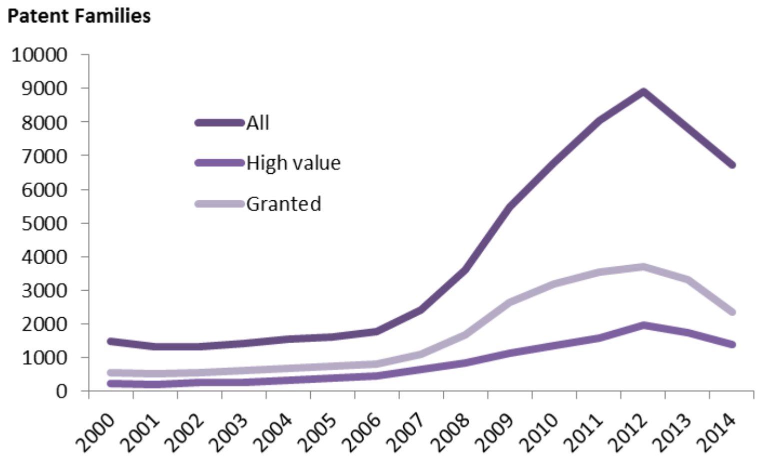


Figure 9 Regional breakdown for patent filings under PV related families (CPC Y02E 10/50 series).

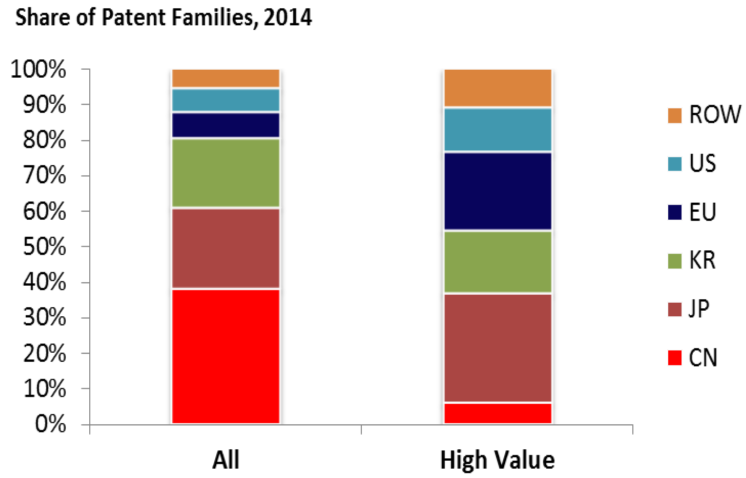


Figure 10 Evolution of the specialisation index, representing the patenting intensity of selected countries and regions compared to the global average [26].

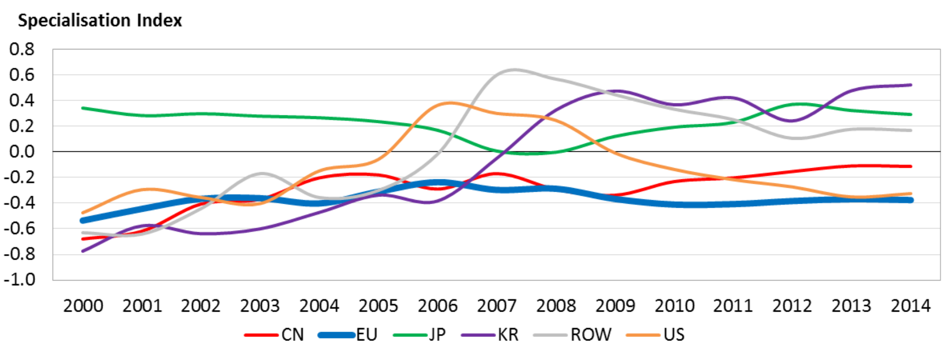


Table 2 Top 50 organisations for high value patents in 2014 (EU-based shown in bold)

Organisation	Patent Filings		
LG ELECTRONICS INC	42	BOEING COMPANY	16
TOSHIBA	40	**Evonik Degussa Gmbh**	**16**
SHARP CORPORATION	37	MITSUBISHI MATERIALS CORP	16
SAMSUNG ELECTRONICS CO LTD	35	MOTECH IND INC	16
CEA	**33**	**Robert Bosch Gmbh**	**16**
SUNPOWER CORP	33	ROHM & HAAS ELECT MATERIALS	16
Shin-Etsu CHEMICAL CO	32	**Sabic Global Technologies B V**	**16**
PANASONIC INTELLECTUAL PROPERTY MANGEMENT CO LTD	28	TORAY INDUSTRIES	16
ECN (now TNO)	**27**	UNIV KYUSHU NAT UNIV CORP	16
HYUNDAI MOTOR COMPANY	26	**ARCELORMITTAL FRANCE**	**15**
SEKISUI CHEMICAL CO LTD	25	LG CHEMICAL LTD	15
FUJIFILM CORP	23	**Merck Patent Gmbh**	15
KYOCERA CORP	23	NITTO DENKO CORPORATION	15
RICOH COMPANY	23	**TNO**	**15**
UNIV MICHIGAN	23	**ABB TECHNOLOGY AG**	**14**
HERAEUS PRECIOUS METALS NORTH AMERICA CONSHOHOCKEN LLC	22	DOW GLOBAL TECHNOLOGIES LLC	14
IND TECH RES INST	22	DU PONT TEIJIN FILMS US LTD	14
KANEKA CORP	22	HITACHI CHEMICAL CO LTD	14
SAMSUNG SDI CO LTD	22	SOLARCITY CORPORATION	14
BEO TECHNOLOGY GROUP CO LTD	21	SUNSHINE PV CORP	14
Fraunhofer Society	**21**	Brookhaven Science Associates, LLC	13
Heraeus Deutschland GmbH	**21**	**Cambridge Enterprise Ltd**	**13**
MITSUBISHI ELECTRIC CORP	21	**Eni Spa**	**13**
TOKYO INST TECH	21	JAPAN SCIENCE & TECH AGENCY	13
CNRS - Centre national de la recherche scientifique	**20**		
LSIS CO LTD	20		
KING ABDUL AZIZ CITY FOR SCIENCE AND TECHNOLOGY	19		
SUNGROW POWER SUPPLY CO LTD	19		
ADEKA CORP	18		
IBM (INTERNATIONAL BUSINESS MACHINES CORPORATION)	18		
TOKYO OHKA KOGYO CO LTD	18		
ASAHI GLASS CO LTD	17		
IMEC	**17**		
SUMITOMO ELECTRIC INDUSTRIES	17		
TOTAL MARKETING SERVICES	**17**		
Basf Se	**16**		

3 MARKET OVERVIEW

3.1 PV Value Chain and Jobs

The photovoltaic industry has grown rapidly from a small group of companies and key players into a global business. It takes in an extensive value chain, from raw materials to device production to system installation, operation and recycling. Annual global investment in solar energy was US$ 141.1 bn in 2018 [24]. This is down 22% on 2017, but overall has been growing with average CAGR of 20% since 2004 (albeit with falls in 2012 and 2016 due to specific market conditions). The reasons for the 2018 drop relate to both lower capital costs for PV systems and a decline of PV installations in China compared to 2017.

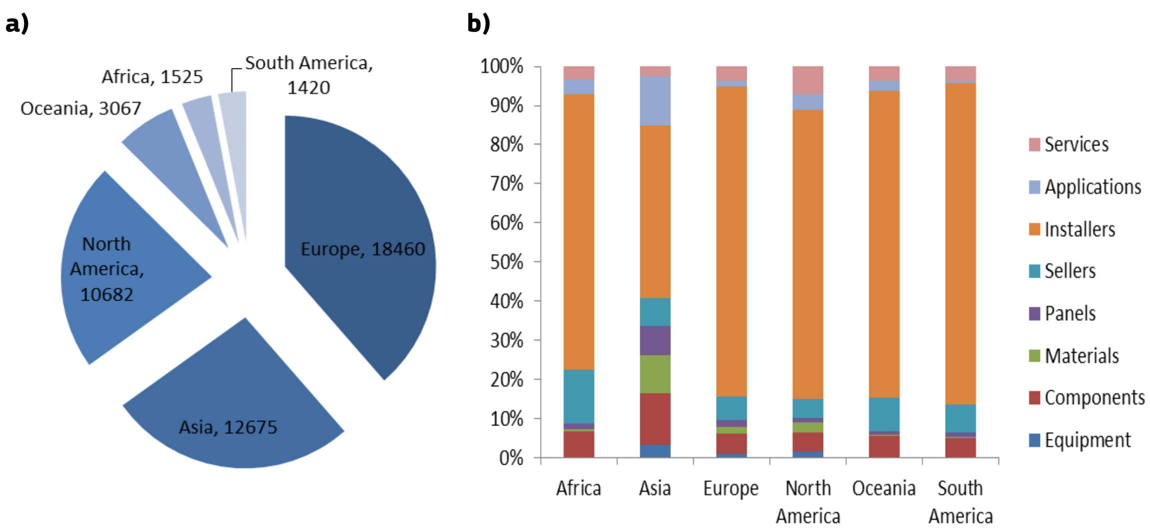
The PV sector provided 3.265 million jobs in 2017 [27], the largest of all the renewables. The ENF industry directory list almost 48 000 companies worldwide[6] and gives some insight on the distribution and sector-breakdown. Figure 11 shows the number of entries per continent and the corresponding breaking down into seven categories covering the value chain. Installers are by far the largest single category. That said, in Asia the proportion of installers is less than for other continents. This may reflect hat installations in the large Chinese market are typically large-scale ground mounted systems, whereas in Europe and the US the residential rooftop market has been significant, involving large numbers of smaller companies.
The EU PV market was reportedly EUR 11.2 billion in 2017 [28]. Approximately 18 000 European companies are active in all segments of the value chain (Figure 13), although their pioneering role in PV cell and module production has been eclipsed by the rise of the Asian manufacturers. Areas of continuing strength include silicon production, equipment manufacturing, inverters and project development and management [29, 30]. Figure 13 shows the distribution of companies in the EU member states, and is dominated by those with high PV deployment and a strong industrial base (the top five are Germany, UK, Italy, the Netherlands and Spain). In trade terms, the EU remains a net importer, with a negative balance of EUR 212 million in 2016 [26].

In terms of employment, EurObserv'ER report 90 800 jobs (direct and indirect) in the EU in 2017 [28], with Germany accounting for almost one third of these, followed by UK, Italy, France and the Netherlands. In terms of the breakdown over the value chain, SolarPow-

[6] The ENF directory provides a listing of companies and certain details on the category (or categories) in which they are active. It does not track turnover, staff or volume of output. In many cases, solar PV may be only one part of a company's activities and it may not report disaggregated operational data. Also the rapid growth and changes in the PV industry and its dispersed nature pose challenges for keeping information up to date. Despite these caveats, we consider the directory to provide a good indication of the breakdown and scale of activities.

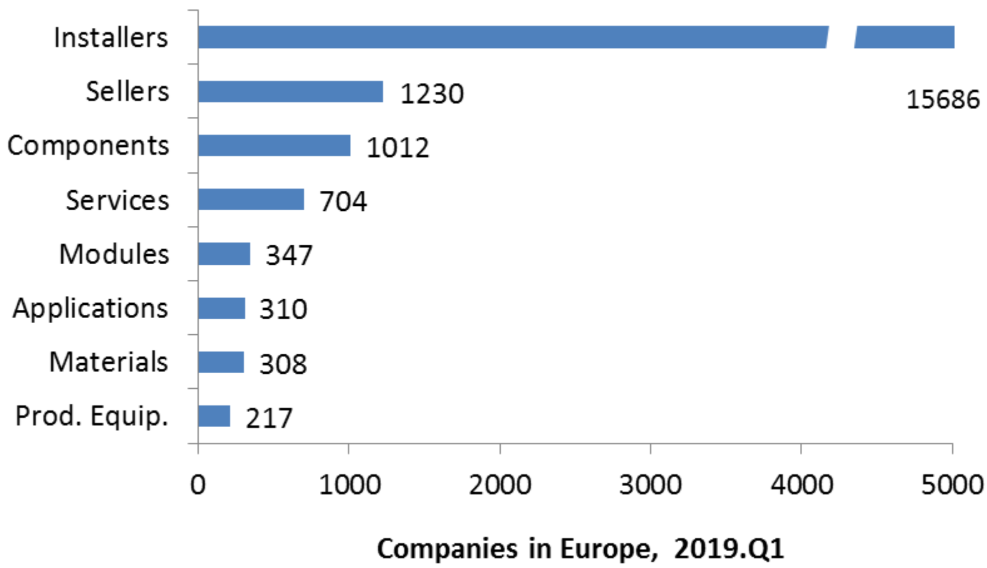
erEurope's analysis in 2016 [31] concluded that the upstream part (materials supply and component manufacturing) account for 25%, with 75% on downstream side (engineering, installation, O&M and decommissioning). The same study predicts that the sector can provide over 300 000 jobs by 2030, assuming PV capacity rises to well over 300 GW to help achieve the EU's 2030 target for renewable energy.

Figure 11: Breakdown of ENF industry directory entries by a) continental coverage, and b) by continent and sector



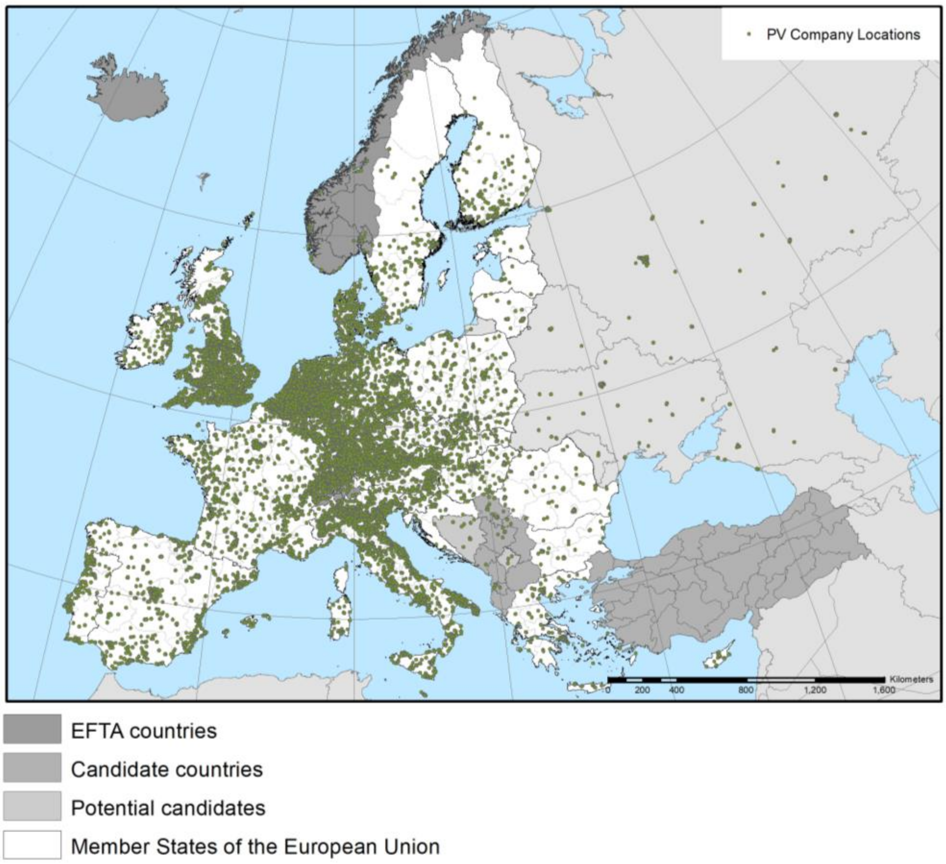
(data: ENF Industry Directory 2019/Q1, analysis : JRC)

Figure 12 Sectorial breakdown of companies in the EU and Switzerland.



(data: ENF Industry Directory 2019/Q1, analysis : JRC)

Figure 13 Locations of ENF industry directory entries (all sectors) in Europe



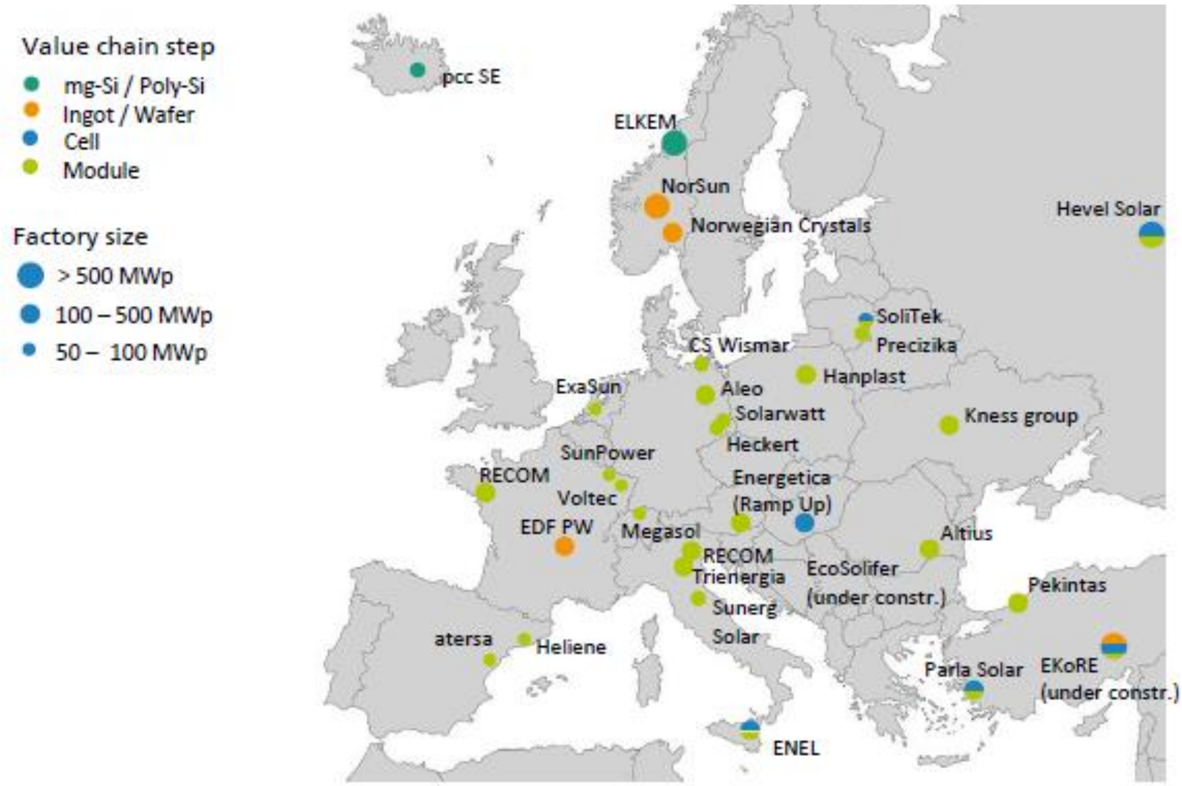
(data: ENF Industry Directory 2019/Q1, analysis : JRC)

3.2 Manufacturing Sectors

Over the last 20 years, the photovoltaic industry has grown from a small group of companies and key players into a global business where information gathering is becoming increasingly complex. The PV industry consists of a long value chain from raw materials to PV system installation and maintenance. Often there is a strong focus on solar cell and module manufacturers, but there is also the so-called upstream and downstream industries. The former include materials, polysilicon production, wafer production and equipment manufacturing, while the latter encompasses inverters, balance of system (BOS) components, system development, project development, financing, installations and integration into existing or future electricity infrastructure, plant operators, operation and maintenance, etc. In the near future, it will be necessary to add (super)-capacitor and battery manufacturers as well as power electronics and IT providers to manage supply and demand and meteorological forecasts.

Along the value chain of photovoltaics, European Union companies and institutions still have a reasonable market position in the areas of manufacturing equipment, polysilicon production, materials & chemicals, inverters and electrical components, project development, EPC, operation and maintenance as well as topics related to grid integration, electrical system design, fundamental and applied research. However, solar cell and module manufacturing has declined sharply since 2010. Figure 14 shows Fraunhofer's analysis of the situation in 2018 for silicon production, cell and module manufacturing – the majority of units are at the scale of 100s of MW [32].

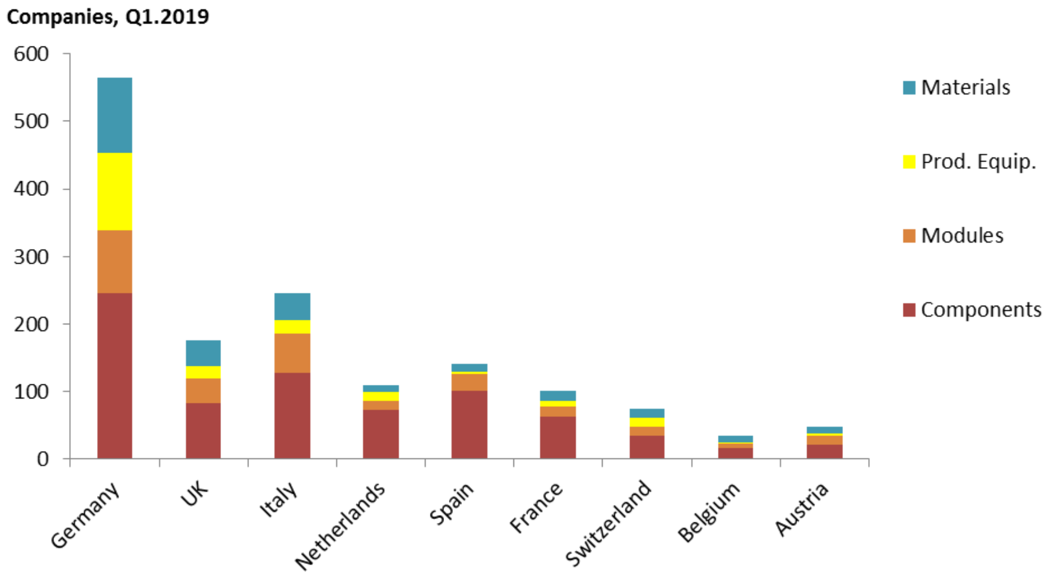
Figure 14 Companies and production sites in Europe for PV manufacturing (source Fraunhofer [32])



3.2.1 Manufacturing Equipment

Most of the equipment manufacturers are not pure solar players. In general, these companies manufacture equipment for a wider range of process technologies and industries. If a company does not report the share of the solar business segment in its accounts, it is impossible to evaluate the respective percentage or value. The ENF directory lists 2017 companies in the production equipment category, with a strong concentration in Germany (Figure 15).

Figure 15 Upstream PV value chain, showing the distribution of companies from the EU and Switzerland involved in the upstream part of the value chain; note concentration of production equipment in Germany.



(data: ENF Industry Directory 2019/Q1, analysis : JRC)

3.2.2 Polysilicon Production

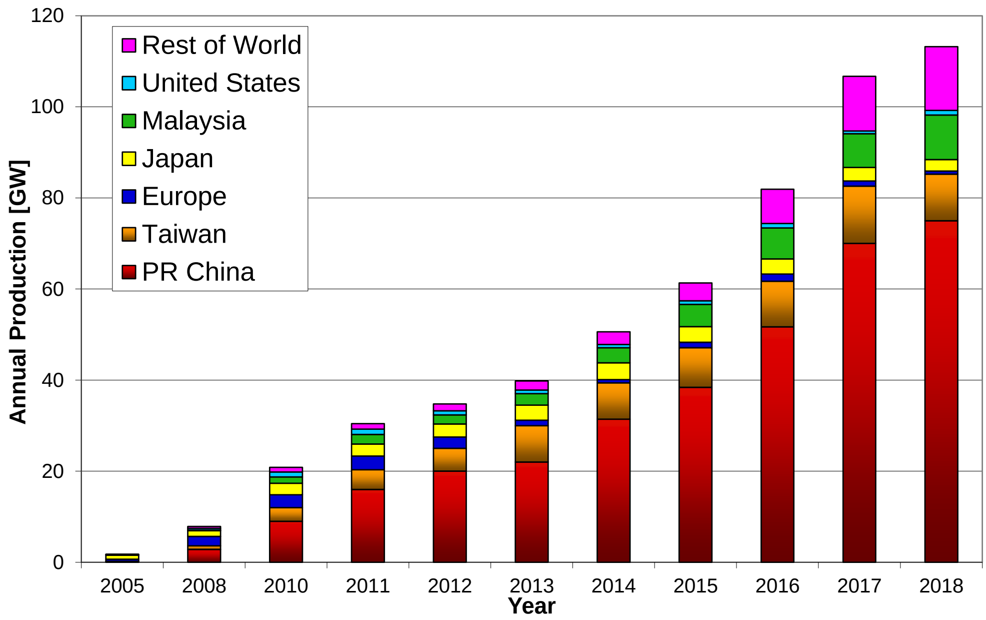
Since 2000, the rapid growth of the PV industry led to a situation where, between 2004 and early 2008, the demand for polysilicon outstripped the supply from the semiconductor industry. Prices for purified silicon started to rise sharply in 2007, and in 2008 prices for polysilicon peaked at around USD 500/kg, resulting in higher prices for PV modules. This extreme price hike triggered a massive capacity expansion, not only by established companies but also amongst many new entrants. The top 3 silicon manufacturers produced about 45% of the total 2018 production. In September 2018, polysilicon spot prices were in the USD 7 to 13/kg (EUR 6.09 to 11.30/kg) range

Projected silicon production capacities for 2018 vary between 475 000 tonnes [20] and 578 000 tonnes [21]. It is estimated that about 30 000 tonnes will be used by the electronics industry. In addition, possible solar cell production will depend on the material used per Wp. The current average worldwide is about 3.5 g/Wp for mono- and 4.3 g/Wp for multicrystalline silicon solar cells.

3.2.3 Solar Cell Production

Figure **16** shows the growth of global cell[7] production from 2005 to 2018. The reported data for 2018 vary between 110 GW[8] and 120 GW and estimates for 2019 are in the 125 to 140 GW range. The uncertainty in these is due to the highly competitive market environment, as well as the fact that some companies report production figures, while others report sales and again others report shipment figures. JRC analysis of stock market reports of listed companies, market reports and information from colleagues led to an estimate of 113 GW [33]), representing an increase of about 7% compared to 2017; an increase in the lower two digit range is expected for 2019.

Figure 16 World PV cell/module production from 2005 to 2018 [33]



Uncertainties in Production Statistics:

- Only a limited number of companies report production figures for solar cells.
- Shipment figures can include products from stock, already produced in the previous year.
- Some companies report shipments of "solar products" without a differentiation between wafers, cells or modules.
- The increasing trend towards Original Equipment Manufacturing (OEM) increases the potential of double counts.

7 **Solar cell production** means:
- In the case of wafer silicon based solar cells, only the cells
- In the case of thin-films, the complete integrated module
- Only those companies which actually produce the active circuit (solar cell) are counted
- Companies which purchase these circuits and make solar modules are not counted.

8 All values are based on the available data in February 2019.

After the rapid increase of the annual production in China and Taiwan since 2006 a new trend emerged in 2014 to increase production capacities in other Asian countries like India, Malaysia, Thailand, the Philippines or Vietnam. However, Chinese companies make the lion's share of these investments. Another trend was the rapid increase in OEM volumes since 2011, which allowed larger companies to increase their shipment volumes significantly without adding new capacity of their own.

One of the fastest growing companies is Tongwei Solar, part of the Tongwei Group, a private company with core business in agriculture and new energy, set up only five years ago in 2013. In 2011, Tongwei Group signed an integrated PV strategic cooperation agreement with Xinjiang Government, which included 50 000 tonnes solar-grade polysilicon project, 3 GW solar wafer and solar cell project, as well as 5 solar power plants. In 2018, Tongwei reported an increase of its annual production capacity to 80 000 tonnes of polysilicon, 12 GW for solar cells and solar modules. With a polysilicon production of about 17 000 tonnes and solar cell shipments of 3.85 GW, the company already ranked 6th for both products in 2017 [3].

The European market share in solar cell manufacturing had peaked in 2008 in percentage terms with 26% (2.1 GW) and in 2010 in terms of power capacity with 3.1 GW (12%). In 2018, European production only accounted for about 1 GW - less than 1% of the worldwide cell production.

3.2.4 Solar Module Production

Companies with annual sales it the GW range increasingly dominate module production. Table 3 shows the "top-10" for 2018 as analysed by IEA-PVPS [34]. Nonetheless, actual manufacturing volumes are extremely difficult to monitor, because integrated manufacturers sell both modules made in house and as "own label" but contracted to an original equipment manufacturers (OEM), which may manufacture modules for a number of different companies.

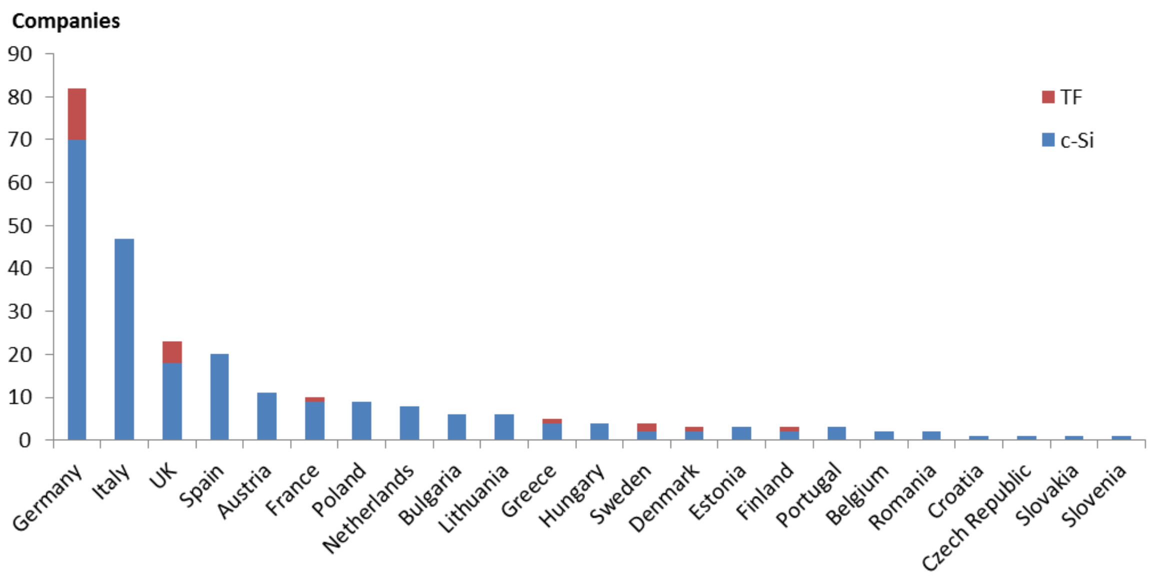
Germany-based RECOM's overall production capacity (including plants in France and Italy) reportedly exceeded 1 GW in 2018, making it the largest European producer. In June 2018 Recom announced it had bought the machinery of the Polish factory of Jabil (2 GW). Manufacturing should restart in the first half of 2019, probably in Armenia. Overall, however, the situation in Europe remains fragmented. The ENF directory lists over 250 companies spread of 22 countries, as shown in Figure 17.

Although it does not specify individual production capacities, given that total EU module production is about 2 GW, the implication is that that most of these operations are at low volume. Figure 18 shows the situation for speciality products for roofs and buildings. Considerable activity is taking place with over 90 companies involved, although the market share for such products remains very small.

Table 3 Leading PV module manufacturers 2018 (source [34])

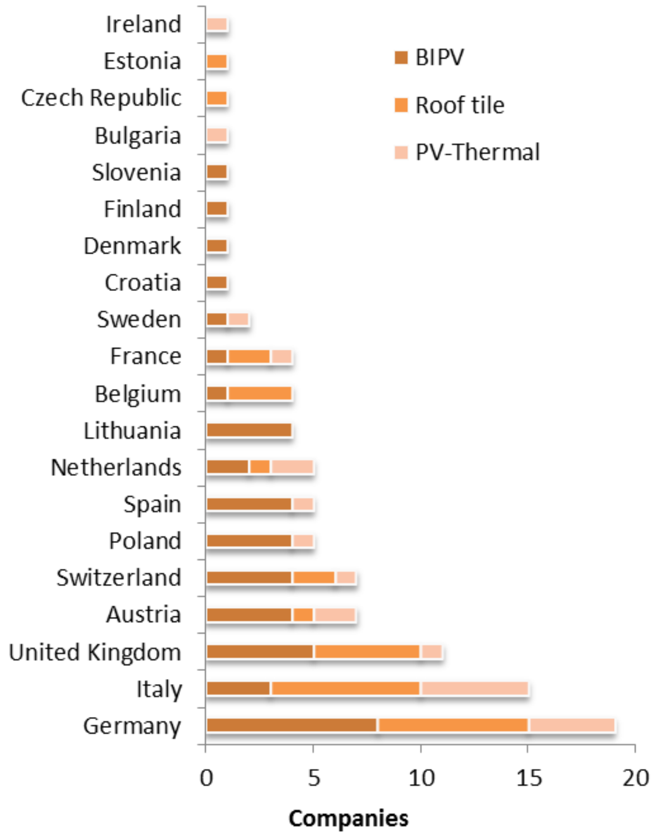
RANK	COMPANY	COUNTRY	VOLUME GW
1	JinkoSolar	Cjhina/Malaysia	11.17
2	JA Solar	China/Malaysia	8.50
3	Trina Solar	China/Thailand/Vietnam	7.54
4	Canadian Solar	Canada/China/Brazil/Vietnam	6.82
5	LONGi Solar	China	6.58
6	Hanwha Q CELLS	Korea/China/Malaysia	5.60
7	GCL System Integration Technology	China	4.57
8	Risen Eenrgy	China	3.35
9	Shunfeng Int. Clean Energy/Suntech	China	3.30
10	Chint Electrics	China	3.15

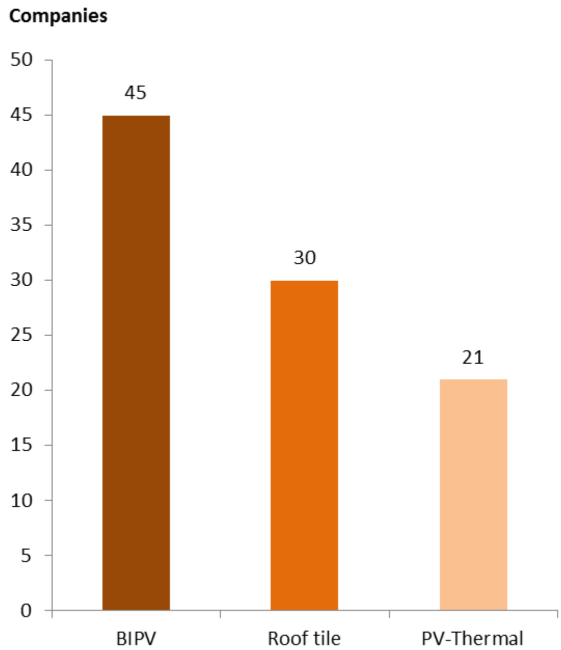
Figure 17 Country breakdowns of European-based companies involved in manufacture of crystalline silicon and thin film modules.



(data: ENF Industry Directory 2019/Q1, analysis : JRC)

Figure 18 Distribution of European companies involved in manufacture of building integrated (BIPV), roof tile (shingle) and PV - thermal hybrid products



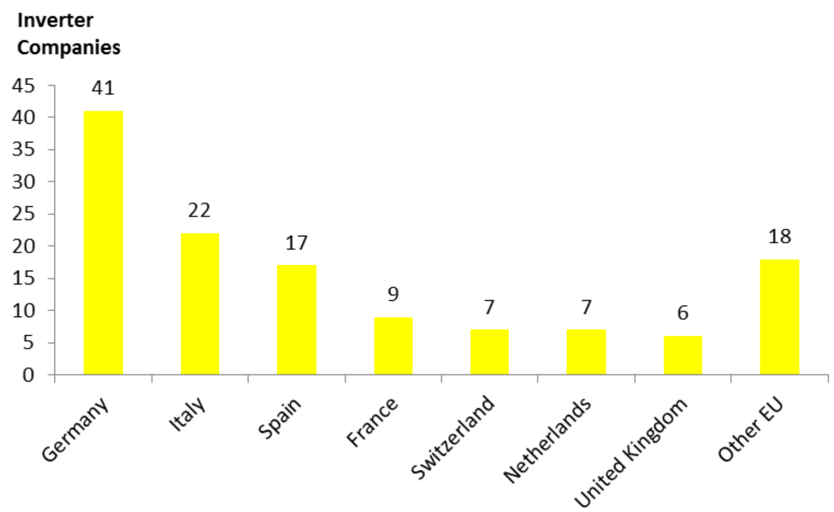


(data: ENF Industry Directory 2019/Q1, analysis : JRC)

3.2.5 Inverter Production

The worldwide market value for inverters in 2018 is in the range of USD 4.5 to 5 billion. Table **4** includes a listing of the top providers of inverters for utility scale systems (> 4 MW) in 2018. Almost 40 European companies are active in this area and five are in the top 10. German and Italian-based companies are particularly strong in this area.

Figure 19 Leading European countries in terms of number of companies in inverter sector.



(data: ENF Industry Directory 2019/Q1, analysis : JRC)

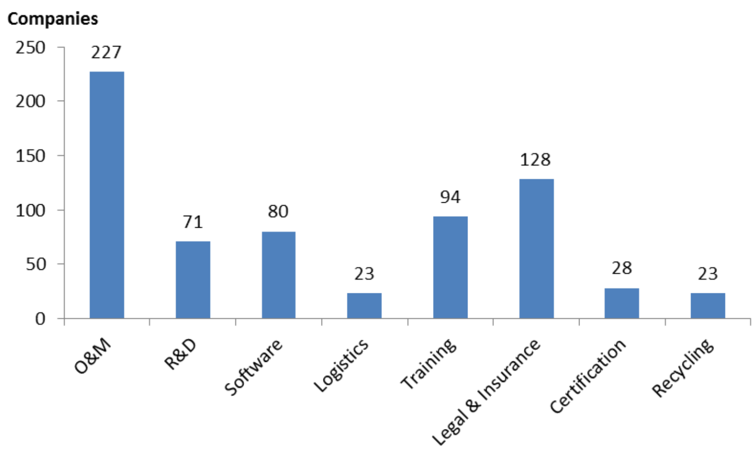
3.3 Downstream Sector

The downstream sector constitutes a very significant part of PV system investments. It includes project development, engineering, procurement & construction, operations and maintenance and decommissioning. These involve number of rapidly developing technology areas: e.g. system integration, digitisation, grid support capabilities, meteorological forecasting and now-casting, operational data processing, system condition monitoring, innovative maintenance, end of life management etc.. Table **4** shows a listing of leading contractors for EPC and O&M, and includes a significant European presence. As for manufacturing, the majority are not pure solar players. Several EU companies are major international players for PV systems development and operation: EU companies are also at the forefront of PV module re-cycling technology, although the volume of decommissioned products is still insufficient for full commercial viability. The ENF Directory uses a slightly different definition of subcategories, but as shown in Figure 20, the number companies (704) and broad range of activities confirms the economic weight of the downstream sector.

Table 4 Wiki-Solar listing of inverter manufacturers, engineering, procurement and commissioning (EPC) and operation and maintenance (O&M) contractors for utility scale systems at end 2018 [35]

Inverters	EPC	O&M
SMA Solar Technology [DE]	First Solar [US]	First Solar [US]
Ingeteam [ES]	Sterling & Wilson [IN]	SunEdison [US] (in insolvency)
Asea Brown Boveri [CH] including Power-One [US]	Swinerton Renewable Energy [US]	Enerparc [DE]
Schneider Electric [FR]	Abengoa Solar [ES]	juwi AG [DE]
TMEIC (Toshiba Mitsubishi-Electric Industrial Systems) [JP]	juwi AG [DE]	Bharat Heavy Electricals [IN]
SunGrow [CN]	Enerparc [DE]	Elecnor [ES]
GE Energy [US]	SunEdison [US]	Cypress Creek Renewables [US]
TBEA (Tebian Electric Apparatus) [CN] including SunOasis	Belectric [DE] (now part of: Innogy)	EDF Energies Nouvelles [FR]
Fimer SpA [IT]	Bharat Heavy Electricals [IN]	IB Vogt Solar [DE]
Siemens [DE]	Mortenson Construction [US]	Conergy [DE] (now part of: Kawa Capital)
Santerno [IT]	Acciona Energía [ES]	Signal Energy [US]
AE Advanced Energy [US]	Elecnor [ES]	Martifer [PT] (now part of: Voltalia)
Emerson [GB]	McCarthy Building [US]	TBEA SunOasis [CN]
Bonfiglioli [IT]	Mahindra [IN]	BayWa r.e. [DE]
Satcon [US]	SunPower Corporation [US]	Sterling & Wilson [IN]
Kaco [DE]	Bechtel [US]	SunPower Corporation [US]
Fuji Electric [JP]	Canadian Solar [CA]	Canadian Solar [CA]
Huawei [CN]	ACS Group [ES]	Saferay [DE]
GP Tech [ES]	TSK Group [ES]	Biosar Energy
Hitachi [JP]	Kawa Capital (incl. ex. Conergy [DE])	SMA Solar Technology [DE]
Guanya [CN]	Eiffage [FR]	Grupo Ortiz [ES]
	Tata Power [IN]	DEPCOM Power [US]
	Hanwha Q.Cells [KR]	Vikram Solar
	RCR Tomlinson [AU] (in insolvency)	TSK Group [ES]
	BayWa r.e. [DE]	Metka-Egn [GR]
	IB Vogt Solar [DE]	Kyudenko Corporation [JP]
		Consolidated Edison Development [US]
		RES Group [GB]
		EDF Renewable Energy [US]

Figure 20 Breakdown of European-based companies providing services to PV manufacturers and operators.



(data: ENF Industry Directory 2019/Q1, analysis : JRC)

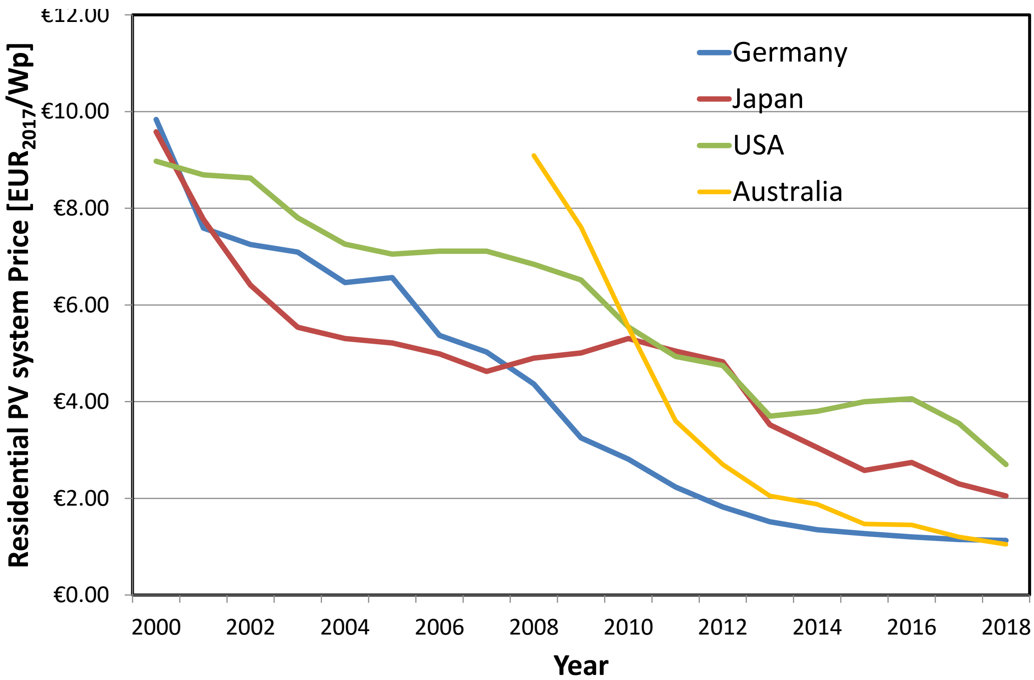
3.4 PV System Prices

3.4.1 Residential Photovoltaic System Prices

Over the last decade, prices for residential grid-connected PV systems have decreased significantly, as shown in Figure 15. The increase in PV system prices in Japan, between 2007 and 2010 as well as the increase in the USA from 2014 to 2016 are due to changes in exchange rates; in the local currency the prices fell. Please note that customers in the USA still receive a 30% federal tax credit, which in part is responsible for the overall higher prices.

In September 2018 the online site PVinsights gave a worldwide average price for a residential system without tax as USD 1.32/Wp (EUR 1.15/Wp) [36]. Adding a surcharge of EUR 0.15/Wp for fees, permits, insurance, etc., the benchmark for installed PV system costs is EUR 1 300 /kWp without financing and VAT.

Figure 21 Residential PV system price development [3]



(*Sources*: IEA PVPS, BSW, DoE SunShot Initiative, Eurostat, Solar Choice, OECD key economic data)

3.4.2 Power Purchase Agreement Prices

Since 2009 the prices for power purchase agreements (PPA[9]) have decreased by almost 70% reaching 50 USD/MWh in sunnier regions of the world with reasonable financing costs. 2016 already saw a number of record breaking power purchase agreements (PPA) contracts and bids below USD 30/MWh and the trend for bids below 25 USD/MWh has accelerated in sun rich regions in 2017 and 2018. These very low bids and PPAs, especially in the Middle East, but also Chile and the USA are only possible through a combination of excellent solar resource, high debt shares and very low debt costs as well as the fact that some tariffs are indexed to inflation.

Besides these extremes, it is noteworthy to mention, that the first joint solar and wind auction in Germany in April 2018 ended with contracts awarded only to solar projects for an average price of EUR 46.70/MWh [37]. In Spain private PPAs are increasingly used to install large PV plants. Until October 2018 PPAs with more than 1.8 GW were already signed. Other examples are:

- The Salvadorean energy distribution company DelSur opened a renewable energy auction for the procurement of 170 MW capacity in October 2016. The results were made public in January 2017. 4 PV projects with 120 MW capacity were successful at prices between USD 49.55 and 67.24/MWh (EUR 41.29 and 56.03/MWh)
- In July 2017 the Polish Energy Regulatory Office (ERO) published the results of the auction held on June 2017. This auction addressed RES installations with less than 1 MW of installed power. The largest share of bids came for PV installations, but wind and small hydro was eligible as well. The range of winning bids was between PLN 195 and 408/MWh (EUR[10] 45.25 – 94.88/ MWh). It is believed that the winning solar bids are more at the higher end.
- In April 2018 Senegal's Commission de Régulation du Secteur de l'Electricité (CRSE) announced the tender results to build two 60MW solar PV plants. The winning bids were EUR 38.026/MWh and EUR 39.83/MWh. The projects will be financed under the IFC-backed Scaling Solar initiative.
- In July 2018 the results of the 2 GW Solar Energy Corporation of India solar tender were announced. The winning bids ranged between INR 2.44 and 2.71/kWh (EUR[11] 0.029 – 0.032/kWh),

[9] A PPA is a contract between two parties, one that generates electricity (the seller) and one that seeks to purchase electricity (the buyer). It defines all of the commercial terms for the sale of electricity between the two parties, including when the project will begin commercial operation, schedule for delivery of electricity, penalties for under delivery, payment terms, and termination. A PPA is the principal agreement that defines the revenue and credit quality of a generating project and is thus a key instrument of project finance. There are many forms of PPA in use today, varying according to the needs of buyer, seller, and financing counterparties.
Source Wikipedia: https://en.wikipedia.org/wiki/Power_purchase_agreement#cite_ref-1

[10] Exchange rate: 1 EUR = 4.3 PLN

[11] Exchange rate: 1 EUR = 84 INR

- In July 2018, the French Ministry of Ecological and Solidarity-based Transition announced that it awarded 720 MW of PV to 103 projects in its fourth major large-scale solar auction, for projects ranging between 500kW and 17MW capacity. The average price for all projects was EUR 58.20 and for the category of PV plants with capacities between 5 and 17 MW it was EUR 52.00/MWh.
- In September 2018, the results of Jordan’s Round 3 solar PV auction were announced. The auction received bids between USD 24.88 and 35.81/MWh.

However, PPAs do only reflect partly the actual economic competitiveness of a solar project. When comparing it to other projects, it is also important to know what the tax regime for such a project or competing power projects have, e.g. in the USA PV projects qualify for the federal energy ITC programme (30 %) and the Modified Accelerated Cost Recovery System depreciation (five-year MACRS). The ITC is 30 % until 2019, then reduced to 26 % in 2020 and 22 % 2021. After 2023, the residential credit will drop to zero while the commercial and utility credit will drop to a permanent 10 %.

3.5 Current Deployment Market Status

3.5.1 Global Market

In 2018 annual installations (Figure 15) increased by approximately 10% to 109 GW [33]. Most, but not all market analysts expect a higher growth rate in 2019, with forecasts of between 107 GW and 140 GW [9, 38]. The IEA's Renewable Energy Market Report 2018 forecasts world-wide a new installed photovoltaic power capacity between 575 and 720 GW between 2018 and 2023 [6].

At the end of 2018, about one third of the global installed PV capacity was in China (180 GW) followed by the European Union with about 23% or 117 GW and the United States of America with 12% or 63 GW (Figure 16).

Uncertainties in Market Statistics:

- This report uses nominal DC peak power (Wp) under standard test conditions (1000 W irradiance and standard nominal 25ºC) for reasons of consistency.
- Not all countries report DC peak power (Wp) for solar PV systems, but especially for larger scale system the utility peak AC power, which is relevant for the transmission operator. Even in the EUROSTAT statistics the two capacities are mixed.
- Some statistics only count the capacity which is actually connected or commissioned in the respective year for the annual statistics, irrespectively when it was actually installed. This can lead to short term differences in which year the installations are counted, levels out in the long-run, if no double counting occurs. The construction period of some large solar farms spread over two or more years.
- Some countries lack official statistics on the capacity of solar PV system installations or sales statistics of the relevant components.

Figure 15 Annual photovoltaic system installations from 2010 to 2019 (data source: [39, 40, 41] and JRC analysis)

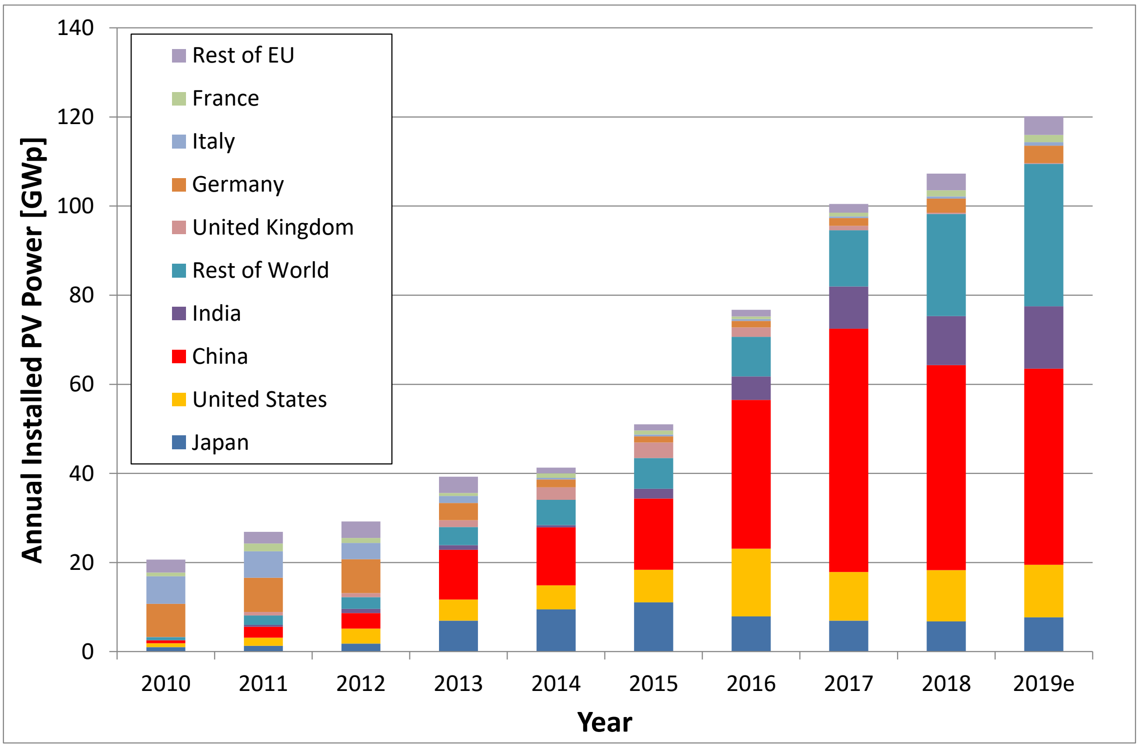
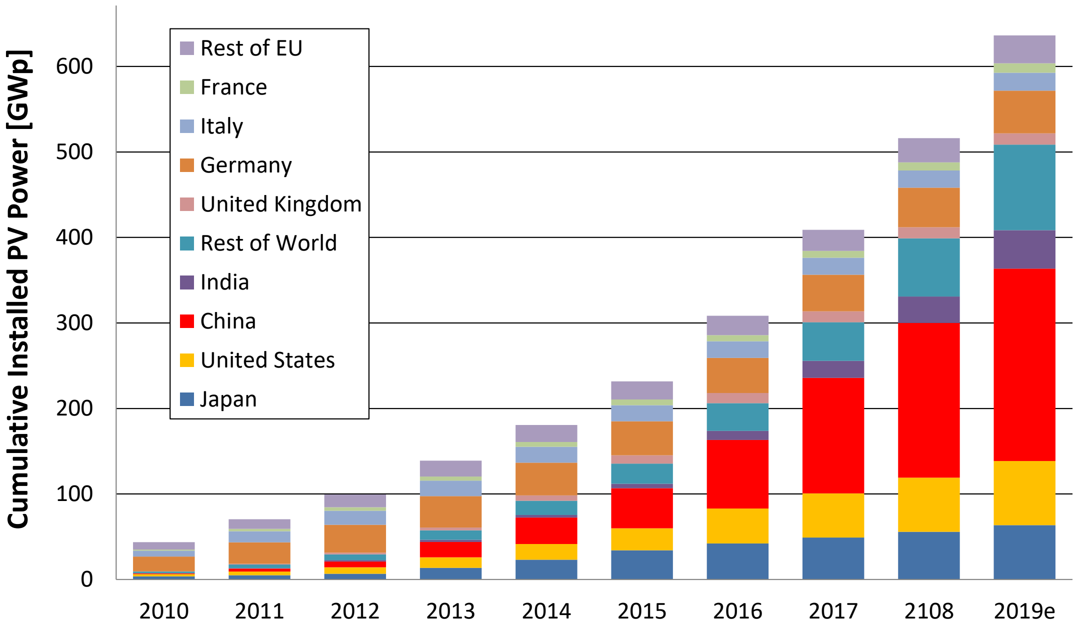


Figure 16 Cumulative Photovoltaic Installations from 2010 to 2019 (data source: [39, 40, 41] and JRC analysis)

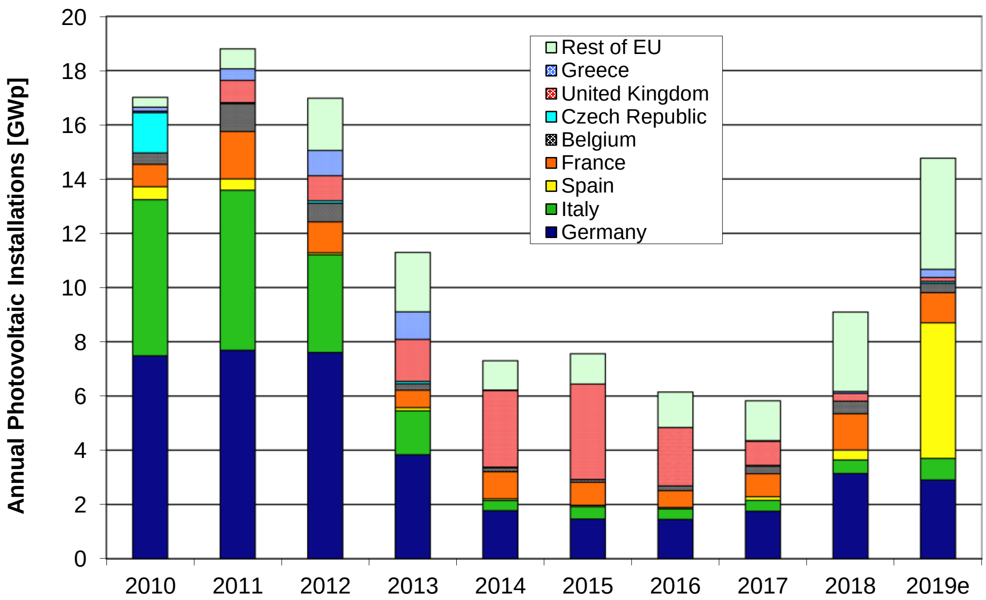


3.5.2 Regional Markets

European Union:

After its peak in 2011, when PV installations in the EU accounted for 70% of worldwide installations, six years of market decreases and stagnation followed. This trend finally reversed in 2018 when the EU PV market increased almost 50% from about 6 GW in 2017 to 8.8 GW (). This was due to stronger than expected markets in Germany (3.1 GW), the Netherlands (1.4 GW), France (> 1 GW) and Hungary (> 0.5 GW). Continued expansion is foreseen for 2019, in particular due to a revitalised Spanish market.

Figure 22 PV installation in the EU for2010 to 2019 [40]



Africa: Despite Africa's vast solar resources and the fact that in large areas the same PV panel can produce, on average twice as much electricity in Africa as in Central Europe, there has been only limited use of solar PV electricity generation up to now. Until the end of the last decade, the main application of PV systems in Africa was in small solar home system (SHS) and the market statistics for these are extremely imprecise or even non-existent. However, since 2012, major policy changes have occurred and a large number of utility-scale PV projects are now in the planning stage. In 2018 about 1.6 GW of new PV capacity was installed. The main markets were Egypt (>600 MW), Algeria (>200 MW) and Ruanda (180 MW).

Overall, the (documented) capacity of installed PV systems was close to 4.5 GW by the end of 2018. Current African PV targets for 2020 are in excess of 10 GW.

Asia & Pacific Region: Despite the 20% decrease of new photovoltaic electricity system installations in China, the market remained almost stable due to significant market increases in Australia, India and South Korea as well as market uptakes in a number of countries in the Middle East and South East Asia. The largest market was again China with over 44 GW, followed by India with almost 11.7 GW, Japan with over 6.7 GW and Australia at 3.8 GW. For 2019 a slight increase to about 80 GW could be possible under stable policy conditions.

Americas: Markets in North and South America increased by over 25% and added about 17.5 GW of new solar photovoltaic power in 2018. The three largest markets were the USA (11.4 GW), Mexico (2.5 GW) and Brazil (1.5 GW). The number of countries embracing solar photovoltaic energy in Central and South America is increasing and six countries had a PV market larger than 100 MW in 2018.

4 MARKET OUTLOOK

4.1 Technology Readiness and Cost

Available PV technologies range those broadly classified as "commercial", i.e. being used in mass production, "emerging" i.e., small production volumes and "novel", i.e. concept or early laboratory stage. Mono- and multicrystalline silicon wafer based photovoltaics are by far the dominant technology on the market, with a 2018 share of over 95 %. Other commercial products include thin-film technologies, in which the active material layers of a few microns thickness are deposited on glass or metal substrates, and concentrating photovoltaics. Organic and hybrid photovoltaic products are available but represent small niche markets up to now. Crystalline silicon products are expected to dominate the market for the next ten to fifteen years. In the medium- to long-term multi-layer, multi-junction devices appear the most promising route to mass production products with higher efficiencies.

Large-scale systems (the most cost effective) using crystalline silicon modules can already produce electricity at competitive prices in many EU locations. Several studies show that the cost of utility-scale PV electricity is already below 50 €/MWh in many EU locations. However, values for residential and smaller commercial PV systems can be significantly higher, depending on a variety of factors, many unrelated to the technology cost.

There is large potential to substantially further reduce the cost of PV systems, through a combination of increased module and inverter efficiencies, advanced production technologies and improved reliability. A study performed in the European PV Technology Innovation Platform [43] estimates that CAPEX for utility-scale systems can fall from 500 €/kWp in 2018 to 175 EUR/kWp by 2050 (-65%). Already for 2019 they calculate the PV LCOE values of 24 EUR/MWh in southern Spain and 42 EUR/MWh for Helsinki, Finland (7% WACC). With these trends PV may well be the cheapest form of electricity generation in most countries.

However, LCoE alone is not sufficient to assess the economic potential of a given technology. Increased penetration levels present two overall challenges:

a) Need for a flexible system adapted to renewables, incorporating also supply and demand coordination;

b) Developing of a fit-for purpose electricity market design

Renewables can adopt strategies favourable to integration. For PV these include:

i. power management technology coupled with forecasting as part of demand-supply management

ii. optimising deployment location with demand

iii. locally integrated energy supply solutions, for instance with storage options (real or virtual) and "power to X"[12] energy conversion systems.

4.2 Industrial Value Chain

The PV industry has changed dramatically over the last few years. China has become the major manufacturing location followed by Taiwan and Malaysia [3]. It is important to remember that the PV industry is more than just cell and module manufacturing and to grasp the whole picture one has to look at the entire value chain. Besides the manufacturing of solar cells and modules, the upstream industry (e.g. materials, polysilicon production, equipment manufacturing), as well as the downstream industry (e.g. inverters, BOS components, system development, installations) has to be looked at. Table 5 summarises the European position in the various parts. The SET-Plan implementation plan for PV recognises the need to maintain an overall global leadership role in the sector, with a coordinated effort between public and private sectors. The need for a coordinated approach across the entire value chain is further underlined by policies papers from the PV European Technology and Innovation Platform [45, 46] and by SolarPower Europe trade association [47], as well as the launch in 2018 of the a European Solar Manufacturing Council specifically to promote the interests of the manufacturing sector.

Table 5 Overview of the role of EU companies in the PV value chain for 2015 (JRC analysis)

Value Chain Element	Estimated EU position 2018
Manufacturing Equipment	Traditional strength across all PV technologies, but not possible to evaluate percentage market shares
Polysilicon production	~15% global market share
Cell Production	~ 1% global market share
Module Production	~ 3% global market share
Inverters	No % estimate but 4 companies in the global top 10
Project developers & EPC	Several prominent EU-based players

It is noted that PV cell and module manufacturing is transforming into a mass-producing industry with multi-GW production sites. This development comes with increasing industry consolidation, which presents a risk and an opportunity at the same time. For major manufac-

[12] Power to X" refers to the conversion of PV electricity to gas, to heat energy, to liquid fuels etc.

turers the relatively low profitability of the industry and hence reduced ability to invest in new technologies is a concern. Small and medium companies face a challenge to survive the price pressure of the very competitive commodity market, and to compensate for the advantages enjoyed by big companies through the economies of scale that come with large production volumes. One strategy is to specialise in niche markets offering products with high value added or special solutions tailor-made for customers. Another possibility is to offer technologically more advanced and cheaper solar cell concepts.

4.3 Global and EU Market Trends

According to investment analysts and industry prognoses, solar energy will continue to grow at high rates in the coming years. Different PV industry associations, as well as Greenpeace, the European Renewable Energy Council (EREC), the Energy Watch Group with Lappeenranta University of Technology (LUT), Bloomberg New Energy Finance (BNEF) and the International Energy Agency, have developed scenarios for the future growth of PV systems [48, 49, 50, 51, 52]. Table 6 shows the different scenarios of the Greenpeace/EREC study, the Energy Watch Group/LUT study, BNEF New Energy Outlook (NEO) 2018 as well as the 2016 and 2018 IEA World Energy Outlook scenarios. It is interesting to note that the predicted PV capacity in the IEA scenarios has significantly increased from 2016 to 2018 but are still at the lower end.

Table 6 Scenarios for the evolution of global PV generation capacity to 2040.

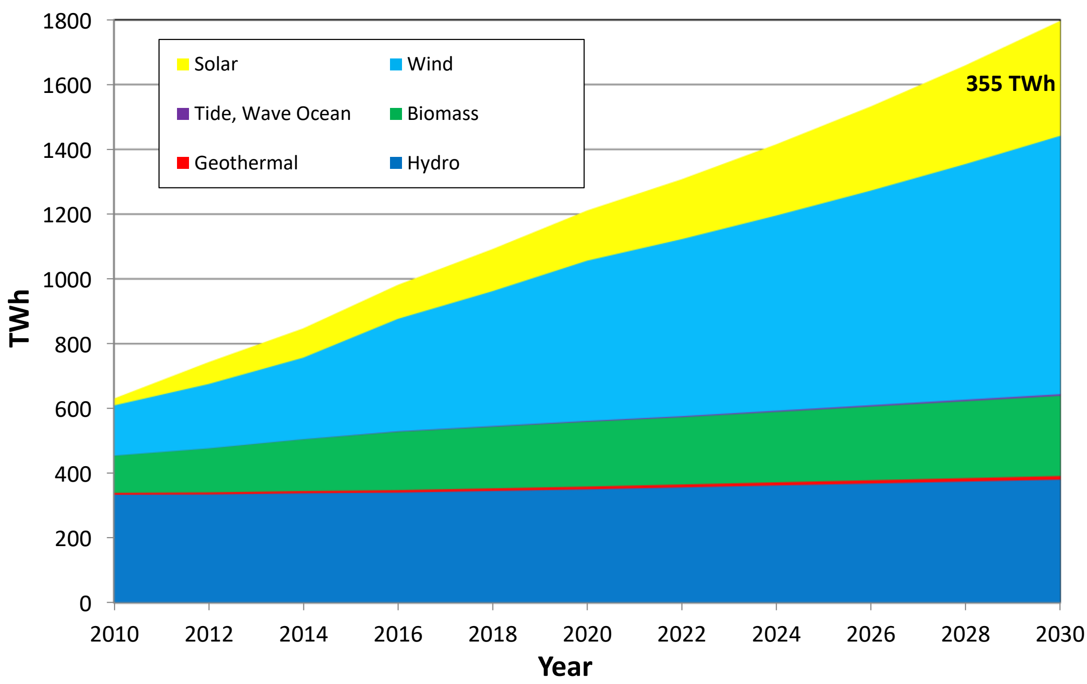
Year	2018 [GW]	2020 [GW]	2025 [GW]	2030 [GW]	2040 [GW]
Existing Installations	**516**				
Greenpeace reference scenario		332	413	494	635
Greenpeace advanced [r]evolution scenario		844	2 000	3 725	6 678
LUT 100% RES Power Sector		1 168	3 513	6 980	13 805
BNEF NEO 2018		759	1 353	2 144	4 527
IEA New Policy Scenario 2016		481	715	949	1 405
IEA 450ppm Scenario 2016*		517	814	1 278	2 108
IEA New Policy Scenario 2018*		665	1 109	1 589	2 540
IEA Sustainable Development Scenario 2018*		750	1 472	2 346	4 240

*) the 2025 value is interpolated as only 2020 and 203 values given

For the EU, the 2030 target of at least 32% renewable energy translates into approximately 65% of electricity production from renewables (Figure 23). The estimated PV contribution lies in the range 300 to 320 GW, corresponding to 340 to 370 TWh. This assumes that growth in renewable electricity will mainly depend on solar and wind, as the availability of biomass feedstock for energy will be limited by industry needs in a bio-based economy [13]. Both values for installed capacity are above the IEA estimates for OECD EU countries, whereas the JRC-EU-TIMES model is more optimistic (see section 4.2.3 below).

This implies that EU PV market growth rate needs to increase from its 2018 value of about 8.8 GW to at least 20 GW/y. This appears feasible from the cost reduction trends described above, but will also require appropriate (and stable) policy measures, as well as efforts to reduce soft-costs for administration and licencing. It is also necessary that the sector takes full advantage of the need for Near -Zero Energy Buildings as stipulated under the Energy Performance of Buildings Directive, as well as embracing innovative concepts such as dual land use systems (e.g. PV and agriculture).

Figure 23 Projection of the development of renewable power production capacity to meet the EU's 2030 goal of at least 32% renewable energy (source JRC).



4.4 Sensitivity to Techno-Economic Factors and Policy Scenarios

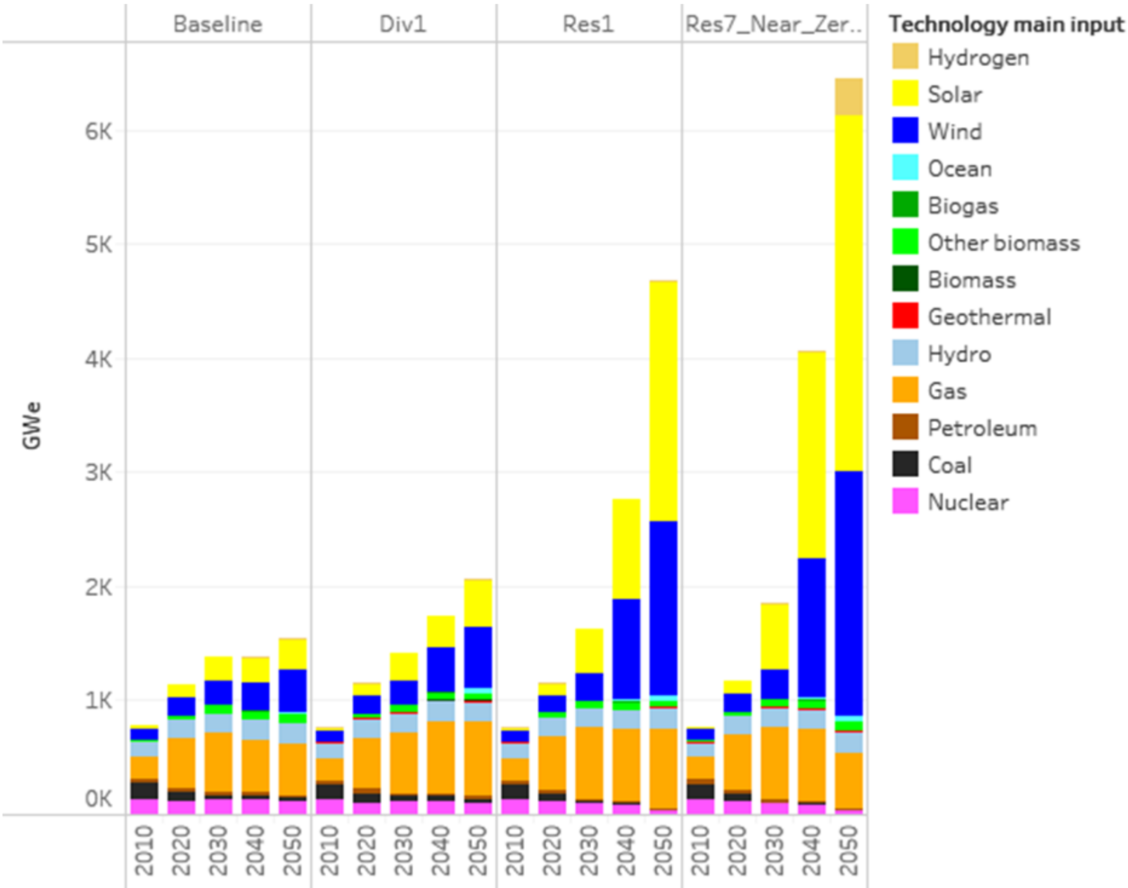
The JRC-EU-TIMES model [53] offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060. Table 7 lists the scenarios considered, while the LCEO report D4.7 [54] presents the model and the overall results. Here the focus is on the medium-to-long term PV market volume and the factors influencing it.

Figure 24 shows the power generation mix under the baseline, diversified (Div1), pro-renewables (Res1), and near zero-carbon (RES8_Near_ZeroCarbon) scenarios from 2010 to 2050. Total electricity production increases in all the scenarios, but particularly in the Pro-RES scenario (Res1), reflecting a deep electrification of transport and the use of electricity to produce hydrogen, synfuels and other previously petrochemical-based products. Solar (essentially PV; CSP has a marginal share) plays a significant role, and particularly in ProRes (Res1) and the near-zero carbon (res7) scenarios.

Table 7 Overview of the JRC-EU-TIMES model scenarios.

Global Scenarios	Model Scenarios	Features
Baseline	Baseline	- 48 % CO_2 by 2050 (continuation of current trends)
Diversified (use of all known options including CCS and new nuclear plants)	Div1	-80% CO2 by 2050
	Div2_LowLR	Lower cost learning rate for all technologies
	Div3_HighLR	higher cost learning rate for all technologies
	Div4_DAC	Includes direct air capture of CO2
	Div5_CheapFossil	Oil price declines to $40/barrel
	Div6_NoCC_InPower	No carbon capture on power plants
Pro-Renewables (no new nuclear; no CCS)	Res1	-80 % CO_2 by 2050
	Res2_LowLR	Lower cost learning rate for all technologies
	Res3_HighLR	Higher cost learning rate for all technologies
	Res4_SET	CAPEX values reach the targets in the SET-Plan
	Res5_DAC	Includes direct air capture of CO2
	Res6_HighForest	Uses full forest potential with forest area equilibrium
	Res7_Near_ZeroCarbon	-95 % CO2 by 2050
	Res8_NoCCU	Further restriction on CO2 use (promotes re-use)

Figure 24 JRC-EU-TIMES results for power generation (TWh) for the baseline, diversified (Div1), pro-renewables (Res1), and near zero-carbon (RES8_Near_ZeroCarbon) scenarios.



PV Capacity Development

Figure 25 summarises the growth in PV installed capacity for all the scenarios from 2020 to 2050, while Figure 26 shows the percentage share of PV electricity generation in 2050. For the diversified scenarios, the role of PV is very modest, with capacity reaching about 240 GW in 2030, while for 2050 the highest scenario foresees only 451 GW. The overall share of PV electricity generation is correspondingly modest, reaching about in 8% in these cases. N.B. These diversified scenarios include significant shares for some technologies that are not currently commercially available (e.g. carbon capture/storage and new nuclear plant designs).

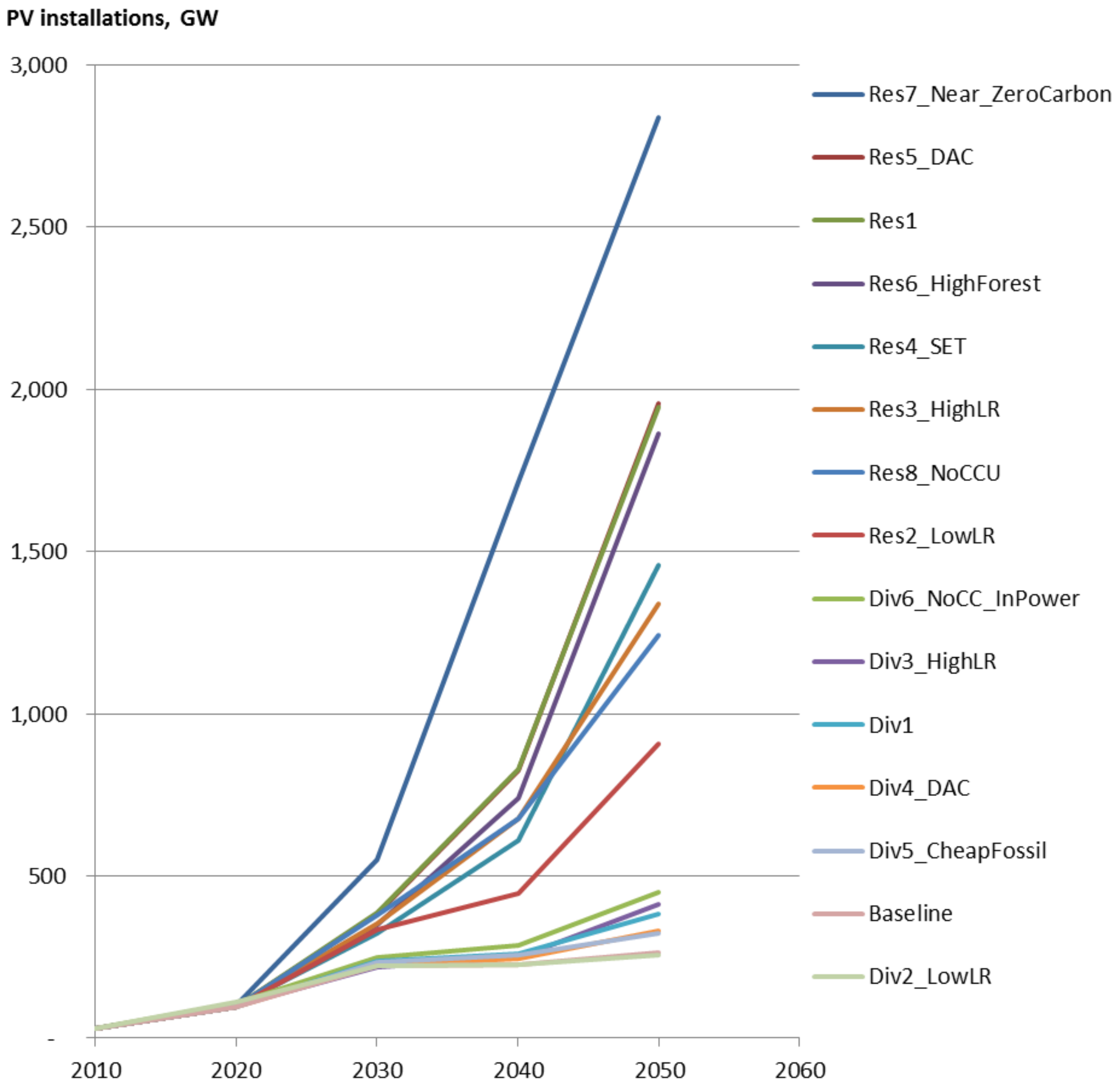
The situation is radically different in the ProRenewables scenarios with no CCS and no new nuclear. PV grows strongly, particularly in the 2030 to 2050 timeframe. In the main Res1 scenario, installed PV capacity reaches 385 GW in 2030 and 1 944 GW in 2050. For 2050, results for other scenarios range from 1 242 GW (Res8_noCCU) to 2 838 GW (Res8_Near_ZeroCarbon). Correspondingly the PV share of generation is significant, reaching

28%, again for the near-zero carbon scenario. It is noted that even for multi-terawatt scale PV deployment, land use is not is not a technical issue [55].

Investment Costs and LCoE

Overall, the investment needed in new capacity increases for the scenarios with higher shares of renewables and low carbon emissions. This reflects the fact that capital investment for renewable technologies is higher than for conventional fossil plant, although there are no fuel costs during operation. Unit capital costs for PV decrease with higher deployment levels reflecting the impact of economies of scale and technology learning effects (Table 8).

Figure 25 Growth of PV capacity over time in the baseline, diversified and Pro-Res scenarios.



The model output has also been used to calculate a levelised cost of electricity value. Table 9 shows the 2050 values for selected renewable technologies, including sensitivity to the discount rate and to location (in terms of resource). PV emerges as highly competitive: the cost per MWh for utility scale PV in favourable locations is the lowest overall, and the cost even in a less favourable location is only bettered by onshore wind in a favourable location. Nonetheless it is acknowledged that effective integration of PV in the system may incur increased storage capacities, that are not included here.

Table 8 JRC-EU-TIMES model: capacities and costs for PV under different scenarios.

Scenario	Capacity 2050 GW	Investment EUR bn	Unit MW Cost m€/MW
Baseline	269	269	1 000 000
Diversified	384	308	802 083
Pro-RES	1 944	1 039	534 465
Res7 Near Zero Carbon	2 838	1 583	557 787

Table 9 Levelised costs of electricity in 2050 for selected renewable technologies from the JRC-EU-TIMES model SET-Plan scenario (Res4)

LCoE, EUR/MWh	9% discount rate		3% "social" discount rate	
Resource	Less fav.	Favourable.	Less fav.	More fav.
Wind offshore	128	56	81	35
Wind onshore	133	37	88	25
PV utility	**40**	**25**	**23**	**14**
PV residential	**68**	**42**	**32**	**20**
Wave	91	59	65	42
Tidal	74	48	53	34
	Min-max range		Min-max range	
Geothermal	34 - 109		17 - 54	
Biomass	49 - 117		31 – 63	

Member State Breakdown

Figure 27 shows the breakdown of PV electricity share in the Member States for 2050. Two distinct groups are apparent: the first is of eleven countries with high PV penetration ranging from 40 to 80%, while a second group shows rates of 10-20%.. The former includes the Mediterranean countries, but less intuitively also Luxembourg (44%) and Belgium (53%). These cases appear to reflect a relative lack of wind resources. The model deploys no PV in only one country (Ireland), presumably reflecting the high economic potential of its abundant wind resources.

Overall, the JRC-EU-TIMES results confirm that PV can offer a cost competitive source of electricity and provide a very substantial part for future electricity demand.

Figure 26 JRC-EU-TIMES results for the share of PV in total EU electricity production in 2050.

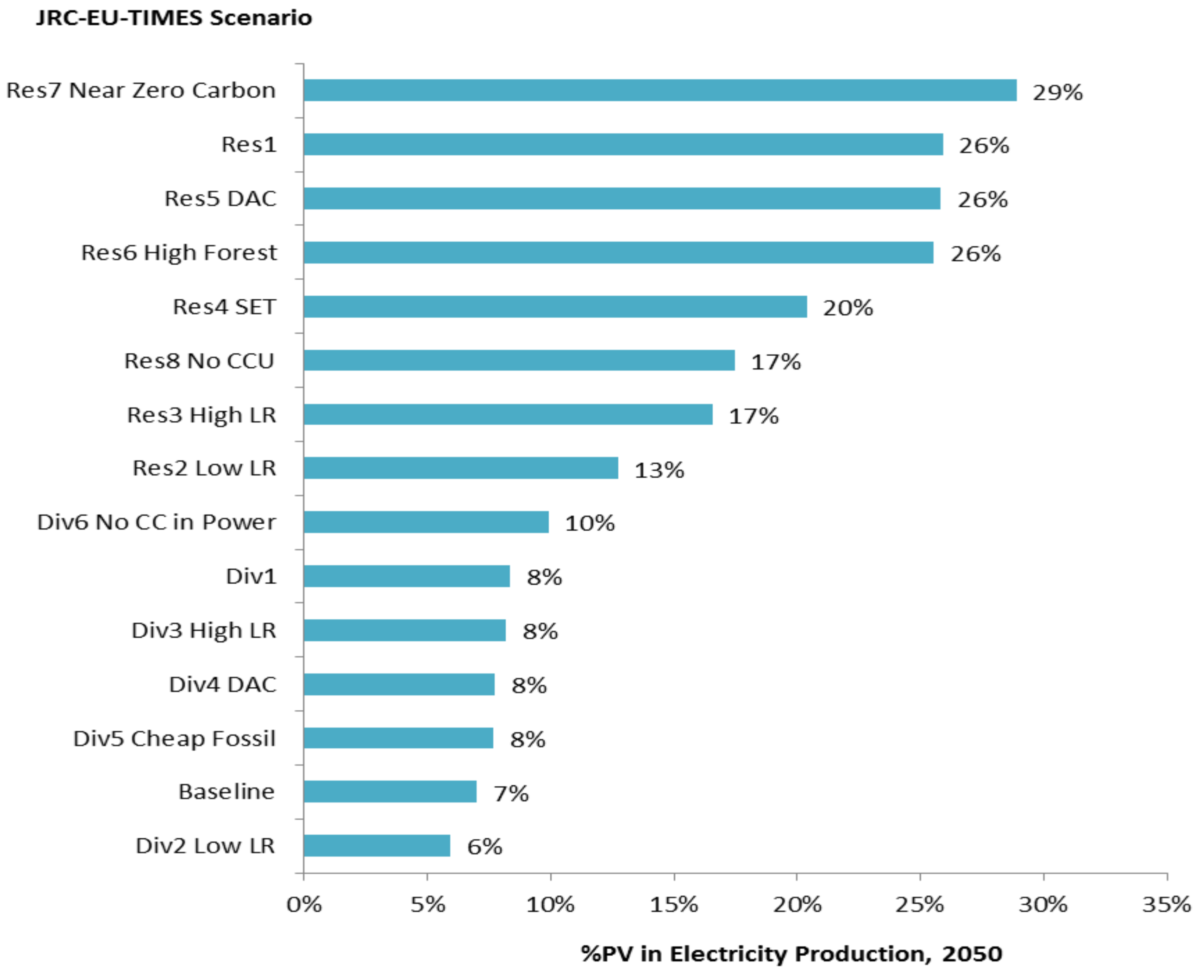
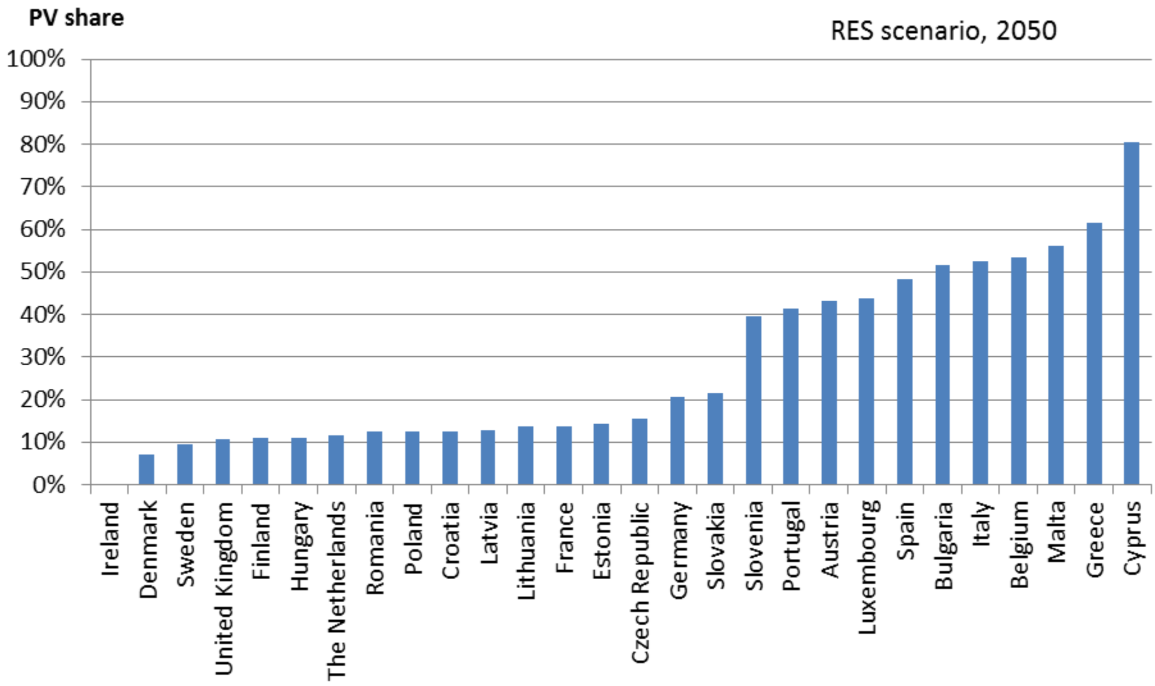


Figure 27 PV share of electricity production for EU countries in 2050 under the RES1 scenario.



5 SUMMARY AND CONCLUSIONS

Over the last two decades, grid-connected solar photovoltaic (PV) systems have increased from a niche market to one of the leading power generation capacity additions annually. In 2018, over 100 GW of new PV power capacity was added globally, putting total installed capacity in excess of 500 GW. China continues to be the largest single market, but notable growth took place also in other parts of Asia. PV systems combined with local battery storage have substantially increased. The EU PV market rebounded to approximately 8 GW in 2018, and the cumulative installed capacity now stands at 117 GW. It accounts for approximately 4% of electricity generation. In terms of technologies, silicon wafer based photovoltaics are dominant technology with a market share of over 95 %.

There is broad consensus among investment analysts and the industry that solar energy will continue to grow at high rates in the coming years. In the EU the 2030 target of at least 32% renewable energy and this implies a PV contribution of 340 to 370 TWh (300 to 320 GW). Looking towards 2050, the EU's decarbonisation policy points to PV deployment at the terra-watt scale, and the JRC-EU-TIMES modelling results confirm that PV can offer a cost competitive source of electricity and provide a very substantial part for future electricity demand.

The PV manufacturing industry has changed dramatically over the last few years. China has become the major manufacturing location for cells and modules followed by Taiwan and Malaysia. It has also become an industry that requires GW-scale production to reduce costs and continues to feature very tight profit margins for manufacturers.

The overall value chain is much more extensive, with both an upstream industry (e.g. materials, polysilicon production, equipment manufacturing) and a downstream one (e.g. system development, installations, operation and maintenance, end-of-life management). In this overall ecosystem Europe maintains a rich industrial fabric with over 18 000 organisations involved. In many areas EU companies are technology leaders, as evidenced for instance by the data for "high-value" patents i.e. applications in more than one jurisdiction. At the same time, the signs of a plateauing or even decrease in public funding for PV research in the member states is a cause for concern going forward.

A development strategy for the PV sector in Europe needs a holistic approach, including also storage, digitalisation and market aspects. A dynamic EU home market is important, and indeed a PV deployment rate of at least 10.5 GW/year is needed to meet the 2030 target for 32% renewable energy, and an even higher rate to honour COP-21 commitments. At the same time, the heterogeneity in market conditions across the EU need to be addressed, as this strongly influences the cost and economic attractiveness of PV systems, especially for potential prosumers. The EU rooftop market can be an important driver for the PV sector, and this should a key part of sustainable urban development policies (for instance, under the Covenant of Mayors). Finally yet importantly, PV deployment can have a significant social benefit, particularly since 75% of jobs are in the downstream sector and predominantly local.

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