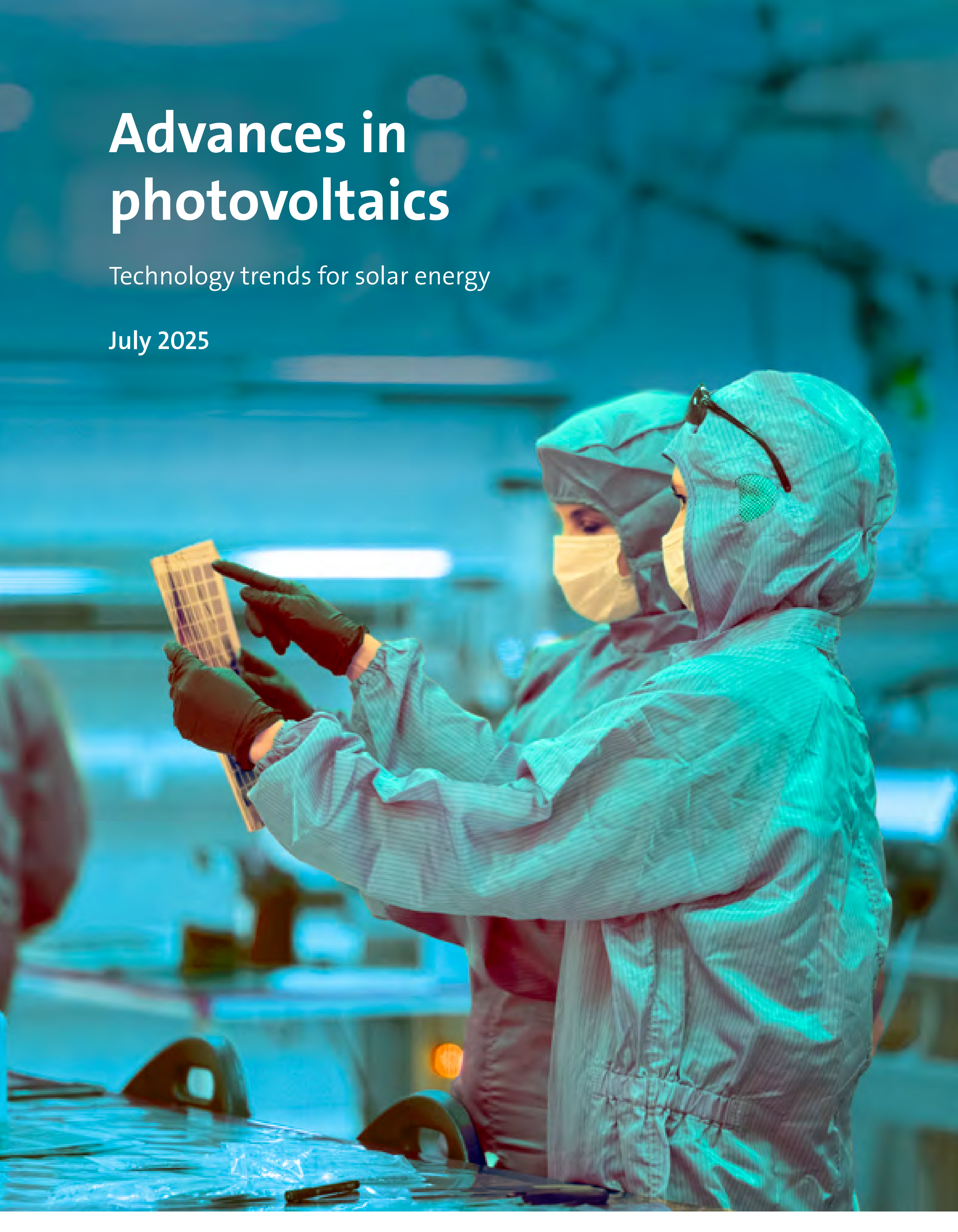
Advances in photovoltaics

Technology trends for solar energy

July 2025



Europäisches Patentamt
European Patent Office
Office européen des brevets

In collaboration with
European Innovation Council

Contents

List of tables and figures

Tables

Figures

List of abbreviations

AI	Artificial intelligence
CAGR	Compound annual growth rate
IPF	International patent families
EPC	European Patent Convention
EPO	European Patent Office
OPV	Organic photovoltaics
PCT	Patent Cooperation Treaty
PSC	Perovskite solar cells
PV	Photovoltaics
R&D	Research and development
RTA	Revealed technology advantage
SDG	Sustainable Development Goals
WTO	World Trade Organization
UNCTAD	UN Trade and Development
UNEP	United Nations Environment Programme

List of countries and world regions

AT	Austria
AL	Albania
BE	Belgium
Benelux	Belgium, the Netherlands and Luxembourg
CA	Canada
CH	Switzerland
CN	People's Republic of China
DE	Germany
ES	Spain
EU	European Union
Europe	Europe is referred to in this report as the 39 Member States of the European Patent Convention (EPC)
Eurasia	Russian Federation; and former Soviet Union
FI	Finland
FR	France
IN	India
IS	Iceland
JP	Japan
KR	Republic of Korea
LI	Liechtenstein
MC	Monaco
ME	Montenegro
MK	North Macedonia
NO	Norway
Other Europe	European countries which are not EPC member states
RoW	Rest of world
RS	Serbia
SA	Saudi Arabia
SE	Sweden
SM	San Marino
TR	Türkiye
UK	United Kingdom
US	United States
TW	Chinese Taipei

Executive summary

Photovoltaics is the branch of technology that deals with using solar cells to convert sunlight into electricity. It plays a vital role in today's economy and enables cleaner and renewable energy production, reduces the dependence on fossil fuels and contributes to global efforts to combat climate change. Photovoltaics also makes an important contribution to energy security, lowers electricity costs in the long term and creates jobs in manufacturing, installation and maintenance.

As the efficiency of solar panels improves and costs continue to decline, photovoltaics are becoming more accessible worldwide in industrialised and developing regions alike. Looking ahead, advancements in materials, storage integration and smart grid technologies are expected to further enhance photovoltaic systems, making solar energy a cornerstone of sustainable, decentralised and resilient global energy infrastructure.

With that, photovoltaics helps to achieve several UN's Sustainable Development Goals (UN SDGs), namely SDG 7 (Affordable and clean energy), SDG 9 (Industry, Innovation, Technology and Infrastructure), SDG 11 (Sustainable cities and communities), and SDG 13 (Climate action).

Photovoltaics already represent an important market which was valued at USD 96.5 billion in 2023 and is projected to reach USD 155.5 billion by 2028, growing at a compound annual growth rate (CAGR) of 10% during the forecast period.[1]

This technology insight report presents technology trends in the field of photovoltaics over the span of five decades. To this end, it closely monitors patenting activities across more than 30 technologies in four sub-areas in the field. Drawing on the latest patent data and leveraging the expertise of the European Patent Office (EPO) and of the European Innovation Council (EIC), this technology insight report delivers a comprehensive overview to inform decision-making processes in both the private and public sectors.

1 Based on the report "Photovoltaic Market by Component (Modules, Inverters, BOS), Material (Silicon, Compounds), Installation Type (Ground Mounted, BIPV, Floating PV), Application (Residential, Commercial & Industrial, Utilities), Cell Type and Region – Global Forecast to 2028" by MarketsandMarkets.

The EPO technology insight report on advances in photovoltaics in brief:

- This report presents detailed analyses of more than 30 technologies related to photovoltaic materials, photovoltaic devices, the management of these devices and application areas
- These technologies grew seventeen-fold in the past three decades, with a total of 340 000 inventions including 70 000 international patent families identified during the period 1974-2023
- Most of the top applicants related to international patent families, as a standard indicator for inventions with an international focus and confirmed potential, were companies located in Japan, followed by the United States, R. Korea, Germany and France. Leading Chinese innovators did not feature in this list due to their primary focus on domestic patent applications.
- In the past 15 years, patenting activities shifted substantially towards protection in China.
- While its role in photovoltaics production is relatively marginal at the moment, Europe shows specialisation advantages in technologies related to the deployment of photovoltaic energy, such as agrivoltaics and the installation of solar panels on rooftops and buildings.
- European universities have consistently demonstrated a substantial level of inventive activity in the field, and there has been a recent and significant increase in the number of inventions by European startups.

Inventive activity in photovoltaics is ever-growing

The technologies in the field of photovoltaics considered in this report have seen significant growth in the past three decades, with a total of 340 000 inventions, including 70 000 international patent families (IPFs) identified during the period from 1974 to 2023. Over the past three decades, the number of inventions grew more than seventeen-fold (see Figure E.1).

This report examines a range of more than 30 technologies in four sub-areas of photovoltaics: photovoltaic materials, photovoltaic devices, the management of these devices, and application areas.

The focus was set on international patent families as a standard indicator for inventions with international focus and confirmed potential. Device technologies played a key role in the period 1990-2023, accounting for up to 78% of all inventions. In recent years, the role of the other sub-areas has steadily grown. At the beginning of this decade, 48% of all inventions were related to device technologies, followed by applications (25%), photovoltaic materials (17%) and device management (10%).

P.R. China as the current hotspot of photovoltaics patenting

Patenting activities have shifted substantially towards China in the past 15 years, reflecting that country's increasing leadership in photovoltaics manufacturing and deployment. While the number of IPFs has been declining since 2012, the number of patent applications filed only in China has been increasing massively, with nearly six-fold growth from 2010 to 2022. China alone represented 80% of all new inventions in photovoltaics in 2022.

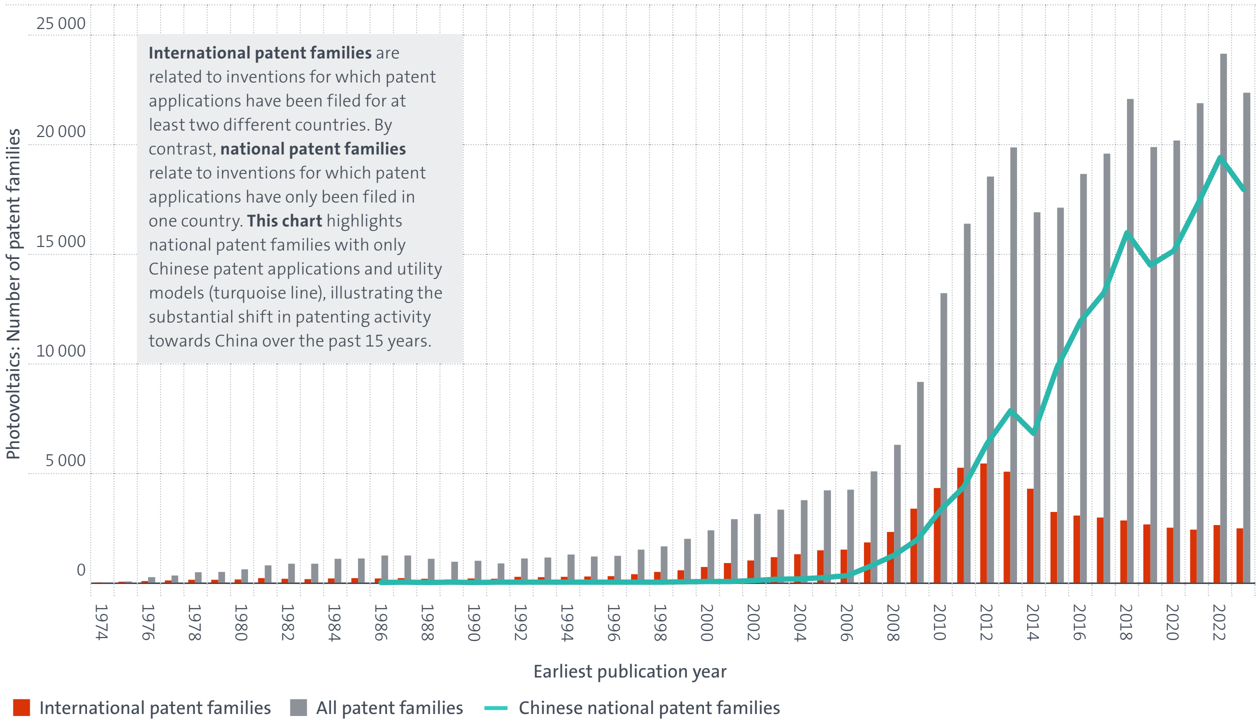
When considering IPFs only, the top 20 applicants in the period 1990-2023 are companies located in Japan (13 applicants), followed by the United States (3), R. Korea (2), Germany and France (one each). Leading Chinese innovators such as the Chinese Academy of Science and State Grid Corporation do not feature in this list due to their primary focus on domestic patent applications.

European startups and universities are fuelling innovation

While most of today's production of photovoltaic panels is taking place in P.R. China, Europe maintains a specialisation advantage in technologies related to the deployment of photovoltaic energy. Examples include agrivoltaics – the simultaneous use of land for photovoltaics and agriculture – and the installation of photovoltaics on rooftops, carports or buildings.

Figure E.1:

Number of inventions in the field of photovoltaics, per earliest publication year of the invention



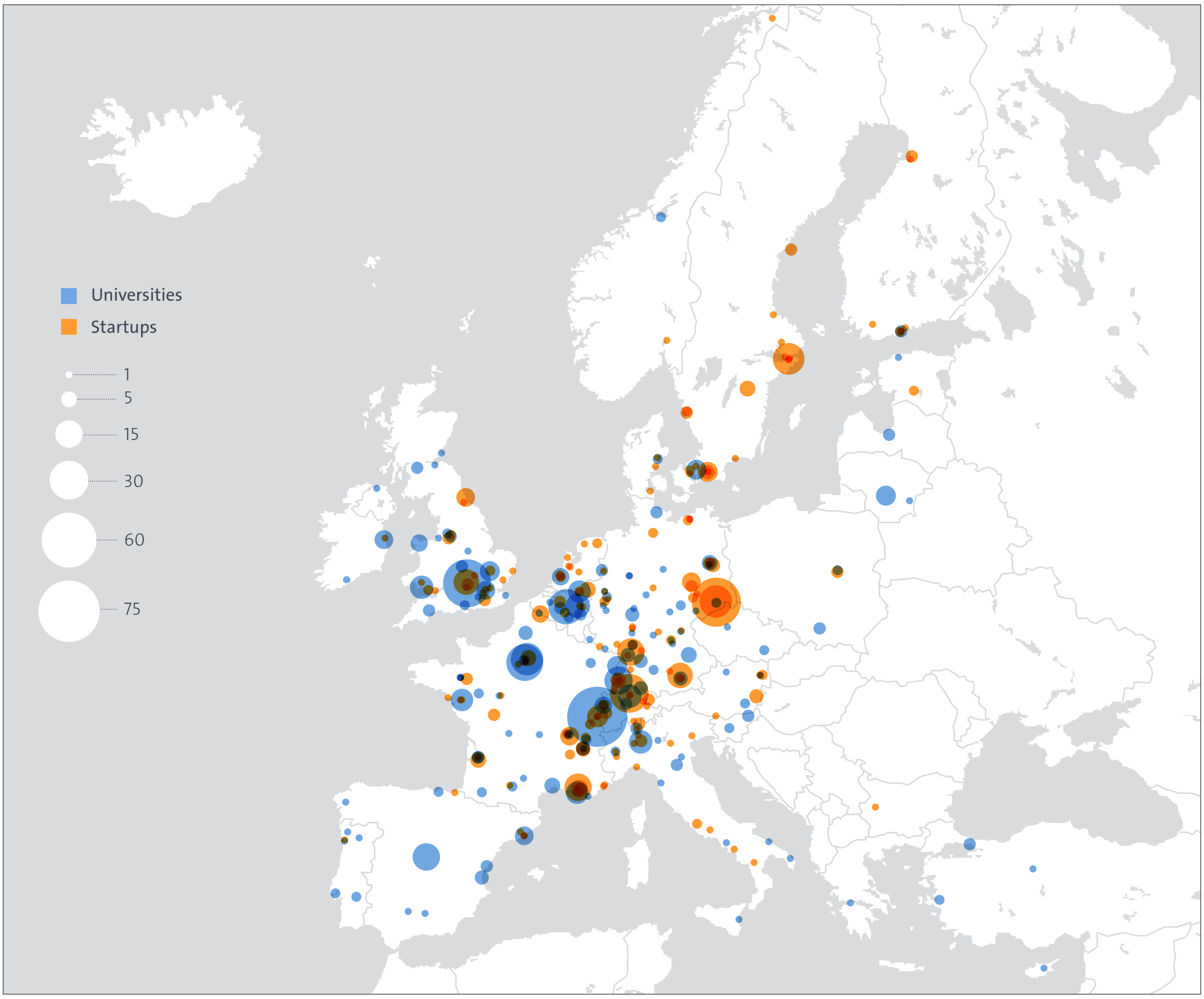
Source: EPO

European universities have consistently demonstrated a substantial level of inventive activity, with a strong focus on photovoltaic devices and materials. The most extensive inventive activity of universities is found in the United Kingdom, followed by France, Switzerland and Germany. When looking at regions rather than countries, several regional hotspots of academic inventive activity stand out, in particular: in the south of England, Belgium and the south of the Netherlands, the Paris area, the Lausanne area, the Upper Rhine region and Madrid area (see Figure E.2, blue circles).

Startups in Europe mainly focus on technologies related to photovoltaic devices, followed by photovoltaic materials and applications, with a recent significant increase in the number of inventions. The highest inventive activity of startups was found in Germany, France, Switzerland and Sweden. Regional hotspots are found in the south of England, Belgium and the south of the Netherlands, the Upper Rhine region, the Zurich region, the Lake Geneva region, the south-east of France, the Dresden area and in the Stockholm area (Figure E.2, orange circles).

Figure E.2:

Geographical origin of European patent applications filed by startups and by universities
(Based on EP patent applications; period: 2010-2023)



Source EPO / © 2025 Mapbox © OpenStreetMap

Glossary

Agrivoltaics	Simultaneous use of land for photovoltaics and agriculture
DOCDB	The EPO's master documentation database with worldwide coverage. It contains bibliographic data, abstracts, citations and DOCDB simple patent family information.
DOCDB simple family	A set of patent documents relating to patent applications claiming priority over the same earlier applications. The technical content covered by the patent applications in a DOCDB simple patent family is considered to be identical.
European patent	The European patent system makes it possible to obtain European patents valid in up to 39 contracting states to the European Patent Convention (EPC) on the basis of a single application. A European patent has the same legal effects as a national patent in each country for which it is granted. As of 2023, it is also possible to request unitary effect for a granted European patent.
European Patent Convention (EPC)	International treaty signed by the member states of the European Patent Organisation. The EPC establishes a single application procedure for obtaining patent protection in Europe.
European Patent Office (EPO)	Executive arm of the European Patent Organisation. European patents are granted by the European Patent Office in a centralised, cost-effective and time-saving procedure conducted in one of the official languages of the EPO (English, French or German). Every European patent application undergoes substantive examination before a European patent is granted to make sure that inventions for which patent protection is sought meet all of the legal requirements set out in the European Patent Convention.
Espacenet	Free online patent searching service developed by the EPO. It includes information on over 160 million patent documents from more than 100 patent offices on all continents. Espacenet is available at worldwide.espacenet.com.
Feed-in tariff	Government policy guaranteeing renewable energy producers a fixed payment for each unit of electricity feed into the power grid.
International patent application	Patent application filed under the Patent Cooperation Treaty (PCT). An international patent application may result in patent protection in more than 150 countries.
International Patent Classification (IPC)	The International Patent Classification system is a hierarchical patent classification system used by the EPO and more than 100 patent offices worldwide. It breaks technologies down into eight sections with several hierarchical sub-levels. The IPC system has approximately 75 000 subdivisions and is updated on an annual basis.
International patent family (IPF)	A set of applications for the same invention that includes a published international patent application, a published patent application at a regional patent office, or published patent applications at two or more national patent offices.
Invention	A practical solution to a (technical) problem. The invention may be a new product, process or apparatus or any new use thereof. To be patentable under the European patent system, an invention must be technical, novel, involve an inventive step (i.e. it must not be obvious to those having ordinary skill in the technical area of the invention), and be considered as susceptible of industrial application.

National patent family	A set of applications for the same invention that consists of published patent applications at a single national patent office.
Patent	Legal title giving the patent owner(s) the right, for a limited period of time (usually 20 years as of the date of filing the patent application), to exclude others from using the protected invention in a commercial context without permission in those countries for which the patent has been granted. The protected invention is defined by the claims of the patent.
Patent application	Request for patent protection for an invention filed with the EPO or other patent office.
Patent classification system	The set of patent classification symbols assigned to categorise the technical subject-matter of a patent or utility model. There are various patent classification systems used today by national, regional and international patent offices.
Patent family	A set of patent documents covering the same or similar technical content, depending on the patent family definition.
PATSTAT	PATSTAT is a group of databases that contain bibliographical, procedural and other context information on millions of patents and utility models from numerous industrialised and developing countries. It is built from the EPO's databases of worldwide patent data.
Patent Cooperation Treaty (PCT)	An international treaty providing for a unified procedure for filing patent applications to protect inventions in its contracting states. Under the PCT, a single international application can be filed for patent protection in up to more than 150 countries. The PCT provides for a centralised procedure for filing the patent application whereby the substantive examination and the grant of the patent lies with the competent national or regional patent office(s).
Photovoltaics	Technologies related to the conversion of light into electricity using the photovoltaic effect
Priority	Inventions can be protected by patents and utility models in more than one country. For a period of 12 months from the date of filing an application for a patent in a member state of the Paris Convention, the applicant or their successor can claim a right of priority from that application for any subsequently filed patent application that concerns the same invention. If the requirements are fulfilled, the date of the earlier application counts as the date of filing of the later application for the purposes of examining novelty and inventive step.
TOPCon passivation	**T**unnel **O**xide **P**assivated **C**ontact passivation. A technique used to improve the efficiency and performance of photovoltaic devices by reducing undesired electronic surface effects.

1. Introduction

The field of photovoltaics has undergone remarkable growth and transformation over the past decades, driven by global trends toward sustainability and security of energy supply, improved technologies and falling costs of production. Whilst photovoltaics were considered a niche for a long time, the field has become a cornerstone of renewable energy strategies worldwide providing affordable, de-fossilised and scalable electricity for all locations and system sizes (Masson et al., 2024).

A major factor in this development has been the rapid improvement and commercialisation of silicon-based solar cells. Crystalline silicon, mainly in the form of monocrystalline cells, remains the dominant photovoltaic material due to its durability, efficiency, and falling production costs. Breakthroughs in manufacturing processes, such as the use of passivated emitter and rear cell technology and, more recently, passivated contacts such as the so-called TOPCon passivation technology, have helped to increase the efficiency of photovoltaic modules to over 20%. Furthermore, economies of scale in production, particularly in countries such as China, have drastically reduced the price of photovoltaic modules (Fraunhofer Institute for Solar Energy Systems and PSE Projects GmbH, 2025; International Renewable Energy Agency, 2024).

In another significant area of development, materials technologies have attracted increasing attention. Thin-film photovoltaic cells, such as those based on cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and organic photovoltaics offer advantages in terms of flexibility and use of materials, which allow them to find niches in specific areas. More recently, next-generation photovoltaic cells offering transparent and printable configurations, including inorganic-organic hybrid perovskite solar cells, have shown promising characteristics in the laboratory environment and pre-commercial manufacturing, with their high conversion efficiency and lower manufacturing complexity. Tandem structures combining perovskites with silicon are under industrial development, offering modules with efficiencies in excess of 30% which may be successful on the market (National Renewable Energy Laboratory, 2025; Tanko et al., 2025).

New, advanced materials are not the only drivers of adoption. There are diverse use cases for photovoltaics due to its integrability into agriculture, buildings or internet-of-things devices. The availability of digital and energy storage technologies has also contributed to the dynamic progress of photovoltaics. Smart inverters, performance monitoring technologies and AI-driven maintenance tools have increased the reliability and efficiency of photovoltaic systems. Combined with falling battery prices, solutions that integrate photovoltaic devices with energy storage make reliable off-grid and hybrid systems possible, further extending the applicability of photovoltaics beyond traditional utility-scale or rooftop installations.

1.1 Policy context

The complex combination of supportive policy frameworks at the national level, international climate commitments and increasing energy demand has significantly accelerated development of photovoltaics (International Energy Agency, 2023; Renewable Energy Policy Network for the 21st Century, 2023).

Among these factors, international agreements and support policy mechanisms have played a critical role in shaping the global photovoltaic industry, driving innovation, investment and adoption (see Box 1 for an overview). These policy frameworks have not only set the strategic direction, but also established financial mechanisms – from feed-in tariffs, direct subsidies and tax credits to competitive calls for tender and feed-in premiums – necessary to stimulate market demand and partially off-set the production and implementation costs of photovoltaic technologies. Various types of subsidies are being employed globally to accelerate photovoltaics, including the following:

— Direct subsidies and tax credits. As such measures often face limitations due to their high upfront costs for governments, they are increasingly targeted at specific applications or countries where the photovoltaics market is still in its early stages

— Indirect support mechanisms such as mandates for installing photovoltaic systems on buildings and parking lots, streamlined permitting processes, improved access to electricity markets and favourable grid access policies for prosumers.

In markets with high photovoltaic deployment, recent policies have primarily focused on promoting self-consumption models, energy communities, and innovative forms of collective or remote self-consumption. (Masson et al., 2024).

The progress of the photovoltaics sector over the past two decades – which has resulted in dramatic cost reductions, improved efficiency and increased deployment – cannot be understood without recognising the fundamental influence of policy and co-operation to both combat climate change and mitigate its negative effects.

The Kyoto Protocol, adopted in 1997, was one of the first international treaties to link global climate change with national emission reduction targets. While it established binding obligations primarily on developed countries, it stimulated early investment in renewable energy technologies, including photovoltaics. The Protocol also established carbon emission trading and mechanisms such as the Clean Development Mechanism. It thereby created incentives for industrialised countries to invest in emissions-reducing technologies in developing countries, such as photovoltaic installations. This helped build initial capacity and market viability in regions previously untouched by photovoltaic technologies.

The Paris Agreement adopted in 2015 built on and further developed the Kyoto Protocol, significantly raising the global climate ambition by a commitment to limit global temperature rise to well below 2°C above pre-industrial levels. The agreement required each country to create and regularly update its Nationally Determined Contributions (NDCs), many of which included specific renewable energy targets. The inclusion of photovoltaics in these NDCs created strong political and economic signals, encouraging countries to support solar markets through incentives and regulatory reforms. This policy-driven demand played an important role in creating the economies of scale that have significantly reduced the cost of photovoltaics.

At the national level, climate change mitigation agreements and policies have triggered feed-in tariffs, renewable portfolio standards and tax credits which have had a significant impact on photovoltaic deployment. For example, climate policies in Germany and the United States played an important role in making photovoltaics financially attractive to individuals and businesses, creating early large-scale markets for photovoltaic installations. Similar policies in countries such as China made it possible for them to become major producers of photovoltaic products, as well as by far the largest consumers of these technologies in recent years. Regardless, the ongoing debate over financing the development of distribution and transmission grids continues to influence the evolving regulatory framework, affect utility-scale photovoltaic power plant business models and shape the cost of photovoltaic electricity.

International financial institutions and climate funds have also supported the global deployment of photovoltaic systems, particularly in developing countries.

Moreover, climate change mitigation agreements and policy frameworks have encouraged international collaboration on photovoltaic research and development. Various programmes have been implemented to bring countries together to accelerate clean energy innovation. These initiatives have channelled public funding into advanced materials for photovoltaics, manufacturing processes, and technologies for integrating photovoltaic systems into the power grid infrastructure.

One important target of the REPowerEU strategy[2] of the European Commission (EC) is to leverage the most readily available renewable energy technologies for reducing the EU's reliance on fossil fuels and strengthening energy security and autonomy. To this end, the EC is supporting R&D projects on various photovoltaic technologies through the Horizon Europe Framework Programme.

The EC launched the European Solar Photovoltaic Industry Alliance in 2022 to further accelerate solar photovoltaics deployment, expand the manufacturing of competitive, innovative and sustainable PV products and to diversify the international photovoltaics value chain and raw material supply. In 2024, it took a further step by establishing a formal Co-Programmed European Partnership for solar photovoltaics in collaboration with the European Technology and Innovation Platform (ETIP PV), aiming to address key European challenges through coordinated research and innovation efforts.

To support the development and scale-up of photovoltaic materials, the EC set up the co-programmed European partnership Innovative Advanced Materials for Europe (IAM4EU) that has identified materials for renewable energy sources as one of its four research and innovation priorities.[3]

2 See REPowerEU strategy

3 See Advanced Materials for Industrial Leadership Communication (COM/2024/98 final)

Regulatory harmonisation and setting of standards, which were both influenced by international climate co-operation, have also facilitated the adoption of photovoltaics. Agreements promoting transparency, quality assurance and certification have enabled cross-border trade in photovoltaic technologies. This has increased consumer confidence and reduced the risk for investors in photovoltaic projects, which has ultimately further strengthened the field of photovoltaics.

Box 1: Milestones in policy frameworks and international climate mitigation agreements that have paved the way and fostered progress in the field of photovoltaics

United Nations Conference on Environment and Development (1992) – During the conference, the United Nations Framework Convention on Climate Change was introduced (see next entry)

United Nations Framework Convention on Climate Change (UNFCCC, 1992) – Encouraged parties to reduce greenhouse gas emissions; established the concept of common but differentiated responsibilities of countries, emphasised the needs of vulnerable nations and established a precautionary approach to climate policy

Conference of the Parties to the UNFCCC (COP-1, 1995) – First annual conference of UNFCCC parties to assess progress in dealing with climate change

Kyoto Protocol (1997) – Introduced mechanisms like the Clean Development Mechanism (CDM) to promote investment in renewable energy technologies; extended the UNFCCC; passed during the Third Conference of the Parties to the UNFCCC (COP-3)

Copenhagen Accord (2009) – Negotiated and noted during 15th session of the Conference to the UNFCCC (COP-15); established the goal to keep global warming to two degrees Celsius

Paris Agreement (2015) – Adopted at the 21st session of the Conference of the Parties to the UNFCCC (COP-21); aimed to combat climate change and accelerate actions for a sustainable low-carbon future; main features include: limitation of global average temperature; non-binding nationally determined contributions; climate finance; adaption to climate change and resilience

European Green Deal (2020) – Comprehensive strategy aiming at transforming the European Union into a sustainable and climate-neutral economy by 2050. It focuses on securing a reliable and affordable energy supply while developing a fully integrated, interconnected and digitalised energy market. The strategy emphasises energy efficiency, particularly in improving the energy performance of buildings, and supports the transition to a power sector predominantly reliant on renewable energy sources.

The United Nations Sustainable Development Goals (UN SDGs) – Activities to combat climate change and to mitigate its negative effects also form an important part of the United Nations Sustainable Development Goals. The goals were defined in the United Nation's 2030 Agenda for Sustainable Development adopted in 2015. Photovoltaics, the focus of this insight report, addresses a range of these goals, mainly SDG 7 (Affordable and clean energy), SDG 9 (Industry, innovation, technology and infrastructure), SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action).

1.2 Market situation

The global photovoltaics market was valued at USD 96.5 billion in 2023 and is projected to reach USD 155.5 billion by 2028, growing at a compound annual growth rate (CAGR) of 10% during the forecast period.[4] In 2022, the utilities segment, dominated by monocrystalline Si photovoltaics, accounted for the largest share of the photovoltaic market, and is expected to maintain its leading position through 2028. However, utilities segments – ground-mounted installations – are generating conflict or opposition with agricultural land use. By proposing a combined dual use for both agricultural production and energy production, agrivoltaics offers an acceptable alternative.

4 "Photovoltaic Market by Component (Modules, Inverters, BOS), Material (Silicon, Compounds), Installation Type (Ground Mounted, BIPV, Floating PV), Application (Residential, Commercial & Industrial, Utilities), Cell Type and Region – Global Forecast to 2028", MarketsandMarkets

The widespread deployment of new photovoltaic capacity in multiple countries largely depends on social acceptance and the availability of land. This is especially true in areas experiencing urban growth, ongoing or frequent loss of agricultural land or strong efforts to protect heritage buildings and natural landscapes for cultural and aesthetic reasons.

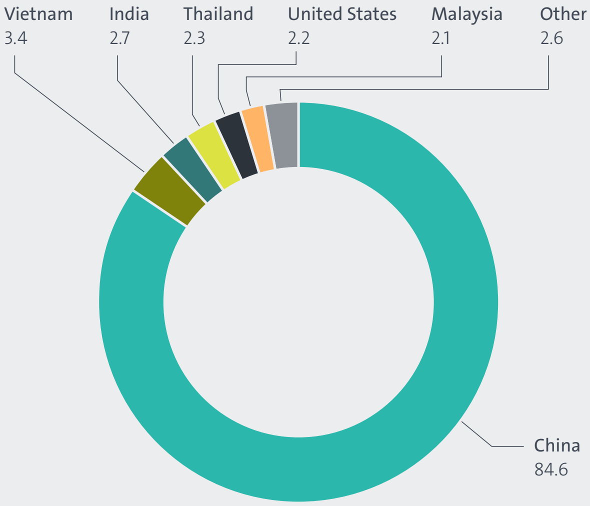
Emerging markets becoming more common are floating solar photovoltaics on natural and artificial lakes and reservoirs or in the sea, as well as the use of other infrastructure such as canopies on canals or noise barriers along highways.

Meanwhile, the residential segment is anticipated to experience significant growth over the same period. Recent advancements in the efficiency, durability, scalability and reliability of emerging photovoltaic

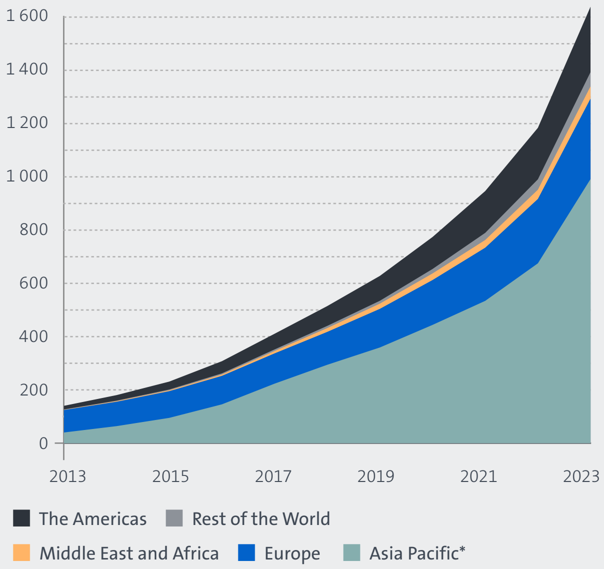
Box 2: Photovoltaics: Global success and regional differences

The photovoltaics sector witnessed impressive growth in the last 15 years. Solar photovoltaic module production grew from less than 40 GW in 2011 to more than 180 GW in 2021,[a)] and there is no end in sight.

In 2023, China accounted for nearly 85% of the solar photovoltaic module production, which is far more than China's share of global PV demand. The list of the largest manufacturing countries is followed by Vietnam and India.[b)]



Almost in step grows the global PV installations, which developed from less 200 GW in 2013 to more than 1600 GV in 2023,[c)] with China accounting for nearly 650 GW alone.[d)]



*inlcudes 42 GW China AC/DC ratio uncertainty
Source: IEA PVPS & Others

References
a) International Energy Agency, Special report on solar PV global supply chains, Background and coverage; Revised version 2022
b) Statista, Distribution of solar photovoltaic module production worldwide in 2023, by country; 2024
c) International Energy Agency, Trends in photovoltaic applications 2024, Report IEA PVPS T1-43:2024; 2024
d) Statista, Cumulative solar photovoltaic capacity globally as of 2023, by country; 2024

materials and technologies, such as perovskite and organic solar cells, are enabling a broader range of niche applications (Tarique and Uddin, 2023). These include building-integrated and vehicle-integrated photovoltaics, wearable electronics and flexible, portable self-charging indoor and/or outdoor internet-of-things (IoT) devices.

The Asia-Pacific region is expected to show the highest CAGR in the photovoltaics market over the forecast period, largely due to the presence of major manufacturing players. Rising manufacturing and policy-driven use of photovoltaics in countries like China and India are driving regional growth. Moreover, rapid urbanisation and industrialisation in these countries are increasing energy demand, creating significant opportunities to expand their renewable energy capabilities.[5]

Technological improvements in the installation and management of photovoltaic power plants to decrease future photovoltaic energy costs affect not only solar cells or modules, but also other balance-of-system (BOS) components, including inverters and cables as well as design, installation and commissioning services. BOS components are increasingly viewed as key areas for cost optimisation and competitive advantage, as they encompass most of the equipment needed for photovoltaic plants and account for 10-40% of the total system cost.

For example, solar trackers have recently gained popularity due to the higher returns they provide to solar developers. The inverter market is anticipated to grow at the highest CAGR in the near future, driven by their widespread adoption in both residential and utility-scale applications, and by offering advanced features such as plant-wide control and monitoring, optimised photovoltaics performance based on radiation and temperature while continuously ensuring grid safety compliance. Accordingly, the inverter market is anticipated to grow at the highest CAGR in the near future.

1.3 Technologies for photovoltaics

As global demand for energy continues to grow, photovoltaic technologies are evolving rapidly in the areas of photovoltaic materials, device structures, system management and practical applications.

For this technology insight report, we selected a range of technologies across all four main areas because of their role in improving the efficiency of photovoltaic devices and the affordability and versatility of photovoltaics for a variety of applications in both industrialised and developing countries.

The range of technologies covered in this insight report is not exhaustive. We plan to further expand the range of technologies in future editions of this technology insight report, e.g. to include technologies such as organic photovoltaics (OPV).

1.3.1 Photovoltaic materials

The foundation of photovoltaics lies in the materials used to convert sunlight into electricity. The last three decades witnessed great progress in terms of the conversion efficiency and usability of photovoltaic materials.

Among these materials, we selected and analysed some classes of materials with high potential for efficiency improvements and cost reductions, namely copper oxides, dichalcogenides, group III-V and II-VI semiconductors, perovskites (inorganic or inorganic-organic hybrid), kesterites, materials for dye-sensitised solar cells and quantum dot-based materials.

Thanks to the extraordinary research and development efforts taking place in both academia and industry, perovskite solar cells have shown excellent module reliability, with most of them passing the IEC standardisation requirements,[6] which is required for commercial silicon solar cells, and the photovoltaics industry is demonstrating their first perovskite solar cells commercial products (Tanko et al., 2025). Perovskites offer tuneable band gaps, both in single junction and tandem configuration, as well as suitability and compatibility with industrial scale-up and low-cost fabrication, making perovskite solar cells prime candidates for next-generation solar cells, and for application in optoelectronic devices such as LEDs and photodetectors (Lira-Cantu and Tanko, 2024; Sharif et al., 2023).

By contrast, group III-V semiconductors are expensive but key to high-efficiency and space applications, while photovoltaic materials such as kesterites offer environmentally friendly alternatives to solar cells based on critical raw materials, in line with the EU's strategic autonomy.

5 Source: See footnote 4

6 IEC (International Electrotechnical Commission) standards are widely recognised technical standards for electrical, electronic, and related technologies.

1.3.2 Technologies related to photovoltaic devices

This area focuses on technological improvements at the solar module level. Innovations such as bifacial solar cells and tandem architectures are pushing the limits of solar module efficiency by capturing more light and combining various photovoltaic materials. Passivated contacts reduce recombination losses, which is a key step in improving silicon-based cells. Meanwhile, thin-film technologies offer lightweight and flexible design of the photovoltaic devices. Finally, technologies such as optics for light management and sun-tracking systems directly increase the energy yield, which is vital for optimising land and material use.

1.3.3 Management of photovoltaic installations

While the effectiveness of photovoltaic systems depends largely on the photovoltaic materials used and on device aspects, these are certainly not the only factors. Once installed, the performance of photovoltaic systems hinges heavily on effective maintenance and system management intelligence. Technologies such as automated panel cleaning, fault detection and soiling measurement of the solar panel surfaces make an important contribution to reducing performance losses. AI-based diagnostics and testing technologies optimise system operation and help predict failures which reduces downtime and maintenance costs. With solar panel waste expected to increase, recycling technologies are essential for closing the business lifecycle and mitigating the impact on the environment.

1.3.4 Applications of photovoltaic devices

The past few decades have seen a significant expansion of photovoltaic applications beyond traditional solar farms and specialised uses in space technologies. Interesting new areas of application include:

— agrivoltaics, with the dual use of land for photovoltaics and agriculture

— floating photovoltaics on water surfaces

— vehicle- and building-integrated photovoltaics which allow solar energy to be harnessed in urban and transport applications (Araki et al., 2025; Faes et al., 2025)

— use for water electrolysis that demonstrate the potential of photovoltaics to facilitate off-grid applications and the production of green hydrogen.

In addition, flexible photovoltaic technologies – suitable to self-power indoor-outdoor IoT devices – have made notable advances, with flexible perovskite and OPV cells achieving power conversion efficiencies above 24% and 18%, respectively, as well as improved mechanical robustness and operational durability.

In contrast, technologies like dye-sensitised solar cells (DSSCs) have progressed more gradually, with fewer headline efficiency gains reported over the past year. Nonetheless, steady improvements are being made in areas such as stability and adaptations for specific applications, including flexible DSSCs (Almora et al., 2024).

These applications illustrate the versatility and scalability of photovoltaic technologies in supporting diverse global energy needs and achievement of the UN SDGs.

Technology does not stand still. Continued progress in materials and photovoltaic devices as well as economies of scale will ensure that photovoltaics continue to play a key role in the global transition to sustainable energy. In the coming years, we can expect to see new materials become more mature and competitive, manufacturing processes become more efficient and environmentally friendly, and photovoltaics become even smarter.

1.4 About this report

In this report, we focus on a selection of technologies that are driving development in photovoltaics or are promising candidates for future growth. Aimed at decision-makers in both the private and public sectors, the report is a unique source of information on these technologies and the technical problems they aim to solve.

This publication draws on the latest available patent information and the expertise of EPO examiners to provide a comprehensive analysis of the innovation trends driving technical progress in photovoltaics (Figure 1). Patent information provides robust statistical evidence of technological progress. The data presented in this report show trends in high-value inventions for which patent protection has been sought in more than one country (IPFs). Further explanations on methodology and sources are provided in Annex 1.

The statistical results are complemented by in-depth qualitative perspectives from case studies and individual patents. Although global in scope, the report has a stronger focus on Europe (defined here as the 39 contracting states that are currently members of the EPO).

This report contributes to the UN Sustainable Development Goals, mainly to SDG 7 (Affordable and clean energy), SDG 9 (Industry, innovation, technology and infrastructure), SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action).

Figure 1:

A cartography of technologies used for this report.

Innovation spotlight: How the European Innovation Council help photovoltaics in Europe shine

The European Innovation Council (EIC) is Europe's flagship innovation programme, established with an indicative budget of EUR 10.1 billion from 2021 to 2027 under the EU Horizon Europe framework programme to identify, develop and scale-up breakthrough technologies and game-changing innovations.

The EIC invested around EUR 700 million in energy generation and storage solutions (EISMEA, 2025). Twenty-one projects related to photovoltaic technologies were funded (eight from the EIC Accelerator and 13 from the EIC Pathfinder funding scheme).

In accordance with REPowerEU and STEP policies and under the European Green Deal framework, the EIC strengthens European industrial competitiveness and strategic independence by supporting the development and manufacturing of critical technologies, such as those related to renewable energy sources. This is achieved through specific Work Programme challenge calls dedicated to photovoltaics:

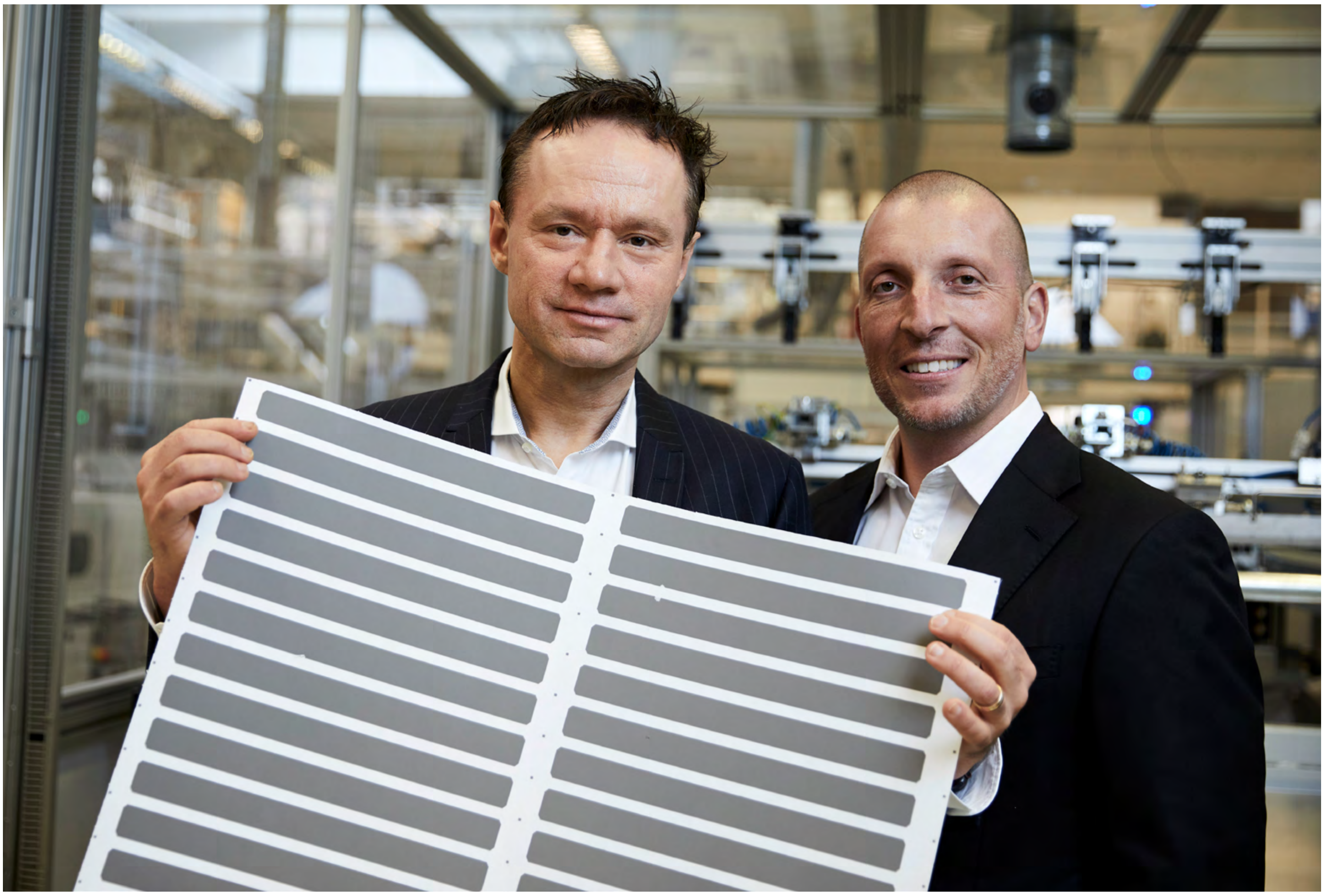
1. The scale-up of the manufacturing of different renewable energy sources, including photovoltaics, and their supply chain of the EIC 2024 Accelerator challenge "Renewable energy sources and their whole value chain". This includes the development of materials and the recycling of components to limit the EU's significant dependency on imports of components, including critical raw materials, to ultimately increase the EU's energy strategy autonomy in the energy sector.
2. The visionary EIC 2023 Pathfinder challenge "In-space solar energy harvesting for innovative space applications". These efforts look for solutions to collect solar energy in space and transmit it, possibly via an appropriate grid of re-translators, to various in-space recipients to be utilised for various in-space applications and novel propulsion approaches.
3. Further development and system integration of renewable energy sources was addressed by the EIC 2022 Transition challenge "Process and system integration of clean energy technologies". This work is aimed at identifying, designing, integrating and testing these technologies for inclusion in existing and new energy systems and devices at component, process or infrastructure level.

The companies funded by the EIC cover a broad spectrum of innovative technologies in the photovoltaic sector, such as:

- manufacturing processes, e.g. wafer production (example: NexWafe) and cells metallisation (Rise Technology; HighLine Technology)
- photovoltaics niche applications ranging from in-space (Deployables Cubed) to greenhouse (BriteSolar) and to internet-of-things devices (Dracula Technologies)
- recycling of solar cells modules (Rosi; Solar Materials).

References

European Commission: European Innovation Council and SMEs Executive Agency, 2025, "Scaling Deep Tech in Europe – European Innovation Council – Impact report 2025", Publications Office of the European Union



Case study: Flexible, printable solar cells

Inventors	Henrik Lindström and Giovanni Fili
Company	Exeger Operations AB
Key patent	EP2625703B1
Country	Sweden
Products	Flexible, printable solar cell film for integration into self-charging electronic devices and low-power applications

As the energy demands of portable electronics and sensor-based technologies continue to rise, so does the need for reliable, low-maintenance alternatives to battery charging. Addressing this challenge, Swedish inventors Henrik Lindström and Giovanni Fili developed Powerfoyle®, a dye-sensitised solar cell (DSSC) film designed to convert ambient light – both natural and artificial –into usable energy. The printed solar material is thin, flexible and customisable, allowing seamless integration into a wide range of consumer and professional products. Commercialised through their company, Exeger Operations AB, the technology targets applications where low power consumption, mobility and design flexibility intersect. From wireless headphones to industrial safety equipment, Powerfoyle supports extended device runtimes and, in many cases, full energy autonomy.

From research to collaboration

The partnership behind Powerfoyle began in 2009 when Lindström and Fili were introduced by a mutual contact. Lindström, then working in advanced materials science, had spent over a decade researching DSSCs, including a PhD at Uppsala University and postdoctoral research in Japan. Fili, an entrepreneur with a background in business and real estate, had recently founded a solar technology venture aimed at commercialising next-generation PV systems.

Their first meeting – held in a Stockholm cafe – quickly revealed a shared ambition to rethink how solar energy could be integrated into everyday life. Lindström brought deep scientific experience, including having produced one of the first flexible DSSCs on plastic. Fili offered a commercial vision grounded in entrepreneurial practice and market engagement. By the end of 2009, Lindström had joined Fili's startup, NLAB Solar AB, as Chief Technical Officer.

The collaboration was shaped from the outset by complementary expertise: Lindström led scientific and technical development, while Fili focused on business development and investor relations. In 2013, the company was rebranded as Exeger, signalling a shift from research and development to industrial-scale manufacturing.

Rethinking DSSC technology

The key technical innovation behind Powerfoyle emerged in 2010 during a flight between Germany and Sweden. Lindström and Fili were discussing the limitations of existing DSSCs, particularly the cost and inefficiency of indium tin oxide (ITO) as a conductive layer. The two began to explore alternative configurations and hit on a new concept: remove the light-blocking ITO layer altogether and reposition the conductive material behind the dye absorber. Lindström then sketched the idea on a napkin.

This adjustment proved pivotal: Lindström developed a proprietary conductive layer with approximately 1 000 times the conductivity of ITO. The new architecture allowed more light to reach the active layer, improving performance without compromising aesthetics. A custom-designed porous substrate was also introduced to support high-temperature processing and maintain structural flexibility.

The resulting solar film is manufactured via a screen-printing process that deposits multiple functional layers – light absorber, conductive material and catalysts – onto the substrate. The method is energy-efficient and compatible with high-throughput production, with a low environmental footprint compared to traditional silicon PV.

Diversified applications and market focus

Exeger has integrated its Powerfoyle technology across a wide array of product categories through various commercial and technological collaborations. The inherent flexibility and light-harvesting capabilities of the material lend themselves to diverse applications, primarily targeting the extension of battery life and enabling self-charging functionalities in everyday devices.

A primary application area is consumer electronics, particularly personal audio devices such as headphones, earphones and portable speakers. The technology is also being incorporated into other portable items like e-readers and various types of remote controls for home entertainment and appliances.

The internet of things (IoT) is another significant sector where Powerfoyle is used to enable or prolong the operational life of low-power devices. This includes a range of sensors for smart home applications (such as door and window sensors), retail solutions like electronic shelf labels, and tracking devices. In these cases, the aim is often to reduce the reliance on disposable batteries and minimise maintenance requirements.

Safety and professional equipment also feature as key use cases. This includes self-charging smart helmets that power integrated safety features, hearing protectors with extended battery life and communication headsets designed for continuous use in professional environments.

The technology has even found applications in transportation infrastructure, such as in the development of self-charging tolling transponders that offer greater longevity and reduced servicing needs.

To support industrial-scale production, Exeger now operates two manufacturing sites in Stockholm, Sweden. Together, these facilities form an integrated production ecosystem combining advanced machinery, robotics and in-house engineering expertise. At full capacity, the company expects to produce up to 2.5 million square metres of Powerfoyle solar cells per year. In-house workshops support automation by designing and calibrating custom manufacturing equipment, with additional innovation driven through strategic partnerships, including with ABB and SoftBank.

Patents and innovation strategy

Recognising the importance of intellectual property early in the project, Lindström and Fili began filing patents soon after formalising their partnership. Their primary European patent covers the solar cells' unique layer configuration, the materials used and the manufacturing methods. Both inventors are named on multiple additional patent applications, forming a portfolio that underpins Exeger's commercial model.

Fili notes that the patent family has been essential in attracting investment and securing long-term business relationships: "Without protection for our technology, we would not have had the freedom to operate or the confidence from our partners." Patent protection has been particularly important in differentiating the company within a competitive solar market.

Powerfoyle operates in a niche segment of photovoltaics, where flexibility, low-light performance and design adaptability are increasingly important. Unlike traditional rooftop solar, its value lies in distributed, embedded energy generation – especially in portable or connected devices with limited power demands. With its growing production capacity, expanding IP portfolio and active commercial collaborations, Exeger is positioning itself to support wider adoption of embedded solar technologies across multiple sectors.

2. Technology trends in photovoltaics

This chapter outlines the results of patent analyses regarding recent developments in photovoltaics, with a special focus on the four sub-areas covered in this report: photovoltaic materials, device-related technologies, management of photovoltaic devices, and applications.

The following sections present important trends in the field from 1974 to 2023, the latest year for which comprehensive data were available for the analyses.

2.1 General technology trends

To approach the area of photovoltaics as a whole, a composite dataset was created based on patent applications for the technical sub-areas mentioned before. Using this composite dataset, filing trends in photovoltaics were assessed first, and the findings then compared to the situation across all fields of technology. Next, the main jurisdictions under which protection was sought were looked at along with the most active applicants. Finally, a similar analysis was performed for the individual photovoltaic technologies.

Box 3

The field of photovoltaics has witnessed impressive progress in the last decades. This development was made possible by various factors, in particular the interaction of technical breakthroughs and advances and the increasing economic efficiency in the manufacture and utilisation of photovoltaic devices.

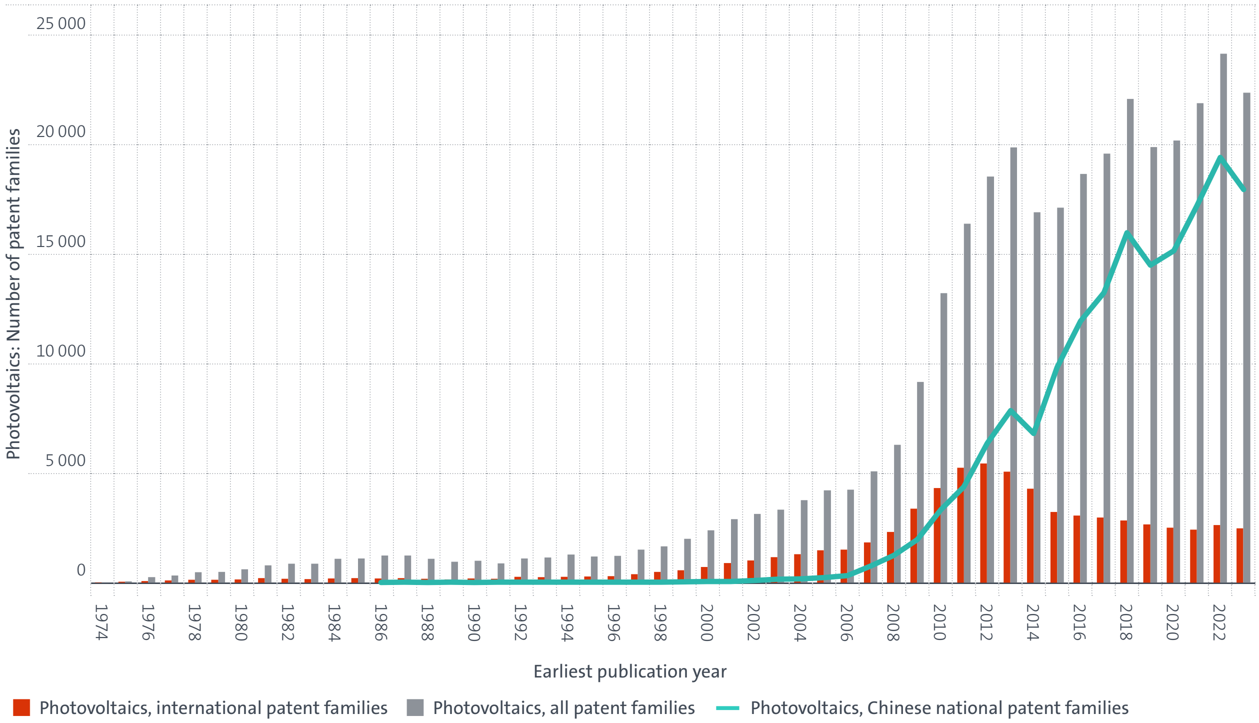
The following sections cover key sub-areas of photovoltaics: photovoltaic materials, photovoltaic devices and device management, and specific applications.

For each sub-area, we present examples of technologies that have contributed to the dynamism, or show particular promise for the future technological development. We also present examples of inventions that exemplify these technologies.

The number of distinct inventions (each protected by a so-called “family” of one or more patent applications) in the field of photovoltaics has increased very dynamically

Figure 2:

Number of inventions in photovoltaics, based on the composite dataset.



Source: EPO

in recent years, as shown in Figure 2 (grey bar). After a long period of moderate inventive activity in the field, the number of inventions started to increase considerably in the late 1990s. This period of accelerated growth turned into a period of very steep growth until around 2013 when the number of inventions dropped by approximately 15%, before growth gained momentum again at a lower growth rate. A total of nearly 340 000 inventions were identified during the analysis, of which 9% were related to photovoltaic materials, 54% to device-related technologies, 13% to the management of photovoltaic devices and 24% to applications of photovoltaic devices.

Figure 2 also indicates the number of international patent families (IPFs, red bars), a standard indicator for inventions with international focus and confirmed technological and economic potential. We identified more than 70 000 such IPFs in the dataset. Their number increased alongside those of all patent families until 2013, albeit at a faster rate, denoting a growing need for international protection of photovoltaic technology. However, the trend reversed afterwards and the number of international patent families has been decreasing continuously ever since, whereas the growth of all patent families kept rising and even accelerated, driven almost entirely by a sharp rise of patent applications solely in P.R. China. In other words, the early 2010s have seen patenting strategies in the photovoltaic industry shift from a regime of international protection to one prioritising protection in China only.

This dramatic evolution can be traced back to a series of shocks around 2012 which accelerated the emergence of China as the world's factory for photovoltaics materials and products. Many companies benefited from the generous and successful public support policies in Europe, the United States and Asia in the 1990s and 2000s[7]. This resulted in high demand for photovoltaic products, combined with a strong expansion of production capacities and the emergence of numerous new market players, many of which were Chinese. These factors increased competition, resulting in substantial price decreases for photovoltaic products. Consequently, many European and US photovoltaic companies were forced to close, whereas others were able to continue production thanks to more cost-effective production conditions and publicly subsidised loans, which helped sustain production even during very challenging periods. At the same time, the transition to aggressive price competition and economies of scale in the photovoltaic industry created barriers for new entrants and alternative photovoltaic technologies, making it difficult for them to gain a foothold against the remaining major producers and their focus on established crystalline silicon technologies.[8] As a result, the Chinese PV industry is today home to the majority of solar module producers worldwide and accounts for more than 80% of solar module production.[9]

A comparison with other technology areas helps put in perspective the dynamics of innovation in the field of photovoltaics. Figure 3 compares the filing statistics in photovoltaics to the development in all technical fields. To this end, the data were recalculated relative to 1990 as a reference year, which represents the beginning of a decade when the field gained considerable momentum. The as-normalised series shows that photovoltaics, although volatile, have outperformed all technical fields combined in the last decades (Figure 3). In particular, the graph illustrates that the remarkable increase in the number of IPFs in photovoltaics by a factor of more than 28 until 2012, compared to the situation in 1990, and the subsequent collapse were domain-specific: in the same period, the increase in the number of IPFs in all technical fields was only about threefold, and without subsequent breakdown. For comparison, Figure 3 also shows the development for all patent families in the field of photovoltaics, with the period of accelerated growth as of the end of the 1990s, the steep increase until about 2012 and the continued but more fluctuating growth since then.

In the reporting period, the share of IPFs related to photovoltaics increased from 0.22% of the inventions in all technical fields combined in 1990 to a peak of 1.94% in 2011, before it declined due to said collapse to about 0.7% in more recent years. In comparison, the share of all patent families in photovoltaics rose from 0.13% of inventions in all technical fields combined in 1990 to a peak of 1.08% in 2011, before declining to 0.5% in 2023 due to the recently higher momentum in all technical fields compared to photovoltaics.

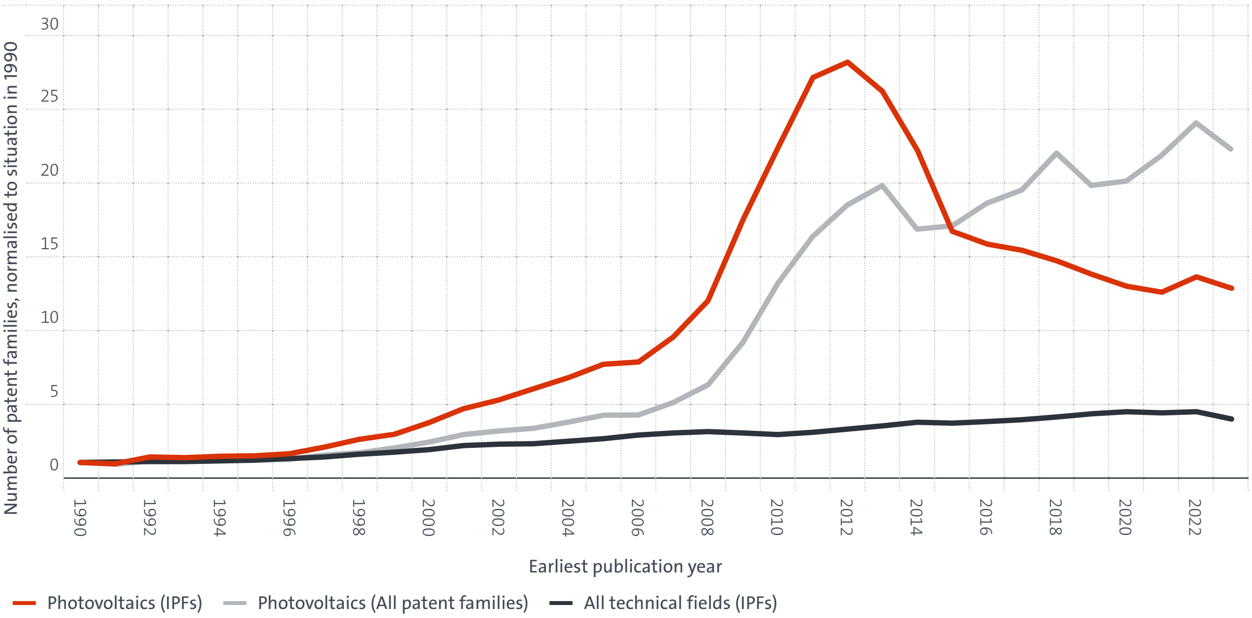
7 Government support in Europe and the United States has made a significant contribution to the rapid development of photovoltaics, particularly through guaranteed feed-in tariffs which accelerated investments in photovoltaic technology.

8 World Intellectual Property Organization, 2017; European Patent Office, 2021

9 Statista, Solar PV - statistics & facts, 2024

Figure 3:

Normalised data for patent families in photovoltaics and in all technology fields (reference year: 1990)



Source: EPO

Remarkably, despite the collapse, the share of IPFs in photovoltaics compared to all technical fields combined remained higher than the share of all patent families in that field in recent years, which is due to the relatively lower momentum of IPFs in all technical fields in the same period.

Patent documents in IPFs, as the main variable in this insight report, were not evenly published by all patent authorities worldwide but show a strong tendency towards a small number of patent authorities representing specific application procedures. The share of these patent application routes in IPFs can be taken as an indication of the commercialisation strategy of the patent applicants in the field, representing the markets for which they seek patent protection. The share may also be an expression of the patent applicants' assessment of where their main competitors are located.[10]

Figure 4 shows the share of patent authorities in IPFs in photovoltaics per earliest publication year. Patent applicants focus strongly on the following patent application routes: International (or PCT) applications[11], US applications, JP applications, CN applications, EP applications and KR applications. In this technical field, the PCT application route has been playing an increasingly important role over the past decades. The CN application route has also become increasingly important, whereas the role of other application routes, such as the EP application route, has remained rather constant or even decreased.

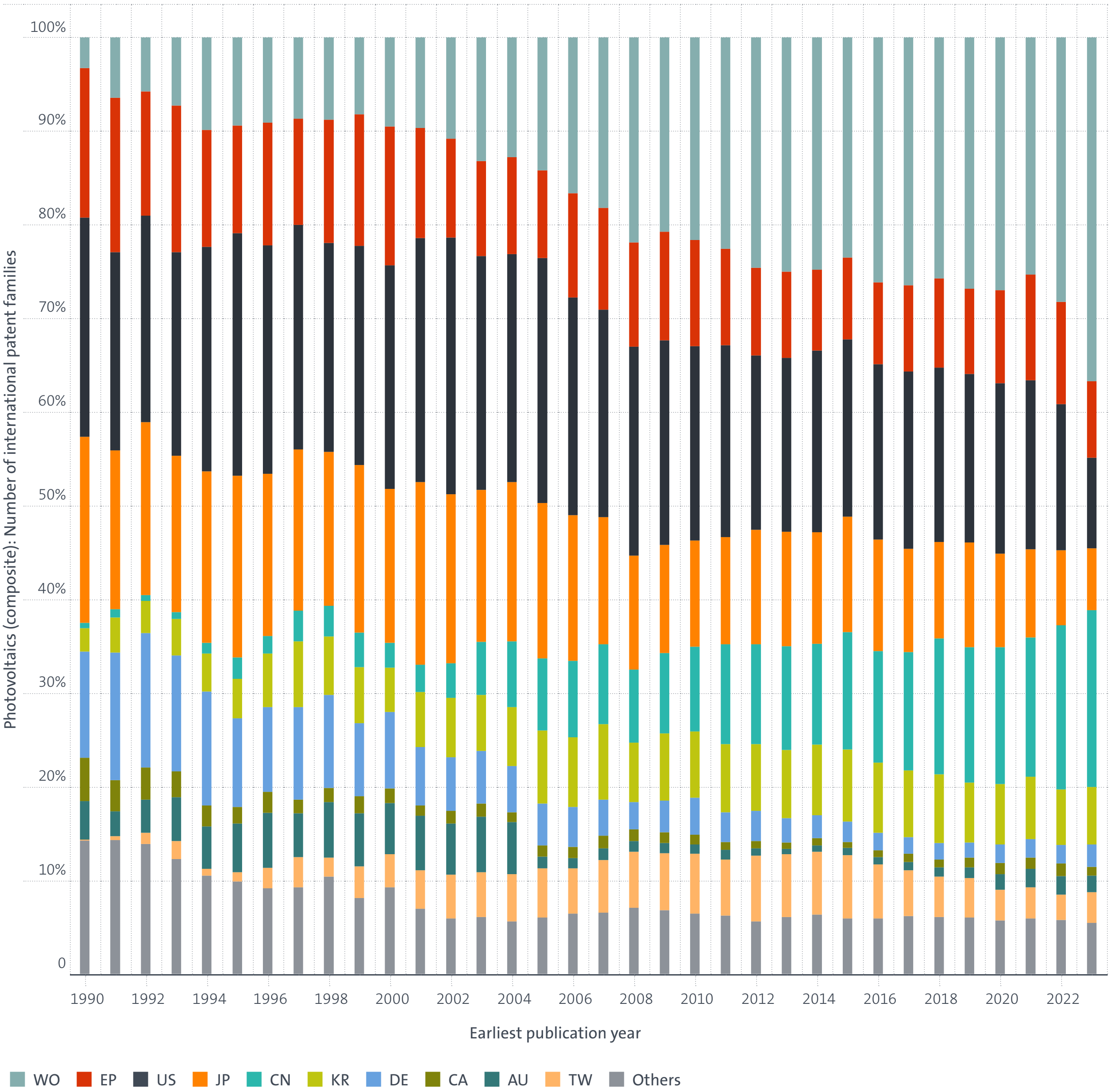
These shifts in the role of application routes took place against the background of an overall decline in the number of international patent families in the technical area covered by this insight report. This decline ran parallel to a steeply increasing role of national patent families. Figure 5 shows how the number of national patent families developed in the reporting period, with Chinese national patent families outnumbering the other national routes by far since the noted upheavals. The change towards protection solely in China is considered to reflect the growing importance of China as a location for research, product development and manufacturing in the field of photovoltaics.

10 The primary reason why patent applicants seek protection in specific countries is to secure the commercial use of their invention in target markets. They also frequently follow other strategic considerations, such as proximity to competitors' operations or key supply chain partners. Additionally, they often target countries with strong IP frameworks where they can enforce their IP rights.

11 Patent applications filed under the Patent Cooperation Treaty (PCT) for example. Accordingly, these patent applications are often referred to as PCT or international patent applications. See wipo.int/pct/en for more information.

Figure 4

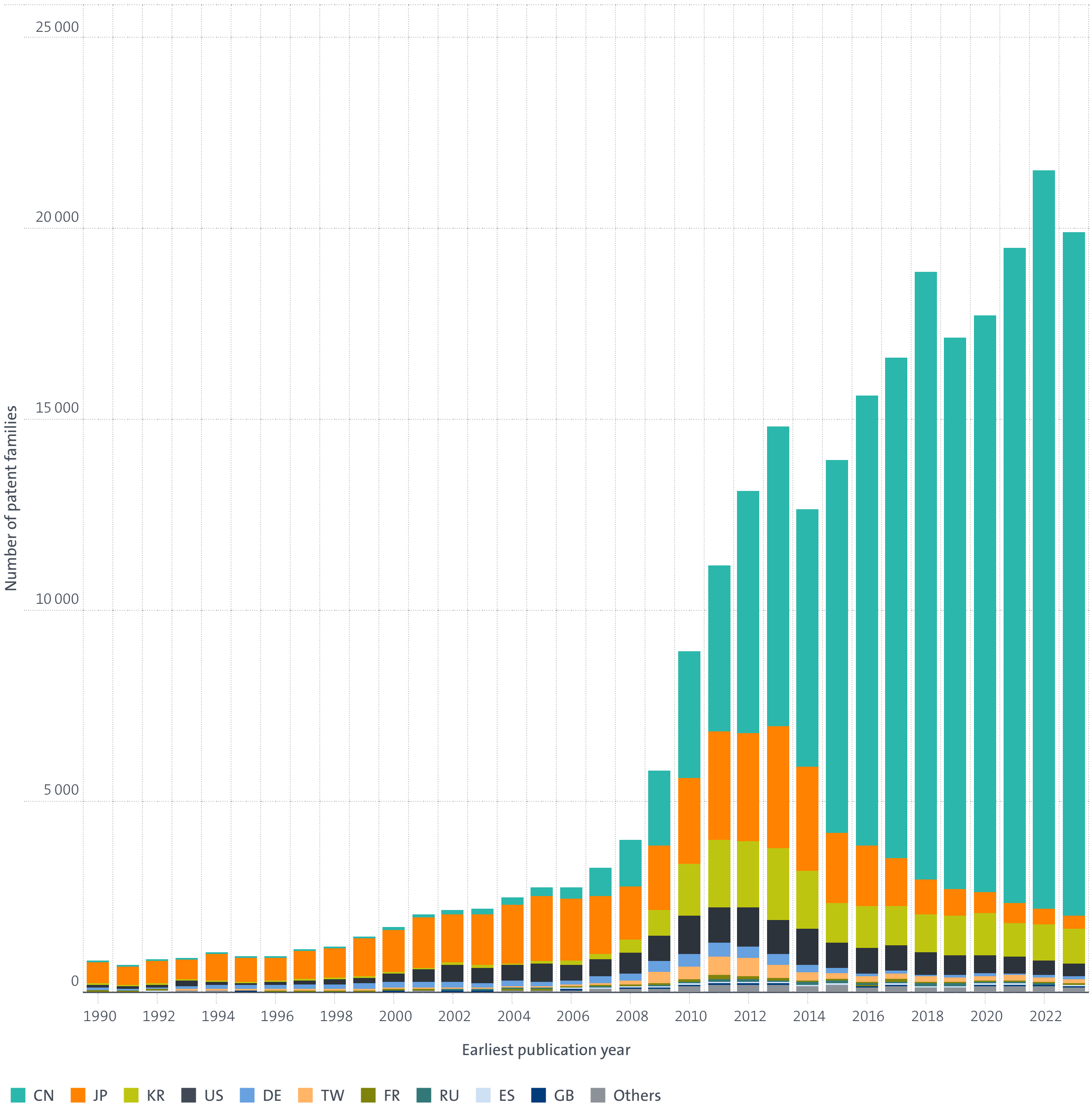
Patent application routes chosen for IPFs in photovoltaics, per earliest publication year. The information is presented as per patent application routes.



Source: EPO

Figure 5:

Number of national patent families in the field of photovoltaics, with a breakdown of patent application routes (period: 1990-2023)



Source: EPO

2.2 Specific technologies

A closer analysis of the various sub-areas related to photovoltaics provided further insights into the drivers of the overall growth in patenting observed in this field.

Table 1 shows the five most patented technologies at the beginning of each decade in the period 1990-2023. It reveals that device technologies and technologies related to specific applications have led the ranking in all decades. While technologies related to tandem cells and thin-film solar cells were in front most of the time in the period investigated, the focus in the recent past has shifted to vehicle-integrated photovoltaics and sun-tracking. At the same time, the top five technologies account for an increasingly smaller share in IPFs, from more than 80% at the beginning of the 1990s and 2000s to less than 70% in this decade. This shift points to a broader technology base in the recent past.

The noted change in focus to vehicle-integrated photovoltaics and sun-tracking is in line with the general trend towards inventions related to the management of photovoltaic devices and applications in the field (see Table 2).

Table 3 provides a more comprehensive overview of the technologies covered in this report. Consistent with the observations in Table 1, three technologies dominated the field in the period 1990-2023: tandem cells, thin-film solar cells and vehicle-integrated photovoltaics.

At the same time, it is possible to identify technologies that still had a relatively low number of inventions in the period under review, but which were very dynamic in that period. These include the following technologies: inorganic-organic hybrid perovskites (growth by a factor of f=986 in this period), artificial intelligence (f=976) and passivated contacts (f=309).

Table 1:

Top five technologies at the beginning of each decade in the period 1990-2023 (IPF-based; cumulative share of IPFs)

1990-1994	
Tandem cells	461
Thin-film solar cells	278
Vehicle-integrated photovoltaics	104
Non-urban space	48
Self-powered objects	46
Total top 5	936
Share in IPF	81%
2000-2004	
Tandem cells	2 706
Thin-film solar cells	1 073
Vehicle-integrated photovoltaics	256
Materials for dye-sensitised solar cells	134
Self-powered objects	126
Total top 5	4 294
Share in IPF	84%
2010-2014	
Tandem cells	8 004
Thin-film solar cells	7 450
Vehicle-integrated photovoltaics	1 180
Sun-tracking	901
Materials for dye-sensitised solar cells	820
Total top 5	18 355
Share in IPF	75%
2020-2023	
Thin-film solar cells	2 098
Tandem cells	1 373
Vehicle-integrated photovoltaics	863
Sun-tracking	526
Inorganic-organic hybrid perovskites	493
Total top 5	5 353
Share in IPF	53%

Table 2:

Share of technical sub-areas in photovoltaics in percent (IPF-based, period: 1990-2023)

Sub-area	1990-1994	1995-1999	2000-2004	2005-2009	2010-2014	2015-2019	2020-2023
Materials	8.1	6.7	7.1	9.9	10.3	15.8	17.0
Devices	68.5	72.8	78.0	73.7	71.4	58.9	47.9
Management	3.2	3.7	2.3	3.8	4.9	7.1	10.1
Applications	20.1	16.8	12.6	12.6	13.4	18.2	25.0

Table 3:

Development of specific technologies (IPFs, 1990-2023)[12]

		1990-1994	1995-1999	2000-2004	2005-2009	2010-2014	2015-2019	2020-2023	Total number of IPFs
Materials	**Inorganic**								
	Copper oxides	7	7	19	56	139	114	80	432
	Dichalcogenides	9	9	22	46	158	219	153	629
	Group II- VI semiconductors	24	22	59	137	405	186	89	986
	Group III-V semiconductors	28	22	51	157	323	190	95	926
	Inorganic perovskites	0	0	0	0	0	3	11	14
	Kesterites	0	0	0	3	135	86	43	266
	Organic								
	Materials for dye-sensitised solar cells	21	60	134	390	820	604	281	2 365
	Inorganic-organic hybrid perovskites	1	8	29	39	91	404	493	1 066
	Others								
	Inorganic-organic heterojunctions in solar cells	4	9	39	169	319	365	310	1 218
	Quantum-dot materials	1	0	8	50	132	163	153	508
Devices	**Constructional**								
	Bi-facial solar cells	2	4	11	19	61	54	62	217
	Passivated contacts	1	3	12	77	119	123	309	645
	Tandem cells	461	945	2 706	3 809	8 004	3 223	1 373	21 595
	High-performance tandem cells	5	3	16	39	99	58	43	267
	Silicon bulk tandem cells	2	1	4	15	47	35	55	160
	Thin-film solar cells	278	442	1 073	3 197	7 450	4 129	2 098	19 155
	Light optimisation								
	Optics	25	43	50	268	727	485	347	2 006
	Sun tracking	23	41	105	336	901	591	526	2 601
Management	**Maintenance**								
	Cleaning panels	21	38	73	265	588	386	351	1 761
	Measure, test								
	Detecting malfunctions	0	1	3	6	49	54	46	160
	Installation testing	0	4	8	26	180	164	117	502
	Measuring soiling	0	2	4	11	63	94	84	258
	Others								
	Artificial intelligence	0	3	3	14	124	217	244	607
	Recycling solar panels	16	27	26	78	186	136	169	652
Applications	**Non-urban**								
	Agrivoltaics	0	0	1	2	5	10	22	41
	Floating photovoltaic	16	38	62	183	425	355	276	1 400
	Solar farms	4	9	14	96	461	243	238	1 077
	Space	48	72	113	103	148	179	154	909
	Others								
	Self-powered objects	46	76	126	205	363	361	337	1 582
	Vehicle-integrated photovoltaic (VIPV)	104	104	256	495	1'180	940	863	4 076
	Water electrolysis	3	3	12	31	82	133	116	397
	Urban								
	Building-integrated photovoltaics (BIPV)	2	3	10	37	171	121	144	489
	Car ports	1	1	2	6	25	17	34	87
	Roofs	12	37	49	167	394	329	329	1 321

12 The statistical concept was based on fractional counting of IPFs. The results shown were rounded to whole numbers.

2.2.1 Photovoltaic materials

In the period under review, 1990-2023, 28 756 patent families including 8 202 IPFs were related to photovoltaic materials, with an 8.8% share with respect to all patent families and 12% for IPFs.

The number of IPFs in this sub-area increased from 18 in 1990 to 439 in 2023, corresponding to a 24-fold increase. However, this growth was not evenly distributed across the analysed technologies in this sub-area. Figure 6 provides an overview of the individual technologies and their development over time.

The largest share of inventions in the field of photovoltaic materials were materials for dye-sensitised solar cells, with over 8000 patent families – corresponding to 28% of all inventions related to photovoltaic materials – of which more than 2 300 are IPFs. Invention activity for this substance group was moderate in the 1990s, but showed strong growth from the 2000s onwards, peaking in the period 2010-2014. Invention activity for this substance group continues to develop at a relatively high level.

Photovoltaic materials that have developed particularly dynamically in the period under review include inorganic-organic hybrid perovskites, quantum-dot materials and inorganic-organic heterojunctions in solar cells. The latter category includes arrangements of organic and inorganic semiconductors and organic materials containing inorganic nanoparticles.

The number of inventions relating to kesterite-type materials and inorganic perovskites was found to be lower than that of the other photovoltaic materials covered in this report. Kesterite-type materials do not appear before 2005, and inorganic perovskites do not appear before 2016. Consequently, these materials are considered to still be in the early stages of commercialisation.

Box 4: Technology spotlight on photovoltaic materials

Among the **various photovoltaic materials,** perovskites- and quantum dot-based materials have particularly stimulated research and development of photovoltaic technologies in the recent past.

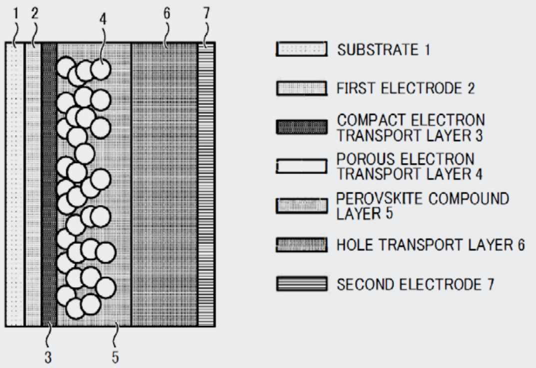
Perovskite-based photovoltaic materials have gained particular attention due to their rapid improvements in conversion efficiency and cost-effective production methods such as screen or ink-jet printing. Since their advent around 2010, these materials have achieved conversion efficiencies at the pilot production phase of above 26% for single junction perovskite and of up to 30.5% in tandem structures with silicon, surpassing traditional silicon-based cells (Tanko et al., 2025).

Their versatility allows manufacturing of perovskite or Si-perovskite tandem solar cells that can be used for different applications ranging from utility-scale to lightweight flexible solar panels which can be integrated into various surfaces, including buildings and vehicles. Challenges related to stability have almost been overcome (Lira-Cantu and Tanko, 2024; Tanko et al., 2025). Ongoing research for alternatives to the use of heavy metals, such as tin-based perovskites, offers hope for more environmentally friendly solutions with limited impact on the final cost of energy supplied.

EP2924755A2

Perovskite solar cell

This patent application presents a thin-film solar cell that has several layers with different functions. One of these layers has a perovskite-type structure and is composed of different chemical compounds including an alkylamine compound, a halogen compound, and a mixture of lead and antimony. The perovskite layer is the 'active layer', or main absorbing material, in the solar cell. As the core component of the solar cell, it is responsible for absorbing sunlight and initiating the process of electricity generation.



Quantum dot-based materials, as a second example, represent another frontier in photovoltaic research. These nanoscale semiconductor materials offer tuneable electronic band gaps by adjusting the size of individual quantum dots, enabling them to absorb a broader range of sunlight. A distinctive feature of quantum dot-based materials is their ability to facilitate specific electronic excitation, potentially boosting power conversion efficiencies. Quantum dot-based materials may be synthesised through solution-based methods, enabling cost-effective and large-scale fabrication on flexible substrates for photovoltaics.

EP2084755A2

Intermediate-band photosensitive device with quantum dots embedded in energy fence barrier

In this patent application, a photosensitive device is presented which may be used as a photovoltaic cell in a certain implementation. The device includes several layers with different functions. One of these layers is a dots-in-a-fence barrier which is a specific structure of quantum dots, small semi-conductor nanocrystals, embedded in a different semiconductor material with specific electronic properties. With that, the quantum dots are confined, preventing them from interacting with each other. This confinement allows the quantum dots to absorb a wider range of wavelengths of sunlight, potentially leading to photovoltaic devices with higher efficiency.

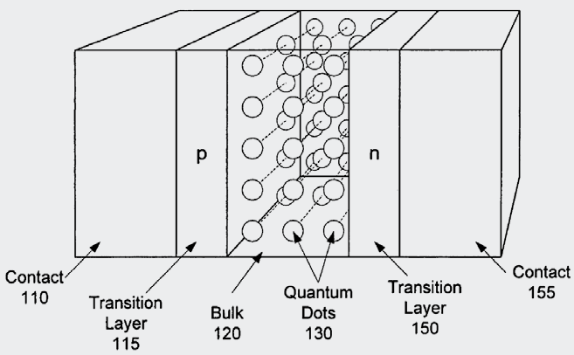
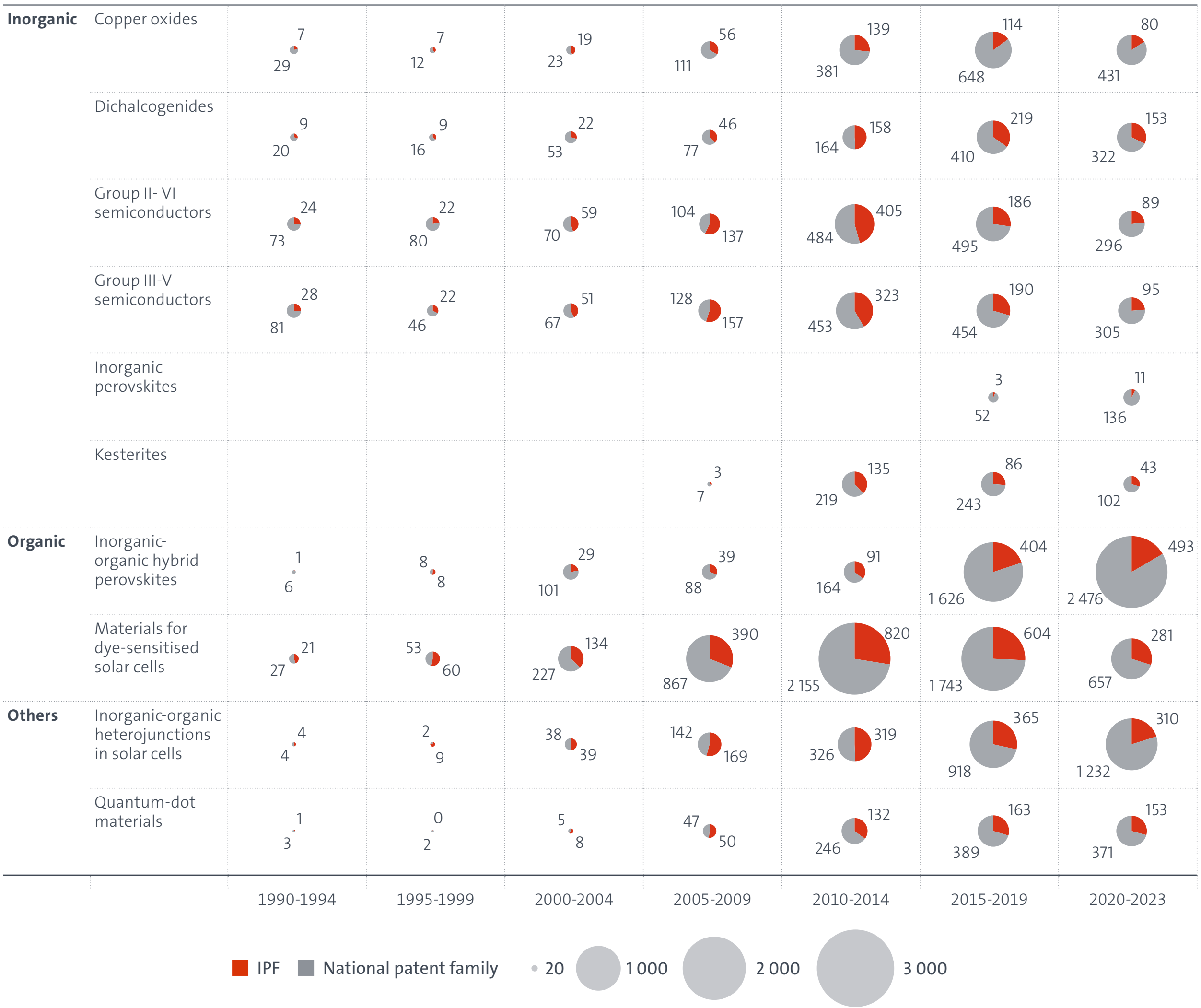


Figure 6:

Development of technologies related to photovoltaic materials (number of IPFs vs. national patent families, 1990-2023)



Source: EPO

2.2.2 Devices

With almost 177 000 patent families, accounting for 54% of all patent families in the dataset, technologies related to devices account for most of the inventions in the period under review, including almost 45 000 international patent families.

Tandem cells and thin-film solar cells account for the largest share of inventions in this sub-area, with nearly 21 000 and 19 000 IPFs, respectively, and also demonstrated a high level of inventive activity during the period 1990-2023 (Figure 7).

The rise of technologies such as sun-tracking and optics is also worth noting, with over 2 500 (sun-tracking) and nearly 2000 (optics) IPFs in that period.

Although passivated contacts demonstrate relatively low invention activity compared to the aforementioned device technologies, this technology nevertheless exhibits remarkable dynamism, experiencing growth by a factor of 309 for IPFs, and by a factor of 1 718 in terms of all patent families during the period under review.

Box 5: Technology spotlight on photovoltaic device

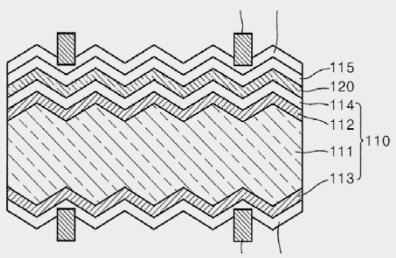
The rapid advancement of photovoltaic technologies has also been influenced by innovations in **device architectures and system-level enhancements**. Among these, tandem solar cells, passivated contacts and bifacial modules integrated with sun-tracking systems have been influential in expanding the boundaries of conversion efficiency and deployment.

Tandem solar cells have emerged as a key development in the solar industry. By stacking photovoltaic materials with complementary electronic bandgaps, tandem cells can convert a wider range of the sunlight into electricity, thus achieving higher conversion efficiencies. This is crucial for meeting the ambitious global renewable energy targets.

EP3637478A1

Method for manufacturing perovskite silicon tandem solar cell

This patent application presents a process for manufacturing a monolithic tandem solar cell in which a perovskite solar cell is laminated and bonded on a textured silicon solar cell. The shorter wavelengths are absorbed by the perovskite solar cell, whereas the longer wavelengths are absorbed by the silicon solar cell. The objective of the invention is to increase the light absorption rate of the solar cell by reducing the reflectance of light and lengthening the path of light. The process involves two steps: firstly, a microporous precursor thin film is sputtered onto a crystalline silicon substrate. The substrate has an unevenly structured texture. Secondly, a halide thin film is formed on the first microporous precursor thin film. Subsequently, the microporous perovskite absorption layer is formed.

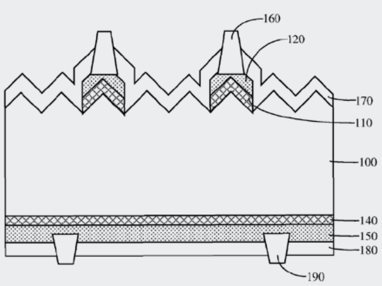


Passivated contacts have also played a vital role in enhancing the performance of photovoltaic devices, enabling higher overall conversion efficiencies.

EP4336574A1

Solar cell and photovoltaic module

This patent applications presents a solar cell with two specific additional layers aligned with the metal contacts used for collecting charge carriers in the solar cell. The objective of the invention is to reduce the recombination of charge carriers by carrier selection at the metal contacts and to correspondingly increase the efficiency of the solar cell. The first additional layer is a tunnel layer which creates a barrier reducing the recombination of specific charge carriers at the interface of the substrate and the metal contact (passivation). The second additional layer is a doped conductive layer which is designed to be conductive for one type of charge carriers while blocking the other to ensure efficient charge collection (selective carrier transport).



Bifacial solar modules, which can absorb light from both their front and rear surfaces, have become increasingly popular, particularly when combined with sun-tracking systems. This combination allows the capture of direct sunlight and reflected light thereby significantly increasing energy yield.

EP3803982A1

Bifacial solar module

The invention described in this patent application presents a bifacial solar module and a solar power kit for increasing power output from a solar module by applying films, foils or coatings which causes direct and total internal reflection of light in the solar module. This redirects the light from blank regions between the cells back to both active cell surfaces.

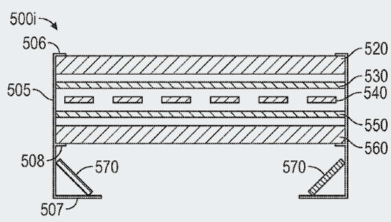
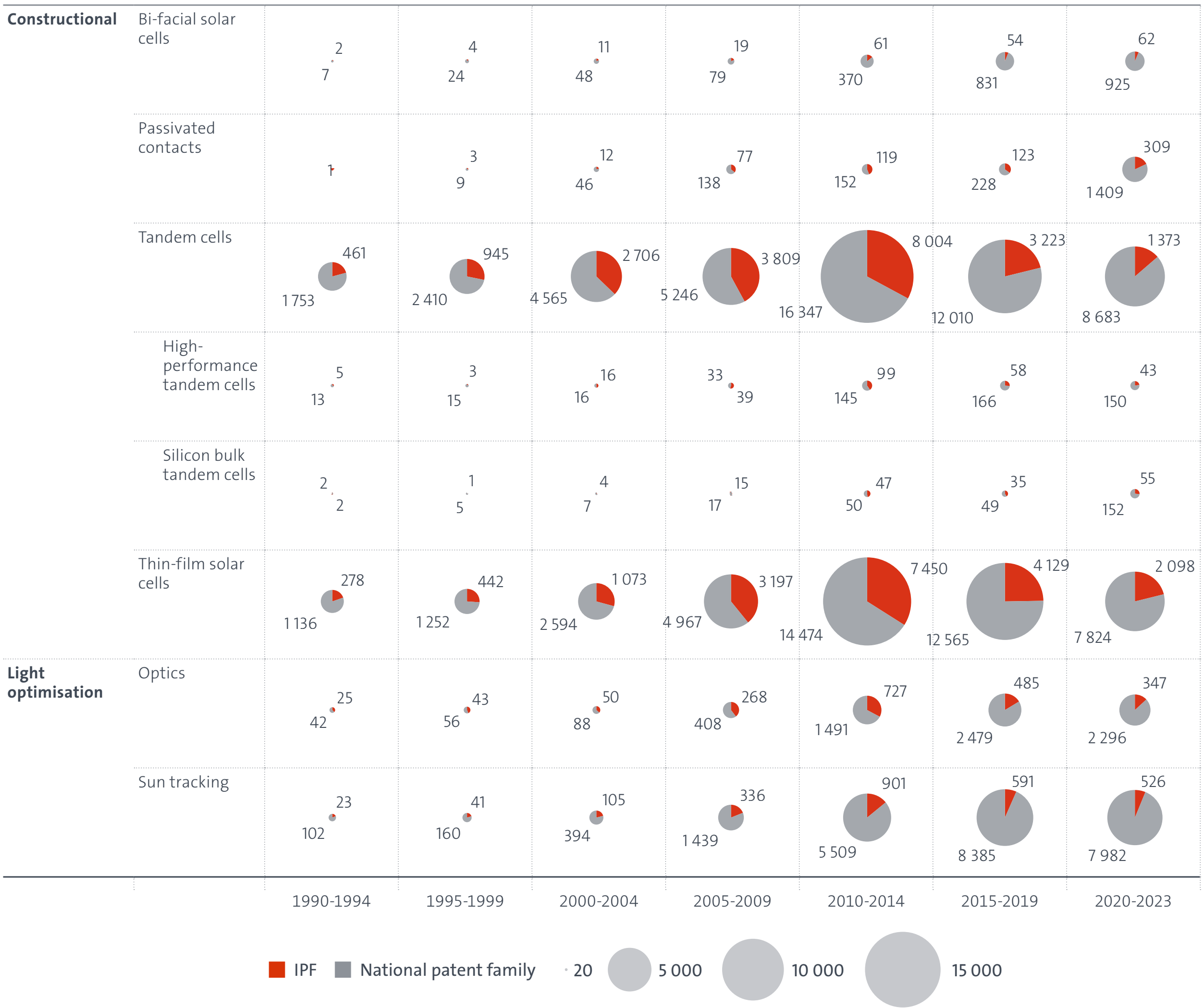


Figure 7:

Development of technologies related to photovoltaic devices (number of IPFs vs. national patent family, 1990-2023)



Source: EPO

2.2.3 Management of photovoltaic devices

Management is the second smallest sub-area, with 43 142 patent families in the period 1990-2023. Only a relatively small proportion of these (3 880) are IPFs, compared to the other sub-areas.

All technologies demonstrated inventive activity and significant dynamism in the reporting period, although some started from a low baseline (Figure 8).

Technologies for cleaning solar panels play the biggest role, with 28 526 patent families, including 1 722 IPFs, followed by recycling solar panels (5 509 vs. 638) and installation testing (3 881 vs. 499).

Two technologies with particularly high dynamics stand out in this sub-area: although absolute inventive activity is still rather low, artificial intelligence has nominal growth factors of 2 349 in relation to all inventions in this sub-sector, and 976 for IPFs in the reporting period. Meanwhile, installation testing has growth factors of 928 and 468, respectively.

Box 6: Technology spotlight on technologies related to the management of photovoltaic devices

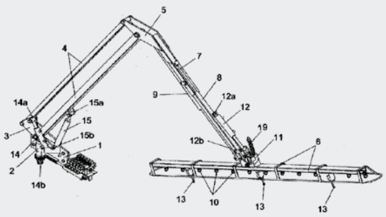
Efficient **management technologies** have become key in maximising the performance and economic efficiency of photovoltaic systems during their business cycle. Among these management technologies, automated cleaning solutions, soiling detection systems and the integration of AI stand out for their significant contributions to the development of photovoltaics and its integration into our everyday life.

Automated cleaning technologies have addressed the issue of soiling which can significantly reduce the efficiency of solar panels. Examples of these technologies include robotic cleaners which offer waterless and energy-efficient solutions and are particularly useful in arid regions. Another example are self-cleaning coatings which repel water and prevent the accumulation of dirt.

EP2369262A1

Cleaning device for photovoltaic panels and thermal solar panels

The invention presented in this patent application is a mountable arm for spraying a cleaning liquid onto the surface of a solar module. The arm can be attached to a tractor vehicle using a support structure so that the arm may be moved between the adjacent solar modules of each row or line of a solar farm.

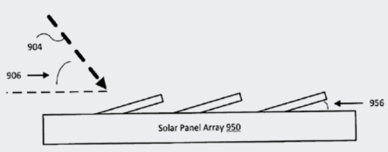


Soiling detection systems provide real-time monitoring of panel cleanliness. These devices may assess the degree of soiling on solar panels. By accurately quantifying soiling levels, these systems help to schedule cleaning activities precisely when needed, providing for an effective management of the solar panels.

EP3387397A2

Airborne inspection systems comprising infrared camera

This invention is related to an air-borne device that uses infrared imaging. The air-borne device may be used to monitor the surface condition of solar modules. The objective of the invention is to improve the monitoring capabilities beyond those of conventional infrared monitoring systems. The air-borne device comprises a logic device that applies radiation adjustment of the infrared images based at least partly on background radiation signals. The device may additionally compensate for various environmental effects, such as the position and/or strength of the sun, atmospheric effects to provide high resolution and accuracy radiometric measurements of targets imaged by the infrared imaging system, and it may comprise further components.



Artificial intelligence has further improved photovoltaic system management by advancing monitoring and predictive maintenance. AI-based technologies enable timely interventions and minimise downtime while also extending the lifespan of photovoltaics systems, just to name a few examples.

EP4468545A1

Energy management apparatus and energy management method

The invention presented in this patent application contains an energy management device and an energy storage device. The energy management device comprises a unit to forecast the amount of electricity provided by a solar panel based on a specific model, and a consumption amount forecast unit including a consumption amount forecast model. This device also comprises a control module to detect an abnormality of a solar panel based on the forecasted amount of electricity provided and to create a correction value, and also to assess the reason for a failure of the solar panel.

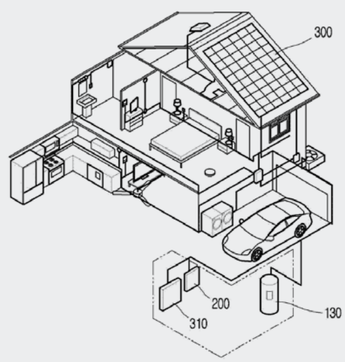
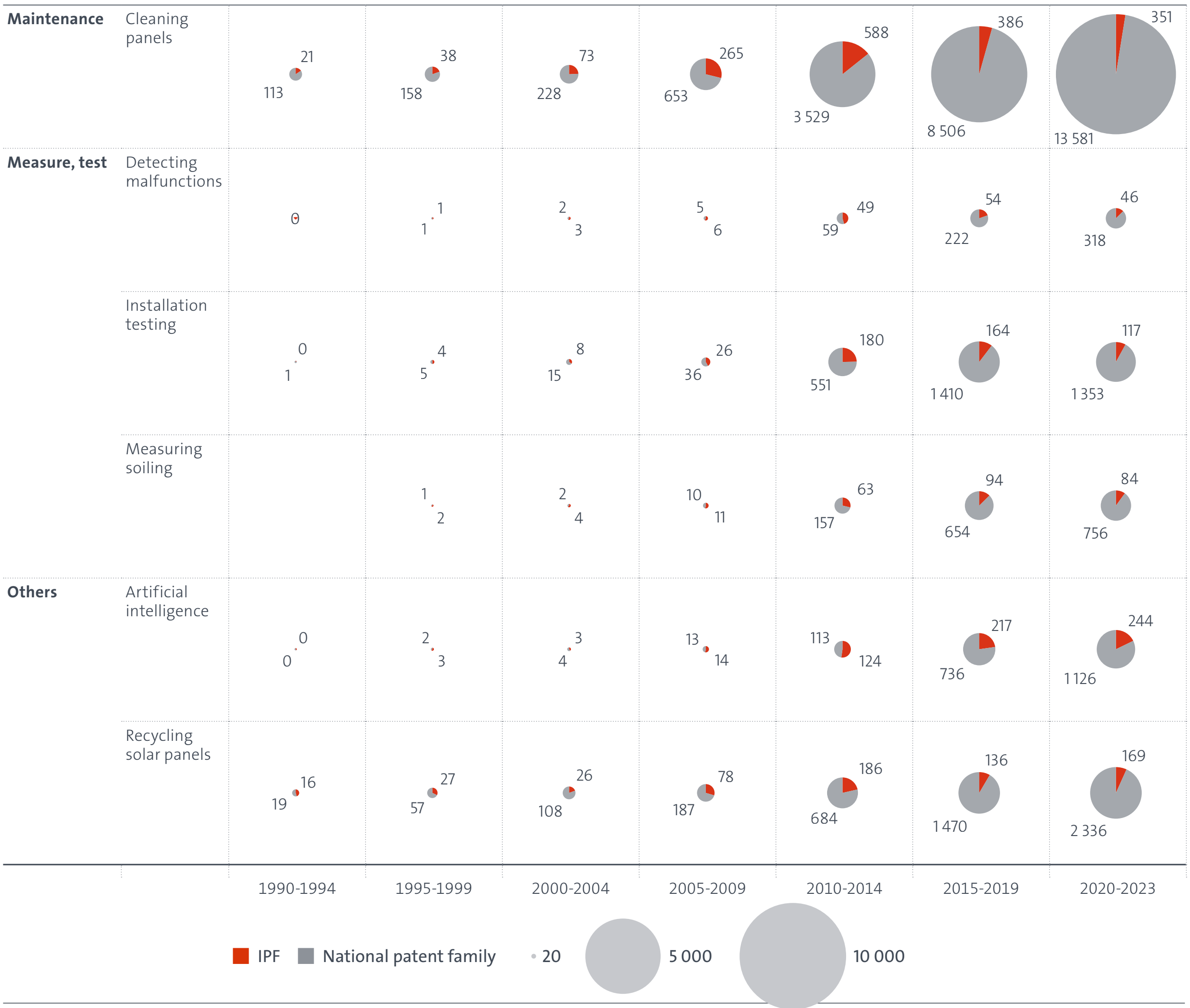


Figure 8:

Development of technologies related to the management of photovoltaic devices (number of IPFs vs. national patent families, 1990-2023)



Source: EPO

2.2.4 Applications

As mentioned in the introduction, due to impressive technical progress and greater cost-effectiveness in manufacturing and operation, photovoltaics is now used beyond solar farms and specialised areas such as space technologies.

In the applications sub-area, 79 678 patent families were identified in the period 1990-2023, of which 11 001 are international patent families. With a share of 16.2% regarding international patent families, this sub-area ranks second among the photovoltaics sub-areas covered in this insight report.

Figure 9 provides an overview of the individual technologies in this sub-area and their development over time.

One area of application that attracted attention early on and demonstrated significant inventive activity throughout the entire reporting period was “vehicle-integrated photovoltaics” with 31 623 patent families, including 3 941 IPFs.

Unlike the other sub-areas, there are only a few technologies with significant dynamics in this sub-area. The technology that experienced the greatest growth during the reporting period was building-integrated photovoltaics, which increased 448-fold for all patent families and 96-fold in terms of IPFs.

Box 7: Technology spotlight on photovoltaic applications

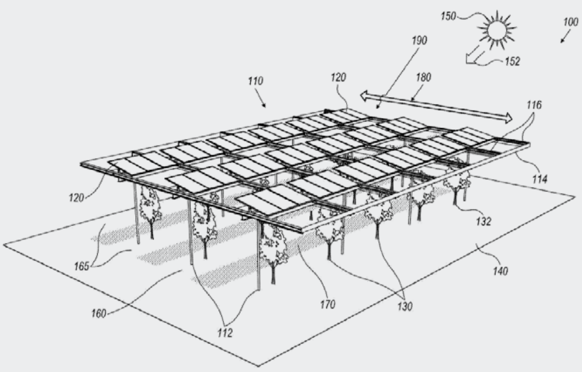
Progress regarding photovoltaic materials, solar devices and the management of solar devices has paved the way for these devices to become part of our everyday life. The prevalence of photovoltaic technologies today indicates not only their versatility but also their potential to address various global challenges.

Agrivoltaics are a prime example of this potential. By using land for both agriculture and solar energy production simultaneously, agrivoltaic systems can enhance land use efficiency, improve resilience of crops to extreme weather and reduce water usage by providing shade for plants and soil. Despite their higher initial costs, agrivoltaic technologies offer long-term benefits to the farmers and contribute to food and energy security.

EP4334651A1

Solar energy system and method for controlling shade in an orchard

This patent applications presents an arrangement of devices for improved concurrent crop and electricity production in an orchard. Solar panels are deployed above the ground in the orchard to capture the solar energy from the sun. A computing unit executes an algorithm to control the shading by the solar panels by moving the solar panels. With that, the quantity and location of sunlight provided to the crops and to the solar panels can be changed dynamically.



Another influential application is **floating photovoltaics,** which are used in particular in regions where land is scarce. By combining solar panels with a suitable supporting structure and placing them on water, these devices not only generate electricity: they can reduce water evaporation. The cooling effect of the water can also enhance the efficiency of these devices which makes them an interesting solution for optimising the conversion efficiency while minimising the impact on scarce water resources.

EP4342075A1

Method for assembling a floating solar system, and corresponding system

The invention presented in this patent application discloses a specific floating photovoltaic installation and a method to fabricate, assemble and launch the installation on the surface of a water site. The floating photovoltaic installation comprises solar panels and floating tube elements that support the solar panels at an inclined angle.

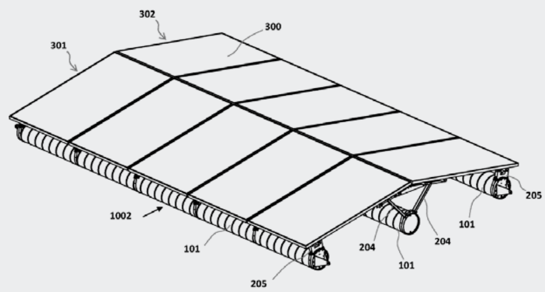
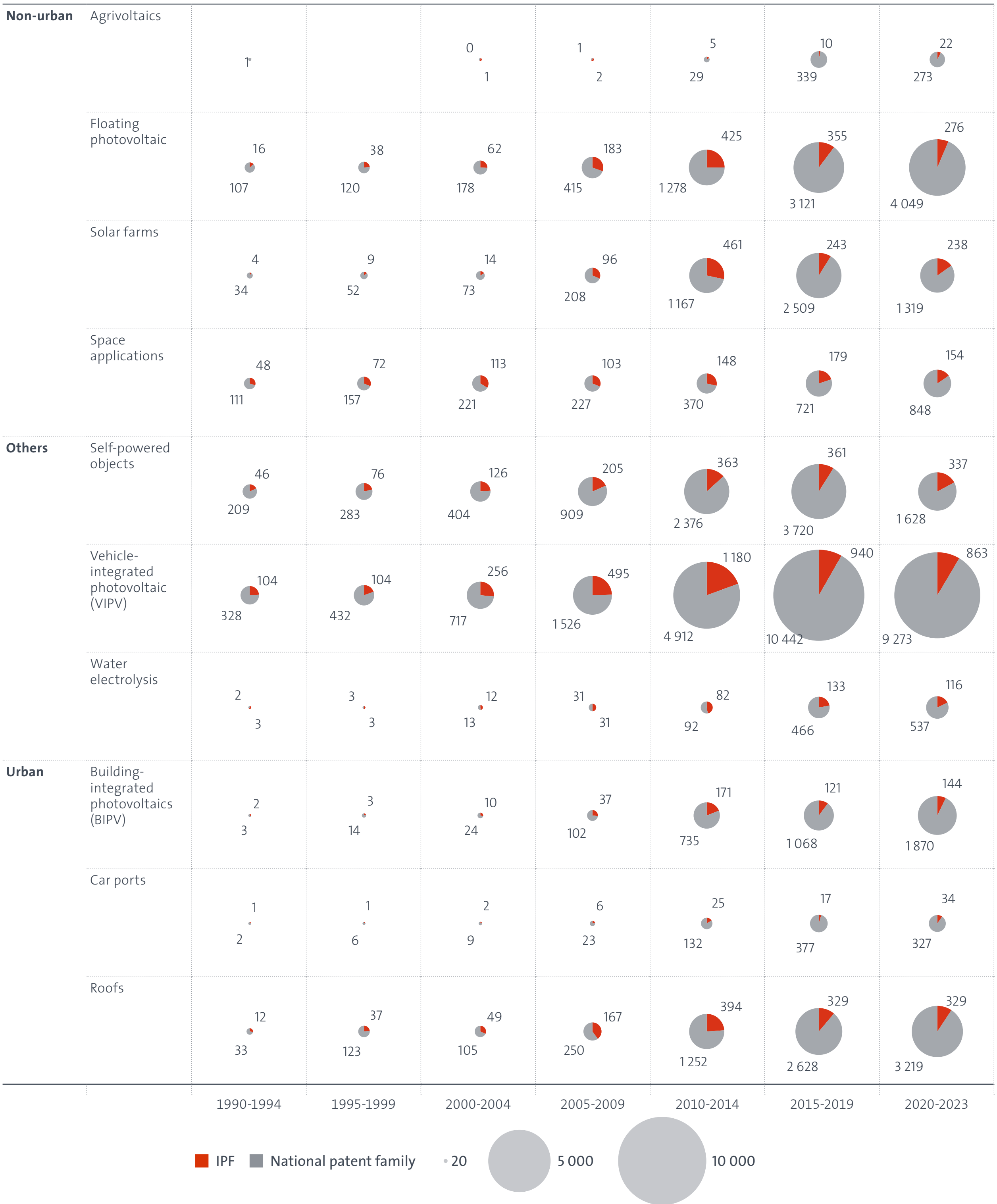


Figure 9:

Development of technologies related to the application of photovoltaics (number of IPFs vs. national patent families, 1990-2023)



Source: EPO

Case study: Floating solar farm solutions

Inventors	Nuno Correia, Carla Gomes and team
Organisations	INEGI (Institute of Science and Innovation in Mechanical and Industrial Engineering) and SolarisFloat Ltda
Key patent	EP3571762B1, EP3515802B1
Country	Portugal
Products	Dual-axis floating photovoltaic platform

With increasing pressure to decarbonise the energy sector and utilise limited land more sustainably, floating solar technologies are gaining attention. Portuguese engineers Nuno Correia and Carla Gomes, along with their team at INEGI, have developed an innovative mooring platform for floating solar farms that dynamically tracks the sun – both by rotating the island and adjusting the tilt of individual panels. The patented system, called PROTEVS, increases energy capture efficiency by up to 40% and offers ecological co-benefits that enhance its appeal to sustainable energy markets globally.

A new chapter in floating photovoltaics

While floating solar systems are not new, many have been static installations. Correia and Gomes were approached by the Portuguese company SolarisFloat to realise a more dynamic vision: a floating island capable of tracking the sun's movement across two axes – azimuth (rotation) and elevation (tilt) – to maximise energy generation throughout the day.

SolarisFloat, which commissioned INEGI to develop the PROTEVS system, is a specialised technology provider focused on innovative solar energy solutions with low environmental impact. It operates as part of jp.group, a Portuguese business conglomerate active in over 70 countries. While jp.group's origins lie in the Information and Communication Technologies (ICT) sector, it strategically extended into renewable energy, with SolarisFloat helping to cement its presence in the floating PV space. The company outsources research and development to accelerate innovation and reduce time to market.

Engineered for efficiency

The INEGI team responded with a modular design: a floating circular platform 38 metres in diameter supporting 180 photovoltaic panels. These rotate during the day to follow the sun and return to their starting position at night. Meanwhile, the panels themselves can tilt between 0° and 45° for optimal solar capture. The result is a system that boosts solar efficiency significantly over fixed installations.

The PROTEVS platform floats on calm inland water bodies, such as reservoirs, dams or water treatment facilities. An autonomous onboard control system coordinates rotation and tilt movements using data from

light sensors, ensuring optimal solar capture throughout the day. Power is supplied by low-friction electric motors similar to those used in small boats, minimising energy consumption for movement.

Structurally, the panels are mounted on cross-shaped supports with inflatable plastic floats underneath. These supports are modular and stackable, allowing efficient transport and deployment. The island is anchored via a flexible mooring system, enabling vertical movement of up to 20 to 30 metres in response to changes in water level. An outer ring adds wave resistance and serves as a connection point for multiple islands when scaling up the installation.

Environmental gains beyond clean energy

The system is constructed from UV-resistant recycled plastic with a design life of 20 years, after which it is fully recyclable. From both performance and environmental standpoints, PROTEVS demonstrates a life-cycle approach to sustainability.

Floating PV systems benefit from passive cooling provided by the surrounding water, which can enhance efficiency by an additional 15% compared to land-based installations. "Having these systems on water means that we're not occupying arable land with the production

of photovoltaic energy," says Correia. "That's important if we're trying to produce a large amount of energy in renewables."

Correia and Gomes' system delivers further environmental advantages: the structure shades the water surface, reducing evaporation by up to 60% – an increasingly important feature in drought-prone regions. It also lowers water temperatures, suppressing algal blooms and improving oxygenation, which helps sustain aquatic biodiversity.

From concept to commercialisation

The development journey took approximately four years, involving over 30 team members at INEGI and external partners. Testing began in local rivers, but eventually moved to controlled environments, including swimming pools and pilot sites. The partnership with SolarisFloat was instrumental in transforming the prototype into a market-ready product.

From the outset, the importance of intellectual property was clear. Correia recalls that discussions around patent protection began early in the project, recognising that commercial success would depend on securing exclusive rights to the invention. "Since the system was always intended for the market, it was crucial to protect what we were developing," he explains.

A few months into the collaboration, the team began reviewing existing patents and found several closely related filings – an early signal of both the market's potential and the competitive landscape. This prompted them to initiate their own applications in 2018, roughly mid-way through the project timeline.

While SolarisFloat retains ownership of the resulting IP, an agreement was reached to include the inventors from INEGI – Correia, Gomes and colleagues – on the patent applications in recognition of their technical contributions. The resulting European patents cover key elements of the innovation: the mooring system for the floating PV platform, the axis movement mechanism enabling sun tracking, and the modular floating structures that support each solar panel. "Patents themselves were a significant cost," says Correia, "but without them, there wouldn't have been investment."

A growing market with global reach

In Portugal, SolarisFloat is actively pursuing tenders, with plans for installations across eight sites totalling more than 200 megawatts of capacity. Pilot projects are also underway: SolarisFloat installed 180 panels on Oostvoornse Meer, a lake in the south-west of the Netherlands, in November 2022.

The primary market for the system is Europe, where deployment opportunities are most advanced. SolarisFloat is also working with partners in India and exploring prospects in South America. Brazil, in particular, presents significant potential: the country's extensive hydropower infrastructure includes some of the world's largest reservoirs, and estimates suggest that covering just 8% of the surface area of 165 major reservoirs with floating solar could meet up to 80% of national electricity demand. Looking ahead, SolarisFloat is also assessing the feasibility of offshore applications as a next step in expanding its technology offering.

3. Origins of innovation

3.1 Regional trends

Asian applicants made the largest contribution to the photovoltaic technologies covered in this technology insight report. Europe and North America are the other two main regions from which new technologies originate.

Figure 10 shows the share of patent families with respect to applicant countries with at least 1 000 patent families in the dataset, broken down by earliest publication year from 1990 to 2023. To provide comprehensive coverage of applicant country information in the data, the analysis was restricted to patent families with at least one EP and/or WO patent family member. Consequently, this restriction inherently limited the analysis to international patent families.

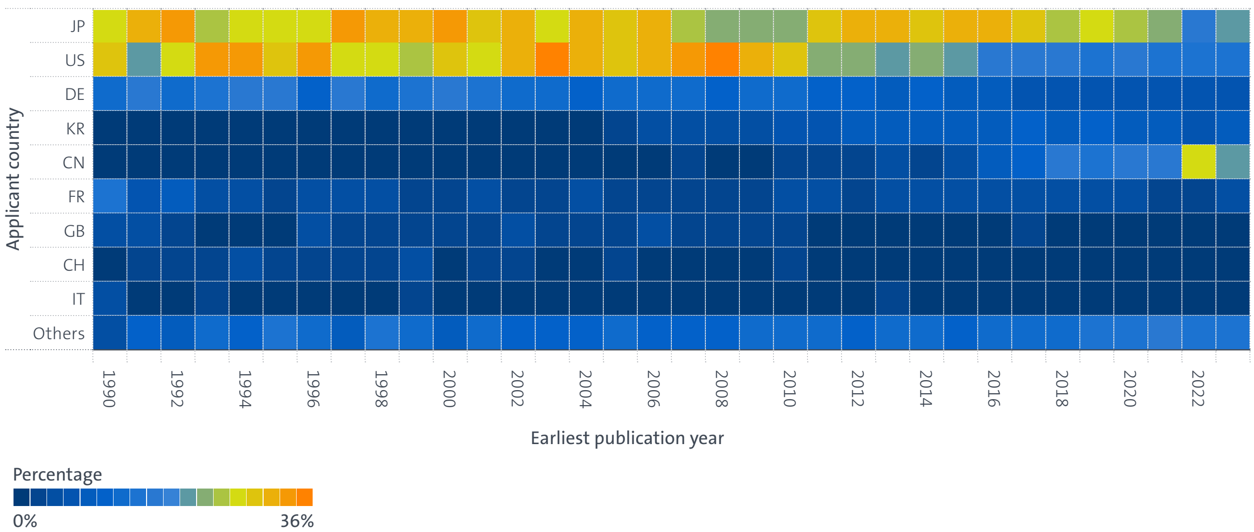
The figure shows that Japanese applicants have played a leading role throughout the reporting period, experiencing certain fluctuations and a recent relative decline to a share of around 20%. In second place is the USA, whose applicants demonstrated a high level of inventive activity until around 2010, after which they lost relative importance in this technical field. In contrast, the share of applicants from China has increased steeply over the last decade. As a result of this development, China overtook Japan for the first time in 2022.

It is also worth noting that five of the nine most active applicant countries are in Europe, and that they have shown consistent inventive activity throughout the entire reporting period. Of the European applicant countries, Germany is in third place overall, although, as with the United States, its relative share has declined in recent years.

This picture is further nuanced if the data are not viewed primarily from the perspective of individual countries, but from the perspective of geographical regions in which invention activity mainly takes place.

Figure 10:

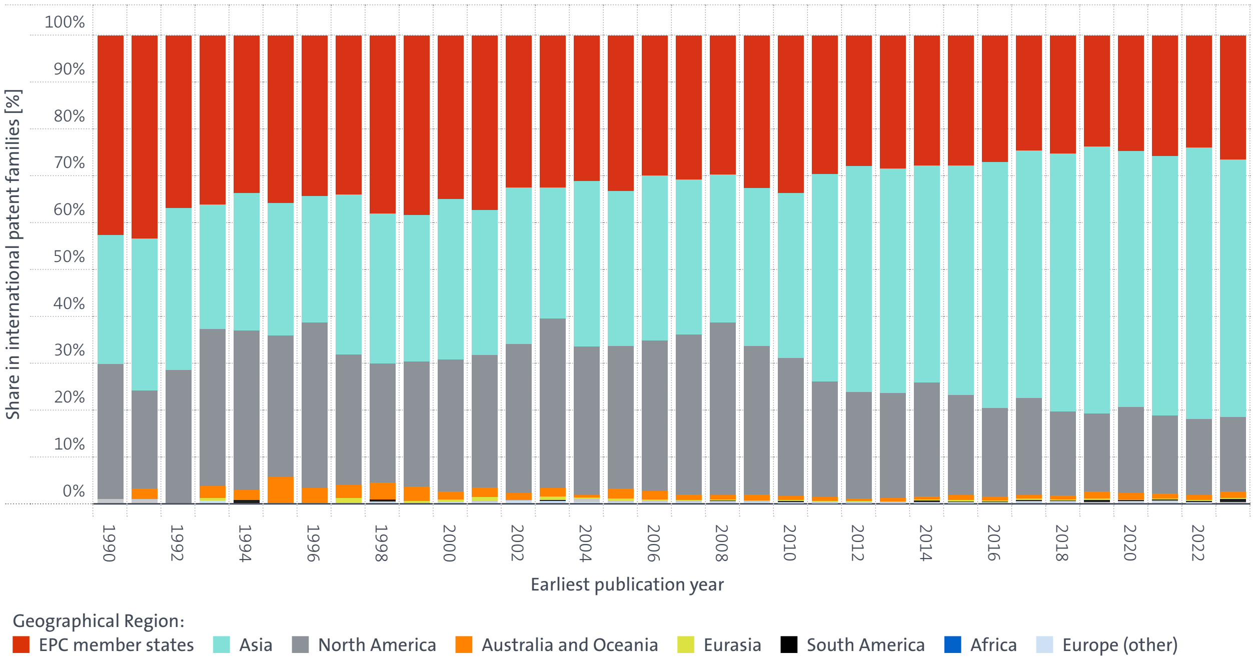
Percentage of top applicant countries in photovoltaics in the period 1990-2023
(applicant countries with at least 1 000 patent families; period 1990-2023; dataset restricted to IPFs with EP and/or WO patent family members for comprehensive coverage of inventor country information; 1990-2023)



Source: EPO

Figure 11:

Geographical origin of patent applicants in the area of photovoltaics
(IPFs; based on inventor country; dataset restricted to IPFs with EP and/or WO patent family members for comprehensive coverage of applicant country information; 1990-2023)



Source: EPO

Figure 11 shows a breakdown of applicant activity by geographical region. Asia's share increased from 27% to 57% in the reporting period and is currently well ahead of Europe (27%) and North America (16%), which gradually receded during the further rise of Asia in the reporting period. This higher share of Asian applicants is mainly due to the increased patenting activity of applicants from China and, to a lesser extent, from the Republic of Korea. The proportion of Asian applicants in the photovoltaics sector was found to be significantly higher than in all technical areas combined, where its share is currently below 50%, and reflects the fundamental changes around 2012 described in Section 2.1.

International competitiveness can be assessed through the technological competencies and specialisation of geographical regions and individual countries. Table 4 shows the specialisation profiles of world regions as measured by the so-called revealed technological advantage (RTA) index. The RTA assesses a region's focus on a specific technological sub-field compared to its overall innovation capacity. It is calculated by dividing the share of a particular technology area in the region's total IPFs by the share of that technology in the technical field as a whole. An RTA value above one indicates that a region or country is specialised in that particular technology.

During the reporting period, Europe demonstrated a focus on technologies related to the application of photovoltaics. Following the collapse of the European photovoltaic industry around 2012 (see Section 2.1), specialisation appears to have not significantly decreased. In the last decade, a certain technological focus was still observed on agrivoltaics, solar farms and building-integrated photovoltaics. By contrast, Asia demonstrated a specialisation in the reporting period in passivated contacts and specific photovoltaic materials, such as perovskites and quantum-dot materials. This specialisation has not changed substantially in the most recent period. Technical specialisation of North America in the reporting period was observed to be related to high-performance tandem cells and specific photovoltaic materials. In the last decade, however, the specialisation pattern changed somewhat. While high-performance tandem cells remained a focus, an above-average specialisation was also observed in other technologies such as space applications and photovoltaics on car ports.

Table 4:

Revealed technology advantage (RTA) related to the photovoltaic technologies covered in this insight report: top 5 sub-fields (IPF-based)

ENTIRE REPORTING PERIOD:

Europe	RTA
Agrivoltaics	2.3
Solar farms	2.2
Roofs	1.7
Car ports	1.7
Building-integrated photovoltaics	1.4

Asia	RTA
Passivated contacts	2.0
Inorganic perovskites	1.7
Quantum-dot materials	1.2
Di-chalcogenides	1.2
Inorganic-organic hybrid perovskites	1.2

North America	RTA
High-performance tandem cells	2.2
Group II-VI semiconductors	1.9
Group III-V semiconductors	1.8
Space applications	1.7
Car ports	1.4

RECENT SPECIALISATION (2014-2023):

Europe	RTA
Agrivoltaics	2.8
Solar farms	2.1
Building-integrated photovoltaics	1.6
Roofs	1.6
Car ports	1.6

Asia	RTA
Passivated contacts	1.7
Inorganic perovskites	1.5
Quantum-dot materials	1.3
Thin-film solar cells	1.2
Cleaning panels	1.2

North America	RTA
High-performance tandem cells	2.4
Space applications	2.1
Car ports	1.8
Group II-VI semiconductors	1.7
Roofs	1.6

3.2 Top applicants

Table 5 shows the top 20 applicants in the field of photovoltaics during the period 1990-2023, based on international patent families. The applicants generated more than 26.5% of all IPFs in the field. Most of these applicants were companies located in Japan (13 applicants), followed by the United States (3), R. Korea (2), Germany and France (1 each). Among these top applicants, only one applicant was not a company but the French public government-funded research organisation (Commissariat à l'énergie atomique et aux énergies alternatives (CEA)). CEA has a broad base in the field of photovoltaics, and has been the source of a large number of inventions, in particular in the recent past.

Expectedly, the picture changes when looking at all patent families. The ranking of the most active applicants is headed again by Japan (13 applicants), followed by P.R. China (4), R. Korea (2) and Canada (1).[13] This shift is considered to reflect the effects of the upheaval described in Section 2.1 and the growing role of P.R. China as a location for research, production development and manufacturing in the field of photovoltaics. Reflecting this development, the fraction of entirely Chinese patent families grew from 34% in 2012 to 80% in 2022.

The technical focus of the top 20 applicants in the reporting period was mainly set on device technologies (15 146 IPFs), followed by photovoltaic materials (3 178 IPFs) and applications (2 517 IPFs). Technologies related to the management of photovoltaic devices currently play only a minor role (1 010 IPFs) for these applicants.

13 The most active Canadian applicant was CSI Solar/Canadian Solar which has strong manufacturing and R&D facilities in China.

Table 5:

Top 20 applicants in photovoltaics (international patent families; period: 1990-2023)

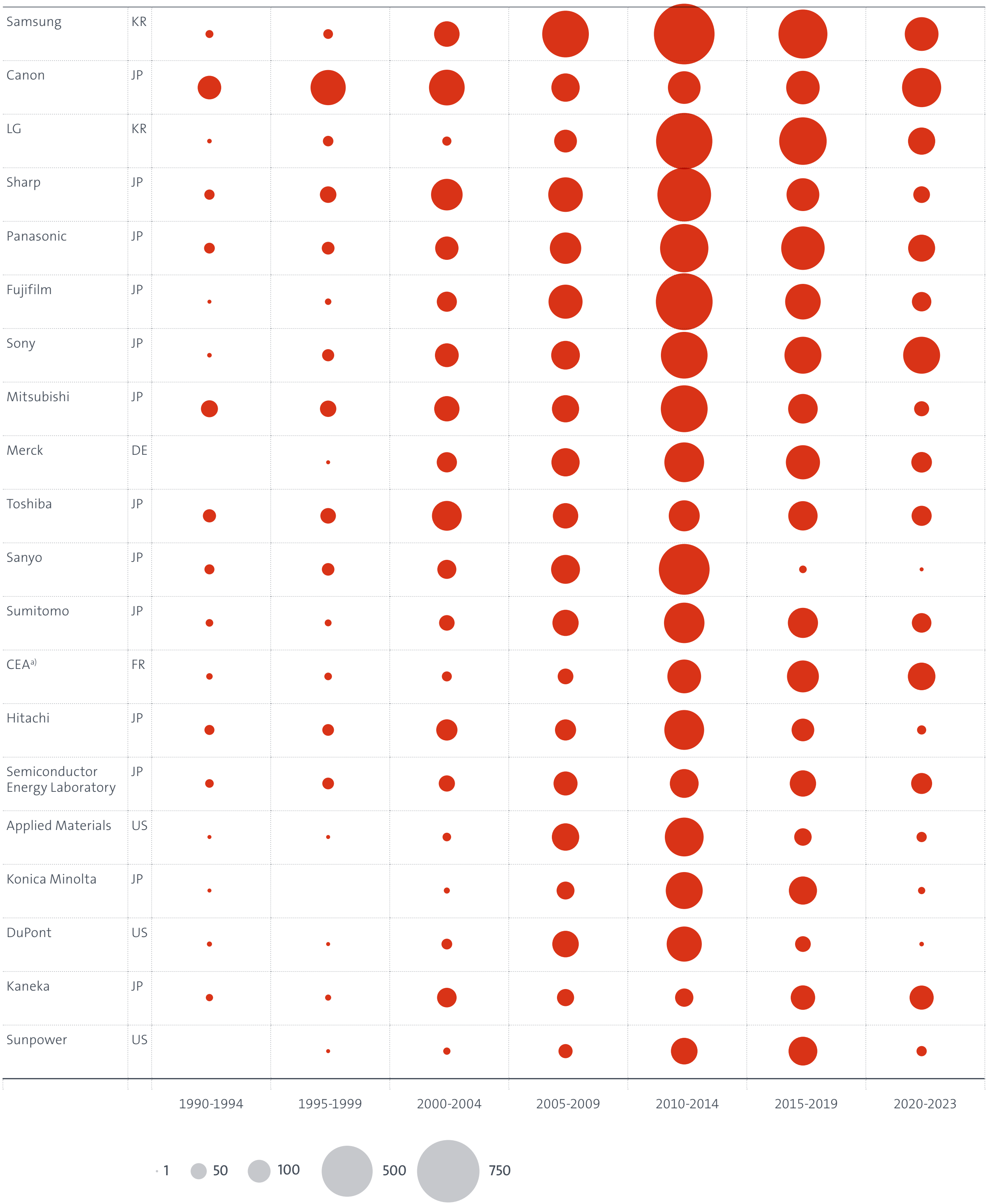
Applicant	Country	Copper oxides	Dichalcogenides	Group III-V semiconductors	Group II-VI semiconductors	Inorganic perovskites	Kesterites	Materials for dye-sensitised solar cells	Inorganic-organic hybrid perovskites	Inorganic-organic heterojunctions in solar cells	Quantum-dot materials	Bi-facial solar cells	Passivated contacts	Tandem cells	High-performance tandem cells	Silicon bulk tandem cells	Thin-film solar cells	Optics	Sun tracking	Cleaning panels	Detecting malfunctions	Installation testing	Measuring soiling	Artificial intelligence	Recycling solar panels	Agrivoltaics	Floating photovoltaic	Solar farms	Space applications	Self-powered objects	Vehicle-integrated photovoltaic (VIPV)	Water electrolysis	Building-integrated photovoltaics (BIPV)	Car ports	Roofs	Grand Total
Samsung	KR	31	48	104	119	0	6	186	58	108	114	2	4	1003	11	2	888	60	22	21	1	7	3	2	3	0	125	4	6	10	157	2	30	0	5	1944
Canon	JP	1	60	15	16	0	0	13	6	14	12	4	50	539	4	7	798	59	36	53	8	15	15	12	5	0	163	2	37	2	242	0	7	2	56	1447
LG	KR	11	18	31	45	0	9	65	47	56	11	22	3	882	14	17	745	77	27	25	1	6	11	14	0	1	9	3	7	18	31	0	23	1	4	1315
Sharp	JP	5	2	64	8	0	4	105	19	25	29	2	9	936	24	3	578	120	67	81	7	23	14	14	8	0	9	6	27	22	32	8	4	3	39	1297
Panasonic	JP	3	59	18	19	0	3	82	92	60	9	6	5	780	7	5	481	110	68	38	5	15	15	19	9	0	37	3	6	3	112	31	2	1	24	1289
Fujifilm	JP	4	10	27	37	0	19	196	153	68	43	3	114	444	8	3	923	15	13	39	0	0	0	0	3	0	24	0	1	1	31	17	1	0	1	1234
Sony	JP	6	72	36	16	0	1	128	51	48	14	1	0	392	3	3	566	15	8	96	2	6	4	3	3	0	190	1	1	9	98	1	1	0	0	1232
Mitsubishi	JP	4	14	16	6	0	3	26	8	8	2	0	3	696	6	7	484	52	29	35	12	19	11	13	6	0	5	11	44	4	62	4	0	0	8	997
Merck	DE	2	25	11	21	0	44	190	48	43	16	1	0	73	2	0	705	10	5	4	0	0	0	0	1	0	0	0	1	6	9	1	4	0	0	835
Toshiba	JP	21	11	10	12	0	21	58	80	41	0	0	0	512	3	6	274	13	23	12	7	13	4	12	3	0	33	1	1	3	40	28	0	0	5	795
Sanyo	JP	0	1	4	2	0	0	7	1	3	1	7	1	701	0	1	351	77	31	37	5	12	10	6	4	0	5	2	4	14	27	0	1	1	14	780
Sumitomo	JP	3	5	10	13	0	0	35	27	31	8	1	16	274	2	2	457	76	64	25	0	4	10	12	0	0	7	2	1	6	38	0	0	0	0	755
CEA[a]	FR	5	13	34	35	0	20	22	52	38	5	15	10	364	15	15	203	40	32	19	27	52	25	50	16	2	10	46	9	5	38	5	15	0	6	641
Hitachi	JP	5	6	4	4	0	1	25	6	14	3	6	16	410	2	1	258	29	23	7	9	17	8	24	4	0	4	11	7	1	36	4	1	0	0	632
SEL[b]	JP	4	8	4	4	0	2	6	6	9	1	1	59	214	0	4	403	11	4	8	0	0	1	0	0	0	5	1	7	3	58	0	0	0	1	574
Applied Materials	US	1	5	23	14	0	2	6	0	6	1	2	0	284	5	3	367	19	23	54	3	20	11	12	1	0	4	0	4	2	8	1	7	0	3	524
Konica Minolta	JP	0	16	3	19	0	1	40	13	175	8	0	2	99	1	15	420	10	14	20	0	13	1	5	1	0	8	1	0	2	7	2	2	0	0	490
DuPont	US	13	15	1	32	0	24	19	1	9	0	0	3	240	1	5	284	10	10	10	0	0	0	0	0	0	5	0	2	2	79	0	1	0	6	449
Kaneka	JP	1	5	1	2	0	2	9	24	20	2	7	1	317	0	10	295	41	12	34	2	6	3	2	1	0	1	3	2	1	32	2	8	2	21	435
Sunpower	US	1	2	4	7	0	2	3	1	1	4	3	7	314	0	1	81	28	73	24	4	13	15	18	1	0	2	18	5	2	6	2	3	7	50	363

a) Commissariat à l'énergie atomique et aux énergies alternatives
b) Semiconductor Energy Laboratory

A more nuanced picture emerges when looking at how the technology focus of these applicants developed over time. Most of the top 20 applicants have been active in photovoltaics over the entire reporting period (see Figure 12). In parallel, the technical focus of the applicants changed to some extent. At the beginning of the 1990s, there was a nearly exclusive focus on device technologies, with more than 90% of all inventions (Table 6 (top)). While the role of device technologies remained strong for the top applicants, the other sub-areas gained in importance. At the beginning of this decade, device technologies continued to play a key role, followed by photovoltaic materials and applications.

Figure 12:

Development of patent activity of the top 20 applicants in the reporting period (1990-2023; IPF-based)



a) Commissariat à l'énergie atomique et aux énergies alternatives

Source: EPO

Table 6:

List of top applicants at the beginning of the 1990s, and in the last decade (IPF-based)

1990-1994:

Applicant	Country	Copper oxides	Dichalcogenides	Group III-V semiconductors	Group II-VI semiconductors	Materials for dye-sensitised solar cells	Inorganic-organic hybrid perovskites	Inorganic-organic heterojunctions in solar cells	Quantum-dot materials	Bi-facial solar cells	Passivated contacts	Tandem cells	High-performance tandem cells	Silicon bulk tandem cells	Thin-film solar cells	Optics	Sun tracking	Cleaning panels	Detecting malfunctions	Installation testing	Artificial intelligence	Recycling solar panels	Agrivoltaics	Solar farms	Space applications	Self-powered objects	Vehicle-integrated photovoltaic (VIPV)	Water electrolysis	Building-integrated photovoltaics (BIPV)	Car ports	Roofs	Grand Total
Canon	JP	0	1	4	3	0	0	0	0	0	0	73	4	4	84	14	3	1	0	0	0	0	3	0	1	0	1	0	0	0	3	106
Mitsubishi	JP	0	0	11	4	0	0	0	0	0	0	39	2	0	19	2	1	4	0	0	0	0	0	0	2	0	2	0	0	0	0	55
Siemens	DE	0	0	1	1	0	0	0	0	0	0	33	0	0	16	2	2	0	0	0	0	1	0	0	0	4	0	0	1	0	2	40
Toshiba	JP	0	0	1	1	2	0	1	0	0	0	19	0	0	6	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	33
Kyanon	JP	0	1	1	1	0	0	0	0	0	0	20	1	2	23	6	1	1	0	0	0	0	0	0	1	0	1	0	0	0	2	27
United Solar Systems	US	0	0	0	0	0	0	0	0	0	0	20	1	0	23	8	0	0	0	0	0	0	0	0	1	0	2	0	0	0	2	24
Panasonic	JP	0	1	0	3	1	0	0	0	0	0	11	0	0	12	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	22
Sharp	JP	0	0	3	1	0	0	0	0	0	0	14	0	0	6	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	20
NEC	JP	0	0	2	0	0	0	0	0	0	0	11	0	0	4	0	0	1	0	0	0	0	1	1	2	0	0	0	0	0	0	20
Sanyo	JP	0	0	0	0	0	0	0	0	0	0	17	0	0	13	3	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	19

2015-2019:

Applicant	Country	Copper oxides	Dichalcogenides	Group III-V semiconductors	Group II-VI semiconductors	Inorganic perovskites	Kesterites	Materials for dye-sensitised solar cells	Inorganic-organic hybrid perovskites	Inorganic-organic heterojunctions in solar cells	Quantum-dot materials	Bi-facial solar cells	Passivated contacts	Tandem cells	High-performance tandem cells	Silicon bulk tandem cells	Thin-film solar cells	Optics	Sun tracking	Cleaning panels	Detecting malfunctions	Installation testing	Measuring soiling	Artificial intelligence	Recycling solar panels	Agrivoltaics	Floating photovoltaic	Solar farms	Space applications	Self-powered objects	Vehicle-integrated photovoltaic (VIPV)	Water electrolysis	Building-integrated photovoltaics (BIPV)	Car ports	Roofs	Grand Total
Samsung	KR	6	32	26	36	0	3	8	9	34	37	0	0	128	1	1	250	12	1	0	0	0	0	2	1	0	47	0	0	3	63	0	0	0	0	457
LG	KR	5	6	22	9	0	6	20	32	35	7	5	0	247	11	12	244	25	8	9	1	4	8	6	0	0	2	0	1	8	5	0	5	0	1	430
Panasonic	JP	1	22	1	2	0	0	37	35	21	2	2	0	190	0	0	108	54	28	6	0	2	7	6	5	0	6	1	3	0	49	17	0	0	16	360
Sony	JP	2	25	14	10	0	1	6	3	18	4	0	0	19	0	0	141	2	0	31	0	1	0	1	0	0	37	0	0	3	14	0	0	0	0	260
Fujifilm	JP	2	1	9	8	0	2	63	60	23	11	0	23	45	0	0	174	4	1	5	0	0	0	0	0	0	0	0	0	0	2	15	0	0	0	241
Merck	DE	0	18	7	9	0	28	85	40	23	2	0	0	8	0	0	181	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	222
Canon	JP	0	13	0	3	0	0	3	3	3	6	1	1	19	0	0	68	1	0	1	0	0	0	0	1	0	48	0	18	0	95	0	0	0	0	214
Sharp	JP	1	0	12	0	0	1	24	7	10	10	0	1	105	2	0	90	15	5	14	0	1	2	0	0	0	1	3	2	4	2	0	1	0	4	205
CEA[a)]	FR	3	3	11	7	0	6	8	15	12	2	6	0	112	7	2	52	16	14	7	13	20	7	19	8	1	0	19	0	2	9	2	4	0	2	194
Sumitomo	JP	2	1	3	4	0	0	8	14	14	2	0	2	51	0	0	85	39	41	3	0	4	8	10	0	0	4	2	0	2	5	0	0	0	0	173

a) Commissariat à l'énergie atomique et aux énergies alternatives

2020-2023

Applicant	Country	Copper oxides	Dichalcogenides	Group III-V semiconductors	Group II-VI semiconductors	Inorganic perovskites	Kesterites	Materials for dye-sensitised solar cells	Inorganic-organic hybrid perovskites	Inorganic-organic heterojunctions in solar cells	Quantum-dot materials	Bi-facial solar cells	Passivated contacts	Tandem cells	High-performance tandem cells	Silicon bulk tandem cells	Thin-film solar cells	Optics	Sun tracking	Cleaning panels	Detecting malfunctions	Installation testing	Measuring soiling	Artificial intelligence	Recycling solar panels	Agrivoltaics	Floating photovoltaic	Solar farms	Space applications	Self-powered objects	Vehicle-integrated photovoltaic (VIPV)	Water electrolysis	Building-integrated photovoltaics (BIPV)	Car ports	Roofs	Grand Total
Canon	JP	0	12	4	2	0	0	2	3	9	6	0	43	5	0	0	119	1	0	3	0	0	0	0	0	0	15	0	15	0	131	0	1	0	1	292
Sony	JP	0	46	17	0	0	0	5	4	11	4	0	0	18	0	0	101	0	0	12	0	0	0	0	0	0	45	0	0	4	54	0	0	0	0	260
Samsung	KR	1	6	22	21	0	1	0	27	12	47	0	0	22	3	0	109	7	2	3	0	0	1	0	0	0	35	2	2	0	35	0	0	0	0	217
JinkoSolar	CN	0	0	1	0	0	0	3	52	9	0	3	84	145	1	5	33	11	10	10	0	3	0	0	0	0	0	0	0	0	0	0	3	0	1	166
CEA[a)]	FR	1	4	3	3	0	0	4	36	12	1	5	10	87	3	12	24	4	4	4	7	18	13	18	8	1	2	12	4	2	7	3	7	0	2	145
LG	KR	0	0	1	9	0	0	4	10	9	2	3	3	46	0	2	79	4	3	2	0	2	2	6	0	0	0	0	1	5	5	0	4	0	0	141
Panasonic	JP	0	22	0	2	0	3	13	47	29	6	0	2	36	0	3	73	7	10	4	3	6	1	9	0	0	1	0	0	0	12	1	1	0	0	139
LONGi Group	CN	2	3	0	2	7	0	0	32	20	2	2	25	88	2	20	46	16	0	8	0	0	0	0	1	0	0	1	1	0	0	1	14	0	13	133
Kaneka	JP	0	0	0	0	0	0	0	15	10	0	2	0	77	0	2	42	3	2	1	1	3	1	2	0	0	0	2	1	0	3	1	3	0	2	111
CATL[b)]	CN	7	3	1	1	0	0	5	37	25	1	0	0	6	0	1	19	3	2	4	0	0	0	0	2	0	1	14	4	0	46	0	0	0	0	92

a) Commissariat à l'énergie atomique et aux énergies alternatives
b) Contemporary Amperex Technology

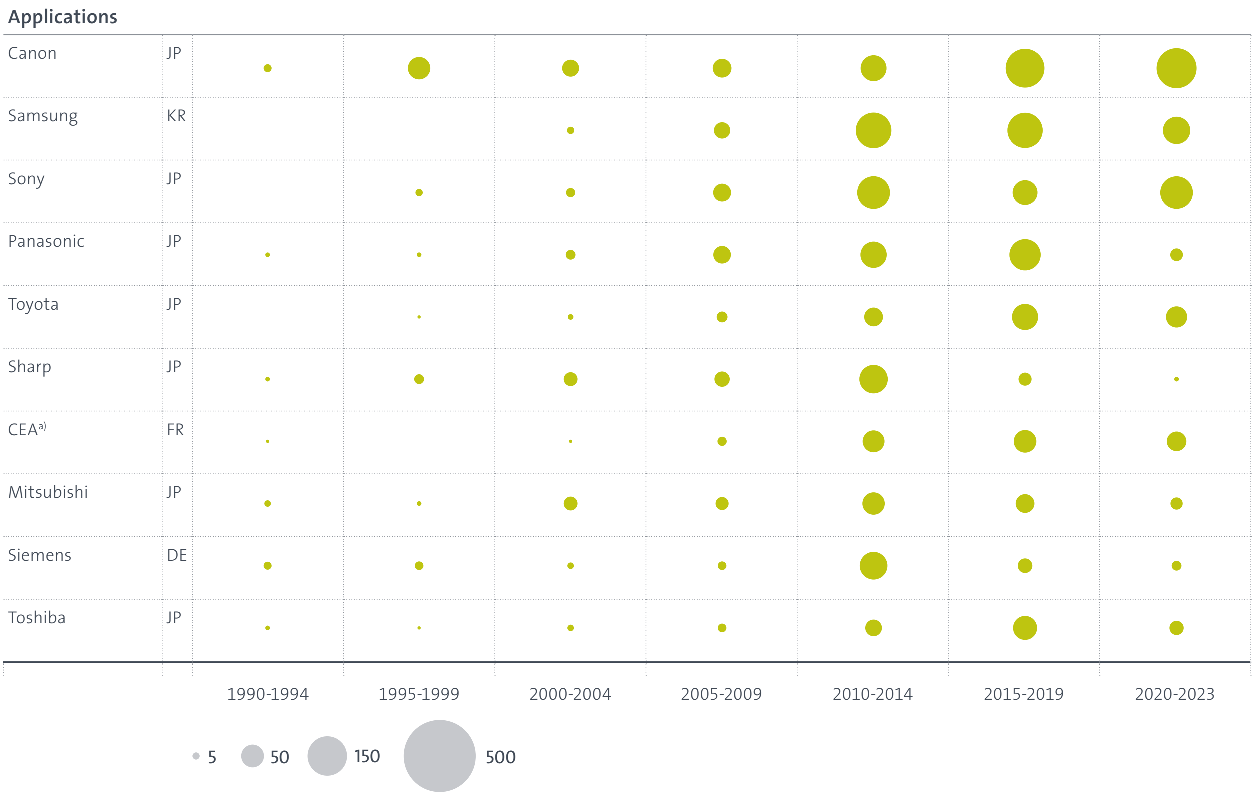
Given the leading role of device technologies in the recent decades, an exclusive focus on the most active applicants in the field of photovoltaics alone would involve the risk of overlooking important niche players. For this reason, Figure 13 shows the list of top applicants in the four sub-areas of photovoltaics covered in this insight report. Two European applicants each rank among the top ten applicants in the sub-areas of photovoltaic materials, device management and applications. Most top applicants in these sub-areas covered a range of different technologies, as opposed to device technologies with its dominance of tandem cells and thin-film solar cells.

Figure 13:

Most active applicants in the four sub-areas of photovoltaics under consideration in this insight report (number of international patent families; period: 1990-2023)

a) Commissariat à l'énergie atomique et aux énergies alternatives

Source: EPO



a) Commissariat à l'énergie atomique et aux énergies alternatives

Source: EPO

3.3 Focus on European startups and universities

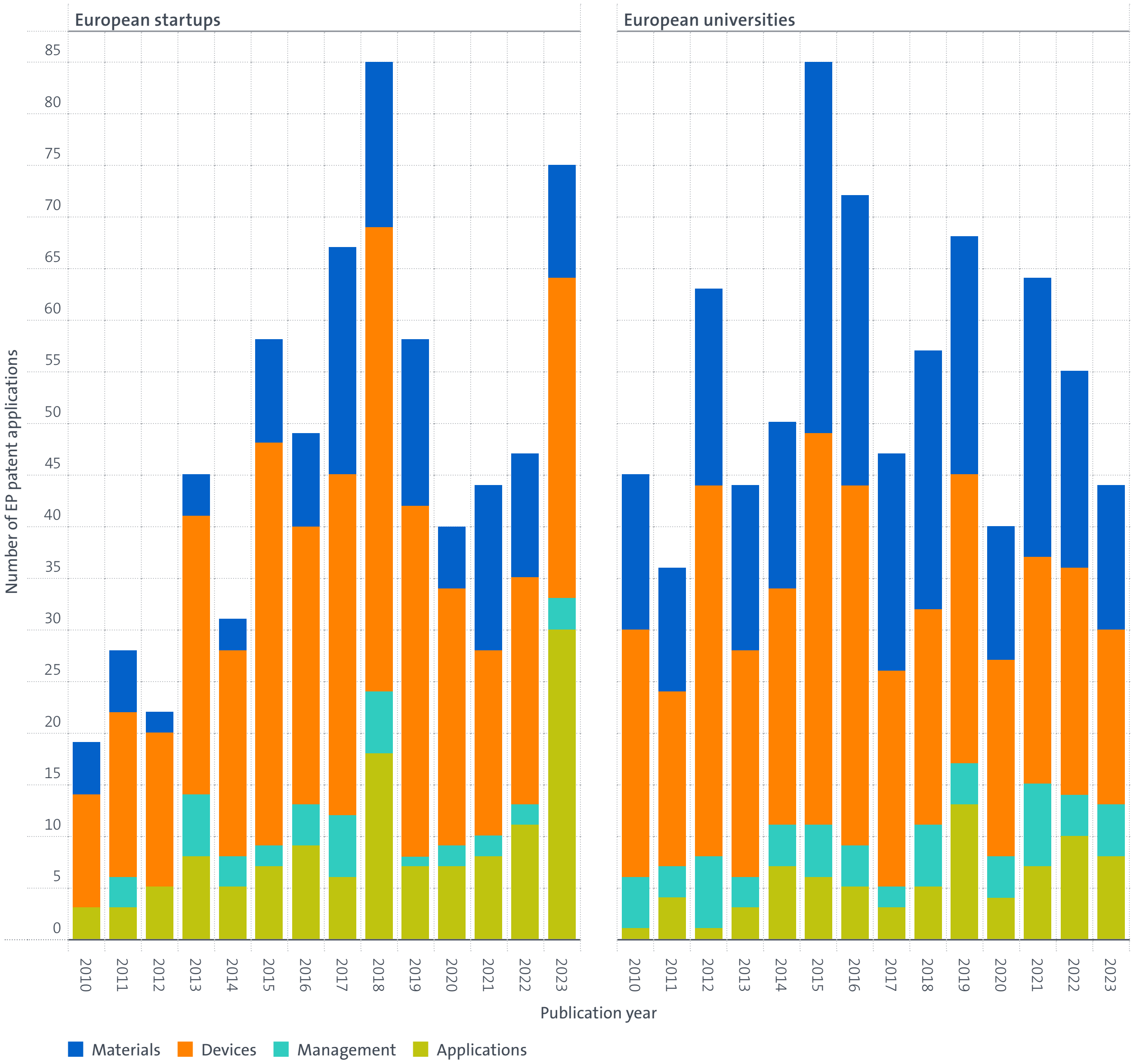
Data from the EPO's Deep Tech Finder provided further insight into the contribution of European startups and universities to progress in the field of photovoltaics. We identified more than 300 European startups and universities that sought patent protection under the European patent system for inventions in the field of photovoltaics in the period 2010-2023. In total, 179 individual startups from 18 of the 39 EPC member states filed 480 EP patent applications in this period. Moreover, 169 universities from 24 EPC member states filed another 554 EP patent applications.

Startups and universities focus on different technological sub-areas in the field of photovoltaics, and show different patenting activities. Startups in Europe mainly focus on technologies related to photovoltaic devices, followed by photovoltaic materials and applications, as opposed to European universities which set a strong focus on devices and materials.

Figure 14 presents these activities over time, with a breakdown according to the technological sub-areas under consideration. While the filing numbers of startups are still rather low, and the corresponding relative fluctuations are still high, three stages could be identified (Figure 14, left). After a continuous increase in filing numbers until 2018, patenting activity decreased steeply before it gained momentum again and has nearly reached the level of 2018 again. In 2023, i.e. the last year of the reporting period, a large part of the patenting activity was due to application-related inventions. Unlike startups, European universities account for a rather constant flow of inventions related to photovoltaics, again on a still rather low level with some fluctuations (Figure 14, right).

Figure 14:

Patenting activities of European startups and universities in photovoltaics, broken down according to the sub-areas photovoltaic materials, photovoltaic devices, device management and application areas (number of EP patent applications, period: 2010-2023)



Source: EPO

Table 7 provides an overview of the technologies in which European startups and universities have shown inventive activities since 2010. Device technologies account for the largest fraction of inventions by both universities and startups, followed by photovoltaic materials. Individual technologies that stand out include thin-film solar cells, tandem cells, materials for dye-sensitised solar cells and inorganic-organic heterojunctions in solar cells. In the sub-areas of photovoltaic materials and management of devices, patent activity occurred in the majority of cases in the university sector, compared to startups. By contrast, patenting activity shifted in favour of startups for device technologies and specific photovoltaic applications. This may indicate an increasing commercial orientation in these latter two sub-areas, and an opportunity to strengthen Europe's technological and economic standing in the area of photovoltaics.

Table 7:

Patenting activity of startups and universities by technological sub-areas (number of EP patent applications, period: 2010-2023)

			Universities	Startups	Grand Total
Materials	Inorganic	Copper oxides	8		8
		Dichalcogenides	13	15	28
		Group III-V semiconductors	12	12	24
		Group II- VI semiconductors	15	25	40
		Inorganic perovskites	1		1
		Kesterites	20	10	30
		Total	*60*	*57*	*117*
	Organic	Materials for dye-sensitised solar cells	151	49	200
		Inorganic-organic hybrid perovskites	73	40	113
		Total	194	73	267
	Others	Inorganic-organic heterojunctions in solar cells	120	37	157
		Quantum-dot materials	9		9
		Total	*127*	*37*	*164*
	Total		**273**	**134**	**407**
Devices	Constructional	Bi-facial solar cells	2	3	5
		Passivated contacts		1	1
		Tandem cells	169	190	359
		Thin-film solar cells	185	176	361
		Total	*305*	*303*	*608*
	Light optimisation	Optics	75	55	130
		Sun tracking	15	43	58
		Total	*86*	*90*	*176*
	Total		**329**	**347**	**676**
Management	Maintenance	Cleaning panels	27	17	44
		Total	*27*	*17*	*44*
	Measure, test	Detecting malfunctions	2	1	3
		Installation testing	21	4	25
		Measuring soiling	7	2	9
		Total	*22*	*5*	*27*
	Others	Artificial intelligence	24	9	33
		Recycling solar panels	7	14	21
		Total	*31*	*23*	*54*
	Total		**61**	**39**	**100**
Applications	Non-urban	Agrivoltaics		1	1
		Floating photovoltaic	2	12	14
		Solar farms	7	14	21
		Space	2	3	5
		Total	*11*	*27*	*38*
	Others	Self-powered objects	9	22	31
		Vehicle-integrated photovoltaic (VIPV)	5	27	32
		Water electrolysis	25	4	29
		Total	*39*	*53*	*92*
	Urban	Building-integrated photovoltaics (BIPV)	20	23	43
		Car ports		1	1
		Roofs	6	39	45
		Total	*25*	*55*	*80*
	Total		72	125	197

As in many other technical areas, inventive activity by universities and startups is not evenly distributed across Europe. Figure 15 shows the geographical distribution of these entities which sought patent protection under the European patent system during the period 2010-2023. The highest inventive activity of universities was found in the United Kingdom (102 EP patent applications), followed by France (99), Switzerland (96) and Germany (79). When looking at regions rather than at countries, several regional hotspots of academic inventive activity stood out. In particular, the following regions showed a high level of inventive activity: the south of England, Belgium and the south of the Netherlands, the Paris area, the Lausanne area, the Upper Rhine region and the Madrid area.

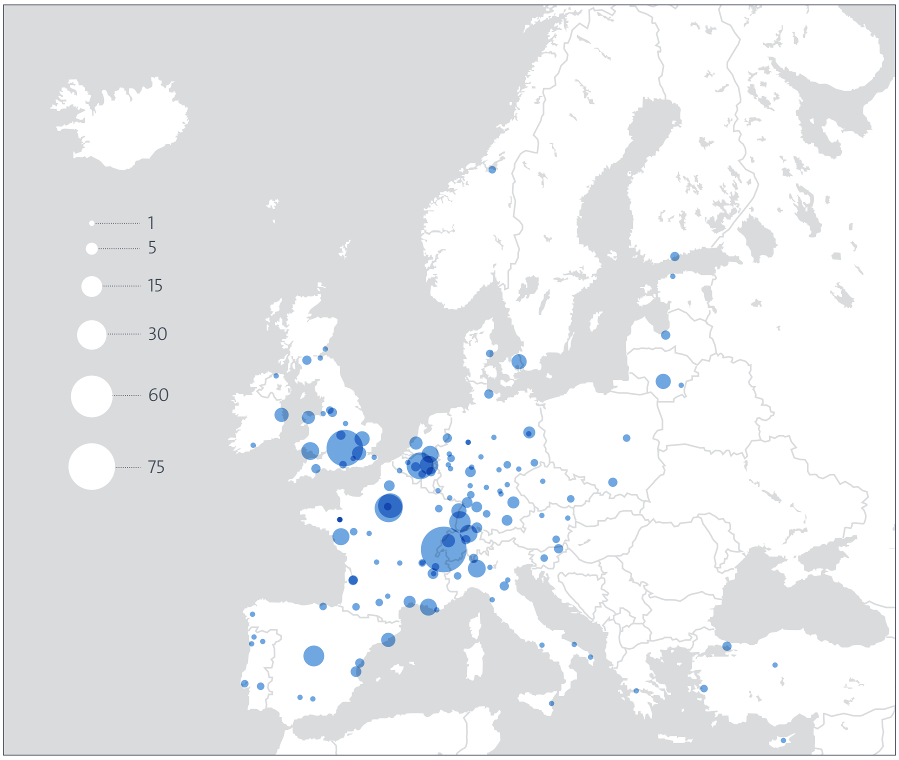
The highest inventive activity of startups was found in Germany (155 EP patent applications), France (86), Switzerland (60) and Sweden (52). Regional hotspots were found in particular in the south of England, Belgium and the south of the Netherlands, the Upper Rhine region, the Zurich region, the Lake Geneva region, the south-east of France, the Dresden area, and in the Stockholm area.

Some of these regions, such as the south of England and Belgium and the south of the Netherlands, are home to universities and startups with inventive activity in the field of photovoltaics, whereas the geographical distribution of European universities and startups is mostly not identical.

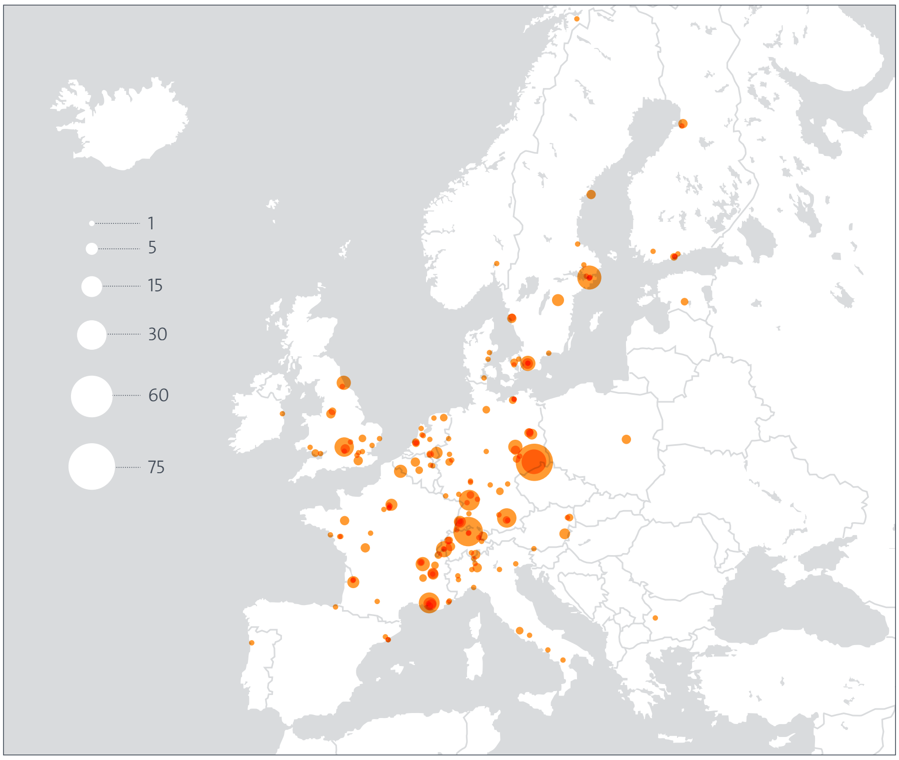
Figure 15:

Geographical origin of European patent applications filed by startups and by universities (number of EP patent applications, 2010-2023)

Universities



Startups



Source EPO / © 2025 Mapbox © OpenStreetMap

4. Conclusions and outlook

This technology insight report sheds light on advances in the field of photovoltaics from the perspective of inventive activity in four sub-areas: photovoltaic materials, photovoltaic devices, device management and application areas.

More than 30 technologies in these sub-areas were assessed. They have seen significant growth in the past three decades. During that period, the number of all patent families related to these technologies grew more than seventeen-fold.

In the period 1990-2023, most of the top applicants related to international patent families, as a standard indicator for inventions with an international focus and confirmed potential, were companies located in Japan, followed by the United States, R. Korea, Germany and France. Leading Chinese innovators did not feature in this list due to their primary focus on domestic patent applications.

In the past 15 years, patenting activities shifted substantially towards protection in China. While the number of IPFs has been declining since 2012, the number of patent applications filed solely in China has been increasing massively, with nearly six-fold growth from 2010 to 2022.

While its role in photovoltaics production is relatively marginal at the moment, Europe shows specialisation advantages in technologies related to the deployment of photovoltaic energy. Examples include agrivoltaics and the installation of photovoltaics on rooftops, carports and buildings. European universities have consistently demonstrated a substantial level of inventive activity, and there has been a recent and significant increase in the number of inventions by startups. Startups in Europe mainly focus on technologies related to photovoltaic devices, followed by photovoltaic materials and applications, whereas European universities set a strong focus on devices and materials.

The outlook for inventions and innovation in photovoltaics remains promising. Continued progress in photovoltaic materials and devices as well as economies of scale will ensure that photovoltaics continue to play a key role in the global transition to sustainable energy. In the coming years, we can expect to see new materials become more mature and competitive, manufacturing processes become more efficient and environmentally friendly and photovoltaics become even smarter.

In light of the ever-growing importance of photovoltaics and its dynamic technical progress, the EPO and EIC plan to update this report in future and possibly expand it to include other technologies in the field of photovoltaics.

5. Bibliography

5.1 List of scholarly sources (articles, chapters)

[Almora et al., 2024] O. Almora et al., 2024, "Device Performance of Emerging Photovoltaic Materials (Version 5)", *Advanced Energy Materials,* Vol. 15, 2404386
https://doi.org/10.1002/aenm.202404386

[Araki et al., 2025]. Araki et al., 2025, "Testing and rating of vehicle-integrated photovoltaics: Scientific background", *Solar Energy Materials and Solar Cells,* Vol. 280, 113241
https://doi.org/10.1016/j.solmat.2024.113241

[Demey and Golzio, 2020] Y.T. Demey and D. Golzio, 2020, "Search strategies at the European Patent Office", World Patent Information, Vol. 63, 101989
https://doi.org/10.1016/j.wpi.2020.101989

[Faes et al, 2025] A. Faes et al., 2025, "Building-integrated photovoltaics", *Nature Reviews Clean Technology,* Vol. 1, 333-350
https://doi.org/10.1038/s44359-025-00059-9

[Han et al., 2025] J. Han et al., 2025, "Perovskite solar cells", *Nature Reviews Methods Primers,* Vol. 5, 3
https://doi.org/10.1038/s43586-024-00373-9

[Larini et al., 2023] V. Larini, et al., 2023, "Frontier research in perovskite solar cells: Following the paths of European research and innovation", *Chem, Vol.* 9, pp. 2738–2756
https://doi.org/10.1016/j.chempr.2023.05.027

[Lira-Cantu and Tanko, 2024] M. Lira-Cantu and K.T. Tanko, 2024, "Perovskite solar cells: What do you mean when you say 'stable'", *APL Energy,* Vol. 2, 030401
https://doi.org/10.1063/5.0239002

[Tanko et al., 2025] K.T. Tanko et al., 2025, "Stability and reliability of perovskite photovoltaics: Are we there yet?", *MRS Bulletin,* Vol. 50, pp. 512–525
https://doi.org/10.1557/s43577-025-00863-5

[Scheu et al., 2026] M. Scheu et al., 2006, "Mapping nanotechnology patents: The EPO approach", *World Patent Information,* Vol 28, No. 3, pp. 204-211.
https://doi.org/10.1016/j.wpi.2006.03.005

[Sharif et al., 2023] R. Sharif et al., 2023, "A comprehensive review of the current progresses and material advances in perovskite solar cells", *Nanoscale Advances,* Vol. 5, No. 5, 3803-3833
https://doi.org/10.1039/D3NA00319A

[Shubbak, 2019] M.H. Shubbak, 2019, "Advances in solar photovoltaics: Technology review and patent trends", *Renewable and Sustainable Energy Reviews,* Volume 115, 109383
https://doi.org/10.1016/j.rser.2019.109383

[Tarique and Uddin, 2023] W.B. Tarique and A. Uddin, 2023, "A review of progress and challenges in the research developments on organic solar cells", *Materials Science in Semiconductor Processing,* Vol. 163, 107541
https://doi.org/10.1016/j.mssp.2023.107541

[Zhu et al., 2024] L. Zhu et al., 2024, "Progress of organic photovoltaics towards 20% efficiency", *Nature Reviews Electrical Engineering,* Vol. 1, 581-596
https://doi.org/10.1038/s44287-024-00080-3

5.2 Other sources (reports, policy briefs)

[European Commission, 2025a] European Commission: European Innovation Council and SMEs Executive Agency, 2025, "Scaling Deep Tech in Europe – European Innovation Council – Impact report 2025", Publications Office of the European Union
https://data.europa.eu/doi/10.2826/1391424

[European Commission, 2025b] European Commission: Directorate-General for Research and Innovation, Steeman, J.-T., Peiffer-Smadja, O. and Ravet, J., 2025, "A comparative analysis of public R&I funding in the EU, US, and China", Publications Office of the European Union,
https://data.europa.eu/doi/10.2777/3869663

[European Patent Office, 2021] European Patent Office, 2021, "Patents and the energy transition. Global trends in clean energy technology innovation", pp. 36-37
https://www.epo.org/trends-energy

[Fraunhofer Institute for Solar Energy Systems and PSE Projects GmbH, 2025] Fraunhofer Institute for Solar Energy Systems ISE and PSE Projects GmbH, 2025, “Photovoltaics report”
https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[International Energy Agency, 2023] International Energy Agency, 2023, “World Energy Outlook 2023”
https://www.iea.org/reports/world-energy-outlook-2023

[International Renewable Energy Agency , 2024] International Renewable Energy Agency, 2024, “Renewable Power Generation Costs in 2023”
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf

[Masson et al., 2024] G. Masson et al., 2024, “Trends in photovoltaic applications”, Report IEA PVPS T1-43:2024
https://doi.org/10.69766/JNEW6916

[National Renewable Energy Laboratory, 2025] National Renewable Energy Laboratory, “Best Research-Cell Efficiency Chart” [last accessed: 22 June 2025]
https://www.nrel.gov/pv/cell-efficiency

[Renewable Energy Policy Network for the 21st Century, 2023] Renewable Energy Policy Network for the 21st Century, 2023, “Renewables 2023 Global Status Report Collection”
https://www.ren21.net/gsr-2023

[World Intellectual Property Organization, 2017] World Intellectual Property Organization, 2017, “World Intellectual Property Report 2017: Intangible capital in global value chains”, chapter 3: “Innovation is transforming the photovoltaic industry”, pp. 71-93
https://www.wipo.int/edocs/pubdocs/en/wipo_pub_944_2017.pdf

6. Annex / Methodology

6.1 Using patent information

In essence, patents are legal rights that give patent holders the right to exclude others from commercially exploiting the patented invention. They can be valid in the country or region for which they are granted. Patents can help attract investment, secure licensing agreements and provide market exclusivity.

Accordingly, patent systems promote innovation, technology diffusion and economic growth by allowing patent holders to secure investment in research and development, education and infrastructure, while requiring them to make their inventions available to the public. The publication of patent applications is a key feature of the patent system, and creates a rich repository of technical and other content known as patent information. Patent information enables other inventors, researchers, engineers, managers, investors and policymakers to build on existing inventions, to access knowledge often unavailable elsewhere and to analyse trends in innovation and market developments. As a result, patent information is at the heart of any patent system.

Patent information enables inventors to build on the published inventions of others and thus avoid the mistake of investing in developing a solution to a problem that has already been solved and potentially protected by others. Patent information contains a wealth of technical and other information, much of which cannot be found in any other source. As the leading provider of high-quality patent information worldwide, the EPO has collected, standardised and harmonised information on more than 150 million patent documents from over 100 countries in its databases, containing more than one billion records. These databases are growing by tens of millions of records every year.

Patent information from these databases is available through numerous free and commercial patent information services provided by patent offices and service providers around the world. The information can be used for a variety of analytical purposes, such as exploring technical trends and the filing strategies of applicants, or calculating indicators of innovation activity, commercialisation and knowledge transfer.

6.2 Methodology of this EPO technology insight report

This EPO technology insight report aims to provide useful insights into specific technologies related to photovoltaics.

The report is based on publicly available patent information and provides an overview of the relevant technologies.

The methodology of this report is based on a three-step process:

Step 1: Create and tune a basic dataset

A basic dataset is created, usually by using various custom search concepts such as building on keywords and on patent classification symbols for specific technologies.

It is usually necessary to remove unrelated patent documents, either automatically or manually, in order to improve the quality of the basic dataset.

The creation of a meaningful basic dataset is critical to providing a reliable basis for sound patent analysis in step 2.

Step 2: Patent data analysis

In this second step, analyses are performed on the basic dataset by aggregating the data to patent families as a representative of inventions, generating descriptive statistics, testing hypotheses and identifying patterns in the data, etc.

Step 3: Further processing and visualisation

In this third step, the data are further analysed and processed and the results visualised and summarised.

6.3 Patent retrieval

For this report, EPO experts developed specific search strategies to identify patent documents related to specific technologies in photovoltaics. The search strategies combine relevant keywords and patent classification symbols (see Box 8: "Photovoltaics and patent classification schemes"). The search strategies

Box 8: Technologies for photovoltaics and patent classification schemes

Patent offices assign patent classification symbols to categorise the technical subject-matter of a patent or utility model. Patent classification symbols are defined as part of what are known as "patent classification systems". There are various patent classification systems used today by national, regional and international patent offices.

Two patent classification systems are of particular importance.

The International Patent Classification (IPC) system is a hierarchical patent classification system used by the EPO and more than 100 patent offices on every continent. It breaks technologies down into eight sections with several hierarchical sub-levels. The IPC system has approximately 75 000 subdivisions, and is updated on an annual basis. Further information about the IPC system is available on a dedicated website.

The Cooperative Patent Classification (CPC) system builds on the IPC system and provides a more granular and detailed classification structure. The CPC system has more than 250 000 sub-divisions and is updated four times a year. It is used by more than 30 patent offices worldwide, including the EPO. Further information about the CPC system is available on the CPC website.

IPC and CPC classification symbols can be used to quickly retrieve relevant patent documents using search interfaces such as the EPO's free search interface Espacenet, available on the EPO website.

For the purposes of this study, sub-divisions in the IPC and the CPC systems were used and combined with other search terms to restrict the resulting dataset to patent documents closely related to photovoltaics. The following table shows a selection of the IPC and CPC sub-divisions used:

Sub-division	Description
F21S	Non-portable lighting devices; systems thereof; vehicle lighting devices specially adapted for vehicle exteriors
H02S	Generation of electric power by conversion of infrared radiation, visible light or ultraviolet light, e.g. using photovoltaic [PV] modules
H10F	Inorganic semiconductor devices sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation
H10K	Organic electric solid-state devices
Y02E10/50	Photovoltaic [PV] energy

were optimised for the EPO's in-house search tools (see Section 1.4, Annex). The patent classification symbols and keywords used for this report efficiently capture documents with a focus on these technologies.

The volume of search results obtained using the search methodology will increase over time due to the dynamic nature of the technical field and the patent databases, as patent documents related to photovoltaics are continuously added to these databases. Accordingly, we intend to update this report in the future, which would also give us an opportunity to review the latest patent trends related to photovoltaics.

6.4 Data sources and tools used

The quality of patent data analysis largely depends on the completeness, correctness and timely availability of relevant patent information in the patent databases from which the basic dataset for the subsequent analysis is extracted.

It is not possible to guarantee the absolute completeness of the relevant patent information since not all data are available from all patent offices. However, there are several patent databases with very good or excellent coverage of patent information from the main patent offices. These patent databases are mostly based on EPO worldwide patent data as a central source of prior art patent information.

EPO worldwide patent data contain bibliographic and other information on more than 160 million patent documents from more than 100 patent authorities on every continent. These data are available via the EPO's patent information products and services, and other major free and commercial patent search interfaces.

Patent searches were carried out for this EPO technology insight report using EPO worldwide patent data from the EPO's internal data platforms and search interfaces such as ANSERA [14] in order to create the basic dataset for subsequent patent analyses.

The resulting basic dataset was combined with value-added data contained from the EPO's PATSTAT product line,[15] which provided the enriched basis for the patent data analysis step and was used for further processing and visualisation of the data.

6.5 Notes on the limits of the study

This report provides a snapshot of specific technologies in the field of photovoltaics taken in the light of patent data.[16] The methodology on which this report is based can be used freely, which means that everyone can adapt the chosen search and analysis approach to their needs, for example to follow trends and developments in other established or emerging technical fields.

This report makes use of publicly available EPO worldwide patent data as well as EPO in-house and publicly available search and analysis tools.

Like many patent analyses, this report is based on specific search strategies combining keywords and patent classification symbols.

For most patent analyses, it is impossible to simultaneously achieve 100% recall, i.e. to retrieve as many relevant documents as possible and 100% precision, which is to exclude as many non-relevant documents as possible. This study is no exception. The search queries chosen to create the basic dataset for the selected photovoltaic technologies were designed to strike a balance between recall and precision in order to provide a meaningful overview of the field.

14 See Demey and Golzio (2020) and Scheu et al. (2006)

15 The Autumn 2024 edition of the PATSTAT product line was used for this report.

16 Date of extraction of the basic dataset from the EPO's internal data platform: April 2025. The basic dataset was combined with data from the EPO's PATSTAT product line (Autumn 2024 edition), which used backfile data extracted from the EPO's master documentation database (DOCDB) in July 2024.

Follow us

- Visit **epo.org**
- Subscribe to our newsletter at **epo.org/newsletter**
- Listen to our podcast at **epo.org/podcast**

Published and edited by
European Patent Office
Munich
Germany

Authors
lead: Christian Soltmann (EPO)
Mauro Boero (EPO)
Johannes Bünz (EIC)
Carina Faber (EIC)
Pierre Favre (EPO)
Francesco Matteucci (Fondazione Bruno Kessler – FBK)
Marie-Annick Le Meur (EPO)

Acknowledgement
The EIC gratefully acknowledges the contributions of
Mónica Lira-Cantú (Institut Català de Nanociència i Nanotecnologia)
and Giulia Grancini (Università di Pavia).

Design
European Patent Office

The report can be downloaded from:
epo.org/insight-photovoltaics

ISBN 978-3-89605-403-6