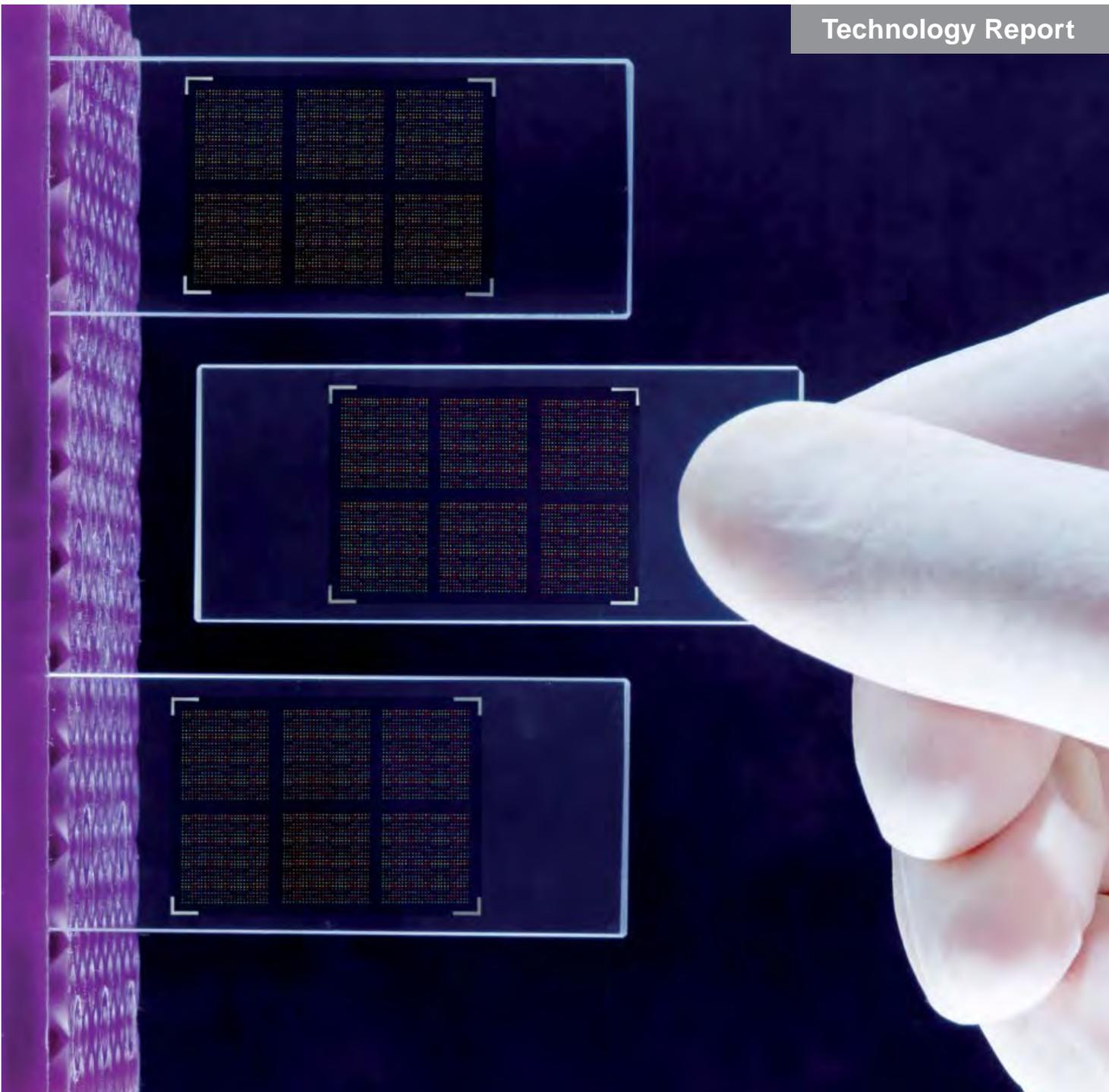


Nanotechnology in the sectors of solar energy and energy storage

Technology Report



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Executive summary

The present publication reports on the future development of products and markets in solar energy and electrical energy storage, insofar as they are influenced by nanotechnologies.

It is based on a forward-looking examination of the research interest in these topics as it has developed over two decades, the actual technologies and their potential improvements, and a wide range of external analyses and events as they will affect the use of the technologies in future.

This Technology Report explains which solar and storage applications are likely to prove the most useful and influence research and development most strongly, and conversely how the potential of known and foreseeable technologies will condition the products which can be manufactured and how they can be used. It takes into account relevant global economic and political conditions, both favourable and unfavourable, and shows the likely results of all this on the market, with an idea of the shape and size of that market over the next 15 years.

As a pilot, this study has also contributed to the IEC's need for a technology and market watch, without which relevant and timely standards cannot be developed.

It concludes that many aspects of solar energy and storage are being and will be influenced by nanoscale materials, and that in some areas nanotechnology may even be a condition of success. Consequently the report will be of great use for those planning the use of solar energy and storage, whether they make products, use those products to generate and store electricity, or organize and regulate the use of the electricity produced.

In the IEC's own activities, several Technical Committees (TCs) will find this report ideal for informing their work on future standards for products, systems and installations; we can mention the TCs on battery, photovoltaic and solar thermal systems.

A few concluding recommendations are made. The TC on nanotechnologies is encouraged to take the lead in allowing standardization to benefit from the information provided, and the whole of the IEC community to help outside stakeholders such as regulators, research institutions and consumer organizations to become involved so as to realize nanotechnology's benefits in the energy sector. Finally, the present results are drawn to the attention of organizations active in investment, product & system design & marketing, installation and regulation of solar energy production and electricity storage.

1 Introduction

1.1 Aim of the project and process

In September 2010 the IEC published a white paper entitled “Coping with the Energy Challenge – The IEC’s role from 2010 to 2030”. One of its recommendations was to set up a market watch and technology prioritization process for technologies and standardization needs in the energy sector. The activities should be related to systems-oriented standards development, as well as application-oriented goal solutions defined by the market.

Fraunhofer ISI was approached by the IEC Market Strategy Board (MSB) to propose a process which allows for a regular review of developments in markets and technologies related to electrical engineering. One tool to be used was a set of workshops involving representatives of the IEC MSB, to set the basis in terms of contents for a regularly updated roadmap and for technology profiles. The objective from the IEC’s point of view was to develop a method to synthesize available market and technology information, and thus produce an early indication of future standardization needs.

Nanotechnology was identified by the IEC as a technology which is likely to have a high impact on the energy sector. That is why the focus in this pilot project is to establish a sound content-related base on the influence of nanotechnology on the energy sectors solar energy and energy storage.

Nanotechnology for this project means material on an atomic and molecular scale <100 nm which affects materials’ mechanical and electrical characteristics. In general, nanotechnology comes with a change in the material’s behaviour, for instance quantum mechanical behaviour, enhanced surface, or self-healing mechanisms. For the energy sector many hopes rest on nanotechnology: micro- and nanostructured surfaces of solar cells are expected to increase efficiency of known solar cells, reduce costs due to less material needed, and hence contribute to a sustainable environment and operations.

The expectations of nanotechnologies related to energy storage and the application of solar energy concern improvements in power and efficiency and the reduction of costs. The most relevant examples are low-cost manufacturing of solar cells, improvements in battery storage density, increased storage capacity, higher performance (e.g. in terms of lifetime, power), and enhanced efficiency in solar power generation.

These links and expectations are documented in the literature. Bibliometric¹ analyses of recent research litera-

ture can indicate past developments and recent trends in nanotechnologies and their contribution to the applications of interest. Technology profiles describing activities in the most relevant nanotechnology R&D fields then link the technology trends to developments in the application fields of the energy sectors. Finally, technology profiles and literature analyses provide a method of checking the descriptions of progress and future trends which can be found in recent worldwide roadmaps on solar energy and energy storage technologies.

Thus an iterative process has been adopted of using bibliometric analyses to give a (quantitative) weight to research in nanotechnologies with relevance to energy applications, using technology profiles in order (qualitatively) to describe the current state of these technologies and their market perspectives, and combining the findings with a simultaneous analysis of roadmaps (“meta-roadmapping”), linking to future technology and market perspectives. This process is considered necessary to establishing a consistent, transparent and plausible methodology for a market and technology watch that identifies the impact of nanotechnology in the energy clusters solar energy and energy storage.

In order to assess the demand side (market pull, market and societal needs and regulatory framework conditions) – in contrast to the technology developments (technology push) – the literature, market reports, roadmaps and worldwide future scenarios have been analyzed. This provides a framework for evaluating the relevance of the technologies and energy sectors considered to global developments.

The methodology and detailed process of this project are described in chapter 2. The results from the “meta-roadmapping” process including bibliometric analyses and technology profiles from nanotechnologies to application technologies, products and global developments, are described in chapter 3. The conclusions are summarized in chapter 4.

Sections 1.2 and 1.3 below provide a general overview of market forecasts for nanotechnology-based products relevant to the two energy sectors, and future scenarios for energy generation and use within the context of global developments and framework conditions. They serve as introductory justification of the relevance of nanotechnology to the selected energy sectors and the relevance of these sectors themselves, and provide a vision of the time frames in which developments are likely to become relevant.

1.2 Nanotechnology vs. energy storage and solar energy markets

Although there are some nanotechnology-related products already on the market, most areas of nanotech-

¹ See section 2.3.

nology are still in the basic research stage. Analyses of potential markets are often vague and inconsistent. Nevertheless, market-relevant applications can be expected in fields such as optics, precision engineering, analytics, chemistry, automotive and mechanical engineering, materials management, medical engineering, pharmaceuticals and biology. Today, the US constitutes the biggest market for nanotechnology, followed by Europe. Both regions are expected to amount to around 35% of the worldwide market in 2015 (1).

The world market being influenced by nanotechnology (more concretely, by nano-enabled products) has been estimated to be in the range of 100 billion to 1 000 billion US\$ between 2005 and 2015 (pessimistic scenario). Market estimates for 2015 even approach 3 000 billion US\$ in a more optimistic scenario (Figure 1), being a significant percentage (about 5%) of the world's gross domestic product (GDP) or about 15% of the global production of goods. The forecasts differ significantly from each other, but have in common that they predict a substantial increase of the market for nanotechnology products, with a take-off at some point in the early 2010s. On the other hand, the forecasts from Lux Research (representing one of the sources in Figure 1) further distinguish between **nanomaterials**, **nanointermediates** and **nan-enabled products**, leading to different dimensions of sales depending on the level or range of the products/markets in the value chain and the underlying definition of nanotechnology (2).

Nanotechnology is said to have the greatest influence on the subfields of materials and production technology, with an increase from 97 billion US\$ in 2007 to 1 700 billion US\$ by 2015, followed by the electronics sector (semiconductors, displays, batteries among others) with a growth from 35 billion US\$ in 2007 up to 970 billion

US\$ by 2015, as well as on the health sector (pharmaceuticals, medical engineering and diagnostics) with a growth from 15 billion US\$ in 2007 to 310 billion US\$ by 2015 (163). Considering this level, even the services related to the nano-enabled products seem to be integrated in the market data.

Some of the studies mentioned above as well as additional studies break down the forecast into further subfields of nanotechnology (3) (4). Among these, the total energy-related market for nanotechnologies is estimated to reach 7 billion US\$ by 2012. For comparison, studies speak of an energy-related market for nanotechnology at around 4.7 billion US\$ in 2009 (3).

However, these assessments provide an incomplete picture of the market potential of nanotechnology, since in each case only a fraction of the multitude of different methods and material classes is considered (4). Correspondingly, they have to be interpreted carefully. So far, many of the forecasts have also proved to be too optimistic. But there is no doubt that demand for nanotechnology products will increase significantly faster than the total market.

A common feature of all forecasts is that they expect a strong increase in market size for nanotechnology products. The most conservative forecasts for specific product groups based on nanotechnology applications estimate an average annual growth rate (at current prices) of about 5%, which is still above the average growth rate for global total manufacturing. The most optimistic forecasts assume an expansion of nanotechnology markets at annual rates of 50% or even more. Forecasts that relate to the total nanotechnology market tend to assume higher growth rates (34% on average) compared to forecasts for specific subfields and better-defined market segments (20% on average) (5).

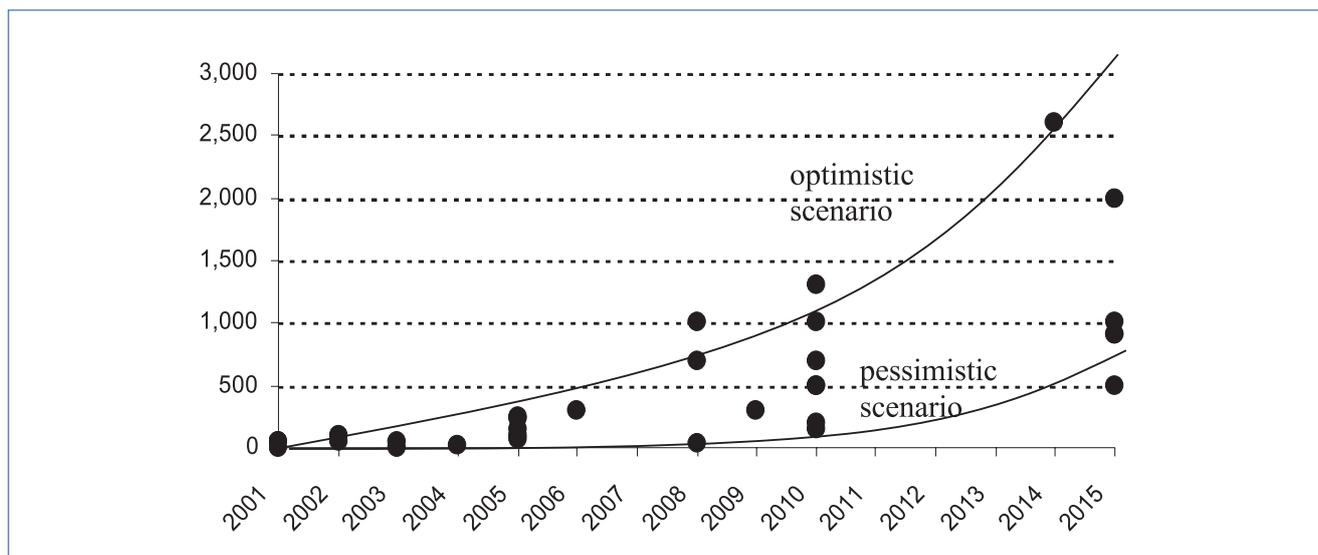
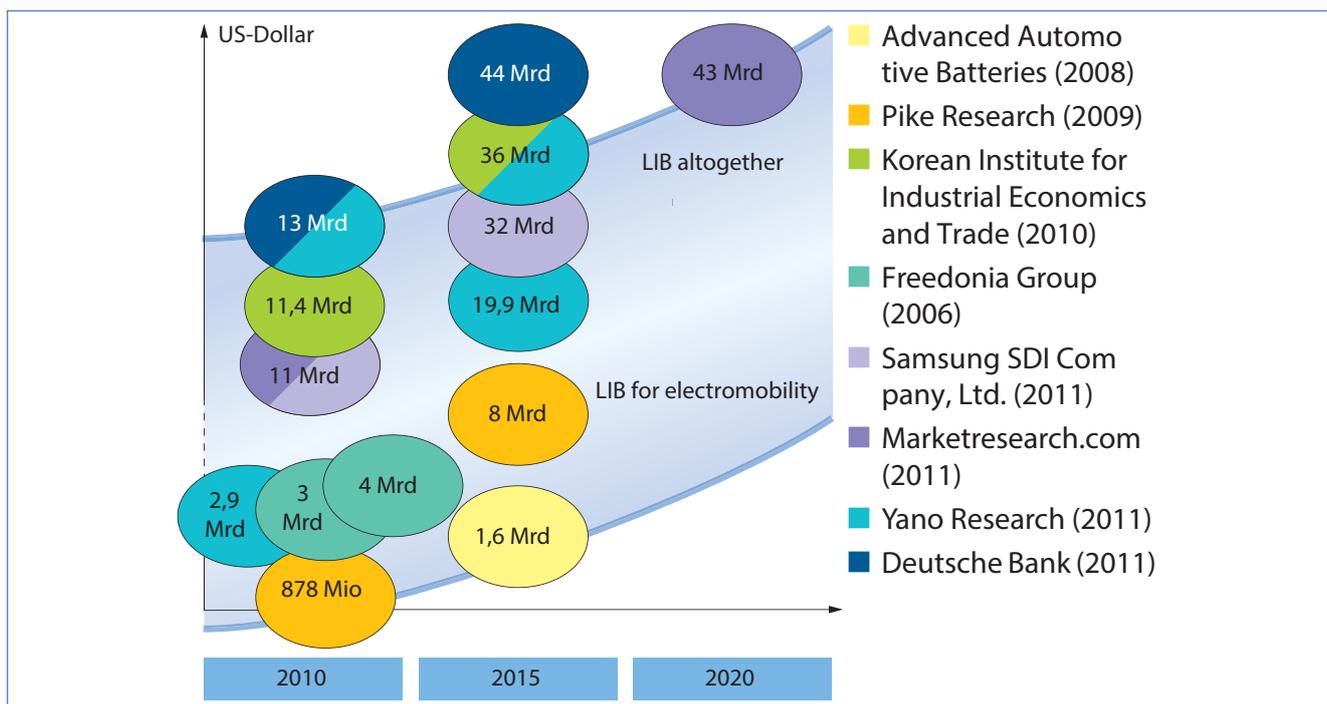


Figure 1 – Estimates of nanotechnology market size (in billion US\$). Scenarios based on 17 sources (3)

Table 1 – Estimates of world nanotechnology-based product market volumes in selected energy market segments (CAGR = compound annual growth rate)

Market segment	World market volume (year)		CAGR	Source
Nano-optimized batteries	US\$169m (2009)	US\$1.1bn (2013)	46 %	(6) (4)
Nano-optimized fuel cells and hydrogen storage (electrodes, catalysts, membranes, nanomaterials for hydrogen production and storage)	US\$2bn (2008)	n/a	n/a	(7) (4)
Supercapacitors	US\$275m (2009)	US\$713m (2014)	21 %	(8) (4)
Applications of superconductivity (magnets, electrical engineering)	US\$2bn (2010)	US\$3.4bn (2015)	11 %	(9) (4)
Catalysts for energy technologies (coal liquefaction, synthetic gas catalysts, reforming, photo-electrochemical water splitting)	US\$4bn (2010)	US\$6bn (2015)	8 %	(10) (4)
Nano-optimized photovoltaics (dye cells, CIGS/CIS, QD-cells, etc.)	US\$68m (2010)	US\$820m (2017)	43 %	(11) (4)
Microenergy harvesting for energy autarkic sensors and switches (e.g. electromagnetic induction, thermoelectrics, photovoltaics, piezoelectrics)	US\$80m (2009)	US\$1.3bn (2014)	74 %	(12) (4)
Thermo-photovoltaic cells	€1bn (2010)	n/a	n/a	(13) (4)

**Figure 2 – Forecasts for world market development of lithium ion batteries, by turnover in billion US\$ (14)**

Against this background, the market forecasts for the selected energy-technology-related market segments (Table 1) have to be understood on the product level, i.e. where nanotechnology-based materials or methods help to improve the performance or quality of products. They define only a fraction of the whole market segment (with nano- and non-nano-based products).

This can be understood on a more concrete level by considering the two examples of batteries (within the energy storage sector) and photovoltaics (within the solar energy sector).

Figure 2 illustrates a number of forecasts for global lithium ion battery market development between 2010 and

2020. The upper limit takes into account all possible application for these batteries (e.g. in consumer electronics, for electric mobility or stationary applications) while the lower limit relies on forecasts for lithium ion batteries in electric mobility only.

For the example of nano-optimized batteries, lithium ion batteries can be expected to have a largely dominant share compared to lead acid, NiMH or other battery types. This market is expected to increase at a compound annual growth rate (CAGR) of 46% from 169 million US\$ in 2009 to 1.1 billion US\$ in 2013. This could lead to a market size of several billion US\$ within the next few years (2015 to 2020), showing that the nanotechnology-based battery market is expected to increase by a factor of about 10 within a time frame in which the whole battery (lithium ion battery) market is only expected to triple, i.e. from 11-13 billion US\$ to 32-44 billion US\$. In fact, such an impact of nanotechnology-based products evolving from a small share, e.g. around one percent and less, to a share of several percent within the next 5 to 10 years, can also be expected on the basis of the technology trends indicated in existing roadmaps and analyzed in this report.

For photovoltaics, the increase in the emerging PV cell market based on nanotechnology (e.g. dye cells, QD-cells, nano-based thin film CIGS) is expected to reach 820 million US\$ in 2017 compared to 68 million US\$ in 2010 with a CAGR of 43%. This could lead to a 2.5 billion US\$ market around 2020. The total market of emerging PV (including organic PV cells, dye cells, CIGS) is expected to increase to 7.7 billion US\$ by 2021 (Figure 3), showing that the nanotechnology-based PV market is strongly linked to emerging PV technologies.

In contrast, the global market for the whole photovoltaic sector is expected to more than double by 2020, increasing from 2010's 30 billion to 70 billion US\$ (18). Other market forecasts already expect a more than 75 billion US\$ market around 2016 (19). Again, as for the example of batteries, nanotechnology-based emerging PV cells could reach a market share of several percent of the whole PV sector within the coming decade. This is also indicated in Figure 4, based on data from the European Photovoltaic Industry Association (EPIA). Here, emerging PV including concentrator PV is expected to reach a 5% market share in 2020.

However, just as for the battery markets, the maturity of different technologies and market segments has to be taken into account. For stationary applications (e.g. large solar parks) silicon and thin film PV are expected to dominate the market. Emerging PV cells are expected to have a high impact on consumer markets, small mobile or large-surface (e.g. building-integrated) applications, and therefore not mainly for primary energy supply. Regarding the battery sector, different scales of battery are relevant for consumer, electric mobility and stationary applications, and depending on the application field lithium ion batteries are dominant, or competing with other battery types, or with different storage technologies, etc.

In summary, nanotechnology is already expected to have a strong market impact on solar power and energy storage applications within the next decade. However, expectations tend to overestimate market opportunities (e.g. by including materials, products, systems and even services in market forecasts), and it is important

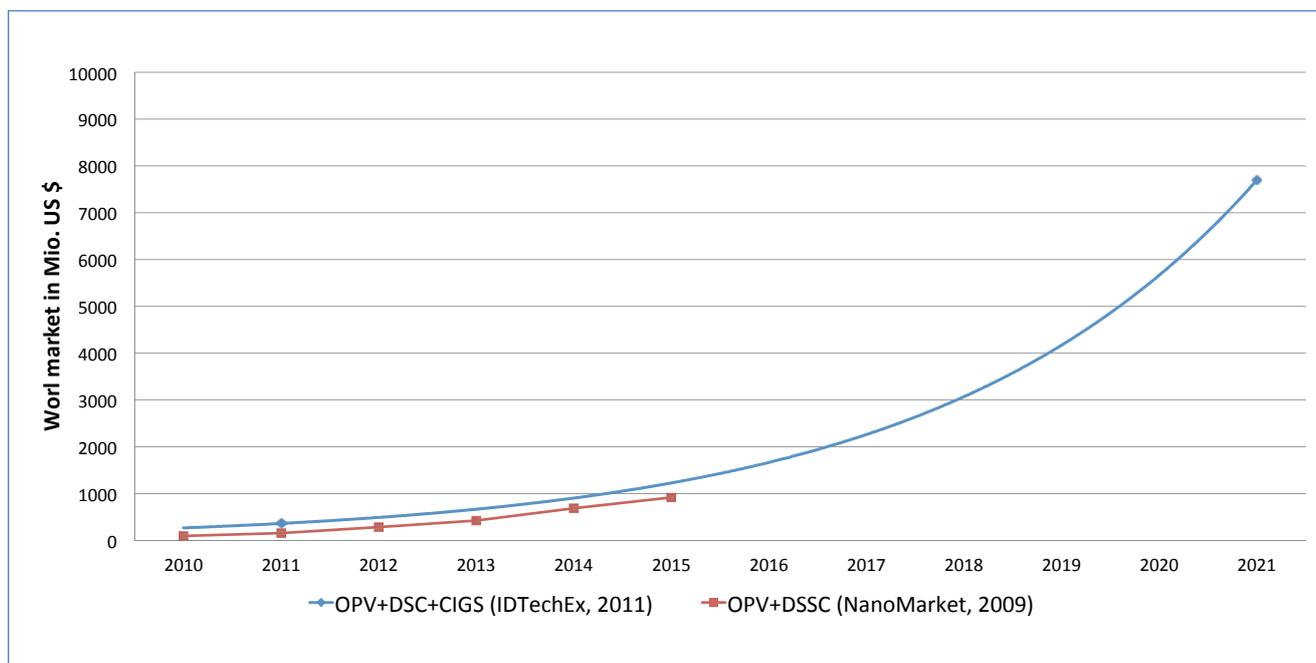


Figure 3 – Forecasts for world market development of emerging PV, with trend curves (15) (16) (17)

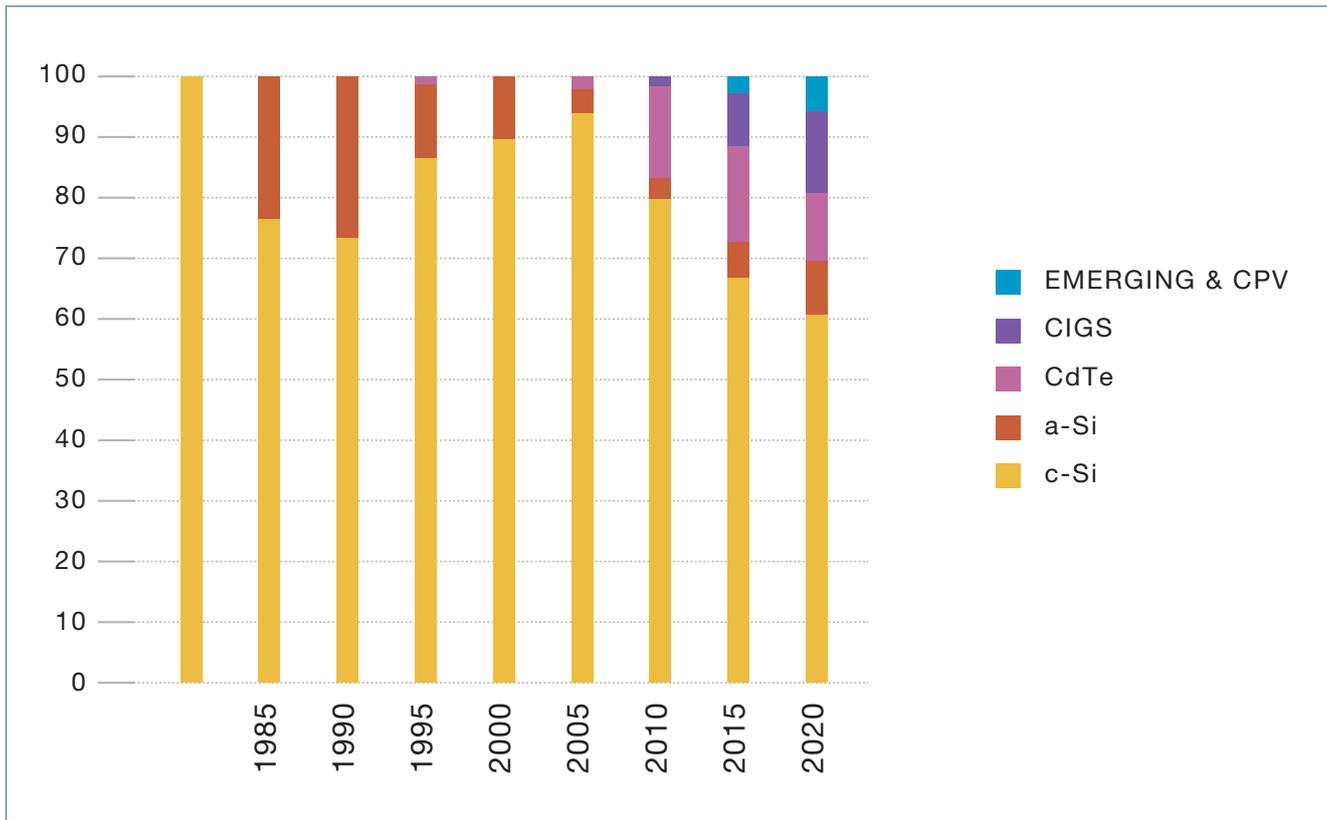


Figure 4 – Historical evolution of PV technologies' market shares, and future trends, in percent (20)

to define carefully which product groups or technical solutions are relevant for which market segments. But the generally growing relevance of nanotechnology-based products to the two sectors can be clearly seen.

Although long-term scenarios for the development of energy storage and solar energy (e.g. until 2030 or even 2050) exist and will be discussed in the next section, a market forecast for nanotechnology-based products beyond 2020 is not feasible.

1.3 Scenarios for future energy generation and use

Although the global financial crisis has affected overall economic growth, global primary energy demand has increased. It rebounded by a remarkable 5% in 2010 compared to the previous year. Increase in the energy demand pushed global carbon dioxide emissions higher. Even though energy demand has increased, the number of people without access to electricity reached over 1.3 billion globally, which is about 20% of the world's population. Even though increasing energy efficiency has been a priority in many countries, energy intensity globally worsened in 2009 and 2010 (21).

It has been estimated that, though economic progress seems uncertain over the short term, demand for energy will increase by one-third from 2010 to 2035. The primary factor in the increased energy demand will be global population, which may increase by 3.5% annually. In the future energy scenario fossil fuels will continue to be used, but their dominance will decline. It has been predicted that the share of fossil fuels in the global primary energy mix will decline to 75% in 2035 from 81% in 2010. On the other hand, the share of non-hydro renewable energy sources such as wind, solar, biomass etc. in power generation will increase from 3% in 2009 to 15% in 2035, related to subsidies for alternative energy technologies. Critically important for renewable energy sources to compete in electricity markets is continued support throughout the projected period. This support will be costly, but it may bring long-term benefits in terms of sustainable energy deployment and environmental protection (21).

As renewables become crucial for the energy mix of the future, the most important issue for their deployment will be cost, unless they can compete with other energy sources they will not be implemented.

Figure 5 shows the forecast growth in global energy demand by 2035 in million tons of oil equivalent, Mtoe

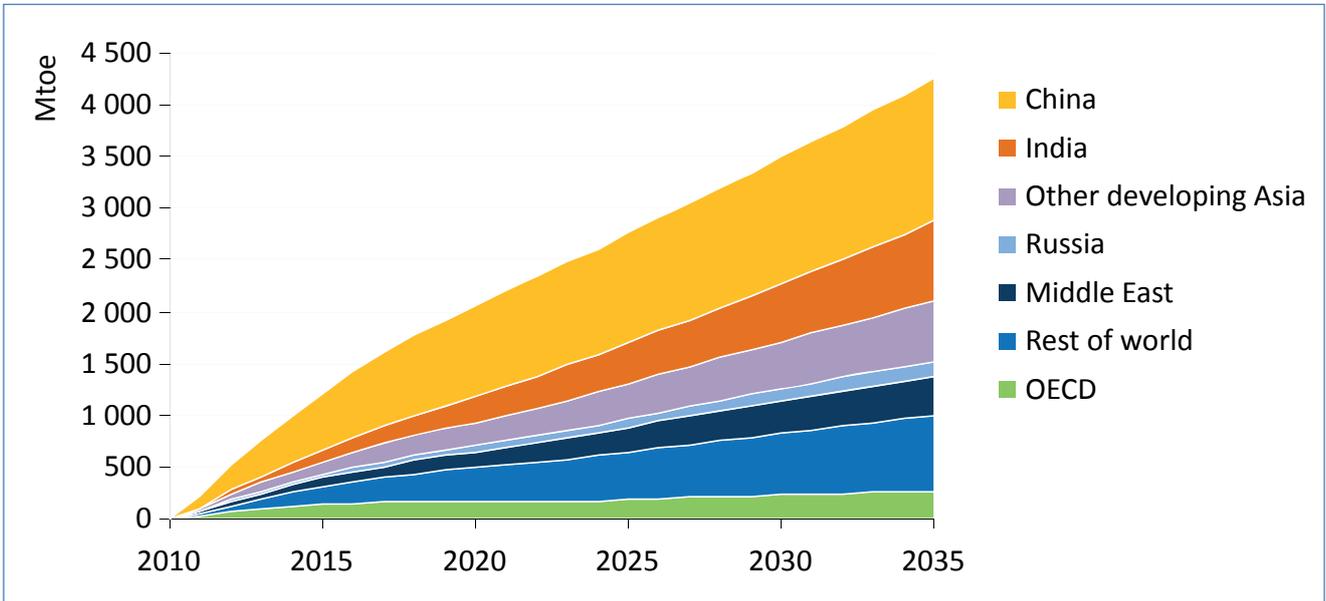


Figure 5 – Growth in global energy demand (22)

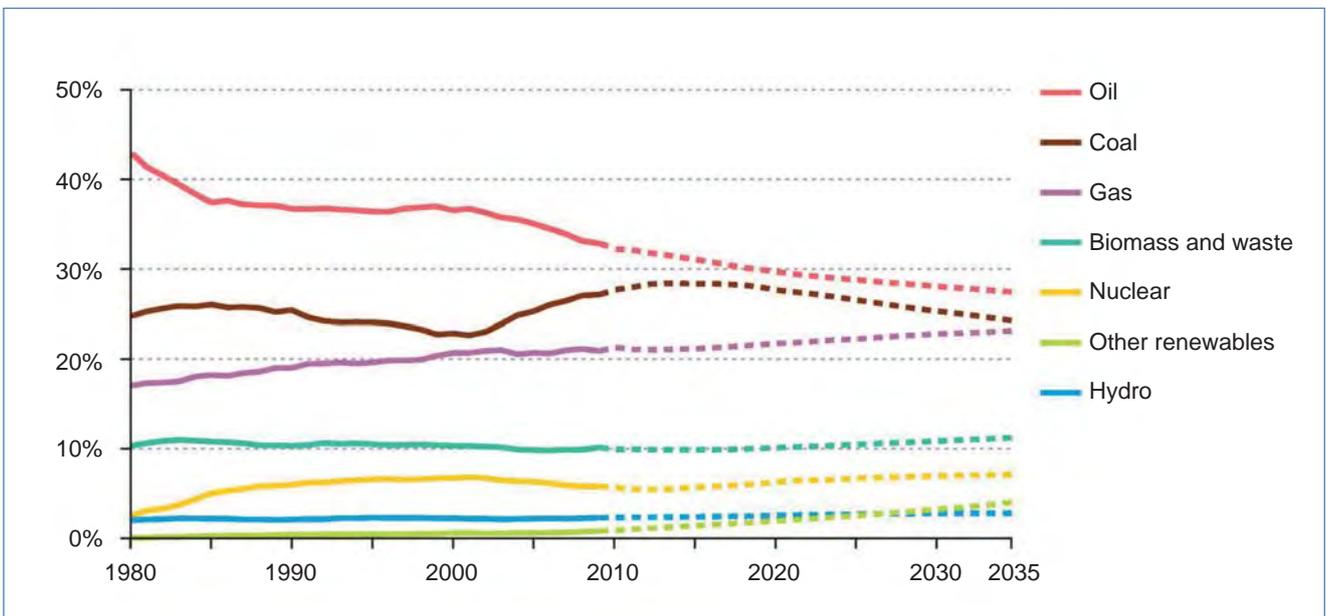


Figure 6 – Shares of energy sources in global primary energy demand (23)

(1 Mtoe = 11.63 TWh). It is evident that the growth in demand is led by emerging economies such as China and India.

Figure 6 shows forecast shares of energy sources in global primary energy demand to 2035. The share of fossil fuels other than natural gas is estimated to decrease. On the other hand, renewable energies including hydropower will increase their share of primary energy demand. In comparison, global energy demand was 12 369 Mtoe (143 851 TWh) in 2008 with about 32 % oil, 28 % coal, 21 % gas, 13 % renewables (including biomass and waste, hydro and other renewables such as solar and wind power), and 6 % nuclear energy. The expected increase in energy demand over the next decades together with an expected increase in non-hydro renewable energy sources points to a strong growth in installations of fluctuating energy sources such as solar and wind power.

Global installed power generation capacity to 2035 is forecast in Figure 7 for different energy sources, and indicates a very strong increase in renewables. About one-third of the new capacity added worldwide (about 3 000 GW according to Figure 7) is expected to be due to renewable energy sources. However, it has to be recognized that the full amount of load hours from fluctuating sources such as wind and solar power is rather lower than from gas, coal, biomass or nuclear power, leading to a smaller amount of energy produced over the year, consistently with the more moderate increase of renewable energy share shown in Figure 6.

From these prognoses, it is clear that renewable energy sources will play a vital role in satisfying the growing energy demand of the future. Simultaneously, renewable energies will only be able to penetrate the market if they are cost-competitive. Thus, reducing the cost of renewable energy production and distribution is of key importance.

Thus, besides technological advances in new, emerging and in particular renewable energy technologies, economic factors (particularly costs) but also ecological and political factors (such as regulations, climate goals, etc.) are fundamental to the future development of energy sectors like solar power and energy storage.

The following paragraphs list some crucial mechanisms relevant to the development of the two energy sectors under consideration in this report.

Global carbon dioxide emissions rose 3% to 31.2 Gt in 2011, according to a new EU report, undermining a UN goal to limit the rise in global average temperatures to 2 °C above industrial levels by 2050 (24) (21). For the

next decades, a worldwide reduction of CO₂ emissions from 31.4 Gt in 2020 to 22.1 Gt in 2035 is required if the 2 °C goal is to be achieved. This indicates that over the coming years and at the latest by 2017 action has to be taken to reduce CO₂ emissions. Otherwise, a further increase of energy-related CO₂ emissions (e.g. up to 35 Gt or 36 Gt in 2020, and as much as 37 Gt to 44 Gt in 2035, depending on the underlying scenario) will lead to long-term average temperature increases of 3.6 °C or more (24).

A promising way to achieve the goal of reducing global CO₂ emissions in the long term is to increase the share of renewable energies. Scenarios assuming a 80%-100% share of renewable energy sources by 2050 have shown that a reduction of greenhouse gas emissions to 80 %-95 % below 1990 levels would be realistic by then (25). Until then, a constantly increasing share of renewable energy sources and new installations will be required. Promoting renewable energies and reducing CO₂ emissions is the major focus of current EU energy policy. Modelled on success achieved in Europe, similar support schemes could be adopted in other countries. This is a major driver for the spread of renewable energy sources such as solar energy.

However, this results in an increasing penetration of fluctuating electricity generation and will increase the grid load. As a consequence there will be more demand for flexibility in the energy system, i.e. grid-balancing measures will be needed. Electrical energy storage (EES) can be a viable alternative to grid extensions in certain cases. However, we must distinguish developments on the transmission and distribution grid levels. Current studies of the transmission grid in Germany and Europe indicate that ESS is of limited relevance below 40% renewable energy share (thermal power plants and renewable energy curtailment can balance the fluctuating demand). At 80% share, a combination of short- and long-term EES (implying a need for different ESS technologies) and curtailment would be effective. For a 100% share compared to a 80% share, EES demand would be increased by a factor of three (26) (27).

However, the use of EES may also be feasible at a lower share of renewable energy when considering the distribution grid. On the distribution grid level, the storage of locally produced energy (e.g. through a combination of rooftop solar panels and storage in private households or industry) is expected to become much more important in the near future.

Also, framework conditions across different countries and regions are different and may lead to a different EES

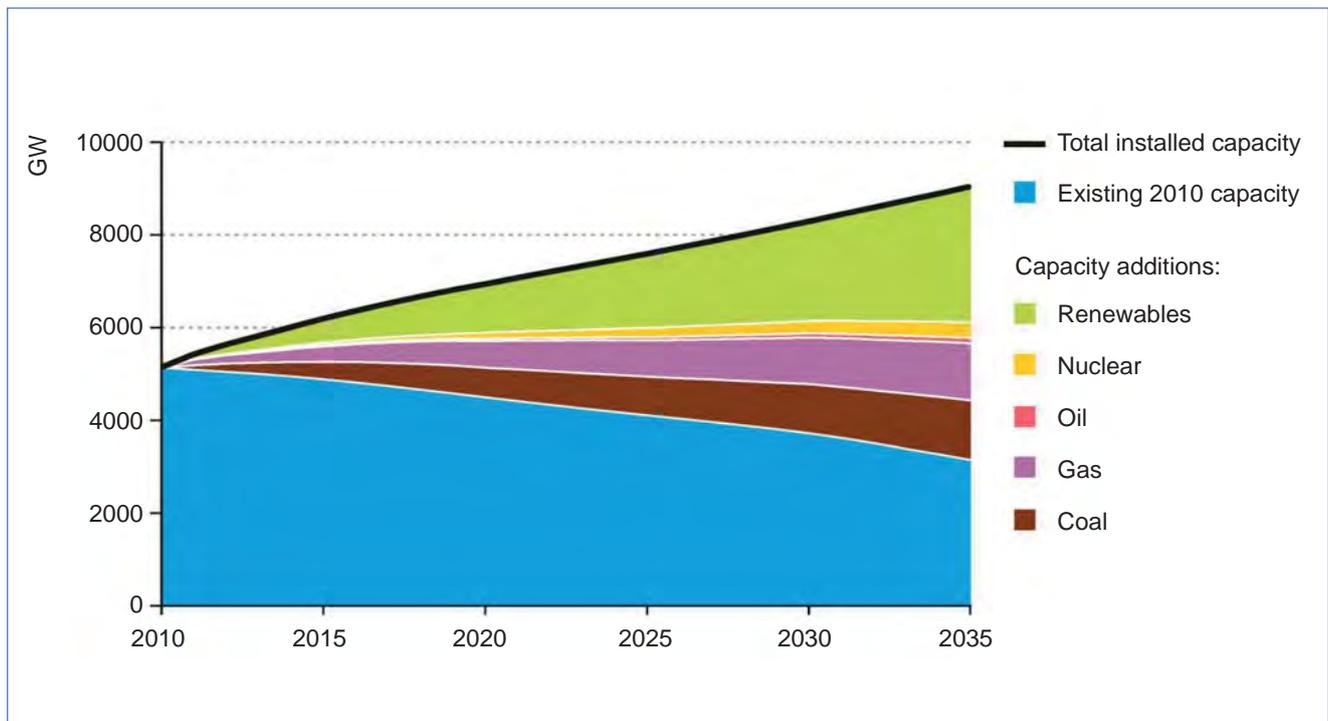


Figure 7 – Global installed power generation capacity (23)

demand in the future. In general, it can be said that the option of building storage facilities is economic only if two conditions are met: many hours of excess energy production can be expected (i.e. where energy production is much higher than energy consumption), and additional grid connections are not feasible to balance the energy produced (e.g. because countries with a corresponding demand for electricity are too far away or they function as “islands”).

To summarize, the political goal of reducing CO₂ emissions and increasing the share of renewables is a major driver for the spread of energy storage as well as renewable production itself. Thus the development of solar energy technologies and markets is linked to the development of and opportunities for EES.

In 2010, about 128 GW of EES capacity was installed worldwide, with a share of more than 99% of pumped hydropower. Compressed air energy storage, batteries and flywheels accounted for less than 1 GW (28). This is about 2%-3% of the power generation capacity globally installed (Figure 7).

Considering the trends and scenarios for renewable energy, smart grids, smart houses, electric mobility, etc. (28), the increasing role of solar power as well as the increasing demand for energy storage solutions becomes obvious. However, the time frame and extent of these developments will depend on the mechanisms described above, and thus on technology developments, market mechanisms as well as different general conditions regarding ecology, economy and politics across countries and regions worldwide.

2 Methodologies used in the project

2.1 Project structure

The project was conducted by using a five-step approach. This approach is illustrated in the following figure. Different methods were used to support the individual steps: workshops, bibliometrics, technology profiles and meta-roadmapping. The five steps were performed mainly linearly over time; in some cases, however, an iterative process was needed to ensure a consistent and fruitful result. The steps in detail were:

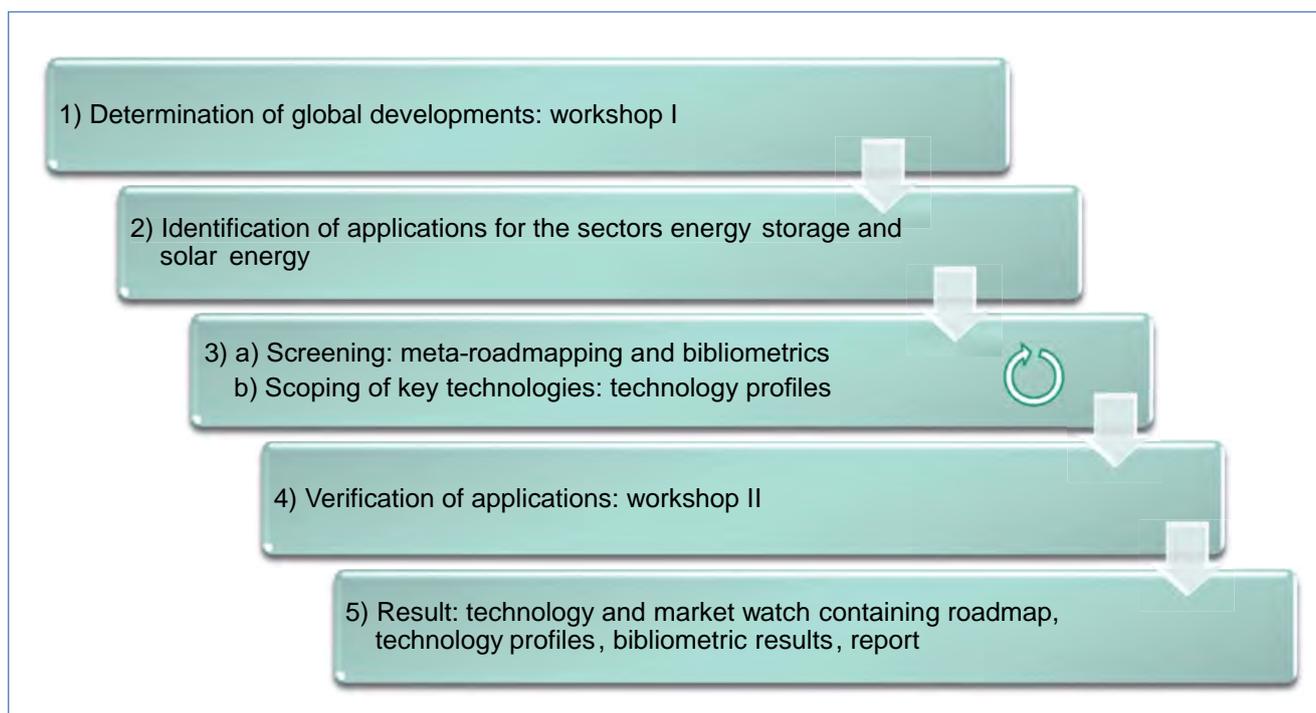


Figure 8 – Project structure

Step 1: workshop I

At the beginning of the project a first workshop was conducted in February 2012 in order to create a common understanding of the project's aims. The architecture or roadmap as well as the design of the technology profiles were discussed. Global developments with an influence on the energy sectors energy storage and solar energy were identified. In addition, a first brainstorming session on applications was held. The first workshop was intended to initiate the project and to agree upon the process and methodologies as well as the contents and levels of detail for the subsequent analyses.

Step 2: identification of applications

By screening over 150 studies, relevant applications for energy storage and solar energy were identified. This information was used as an input for deeper research, bibliometric analyses, meta-roadmapping and the compilation of technology profiles. This research was implemented in the next step.

Step 3: screening and scoping

First a screening of relevant topics was performed by meta-roadmapping and bibliometrics. Key technologies were identified which it was worthwhile to look at on a detailed level. Technology profiles were developed for seven key technologies that have a major impact on the investigated energy sectors. This whole work package was worked on in several loops to ensure that the latest

findings were taken into consideration at every level of analysis. Figure 9 shows the interaction of the different methods used in this work package.

In order to obtain information from complementary research methods and to document meaningful results, the following three methodologies were used iteratively:

1. Bibliometric analyses provided (quantitative) information on relevant nanotechnology topics and their impact in terms of publication share with respect to energy application technologies. The most relevant nanotechnology fields, those with a critical mass of scientific activities, were clustered. Qualitative information from scientific literature as well as literature identified from further desk research fed into technology profiles for the previously clustered nanotechnology fields.
2. The technology profiles gave detailed (background) information on selected technologies also appearing on the meta-roadmap. They linked the qualitative description of clustered nanotechnology fields to application technologies, their market relevance, and key actors in this field.
3. Roadmaps available worldwide and their contents in defined categories of nanotechnologies and energy technologies as well as the time frame from today to 2030 were systematically filed in order to create a "meta-roadmap". Information and topics as well as

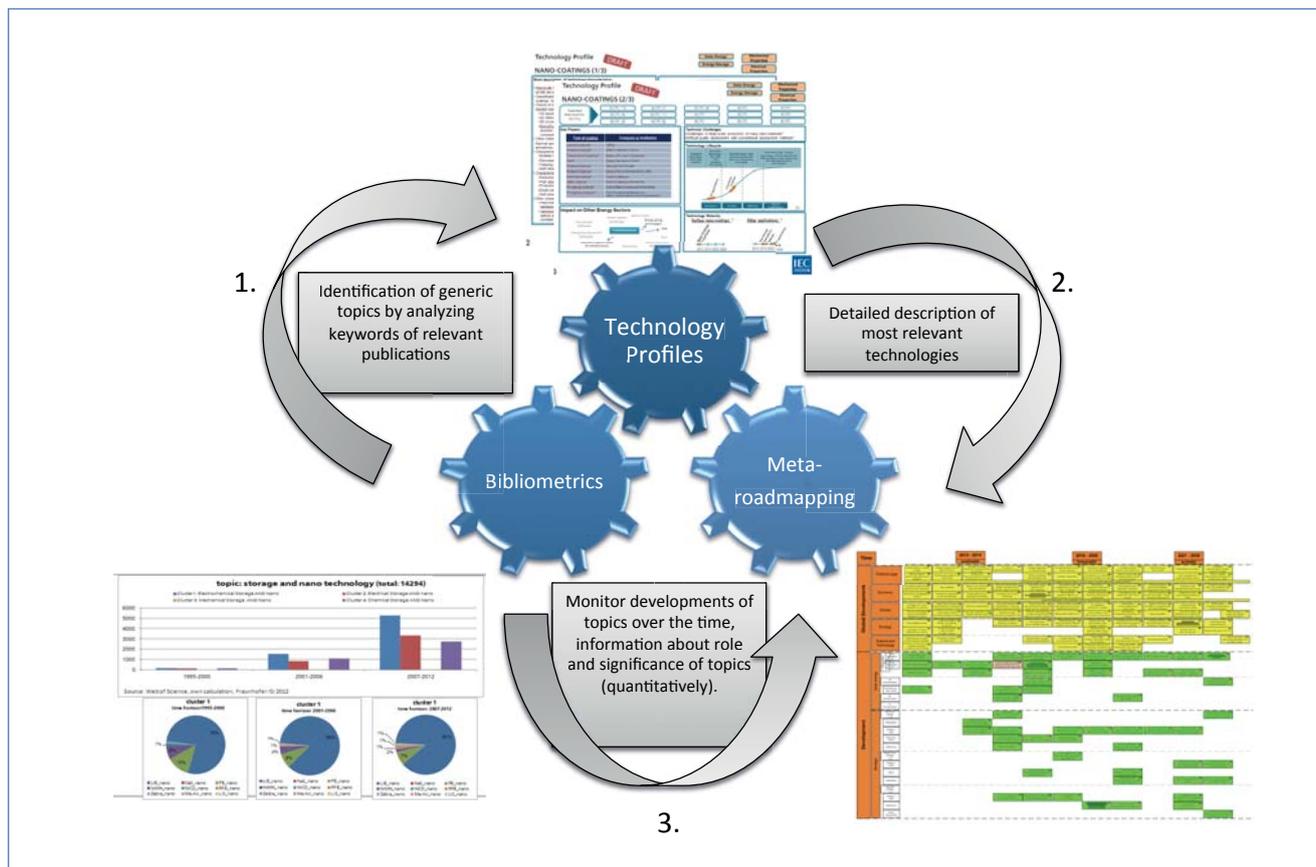


Figure 9 – Interaction of the different methods

results and insights found in the literature, the bibliometric analyses and the technology profiles were included in the roadmap and helped to verify the meta-roadmap.

Step 4: workshop II

In a second workshop, the consistency of the roadmap was verified by internal and external experts. During and after the workshop, e.g. at a further internal Fraunhofer ISI expert workshop and by additional expert interviews, the meta-roadmaps were further elaborated, completed and updated. The technology profiles were evaluated and missing information was supplied. The workshop also reviewed the global developments identified in the first workshop and found them reasonable. The top layer of the roadmap was restructured in consequence and the global developments prioritized.

Step 5: results

The result of this project is a market assessment containing a roadmap, technology profiles, bibliometric results and the present report. It shows the influence of nanotechnology on different applications in the sectors energy storage and solar energy, and places these applications in the context of global trends.

2.2 Roadmapping and meta-roadmapping

Roadmapping is a practical approach to supporting innovation, strategy and policy at company, sectoral or national level. Roadmaps can have different aims and exist on different levels, for instance as market roadmaps, product roadmaps or technology roadmaps. In this project all these levels have been addressed within one roadmap.

More concretely, for the IEC project a meta-roadmap has been created from a variety of publications, such as future studies, roadmaps or scientific papers dealing with nanotechnology for solar power or energy storage. The meta-roadmapping approach provides an insight into the topic from several perspectives; it can thus correctly identify developments in technology and their link to specific applications, as well as global developments within the time horizon defined for the roadmap.

The meta-roadmapping process consisted of a pre-planning phase and three sequential steps.

Pre-planning phase. In advance of the meta-roadmapping process, the elements of the roadmap were defined: the planning perspectives, the roadmap layers, the strategy

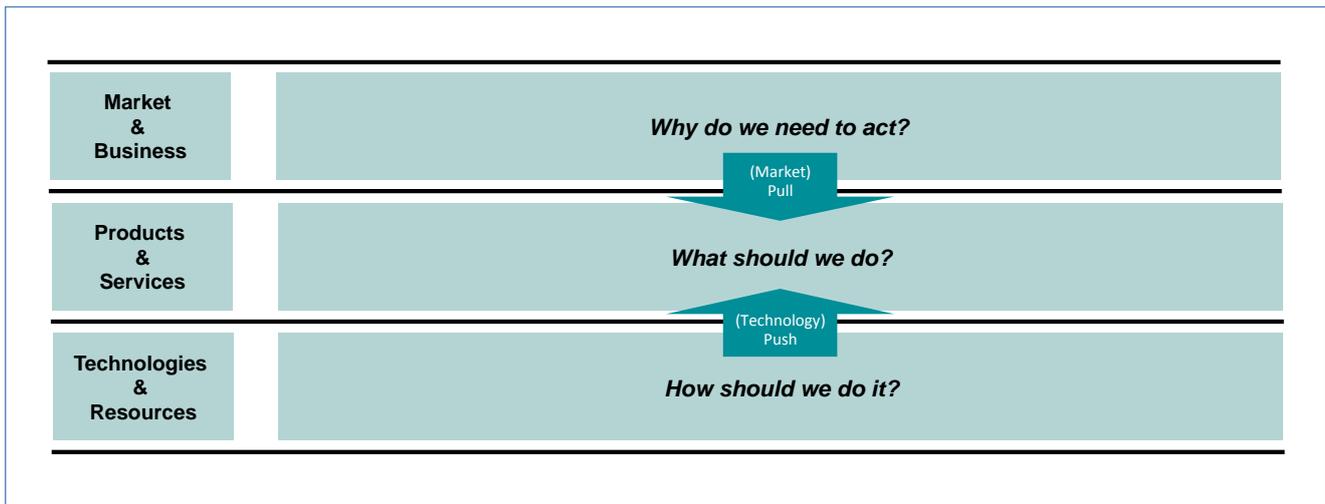


Figure 10 – Introduction to the roadmapping process started in the February 2012 workshop

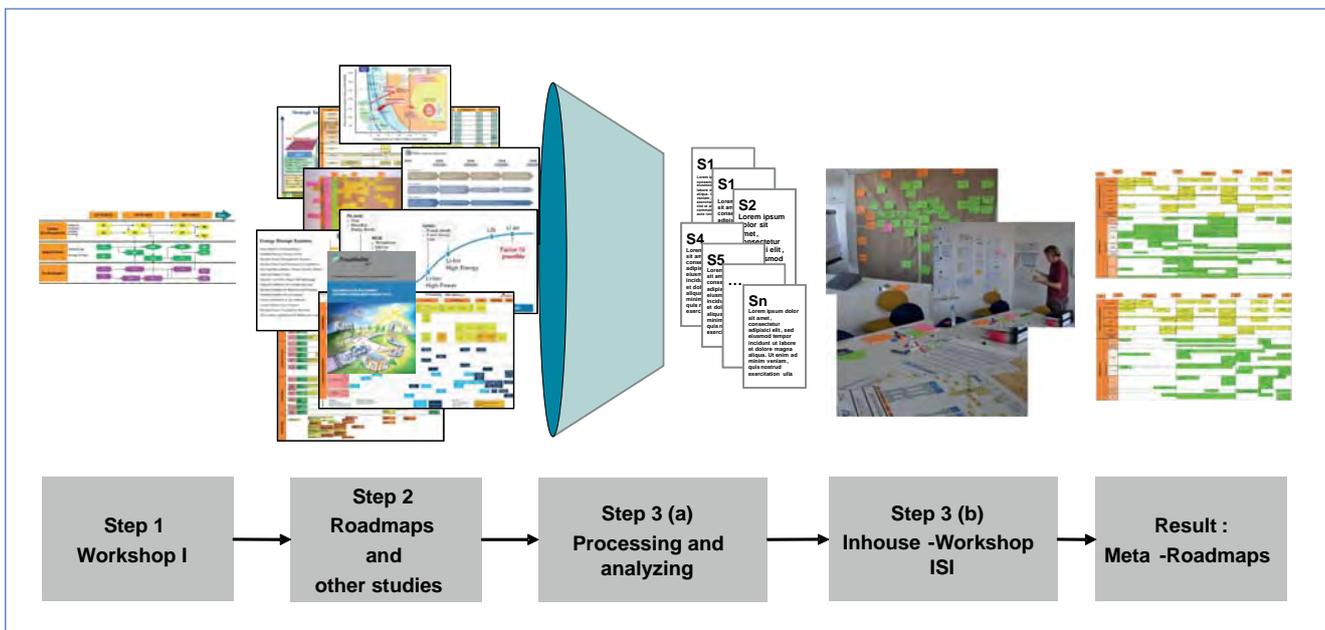


Figure 11 – The meta-roadmapping process (Fraunhofer ISI 2012)

and the time horizon. The layout of the roadmap was developed jointly with the relevant stakeholders from the IEC.

Step 1: workshop I. First ideas about global developments and applications were identified in workshop I at Fraunhofer ISI. As a consequence the approach adopted was a market-based one, and the result was the first draft of a market-based roadmap.

Step 2: roadmaps and other studies. In a broadly-based phase of desk research, future studies, roadmaps and scientific papers containing relevant information on nanotechnology developments in the fields of solar energy and energy storage were identified.

Step 3(a): processing and analysis. The publications identified in Step 2 were analyzed and processed. The key information was extracted and noted on fact sheets.

Step 3(b): in-house workshop. With the information from publications generated in Step 3(a) a workshop with Fraunhofer ISI experts was organized. The objective of this in-house roadmapping workshop was to verify the roadmap from workshop I and to add the collected information to it.

Result. The result of this meta-roadmapping process was the meta-roadmap presented in workshop II. Steps 1 to 3 were repeated after workshop II (i.e. further liter-

ature reviews, a second in-house workshop and expert interviews) in order to correct (where necessary), complete and finalize the meta-roadmap.

2.3 Bibliometric research

Publications are an essential part of scientific work and a measure of the development and dynamic of different topics within subject areas. They are understood as innovation indicators to observe and explain technological changes within a specified field of interest and to recognize new research directions.

Bibliometrics is a method to statistically analyze the numbers of scientific publications. Important research areas in this method are information retrieval, research evaluation and science studies. The basic assumption on which the method relies is that scientists publish their new results at a very early stage of the research and development process. The source of scientific publications can be periodicals, proceedings, scientific books, studies, internally and externally published reports and the Internet. The data for the bibliometric analysis carried out for this report was retrieved from two different scientific databases, SCOPUS® and Web of Science®. This data can be used to identify actors, institutions and specific research fields. Developments at national level can also be seen.

In the current project, bibliometric analysis was used for the sectors of energy storage and solar energy. To obtain reliable results it is important to work with an exact description of the search fields through relevant and concrete search terms or keywords, logically connected with the operators AND, OR and NOT. The search strategy was validated in several loops and the results were also checked by domain experts.

The generated search strings were used to retrieve data from Web of Science® with the following criteria: articles and proceedings, SCI (Science Citation Index), CPCI-S (Conference Proceedings Citation Index – Science), and publication date from 1990 to the present. In addition to statistical and descriptive data analysis, an interpretation of the results is necessary as a last step.

The analysis in this report shows the number of publications, the growth rates in topics, as well as the share of the term “nanotechnology” within the topics and clusters. Detailed analyses of three different time spans were made (1995-2000, 2001-2006, 2007-2012). To identify precisely the publications with relevant contents, the keyword analysis was conducted using publication titles and abstracts. Countries were aggregated to regions to identify key actors, individually for each topic.

2.4 Description of technologies (technology profiles)

Technology profiles help to structure information about technologies in focus and ideally display the information available for different technologies in a comparable way.

For the project a template was developed consisting of four pages:

- General description
- Technical specifics
- Market perspective
- Backup and sources used for information

In the event that these technology profiles are updated regularly, for instance every 1-2 years, this allows on the one hand for the monitoring of changes in the area of interest; on the other hand, people working in a dedicated area of expertise have recent information available about the technologies.

Technology profiles play a role in the technology and market watch process by giving detailed background information about a technology and its environment.

3 Results

3.1 Roadmap

As one main result of this project, two roadmaps have been developed addressing the influence of nanotechnology on the two sectors “solar energy” (SE) and “energy storage” (ST).

Roadmaps are increasingly used as a management technique for supporting innovation, strategy, and policy at firm, sector, and national levels. Throughout its long history the roadmapping approach has evolved, firms and other organizations have adapted the concept to address their particular needs and the changing business context.

The longevity of the method is attributed to its ability to support strategic communication within and between organizations, and the inherent flexibility of the method, which can be readily customized. This flexibility is both an advantage and a challenge, as a standardized “off-the-shelf” approach is rarely feasible. For this project, a classical approach of a roadmapping process was conducted, resulting in two roadmaps with the same architecture.

Each roadmap shows a timescale on the horizontal axis which is split into “predictable” (2013-2015), “foreseeable” (2015-2020) and “probable” (2020-2030) develop-

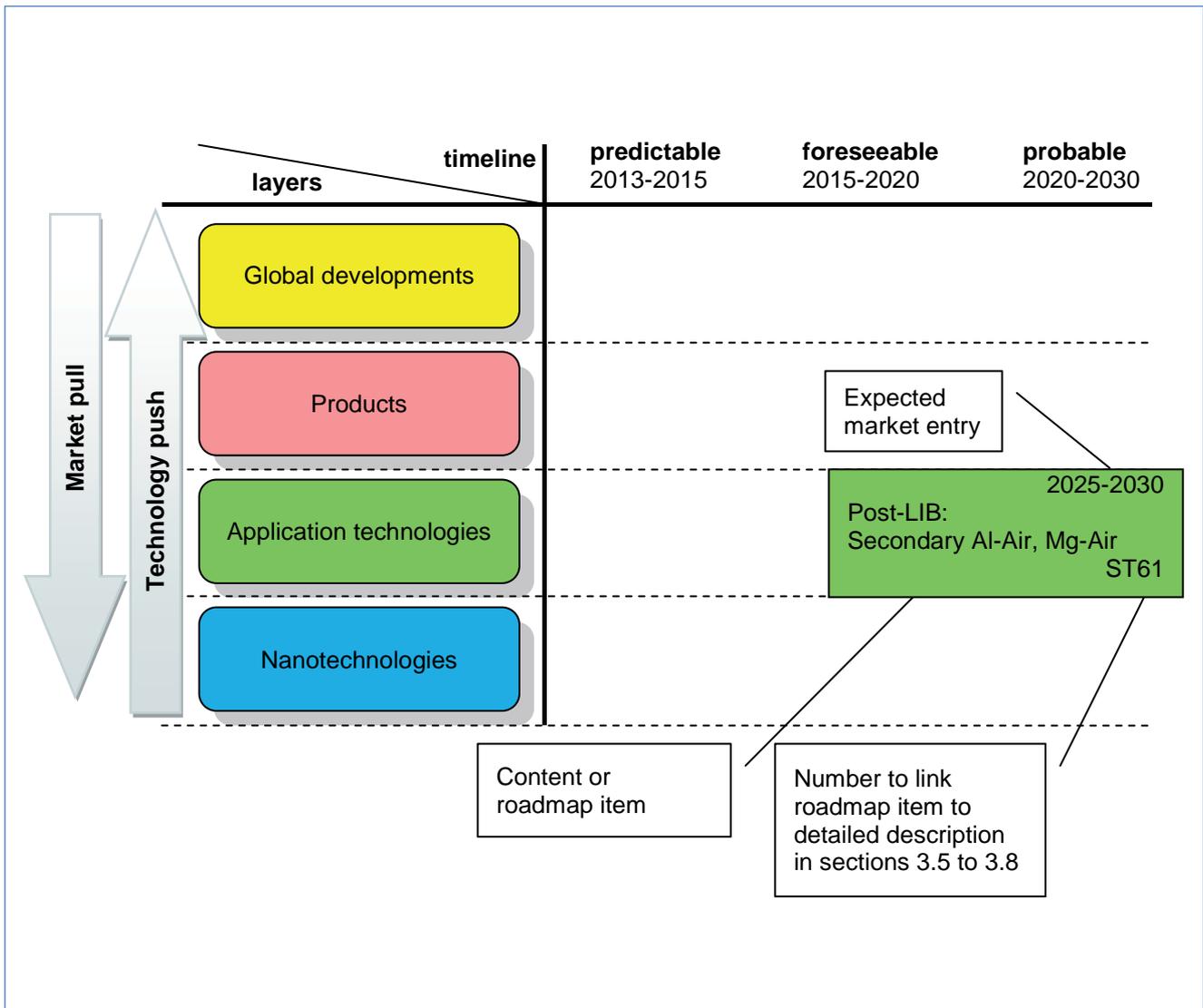


Figure 12 – Architecture of the roadmaps developed in this project

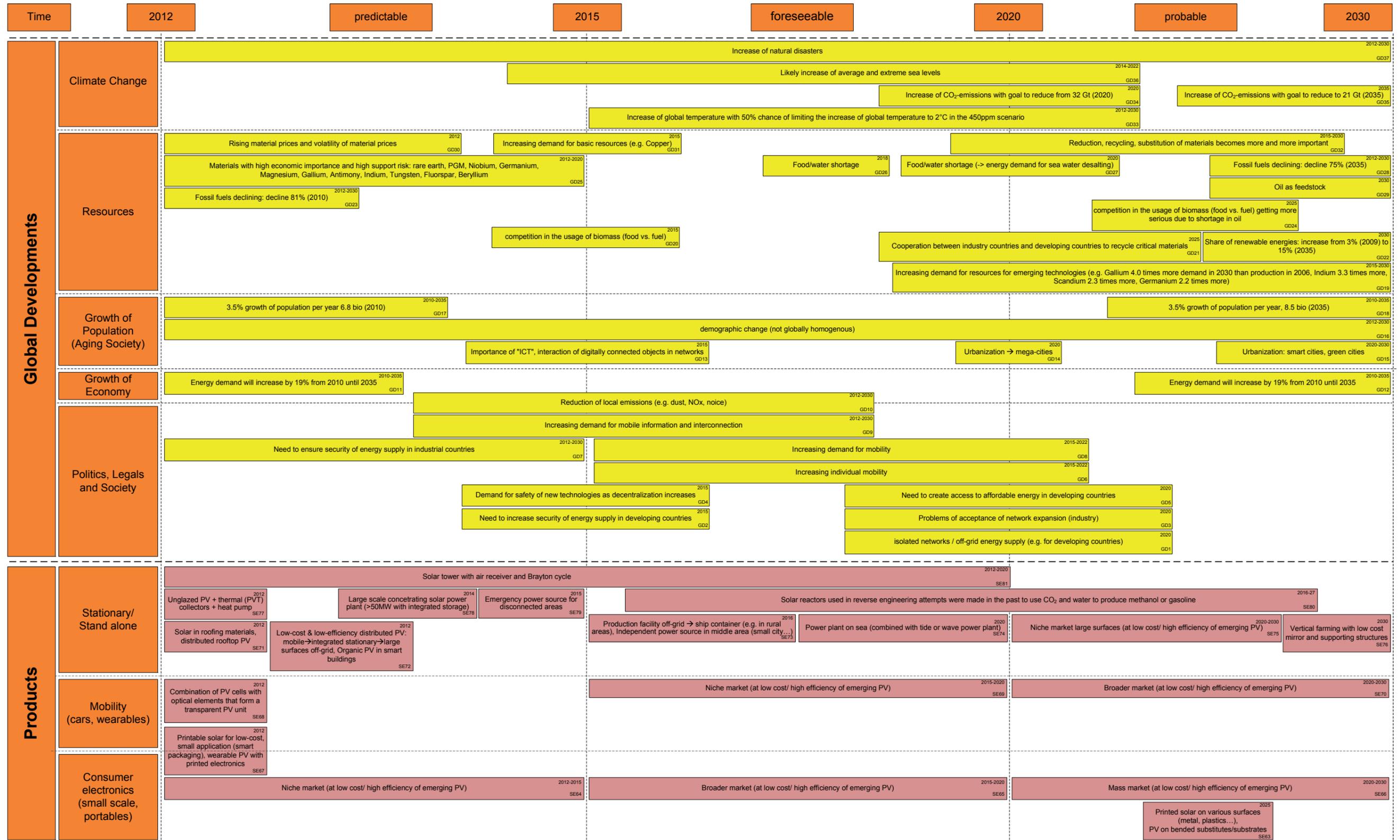
ments. On the vertical scale, each roadmap is divided into four layers. Each layer consists of several sub-layers that are different for solar energy and energy storage. The four main layers are shown in the scheme above.

The discrete items in each layer are positioned at the time the first market entry of the product or technology is expected. Each item contains the topic, the year, and a

consecutive number prefixed by SE for solar energy items and ST for energy storage items. This number links each roadmap item to a detailed description in sections 3.5 to 3.8. An example of a roadmap item is shown in Figure 12.

The two roadmaps Solar Energy and Energy Storage are shown on the next pages as an overview. For better readability, every layer is shown and discussed separately in the following sections.

Roadmap Solar Energy





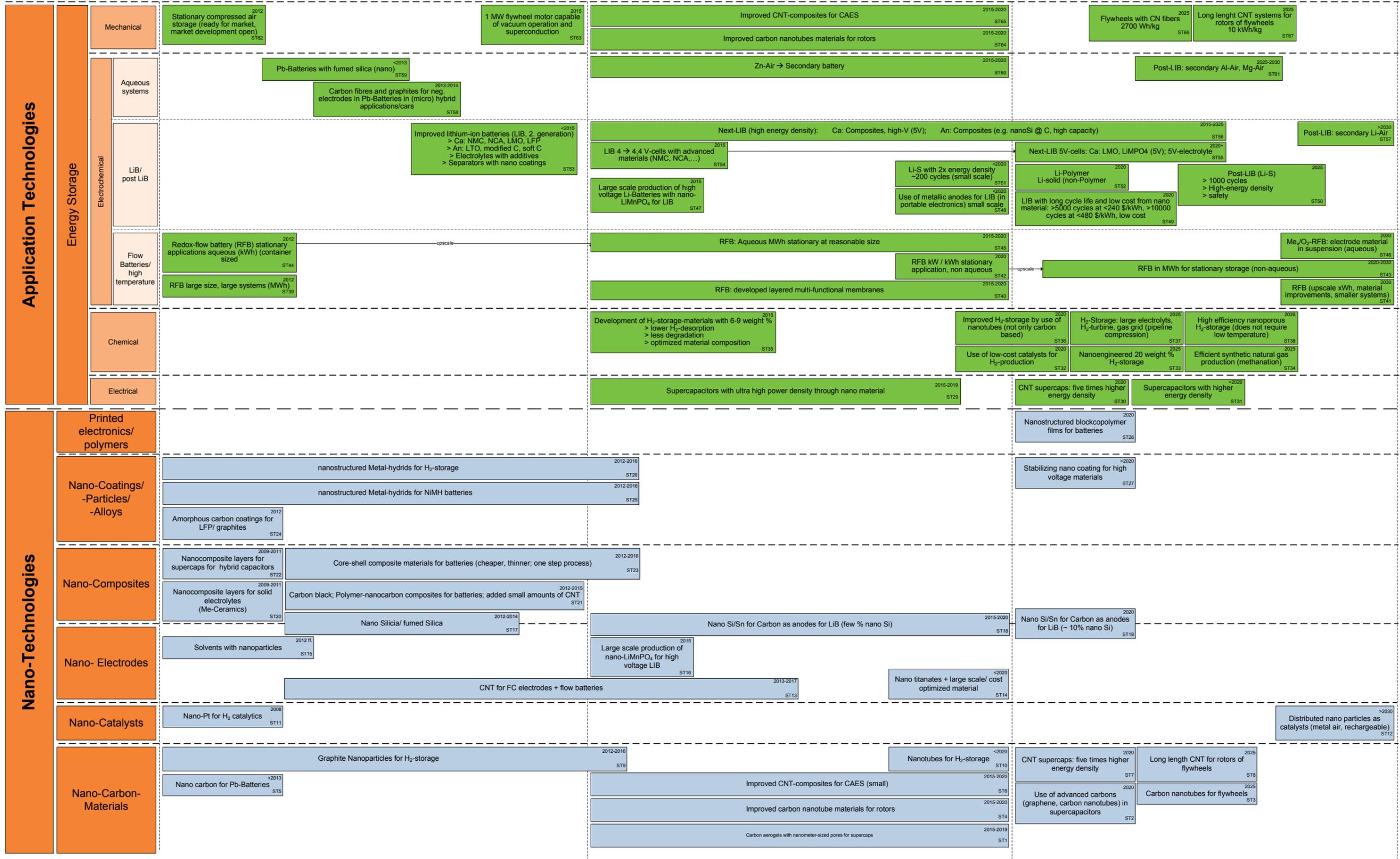
Content	Year	Source
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Abbreviations:	
SWCNT	Single walled carbon nanotube
QD	Quantum Dot
DSSC	Dye-sensitized solar cell
BSF	Back surface field
CIGS	Copper indium gallium selenide
CNT	Carbon nano tubes
RF-PECVD	radio frequency plasma enhanced chemical vapor deposition
MW CVD	Microwave chemical vapour deposition
MO CVD	Metalorganic chemical vapour deposition
ITO	Indium tin oxide
OPV	Organic PV

Literature	
SE1	Sopian, Kamaruzzaman: Solar Energy Technology Roadmap, Malaysia, 2010.
SE2	IEA: Energy Technology Perspectives, 2010.
SE3	Foresight: Technologies roadmap to 2050, 2010.
SE4	Nedo: PV 2030, 2009.
SE5	METI: Cool Earth – Innovative Energy Technology Program. Technology Development Roadmap, 2000.
SE6	IEA: Technology Roadmap - Concentrating Solar Power, 2010.
SE7	IEA: Technology roadmap: Solar photovoltaic energy, 2010.
SE8	Organic electronic association: OE-A Roadmap for Organic and Printed Electronics, 2011.
SE9	EPIA: Global Market Outlook for Photovoltaics until 2014, 2010.
SE10	VDI – Metaroadmap Nanomaterials 2010.
GD1	BGA report: Electronic metals – future demand at critical supply, 2010.
GD2	Critical raw materials for the EU (European Commission).
GD3	IMF: World Economic Outlook 2011, 2011.
GD4	IMF: World Economic Outlook 2012, 2012.
GD5	IPCC 2012, Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) Workshop 1 (February 2012).
WS1	Workshop 2 (September 2012).
WS2	Workshop 2 (September 2012).
IWS	Inhouse Workshop (December 2012).
EI	Expert Interview, 2012.

Roadmap Energy Storage

Time	2012	predictable	2015	foreseeable	2020	probable	2030
Global Developments	Climate Change	Increase of natural disasters (GD37)		Likely increase of average and extreme sea levels (GD36)		Increase of CO ₂ -emissions with goal to reduce from 32 Gt (2020) to 21 Gt (2035) (GD35)	
	Resources	Rising material prices and volatility of material prices (GD30)	Increasing demand for basic resources (e.g. Copper) (GD31)	Food/water shortage (GD26)		Reduction, recycling, substitution of materials becomes more and more important (GD32)	Fossil fuels declining: decline 75% (2035) (GD28)
	Growth of Population (Aging Society)	3.5% growth of population per year 6.8 bio (2010) (GD17)	demographic change (not globally homogenous) (GD16)		Urbanization → mega-cities (GD14)	3.5% growth of population per year, 8.5 bio (2035) (GD18)	
	Growth of Economy	Energy demand will increase by 19% from 2010 until 2035 (GD11)	Importance of "ICT", interaction of digitally connected objects in networks (GD13)		Urbanization: smart cities, green cities (GD15)		Energy demand will increase by 19% from 2010 until 2035 (GD12)
	Politics, Legals and Society	Need to ensure security of energy supply in industrial countries (GD7)		Increasing demand for mobile information and interconnection (GD9)		Increasing demand for mobility (GD8)	
	Products	Stationary	Energy storage in isolated grids (ST91)	RES (Renewable Energy Source)- electricity integration (industrial, distribution, small-scale) (ST92)		Peak shaving (industrial production) (ST93)	RES (Renewable Energy Source)- electricity integration (transmission, large-scale) (ST94)
Mobility	From small to large xEV	Market entry and diffusion of small vehicles (e-bikes, scooter) (ST87)		Market ramp up of „larger“ vehicles (BEV) (ST88)		Market entry and diffusion of large vehicles (buses, transporter, boats) (ST89)	
Consumer electronics	From hybrid to pure xEV	E-mobility dominated by HEV/ PHEV (BEV at small level, first users) → market ramp up (ST83)				Decreasing share of PHEV, increasing share of BEV → diffusion of BEV (HEV may decline/ be substituted) (ST86)	
	From short to long range	short range of e-mobiles (e.g. 80-150km BEV, today) (ST82)	Longer range of e-mobiles (e.g. 200km @2020) (ST84)		Long range of e-mobiles (e.g. >400 beyond 2030-35+) (ST85)		
	From singular to broad markets	2 and 4 wheelers (bikes broader markets and bikes first markets today) (ST79)	Other niche markets (ST80)	First markets for broader range of applications (ST78)		After PHEV/BEV also other concepts come to market diffusion (Buses, Boats, Off-road vehicles, etc.) (ST81)	
		Mobile internet devices (issues: costs, efficiency, off-grid) (ST71)	Mobile phone shipments grow about 10 %, huge growth in Africa (ST72)	MP3 player sales continue to fade towards 1 Mio. shipments (ST73)	Tablet sales grow towards a market of 200 Mio. Unit (up a 100 % from 2012) (ST74)	Mobile phone sales rise with market penetration/ new business models in Africa/Asia (ST75)	Smart phone sales rise as humans worldwide wish for a high mobile availability and functionality (ST76)
		MP3 players become more and more obsolete due to emergence of smartphones that allow for extensive music consumption (ST68)	Smart phone shipments grow about 60%, huge growth worldwide (ST69)			Tablet sales rise as tablets present „mobile computers“ (ST70)	Future developments hard to foresee as technology change very quick in consumer electronics (ST77)



Improved LiB - 2nd generation
 Next LiB - 3rd generation
 Post LiB - 4th generation

Year
 Content
 Source

Abbreviations:

Ca	Cathode
An	Anode
CAES	Compressed air energy storage
CNT	Carbon nano tube
RFB	Redox-flow-battery
Me	Metal
NMC	Nickel-mangan.cobalt
NCA	Nickel-cobalt-aluminium
LMO	Lithium-mangan-oxide
LFP	Lithium-iron-phosphate
LTO	Lithium-titan-oxide
TEES	Thermoelectric energy storage
SMES	Superconducting energy storage
HEV	Hybrid electric vehicle
BEV	Battery electric vehicle
PHEV	Plug-in hybrid vehicle

Literature

ES1 Nedo: Development of Fuel Cell and Hydrogen Technologies – Fuel Cell & Hydrogen 2009-2010.
 ES2 Nedo: Battery Roadmap 2008.
 ES3 Nedo: Battery Roadmap 2010.
 ES4 US Department of Energy: Advanced materials and devices for stationary electrical energy storage applications, 2010.
 ES5 Fraunhofer ISI: Product Roadmap Lithium-Ion Batteries 2030, 2012.
 ES6 NASA: DRAFT Nanotechnology Roadmap - Technology Area 10, 2010.
 ES7 NASA: DRAFT Nanotechnology Roadmap - Technology Area 10, 2010.
 ES8 Fraunhofer ISI: Technologie-Roadmap Energiespeicher für die Elektromobilität 2030, 2012.
 ES9 Fraunhofer ISI: Technologie-Roadmap stationäre Energiespeicher 2030, 2012.
 ES10 Fraunhofer ISI: Roadmapping-Workshop, Münsterland, 23. Februar 2011.
 ES11 M. Talmi: The Rise and Fall of the MP3 Player, 2012.
 ES12 mobiThinking: Global mobil statistics 2012, 2012.
 ES13 Aker et al.: Mobile Phones and Economic development in Africa, 2010.
 ES14 VDI – Metaroadmap Nanomaterials 2010.
 GD1 BGA report: Electronic metals – future demand at critical supply, 2010.
 GD2 Critical raw materials for the EU (European Commission).
 GD3 IMF: World Economic Outlook 2011, 2011.
 GD4 IMF: World Economic Outlook 2012, 2012.
 GD5 IPCC 2012
 WS1 Workshop 1 (February 2012).
 WS2 Workshop 2 (September 2012).
 IWS Inhouse Workshop (December 2012).

3.2 Results of bibliometric analysis

3.2.1 Framework

In the current project, bibliometric analyses have been conducted for the sectors energy storage and solar energy. The sectors were divided into different areas or clusters (e.g. electrochemical or chemical storage, solar cells) and within that into concrete application technologies as shown in Figure 13.

Individual search strings were developed for application areas or clusters and application technologies. Iterative development of the search strings helped fine-tune the search to identify relevant scientific papers, and to obtain information on recent scientific developments in nanotechnology and their impact on energy applications. The identified literature formed an important input for the qualitative analyses and the creation of technology profiles. The bibliometric analyses discussed here were conducted as described in section 2.3.

By combining the keyword searches for the energy application areas with a nanotechnology keyword search, a more in-depth analysis of research on nanotechnology within the energy sectors becomes possible. Systematic

identification and analysis of these nanotechnology-related papers helped to cluster the topics with relevance to the different application technologies. These seven clustered nanotechnology fields (e.g. nanocomposites, nanocarbons, nanoelectrodes) and the energy application technologies bear a relationship to the main layers of the meta-roadmap, and a direct connection of the bibliometric results with the developments described in the roadmap (layers 1 and 2) is made possible.

3.2.2 Solar energy

For the solar energy sector, Figure 14 shows the numbers of publications for photovoltaic (PV) and solar thermal application technologies between 1990 and 2011. Indicated are the four PV generations: crystalline silicon PV (1st Generation), thin film PV (2nd Generation), emerging PV (3rd Generation), high efficiency (single and multijunction concentrator) PV (4th Generation) as well as the field of solar thermal (focus on solar concentrating power, i.e. solar thermal technologies for electricity generation).

The figure shows an extraordinarily strong increase in publication numbers in recent years in the fields of organic solar cells (OPV) and dye-sensitized solar cells (DSSC) as emerging PV, as well as in crystalline silicon

Energy storage				Solar energy	
Electrochemical storage	Electrical storage	Mechanical storage	Chemical storage	Solar cells (photovoltaic)	Solar thermal
LIB & Post-LIB <ul style="list-style-type: none"> ▪ LIB ▪ Me-Air ▪ LiS Flow batteries <ul style="list-style-type: none"> ▪ RFB Other batteries <ul style="list-style-type: none"> ▪ Pb ▪ NaS ▪ NiMH ▪ NiCD ▪ Zebra 	<ul style="list-style-type: none"> ▪ Supercaps ▪ SMES 	<ul style="list-style-type: none"> ▪ Flywheel ▪ PHES ▪ CAES 	<ul style="list-style-type: none"> ▪ Hydrogen ▪ SNG 	Crystalline PV <ul style="list-style-type: none"> ▪ (single-, multi-, thick film) crystalline Si Thin film PV <ul style="list-style-type: none"> ▪ a-Si/mu-Si ▪ CdTe ▪ CIGS ▪ Kesterit/CZTS Emerging PV <ul style="list-style-type: none"> ▪ DSSC ▪ QD ▪ OPV Highly efficient PV <ul style="list-style-type: none"> ▪ Single-Junct. GaAs, Multi-Junct. concentrator 	Solar concentrating <ul style="list-style-type: none"> ▪ Parabolic, Fresnel, Dish, Tower

Figure 13 – Energy storage and solar energy: application areas and application technologies

PV. Crystalline silicon PV is a traditionally large field of strong research activity. In the future it is expected that this technology will dominate the market compared to other PV technologies, and still there is room for scientific and technical improvements. OPV and DSSC in contrast are young technologies with currently very limited markets. They need to be further developed in the next decades and the research challenges are quite severe.

Figure 15 shows the development of nanotechnology-related publications within each energy application technology between 1990 and 2011. Besides OPV and DSSC, quantum dot PV (QD-cells) is also a strongly growing field. This is no surprise, since by definition these three emerging PV technologies make use of nanotechnology: in OPV, fullerenes serve as electron acceptors, modern DSSCs are composed of a porous layer of titanium dioxide nanoparticles covered with a molecular dye that absorbs sunlight, and QD-cells make use of nanosized semiconductor quantum dots. But nanotechnology can also help crystalline silicon solar cells by improving light management and energy harvesting and by making them thinner and cheaper. For the different solar cell types in general, nanomaterials such as carbon nanotubes or graphene are of interest as a potential indium tin oxide (ITO) replacement for the transparent electrodes.

The two Figures 14 and 15 show that emerging PV is an extremely strongly growing field, and for the PV sector as a whole it is in emerging PV that nanotechnology

plays the greatest role. It can be expected that these large publication numbers will also translate into patent applications and markets for these new technologies, as efficiencies increase and costs are reduced through improved manufacturing processes.

Figure 16 shows the development of publication numbers clustered into the four PV generations as well as the solar thermal application field between 1990 and 2011. In Figure 17 the development can be seen for nanotechnology-specific publications in these application fields. The extremely large increase in publications generally as well as nanotechnology-specific ones in particular is evident for emerging PV. However, for first and second-generation crystalline silicon and thin film PV (which behave very similarly) a large growth in publications can also be observed in recent years, in general and also specifically for nanotechnology. Thus nanotechnology also has the potential to improve mature technologies.

In Figure 18, the share of nanotechnology publications within the different application field clusters is indicated in percent. Nanotechnology in emerging PV has had a share of 40%-50% in recent years, meaning that almost every second publication referred to a nanotechnology development. The other publications can be assumed to address other developments of emerging PV, including nanomaterials of course but without focusing on improvements based on nanotechnology.

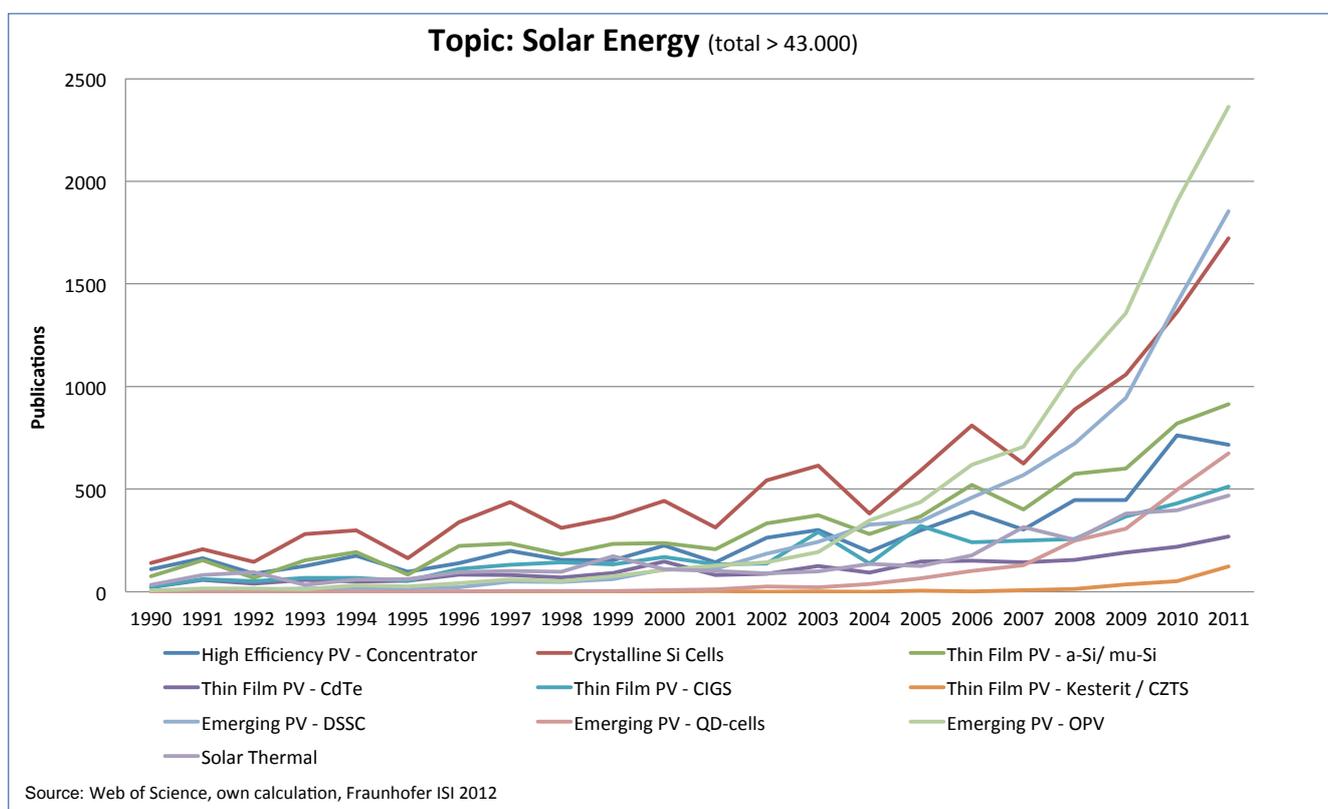


Figure 14 – Development of the number of publications in solar energy

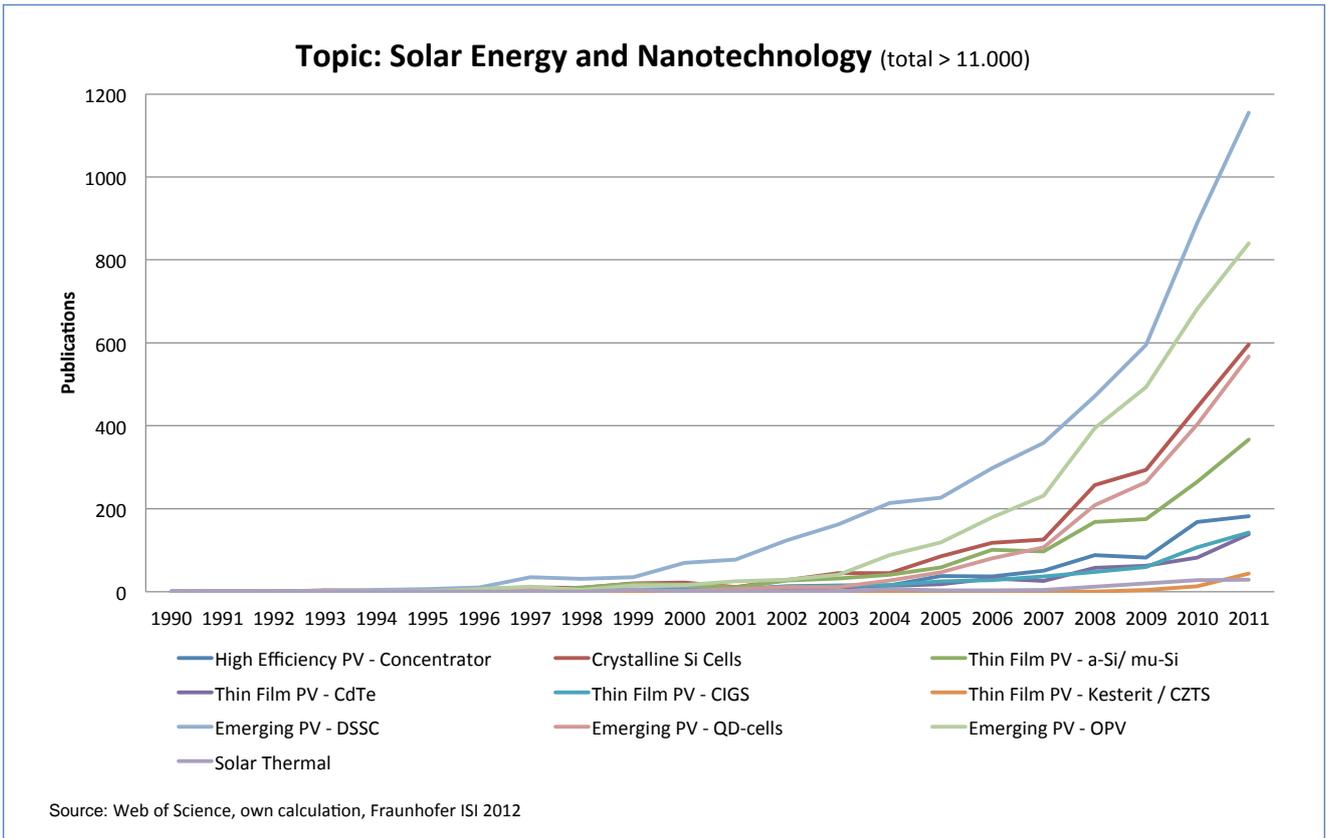


Figure 15 – Development of the number of publications in solar energy concerned with nanotechnology

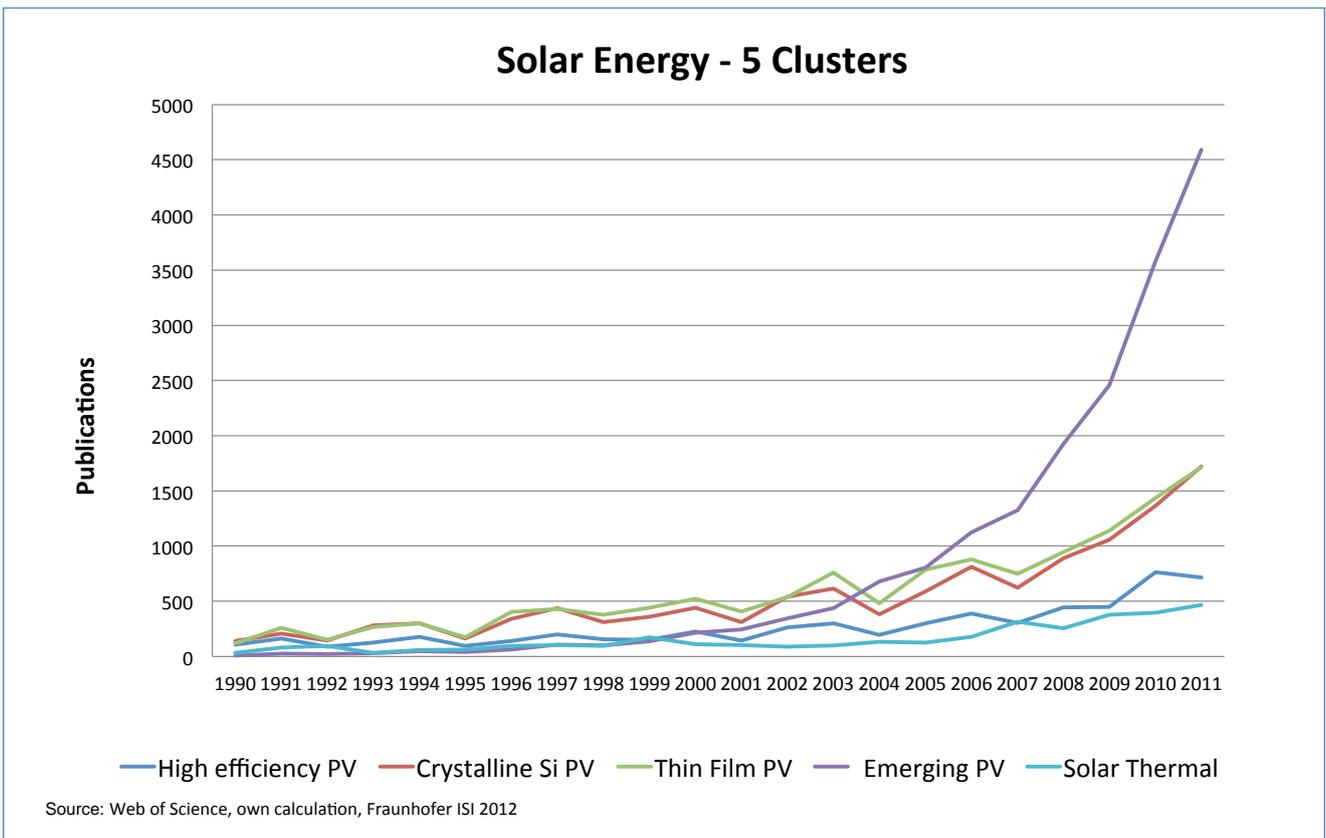


Figure 16 – Development of publication numbers in solar energy by cluster

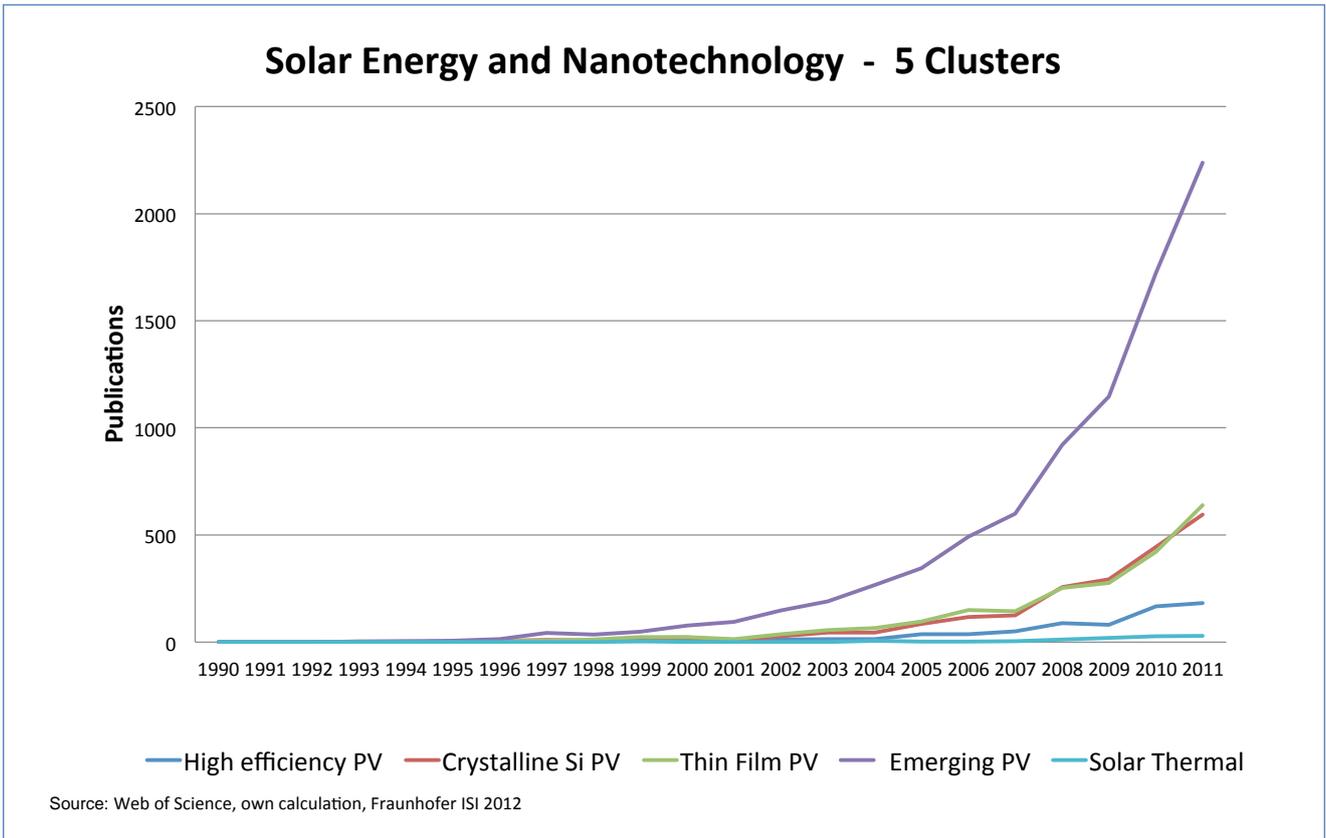


Figure 17 – Development of publication numbers in solar energy concerned with nanotechnology by cluster

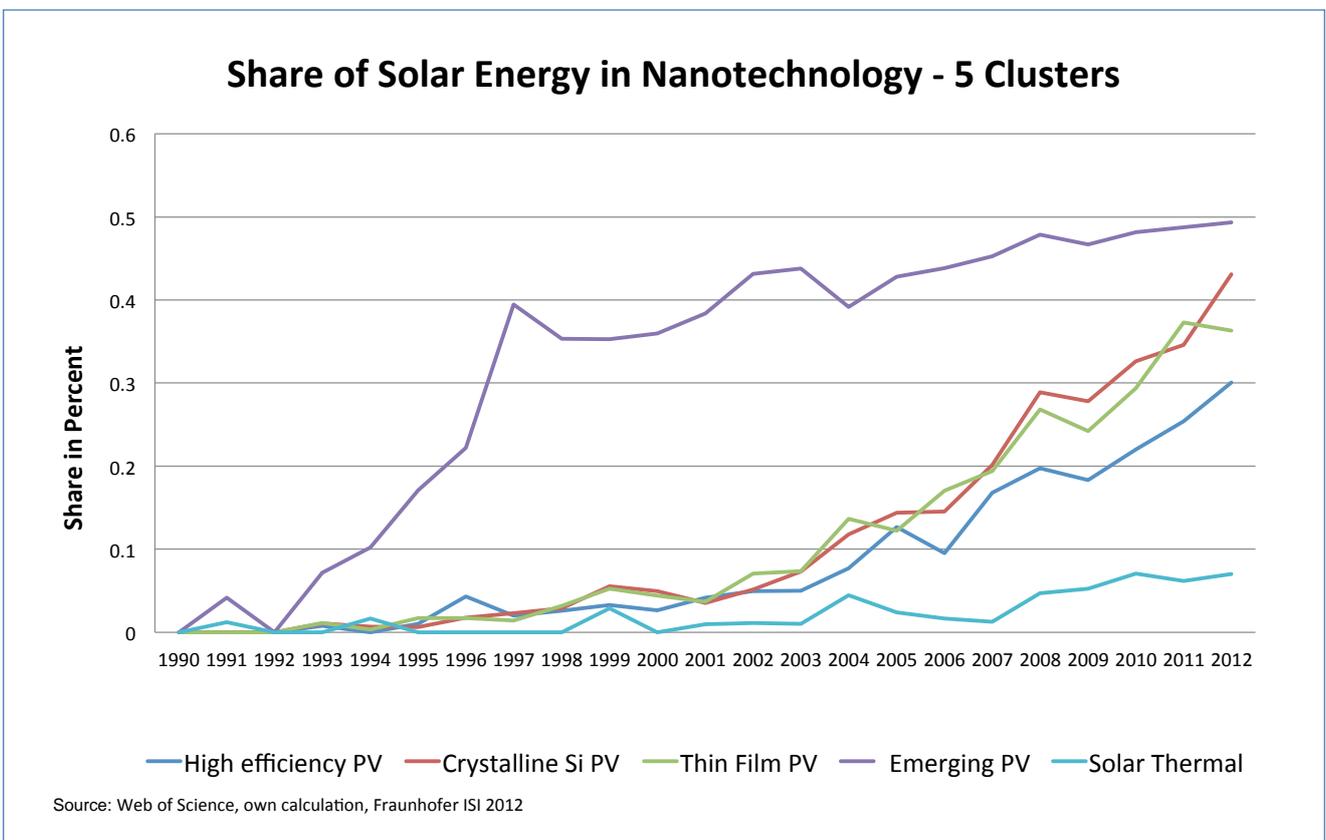


Figure 18 – Share of nanotechnology in solar energy by cluster, in percent

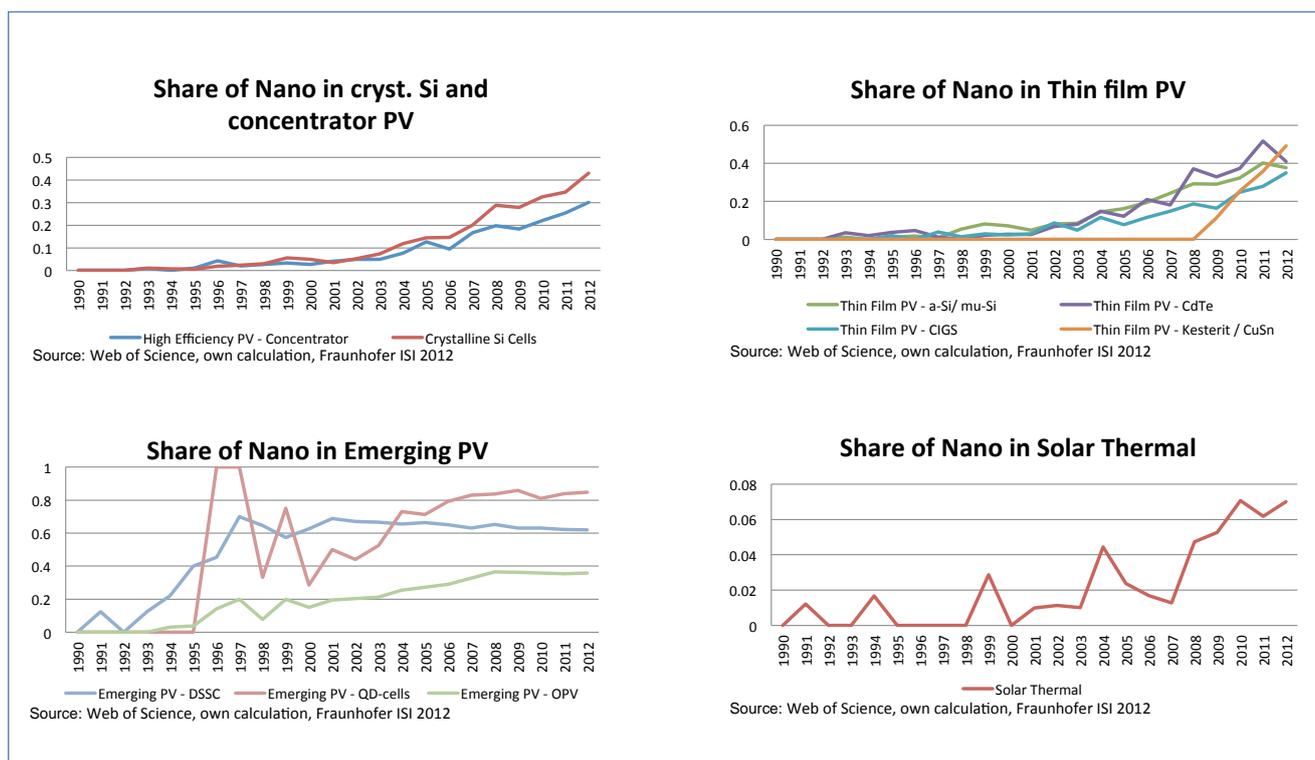


Figure 19 – Share of nanotechnology by application field

For crystalline silicon and thin film PV there has been an increasing share of nanotechnology-related publications in the last ten years, although PV technologies as a whole only show an increase more recently. Nanotechnology may thus be regarded as a precursor for novel developments for these technologies.

In contrast to PV, the relevance of nanotechnology to solar thermal technologies is rather limited. The four graphs in Figure 19 again indicate the share of nanotechnology for the different solar energy application technologies. Whereas nanotechnology for all PV technologies has a publication share of at least 30%, the impact of nanotechnology on solar thermal technology developments has been quite small, with a 5%-7% share in the past few years (Figure 19, bottom right).

The role of nanotechnology in solar concentrating power (e.g. parabolic trough, parabolic dish or solar tower) is due to novel, improved heat transfer fluids for the absorber tubes, e.g. with the addition of metallic nanoparticles, or nanocoatings for tubes and in particular anti-reflective coatings for the collectors. The interpretation might be that the main research focus here is on engineering, construction and other (non-nanomaterial-based) improvements.

Crystalline silicon, concentrating PV and most types of thin film PV have a nanotechnology publication share of

30%-40% (Figure 19, top left and right). Of interest is the strong increase for the Kesterit (CZTS) thin film system, a new material class in thin film PV to substitute indium in CIGS solar cells. The technology has emerged in the past few years and today every second publication relates to nanotechnology improvements (i.e. 50% – Figure 19, top right). For emerging PV the reference to nanotechnology varies. In OPV about 30% of the publications refer to nanotechnology improvements, in DSSCs this is about 60%, and QD-cell publications emphasize the role of nanotechnology with more than 80% (Figure 19, bottom left).

Figure 20 shows the development of publication share by world region over time (for the periods 1995-2000, 2001-2006 and 2007-2012) for all photovoltaic technologies. It can be seen that the previously almost equal distribution of research activities among Asia, North America and Europe has nowadays shifted towards Asia (at least 1/3 of worldwide activities). Europe has a share of less than 30% and North America less than 20%. Other world regions (e.g. South America, Australia, etc.) together still have a share of about 15%.

However, publications reflect science-based activity and, if patent applications and PV production capacities are taken into account as well, a further strong shift towards Asian dominance in the field can be observed.

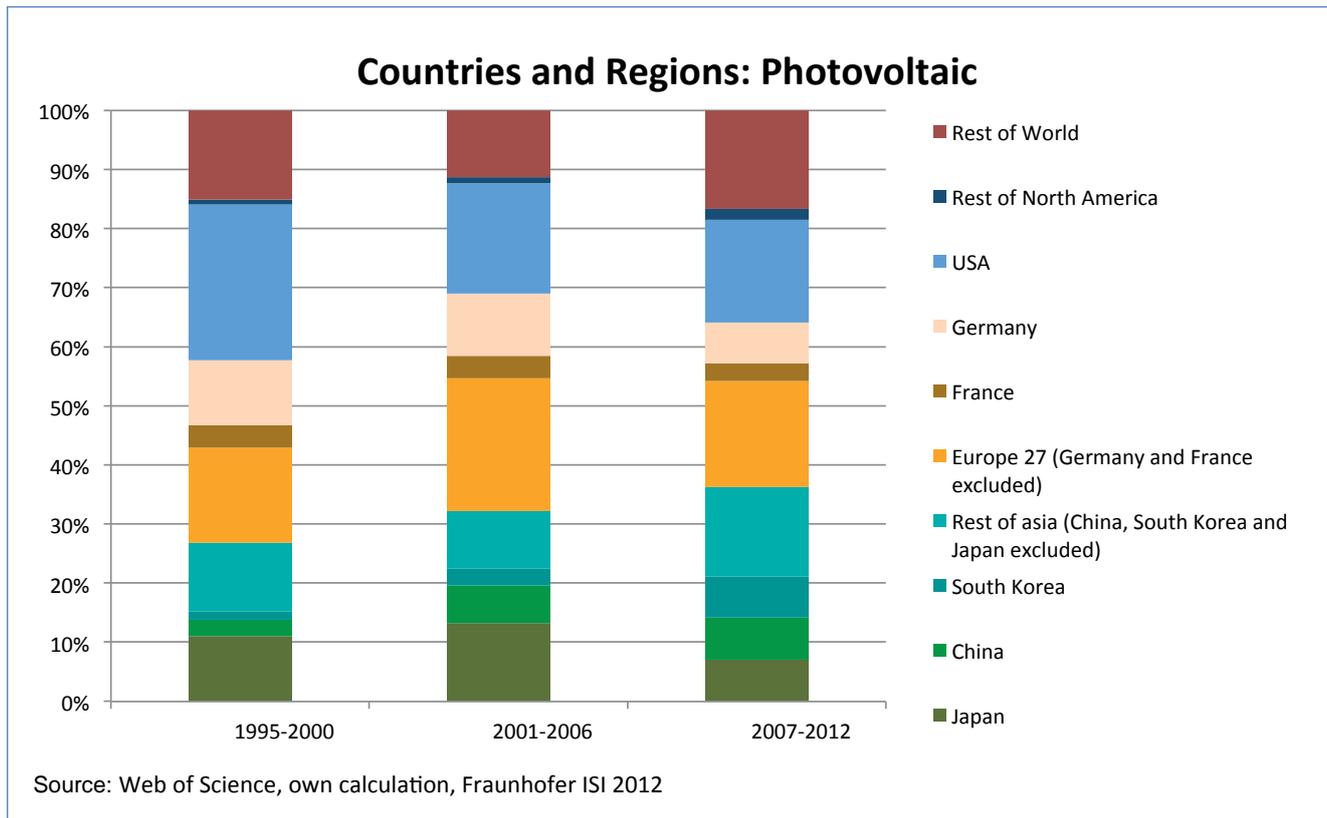


Figure 20 – Development of publication share by regions and countries by time period

3.2.3 Energy storage

For the energy storage sector, Figures 21 and 22 show the numbers of publications for the application technologies listed in Figure 13, and for nano-specific developments within these technologies, between 1990 and 2011. Direct comparison of these technologies shows that lithium ion battery technology (LIB) has become by far the largest and most important battery technology since the early 1990s. LIB is one of the battery designs with the highest energy densities and greatest potential for further improvements in the near to mid-term. The worldwide enthusiasm for electric mobility and the trend towards environmentally friendly, reduced CO₂-emitting, “green” cars has resulted in increased interest in high-power, large-scale energy storage technologies in the past five years. This can be observed in a global increase of LIB publication activities since 2008 (red curve in Figure 21). However, other technologies such as supercapacitors and hydrogen storage are also among the broad technology fields with high publication numbers.

With respect to nanotechnology-specific publications, Figure 22 shows a strong increase in research activities on LIB and supercaps over the last ten years. In contrast, for hydrogen storage as for the rest of the field, numbers have stagnated for several years. This might be connect-

ed to the recently increased focus on LIB (many scientists from hydrogen and fuel cell research have changed to LIB research due to increased funding in that field). But in addition previous research on carbon nanomaterials (in particular CNT) for use in hydrogen storage has not resulted in breakthroughs and there has been some disillusionment with respect to the potential of using pure CNT in this field. Further in the future there is some expectation that these or other nanomaterials may realize their potential. For supercaps (e.g. nanoporous and nanocarbon-based electrodes leading to higher capacities) and for LIB (e.g. nanocomposites leading to higher capacities and energy densities) nanotechnologies are still expected to bring important improvements.

In Figures 23 to 25 the development of publications in energy storage (absolute publication numbers) and nanotechnology in energy storage (absolute numbers and share in percent) are shown between 1990 and 2011 for four clusters or application fields:

- **Cluster 1:** electrochemical storage
- **Cluster 2:** electrical storage
- **Cluster 3:** mechanical storage
- **Cluster 4:** chemical storage

Again, we can observe an increase of publications in electrochemical storage (including LIB) and, at a lower level, electrical (including supercaps) and chemical (although stagnating slightly). This increase is even stronger and more pronounced for nanotechnology-specific publications in these fields. Looking at the share of nanotechnology-based publications, almost 50% (for electrochemical storage) or more than 50% (for electrical storage) of the publications refer to nanotechnology improvements or research. For chemical storage this has been between 20% and 30% over the last ten years, indicating that the stagnation of nanotechnology-based

research at this still-high level is independent of the current funding focus.

For mechanical storage, in contrast, scientific publication activity in general is quite low compared to the other energy storage fields, which might be due to a stronger engineering and construction character of these technologies. Here the numbers and share of nanotechnology-based publications in the field are almost zero. A few activities do exist, on nanocarbons or nanocomposites to improve flywheels or CAES for example.

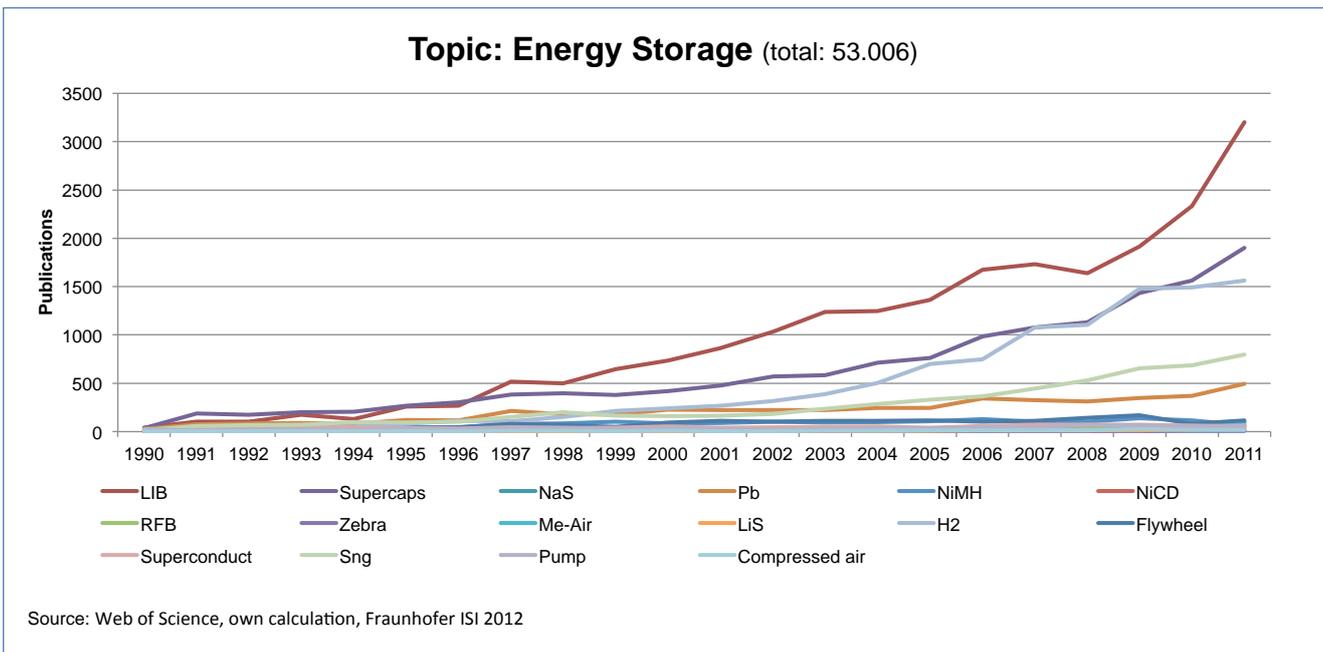


Figure 21 – Development of the number of publications in energy storage

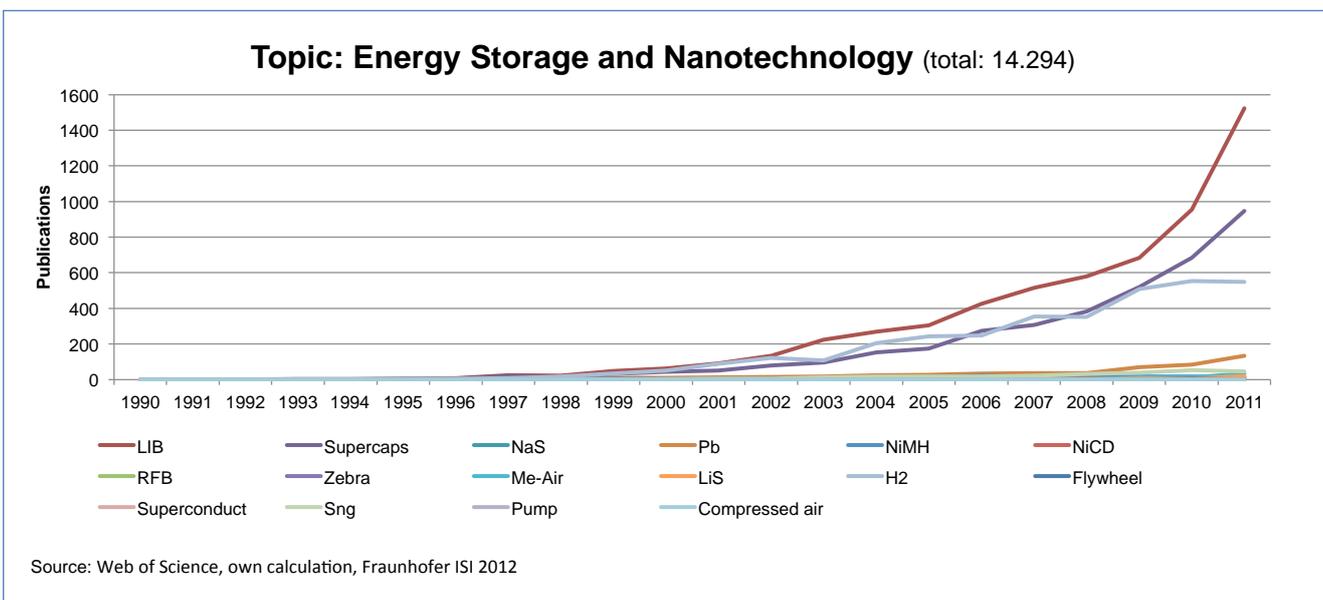


Figure 22 – Development of the number of publications in energy storage involving nanotechnology

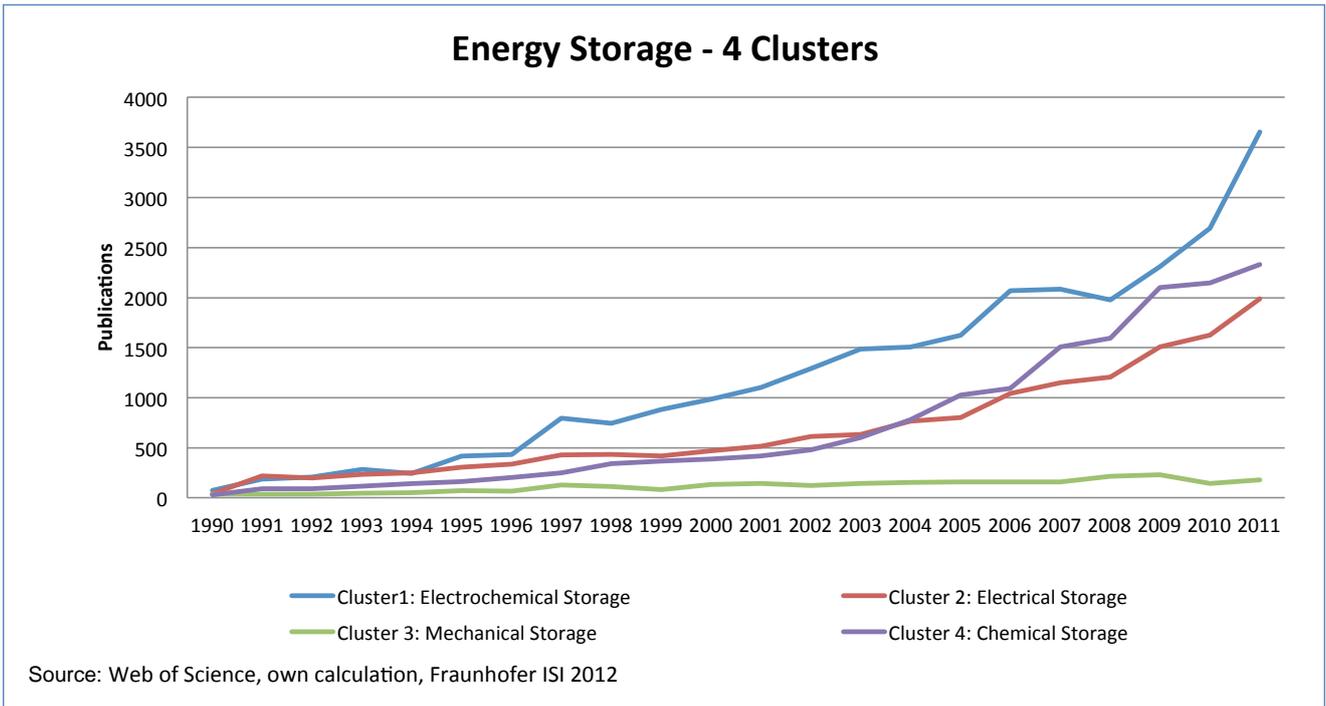


Figure 23 – Development of publication numbers in energy storage by cluster

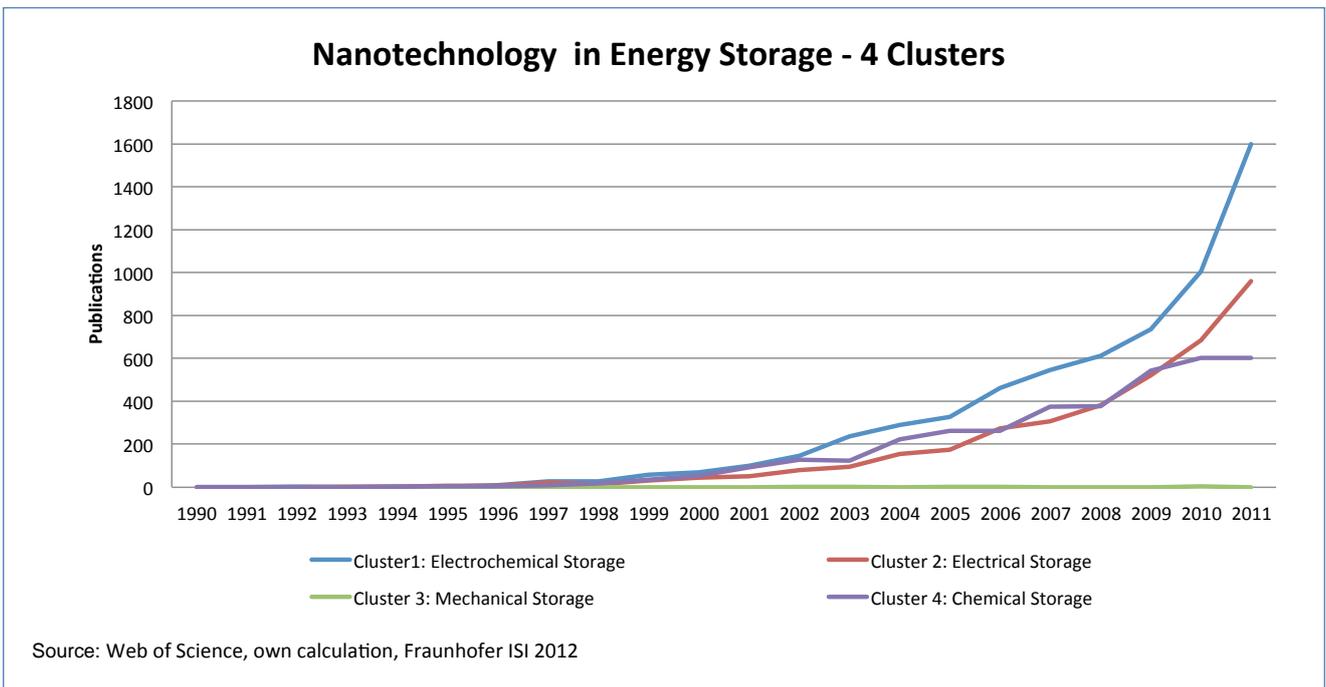


Figure 24 – Development of publication numbers in energy storage involving nanotechnology by cluster

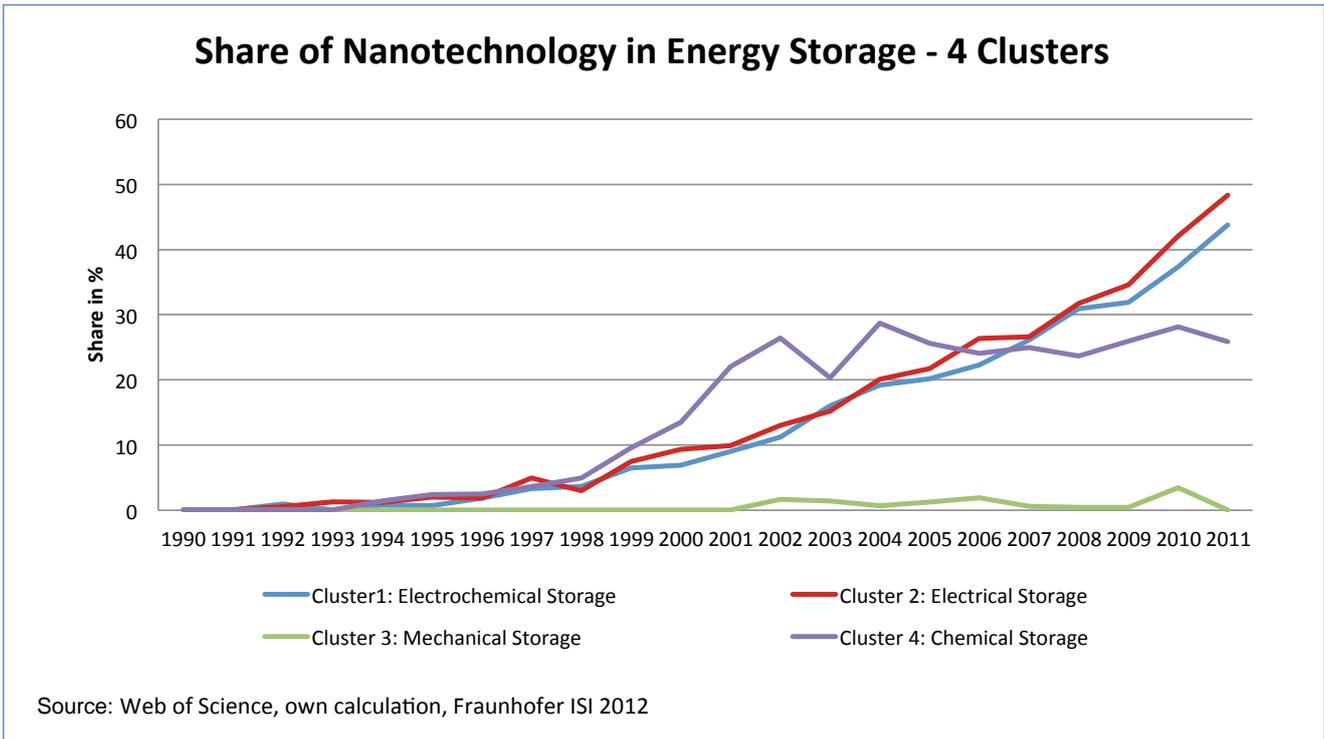


Figure 25 – Share of nanotechnology in energy storage in percent

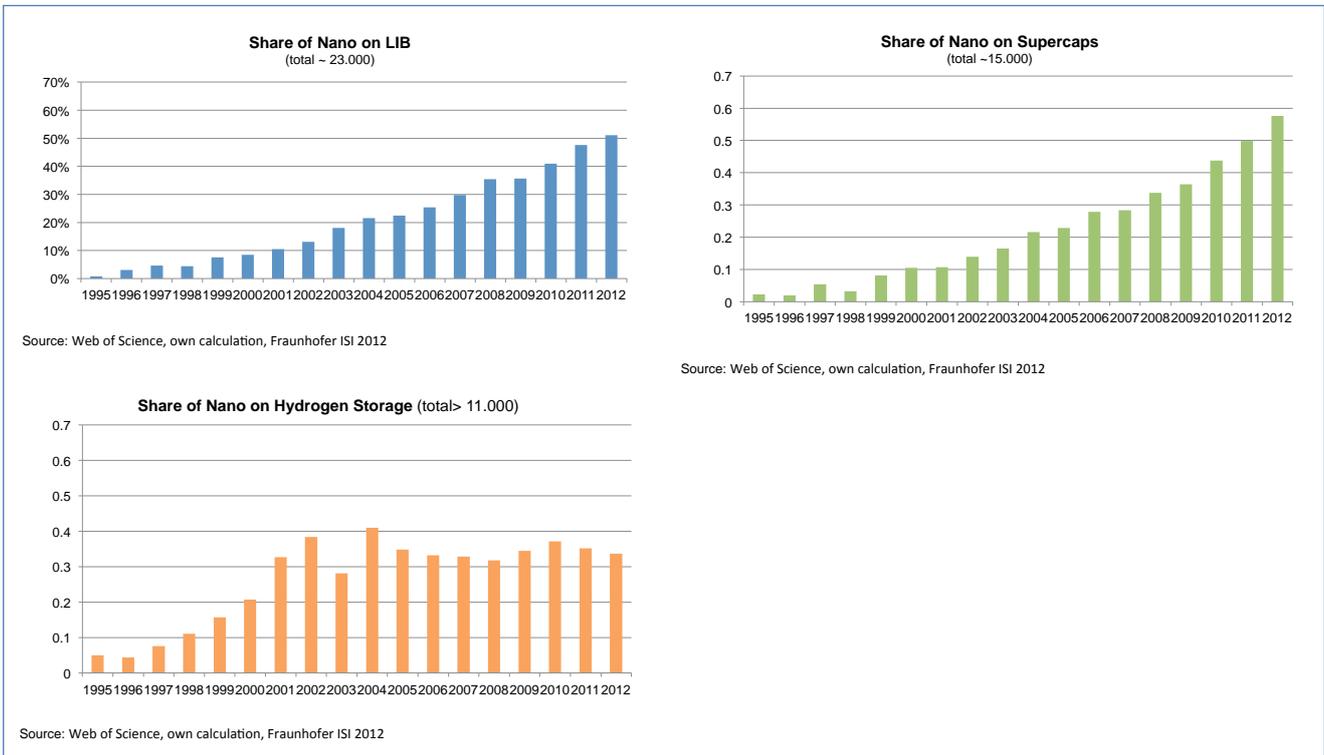


Figure 26 – Share of nanotechnology by application field

In Figure 26 the development of the share of nanotechnology-based publications is shown between 1995 and 2012 for selected energy storage application technologies. For LIB (top left), as the dominating electrochem-

ical storage technology, this share has increased from about 10% to 50% over the last ten years, i.e. today every second publication refers to research efforts or improvements making use of nanotechnology. Although

still at a lower absolute level of research activities, novel, post-LIB concepts (e.g. Me-Air batteries) show a share of 30%-50% of nanotechnology publications as well. In addition to improved nanoelectrodes using nanocoatings or – increasingly – nanocomposites, nanoparticles with a catalytic function may also be used to improve these designs in the future. However, mature technologies such as NiMH or Pb batteries still have potential for further improvement through nanotechnology. The share of nanotechnology publications in these designs has increased to 10%-20% for NiMH and 20%-30% for Pb batteries.

For supercaps as an electrical storage technology the share of nanotechnology publications has increased even more than for LIB, from about 10% to almost 60% over the past decade. Here, the need for and important role of nanoporous structures for improving the capacity of the electrodes, in particular nanocarbon materials, is an important driver for these developments. In other fields of electrical and magnetic storage, e.g. superconducting magnetic energy storage (SMES), the role of nanotechnology and share of publications are both quite small. Since information and roadmaps on SMES are presently very limited, this application technology has not been discussed in more detail in the bibliometric analyses, the technology profiles or roadmap in this report.

For hydrogen as a chemical storage technology, the share of nanotechnology-related publications increased

from less than 10% to 40% around the year 2000, then stagnated and stabilized at a share of about 30% over the past ten years. The reason for this development has been discussed above.

Finally, for mechanical storage technologies the number of publications in general as well as nanotechnology-based publications is quite low, and ranges from single publications to a share of a few percent from year to year (e.g. for flywheels or CAES). Nanotechnology may bring some improvements to these technologies in the future (e.g. mechanical strength, higher densities). The role of nanotechnology for these application technologies is discussed in more detail in the technology profiles and especially the roadmap in sections 3.5 and 3.6.

Figures 27 and 28 show the development of publication share by world region over time (for the periods 1995-2000, 2001-2006 and 2007-2012) for chemical storage (in particular hydrogen) and electrochemical storage (in particular lithium ion batteries). Remarkably, unlike in many other technologies, the share of publications in hydrogen storage for Asia has decreased from a dominant position with about 60% coverage of research activities to about 40% in recent years, which still represents a major contribution. In contrast, Europe in particular and the US have increased their research in this field since 2000.

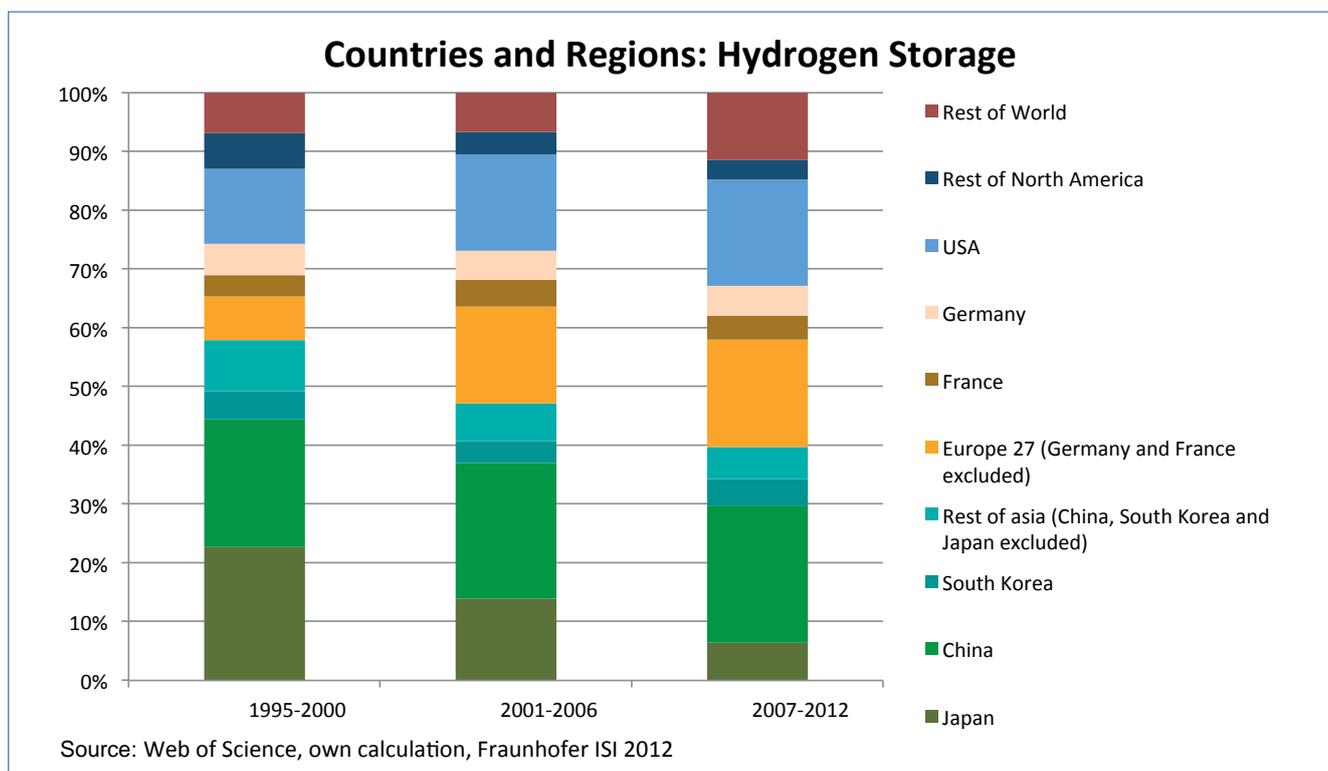


Figure 27 – Development of publication share by regions and countries by time periods

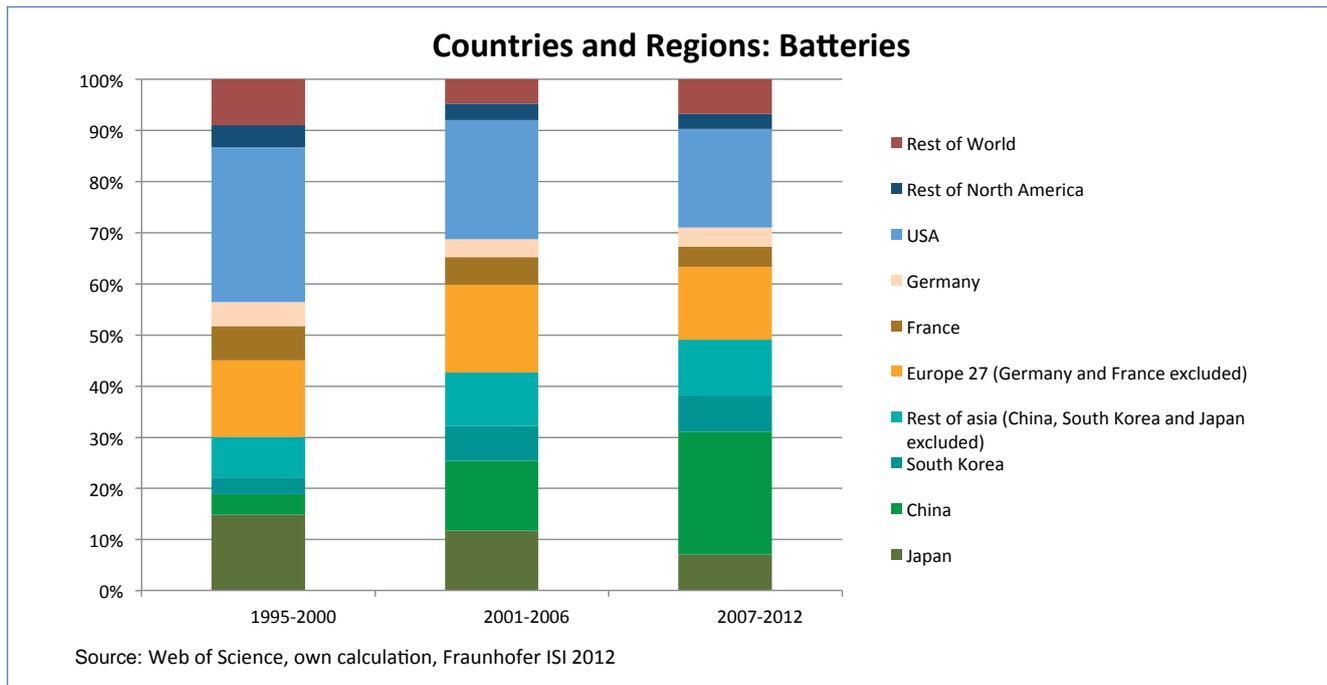


Figure 28 – Development of publication share by regions and countries by time periods

For scientific activities on battery technology, a strong increase from 30% to almost 50% can be seen from 1995 to today. China and South Korea especially have increased their publication activities at the cost of Japan. The share of European publications has decreased but stayed above 20%. North America, in particular the US, has significantly lost share from about 35% to about 20%.

The country and region analyses show that for practically all these technologies a few countries in Asia, North America and Europe dominate research, but their relative weights change for different technologies.

3.2.4 In-depth analysis of solar energy and energy storage

Although a comparison of the publication data with patent data and production capacities would be of much interest, this analysis has limited itself to showing the role of nanotechnology in two energy sectors and their application fields. Quantitative analyses provide an impression of the importance of nanotechnology's role, how it has been developing in the past and how it may develop in the future. Together with the qualitative analyses of technologies, applications, products and markets in the technology profiles, this helps to assess the relevance of the developments as described in the different roadmap layers in sections 3.5 to 3.8.

To contribute to the assessment of the current state and potential future development of the different energy application technologies and the role of nanotechnologies, one final, interesting in-depth analysis of the bibliometric results may be carried out by making use of the so-called "Sharpe ratio":

$$S_a = \frac{(\bar{I}_a - \bar{I})}{s_a}$$

where

\bar{I}_a is the mean of technology *a* activity growth over the given period,

\bar{I} is the mean of all technologies' activity growth over the given period, and

s_a is the standard deviation of technology *a* growth over the given period.

The Sharpe ratio thus compares the average growth of a given technology *a* (here, the different energy application technologies such as LIB for batteries or thin film CIGS for PV) to the average growth of all technologies (e.g. taking all scientific publications or the sum of all publications in the given energy sector or application field). A positive numerator represents a relatively higher growth rate, and conversely for a negative numerator. The difference is normalized by the standard deviation of the annual technology growth over the period under consideration (here 2001 to 2011, i.e. the past 10 years). This accounts for the variability of the growth rates, so that technologies showing stability in their growth rates are less penalized in their score than more volatile fields (which also tend to be smaller in size).

This is shown schematically in Figure 29, where the four quadrants defined by the Sharpe ratio for the energy sector (i.e. solar energy and energy storage) and the nanotechnology contribution to the energy sector are indi-

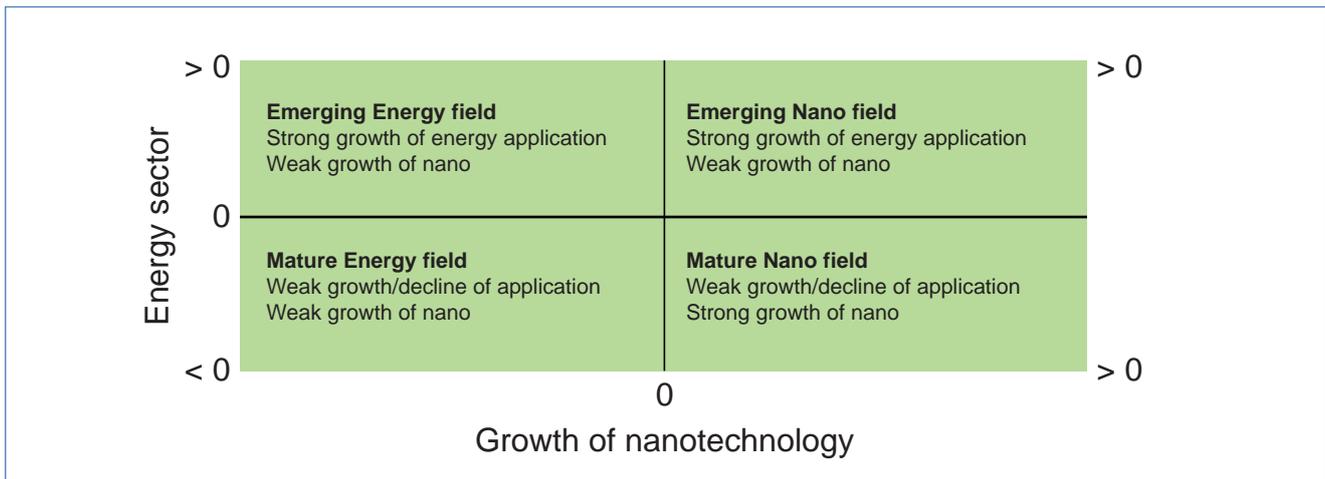


Figure 29 – Visualization of Sharpe ratios: energy sector vs. growth of nanotechnology

cated. Depending on the position of the application technologies, they may be clustered into emerging energy technology or nanotechnology fields as well as maturing energy technology and nanotechnology fields.

The Sharpe ratios for energy storage application technologies are shown in Figure 30. The reference is to all scientific publications, i.e. all technology developments, so that energy storage technologies can be compared to other technology fields. It can be seen that almost all storage technologies are situated in the emerging nanotechnology quadrant (top right), since electrochemical, electrical and chemical energy storage technologies are strong-growth energy application fields with strong relevance to nanotechnology, compared to the large number of scientific publications on all types of technology. Only flywheels and NiMH batteries are in the maturing nano field. It is true that there are more nanotechnology publications which refer to these technologies than to the average of all technologies, but the technologies themselves are growing less strongly or are declining when compared to the average.

In Figure 31 the Sharpe ratios for energy storage application technologies are shown with respect to all energy storage technologies. Now the emergence and maturity of technologies within the group of energy storage technologies becomes visible. Synthetic natural gas (SNG), LIB and supercaps now belong to the group of rather large but maturing technologies, compared to Metal-Air, RFB, LiS battery designs that are emerging, fast-growing but still small technologies. Correspondingly, from the literature (e.g. as discussed in the technology profiles) as well as in the roadmap, storage technologies like NiMH and Pb batteries are expected to be transitional technologies (mature to declining), LIB and supercaps are expected to be important future technologies for the next decades (growing to mature) and the emerging technologies are expected to become relevant further out in the future, e.g. beyond 2020 to 2030.

For solar energy the Sharpe ratios are indicated in Figure 32, again with reference to all scientific publications, i.e. all technology developments. All technologies without exception are grouped into the emerging nanoquadrant, i.e. all these technologies are growing faster than the average technology, and also have a faster-growing nanotechnology share compared to other technologies.

The restriction in Figure 33 to the solar energy field (i.e. the reference system is solar energy publications and not all publications in the Web of Science®) again shows a much better resolution and allows us to identify emerging and mature technologies. The emerging QD-cell, OPV and DSSC technologies lie in the emerging energy technology field without being emerging nanotechnologies. This is consistent, since the growth of nanotechnology activity is measured and the corresponding technologies have a strong but constant nanotechnology share. All other technologies are between the maturing energy and nanotechnology quadrant, which means that they are not growing as fast as the other – in particular the emerging – technologies and that the share and growth of nanotechnology in these fields is like the overall average. One exception is thin film Kesterit (CZTS) technology, which as already mentioned is a new and fast-growing technology intended to replace indium in thin film CIGS technology. It can be regarded as an emerging future technology, where nanotechnology seems to have a strong potential to provide improvements.

The more in-depth analysis shows that application technologies can not only be weighted with respect to absolute developments but even more sophisticated analyses can be done. An assessment and visualization of potential short, medium and long-term impacts and relevance of nanotechnology becomes possible. The results of these bibliometric analyses will prove to be a reasonable fit with the developments identified in the roadmaps on energy storage and solar energy.

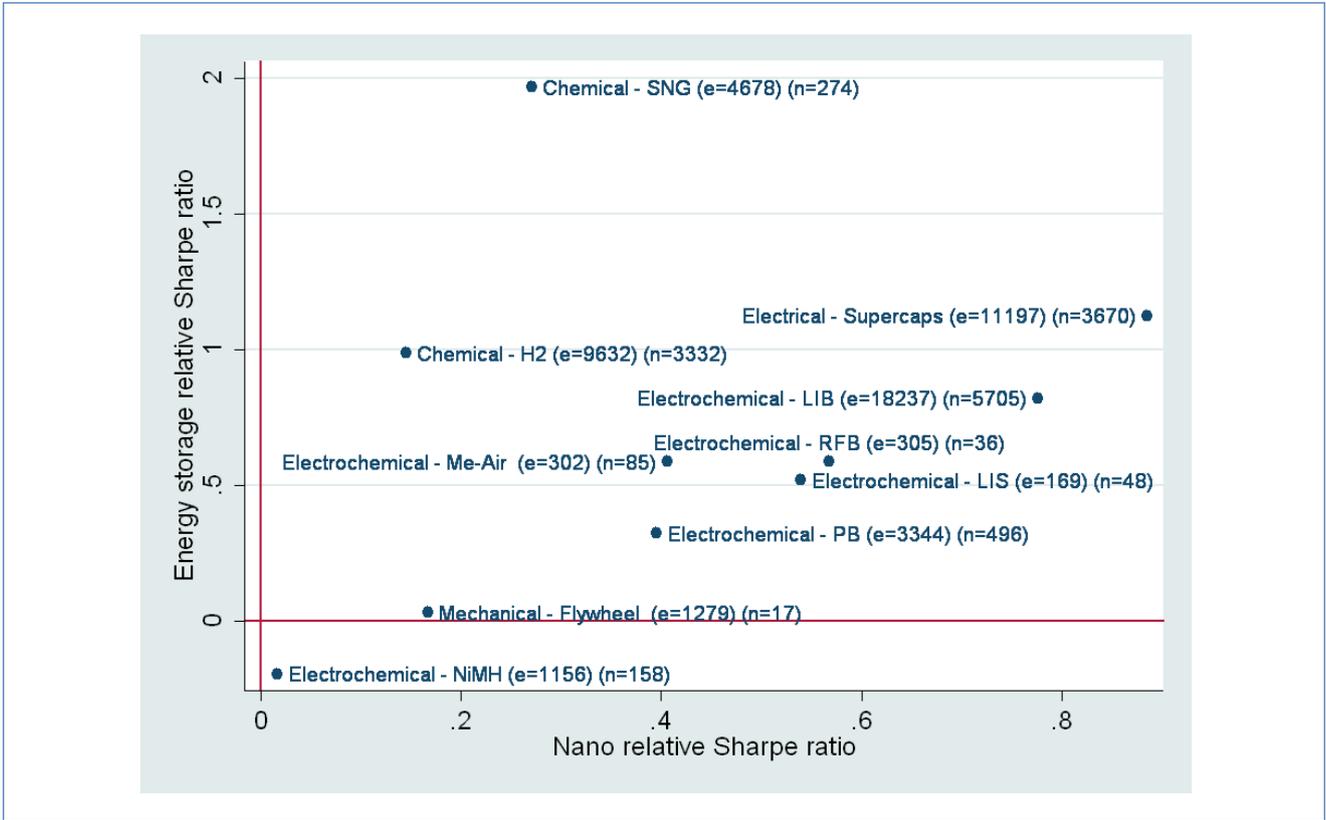


Figure 30 – Plot of Sharpe ratios w.r.t. all technologies: electricity storage vs. growth of nanotechnology

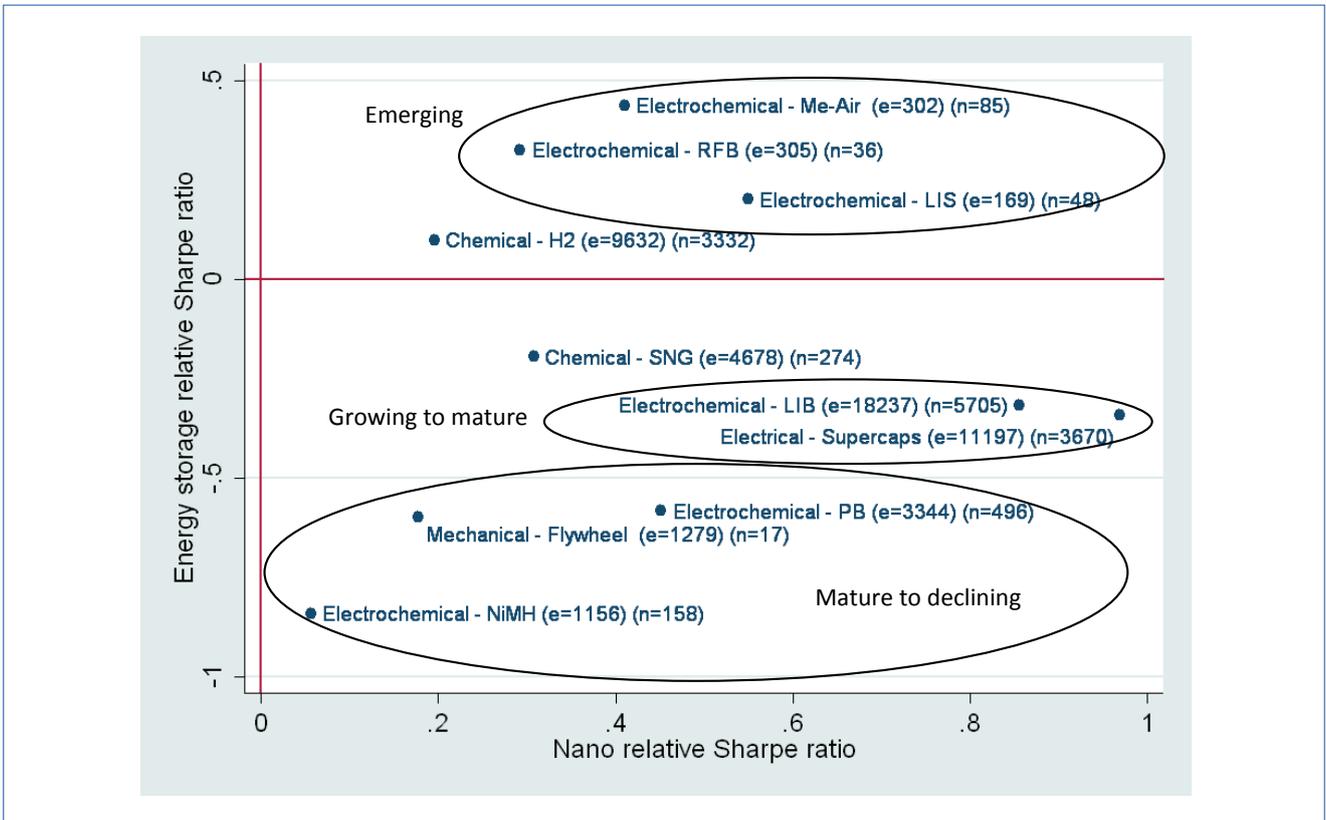


Figure 31 – Plot and visualization of Sharpe ratios w.r.t. storage technologies: electricity storage vs. growth of nanotechnology

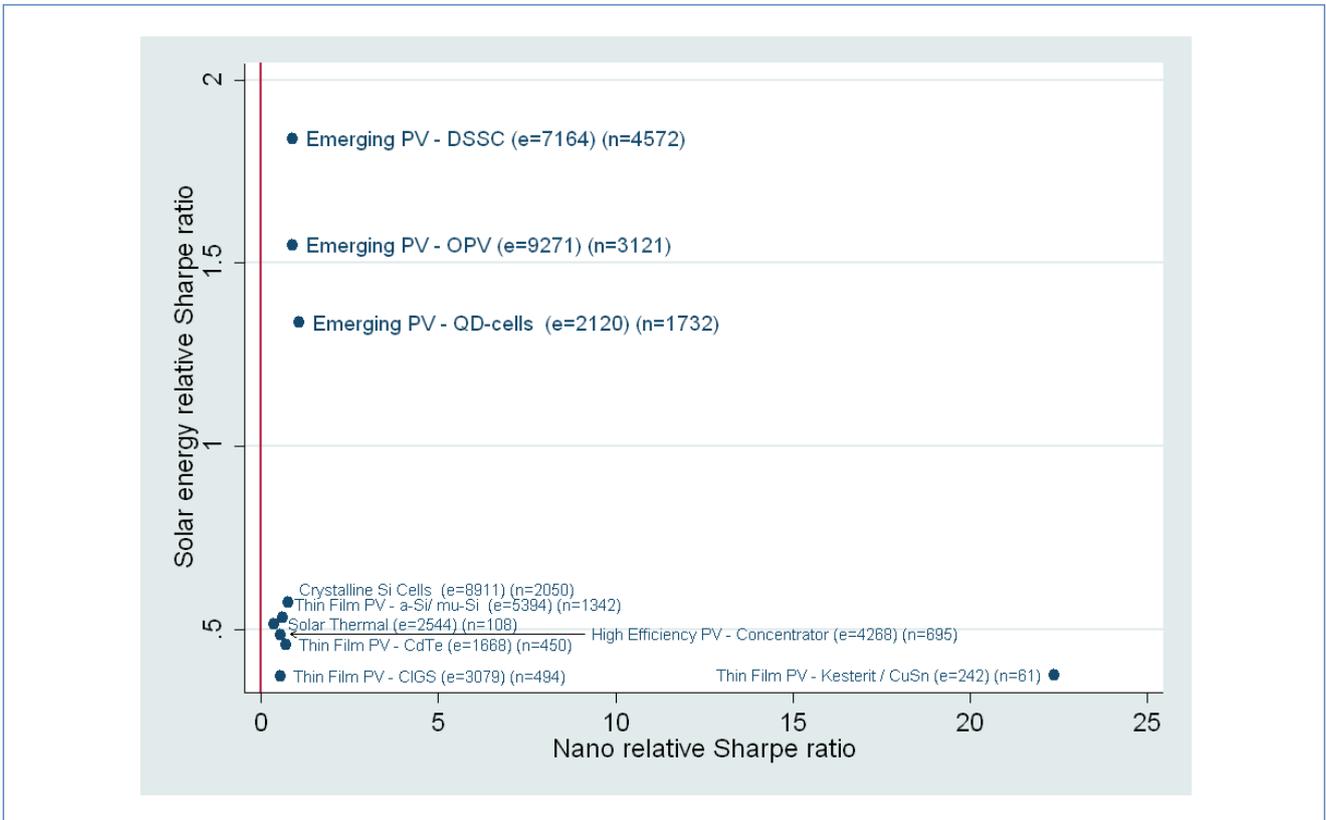


Figure 32 – Plot of Sharpe ratios w.r.t. all technologies: solar energy vs. growth of nanotechnology

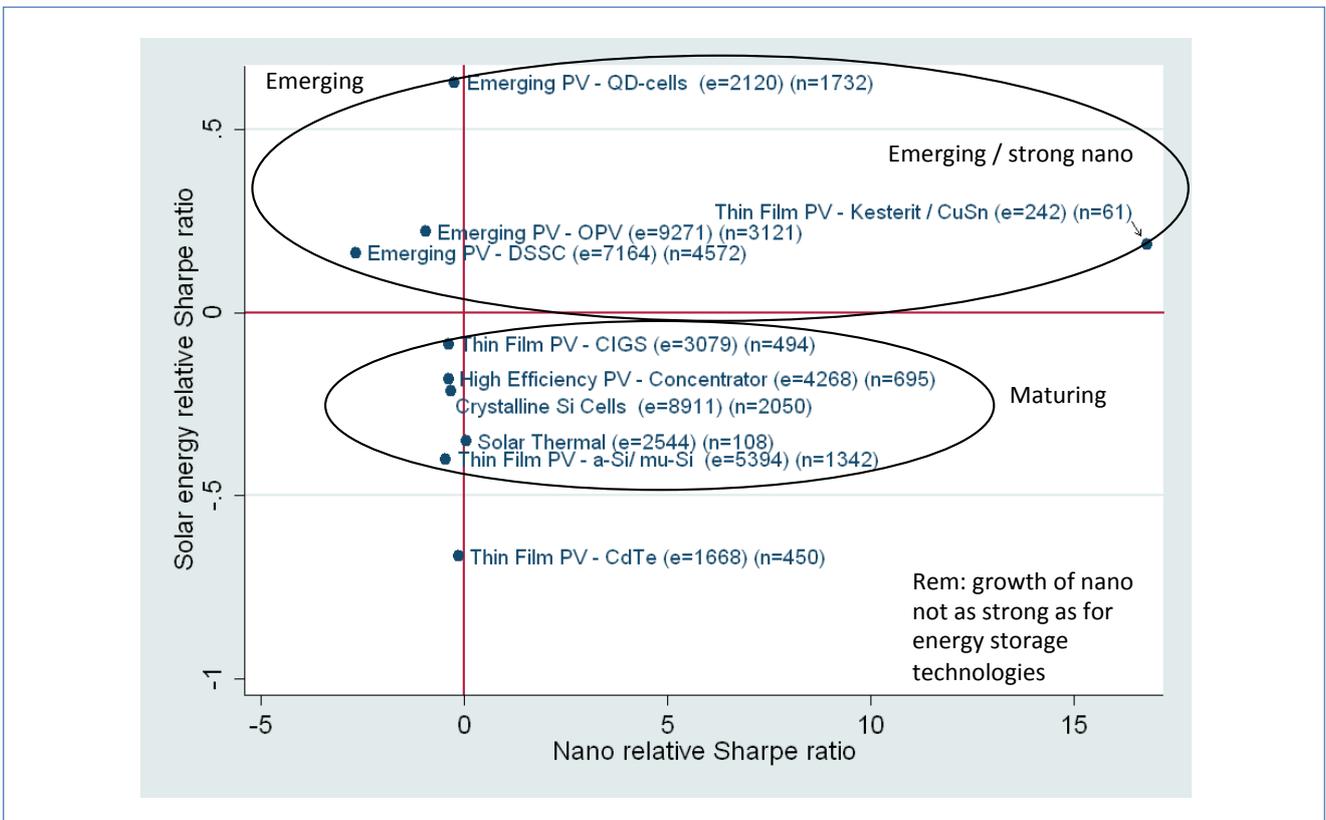


Figure 33 – Plot and visualization of Sharpe ratios w.r.t. solar technologies: solar energy vs. growth of nanotechnology

3.3 Technology profiles

The bibliometric analysis enabled us to cluster nanotechnologies into the most significant fields with respect to energy application technologies. In total, seven fields with relevant R&D activities (e.g. with respect to publication numbers) were identified: nanocomposites, nanoelectrodes, nanocoatings, nanocarbon materials, printed electronics, nanocatalysts, nanofluids. The process was iterative. Some fields were defined before the bibliometric analysis was begun (e.g. printed electronics and nanocoatings), since their relevance was obvious in advance. Other fields were clustered and added later in the process (e.g. nanofluids, nanocatalysts) once their relevance and the critical mass of R&D activities became clear. Thus bibliometrics was also used to verify that the selected clusters of nanotechnology fields broadly capture all relevant activities. Of course clustering and naming of fields is to some extent arbitrary, and nanotechnology developments are often relevant to several fields. The advantage, however, is a better structuring of the developments, often or mostly with a clearer link to applications and markets (e.g. nanoelectrodes for batteries as electrochemical storage in electric vehicles, or nanocomposites for emerging photovoltaics in low-cost solar cells).

The technology profiles link the nanotechnology developments to energy application technologies and relevant markets.

The order of the technologies shows their market relevance in the sectors of solar energy and energy storage. Thus nanocomposites will have a strong impact on the relevant sectors; nanofluids will either have a smaller impact or the forecast is subject to greater uncertainty.

3.3.1 Nanocomposites

The first technology to be described is the technology of nanocomposites, which can be found in numerous applications in the energy sector and which is relevant for both the energy harvesting and storage market. In a first step, the basic characteristics of nanocomposites will be explained, distinguishing between the different types. Secondly, examples of possible applications will be listed. The technical challenges and opportunities will then be illustrated, in order to give an overview of current problems and opportunities of applying nanocomposites. From this the focus of future research on nanocomposites will be identified. Next the maturity of the technology and its phase in the typical technology lifecycle will be presented. There follows a market analysis with a focus on market drivers, challenges, opportunities, developments, key barriers and the relevance of the technology in the market. Finally, some important players in research and industry in Europe, the US and the rest of the world will be listed.

3.3.1.1 Description of the technology

Nanocomposites represent a class of materials that is created by introducing nanoparticulates into a macroscopic sample of material. In this process, the nanoparticulates, with a dimension of up to 100 nm, act as fillers for the macroscopic matrix. Creation of nanocomposites results in drastic property enhancements that can be leveraged with just a small percentage (approx. 5%) of nano-sized particles (29).

Nanocomposites can be classified according to their microstructure (30): nano-layered composites have alternating layers of nanoscale dimension, whereas nanofibrillar composites represent a matrix with embedded nanoscale-diameter filaments. Finally, nanoparticulate composites consist of a matrix with embedded nanoscale particles. The class of nanocomposite used is chosen on the basis of the specific characteristics required, such as light absorption and electron conduction. The characteristics result in drastically enhanced properties for the material, such as mechanical characteristics (e.g. strength and toughness) and electrical conductivity (29). These improvements can be achieved through a drastic reduction of the travel speed, and therefore the mean free path length, of charge carriers in the absorber. This achieves uninterrupted charge travel within the nanocomposite without the need of ultra-high-purity semiconductor materials (31).

Nanocomposites are used for several applications in the energy harvesting and energy storage market. The main reason for their use is the possibility of avoiding costly hyper-pure semiconductors and optimized energy storage (31) (32).

3.3.1.2 Examples of application

Nanocomposites exist in several applications within the energy market, such as solar thermal devices and energy storage systems.

The solar energy sector brings multiple application possibilities. Firstly, nanocomposites can be found in **nano-structured solar cells and PV** (e.g. in polymer-inorganic PV cells, or as polymer gel electrolytes in dye-sensitized solar cells **DSSC** or quantum-dot sensitized solar cells **QDSSC**) (33) (34) (35) (36). Nanocomposites are also used for the capture of energy in silicon-based solar cells, typically in the form of nanowires (31) (36). Nanocomposites can also be found in **antireflection coatings** and higher **solar transmittance coatings** on collector glazing (e.g. Ti-Si-O films via sol-gel-method) (33).

In the field of **energy storage** the advantages of nanocomposites are needed in thin, flexible energy storage devices with nanocomposite units, e.g. supercapacitors, Li-ion batteries and hybrid devices (32) (37).

Additionally, nanocomposites can be used in the process of semiconductor-assisted **photocatalysis for fuel production** in order to obtain solar hydrogen or methanol (34). For example, the nanocomposites applied here are TiO₂-Gold composite nanoparticles or semiconductor-semiconductor composites (34) (35) (31). Another field of application lies in the wind energy sector, where lightweight nanocomposite materials are mainly used for **rotor blades** (32).

3.3.1.3 Technical opportunities and challenges

While nanocomposites embody several useful characteristics for the energy market, their extended integration is also limited by technical challenges. The following section gives a brief overview of the main opportunities and current problems.

Technical opportunities

In solar energy harvesting and conversion, nanocomposites are utilized to overcome limits of single materials in solar spectrum response (band-gap engineering), transport of electrons within the material (defect engineering) and reaction of electrons with chemicals (catalyst engineering), as well as to reduce costs (34). These characteristics result in improved charge separation and therefore in enhanced photovoltaic efficiency (34) (35). Nanocomposite papers also show high mechanical flexibility and enhanced ionic conductivity and thermo-mechanical robustness (32) (37).

Due to these advantages, future energy storage devices of improved efficiency (with nanocomposite structures) are seen as a chance to ease the integration of these applications into a smart grid. This attributes a high importance to nanocomposite technologies in the coming years, since the high share of renewable energy systems will require reliable large-scale energy storage solutions (29) (32). Nanocomposite technologies are also regarded as having a high potential for use in devices for converting carbon dioxide into hydrocarbon fuels (e.g. methanol) (35), and nanocomposite sheets allow new kinds of merged hybrid devices (32) (37).

Technical challenges

Within the solar harvesting sector, general fabrication problems restrict the usage of nanocomposites. For example, the manufacturing costs of photovoltaic systems depend closely on coating (process) technologies, which are currently still cost-intensive (31). If future research overcomes these challenges and results in cost-efficient and fully automated mass production, a widespread application of photovoltaic systems is to be expected (30).

Looking at solar cells using nanocomposites, the degree of efficiency is not yet sufficient for a full market roll-out (36). Furthermore, the problem of physical limits needs to be considered when using nanocomposites (34).

Further research is also needed into heat resistance and corrosion prevention of the nanocomposites used (33).

Focusing on energy storage, the field expulsion within the matrix lowers the overall energy storage density and increases the probability of a matrix breakdown (37). Additionally, the agglomeration and percolation decrease the dielectric strength of the energy storage device (37). These technical challenges call for extended research.

3.3.1.4 Technology maturity and lifecycle

Nanocomposites are used in several industrial sectors including the packaging industry and the automotive sector (29). For example, nanocomposite structures are already widely used in commodity plastics, whereas full technology maturity in the energy sector is only expected in the future (29) (30).

Most of the technologies using nanocomposite architectures are still at an early stage of the technology lifecycle. For example, DSSC and QDSSC using nanocomposites have not yet achieved the required efficiency levels and are not yet in the process of market roll-out. Nanocomposite coatings and storage devices such as batteries are at a more developed stage and are currently in market roll-out (33) (34) (37).

3.3.1.5 Market analysis

In this section, current market developments in nanocomposites will be analyzed in order to give an overview of future applications and opportunities for these technologies.

Key drivers (market perspective)

The key drivers of the spread of solar cells in the energy market are improvements in efficiency, energy yield, stability and lifetime due to nanocomposite architectures (29). The environmental sustainability of the new technologies is also much improved when compared to previously used applications (34) (36). Low manufacturing costs enable broad use of these technologies, since less material and cheaper material is used (avoidance of hyper-pure semiconductors) (31) (35). The new technologies allow efficient manufacturing processes for photovoltaic systems: the material can be applied directly onto flexible plastic foil (roll-to-roll), which decreases costs and improves manufacturing times. Thus broad use in PV and extensive market penetration is expected (30).

For energy storage nanocomposite units provide high, long-term stability, higher energy density and mechanical flexibility. In addition, the new technologies require minimum space, adapt to shape requirements and are environmentally friendly (32) (37). These improvements result in more efficient energy storage, which leads to a higher return on investment for the companies involved. Due to scale effects, mass roll-out is expected in the

near future, which also includes the formation of new markets (30). This development is also accelerated by the global funding for nanotechnology ventures (29).

Opportunities (market perspective)

Throughout all the sectors considered where nanocomposite technologies can be applied, the current improvements result in a fast-growing market and extended usage of nanocomposite systems. For example, photovoltaics are expected to contribute 9% of worldwide electricity demand by 2030, which represents an annual growth rate of 65% for this market in the period from 2005 to 2010 (38). Since nanocomposites are so versatile, market relevance of the technology is expected to be high for both the solar energy and energy storage sectors on a medium to long-term horizon (29). Due to the fast growing markets, the annual growth rate of nanocomposite applications is estimated to reach 29% in the period from 2005 to 2020 (38).

Developments to watch

The application of nanocomposite technologies is highly influenced by global developments in the energy sector. For example, the introduction of a smart grid with a high proportion of renewable energies strongly depends on efficient energy storage solutions and is therefore directly linked to the use of nanocomposite systems (30). At the same time, further incentive campaigns in favour of nanotechnology are expected to be introduced in several countries in the near future (38). While the US and Europe lead the world in market share of nanocomposites with 80%, a rapidly expanding Asian market is developing (39).

Not only general energy market developments but also specific technology improvements will shape the future use of nanocomposites. For example, DSSC and QDSSC are constantly increasing in efficiency, and they are reported as approaching the efficiency levels required for market competitiveness (31). The recent improvements in nanocomposites also open new markets for these technologies, such as high-speed machining, optical applications, magnetic storage devices, smart cards and displays (32) (36).

Key barriers

While nanocomposite technologies can enable crucial improvements in recent solar energy systems, some important barriers should not be neglected. Social factors such as health, safety and environmental risks of the new

technologies can profoundly influence successful market penetration (29). In the short term small profit margins caused by high research costs could limit the needed investments in the new technologies (29).

When evaluating nanocomposite technologies for solar cells, it must be underlined that even with the current improvement, solar cells still have a low efficiency in comparison to alternative energy sources (34) (35) (36). Within the energy storage sector, negative characteristics of nanocomposite papers (e.g. agglomeration and percolation) have only been improved recently and the problem of field intensification still remains (32) (37).

Economic challenges

A major economic challenge for the use of nanocomposite technologies is the cost of the electricity produced. Power produced by applications using nanocomposite structures (photovoltaics and solar cells) cannot yet compete with electricity from fossil energy sources (29). Other limiting factors are insufficient quality and reliability of the technologies as well as technical limitations (30) (36).

Furthermore, the standards and methods needed to ensure successful and low-risk mass roll-out are not yet available (29). Regulations for future developments must be defined and communicated through the entire energy sector (29). Due to such limiting factors, it is still unclear whether nanotechnology will definitely become the key technology in the PV sector (30) (36).

3.3.1.6 Key players

Research and development activities in nanocomposites can be found worldwide (29). One of the major research associations is the COST Action, merging the nanocomposite research activities of 31 countries. The table below gives a brief survey of regional research institutes that address nanocomposite technologies (40).

Since nanocomposite technologies are applied in numerous industrial sectors, the key players represent a wide range of product portfolios. As the table illustrates, several key players can be found in the energy sector, offering energy harvesting and energy storage devices with integrated nanocomposite architectures. At the same time, other industrial sectors, such as the plastic industry, also make large-scale use of nanocomposite technologies (33) (34) (37).

R&D	
	Nanocomposites COST Action, 31 countries
USA	Advanced Materials Research Center (AMRC), Sheffield
	Texas A&M University (Polymer Nanocomposite Lab)
	Nebraska Center for Materials and Nanoscience, University Nebraska
	California Institute of Technology

R&D	
Europe	European Technology Platform, European Commission
	Helmholtz Zentrum Berlin for materials and energy (HZB): thin film solar cells via ion layer gas reaction (ILGAR-technique)
	Netherlands Organisation for Applied Research (TNO): R&D on integration of new energy systems
	Christian Doppler Laboratory for Nanocomposite Solar Cells, TU Graz
	PV- MIPS Project, 10 European countries
Rest of World	Swiss Federal Institute for Technology (EPFL): Solar energy conversion
	Asian Institute of Technology (Thailand)
	Beijing National Laboratory for Molecular Science (China)
Industry	
Coatings for solar absorbers	Alanod-Solar GmbH, 3M ESPE, DSM Somos, Elementis Specialties Inc, Inframat
DSSC	Merck & Dyesol Limited
Other energy sectors (wind)	Arkema Group, Evonik Degussa GmbH
Plastic industry	Inc, Hybrid Plastics, Nanocor Incorporated, Unitika Ltd
Emulsion polymers, fillers	BASF SE, Cabot Corporation
Tooling products	Cyclics Corporation
Films for electric devices	BASF SE, Du Pont (E.I.), Showa Denko K.K.
Energy storage (battery applications)	eSpin Technologies Inc, Nanophase Technologies Corporation, Powdermet Inc

3.3.2 Nanoelectrodes

Nanoelectrodes have a strong potential to critically influence and improve applications in the energy storage sector (e.g. batteries, supercaps, fuel cells), and are also very important for solar energy applications (especially transparent electrodes for PV). The following technology profile describes the characteristics of nanoelectrodes as well as possible applications, technical challenges and the maturity and status of the technology within the technology lifecycle. Important players in both research and industry are identified, along with other sectors that might be impacted by nanoelectrodes. Adopting a market perspective, the technology profile gives an overview of critical drivers, opportunities and developments to be watched on the market. It gives an idea of what economic challenges and key barriers the technology has to overcome to become commercially usable in applications and successfully enter and impact the market.

3.3.2.1 Description of the technology

Nanoelectrodes are electrodes with a critical dimension in the range of one to hundreds of nanometres and include individual nanoelectrodes, nanoelectrode ensembles (NEE) and nanoelectrode arrays (NEA) (41). Their nanostructures range from 0D ("zero-dimensional", e.g. magnetic nanoparticles) to 1D (e.g. carbon materials/nanotubes, metallic/

metal oxide nanowires) to 2D (e.g. nanosheets and nanoflakes, core-shell structured nanomaterials) (41).

Nanoelectrodes offer a vast array of advantages (41) (42) (43) (44) (45): a high surface-to-volume ratio, with the increased surface area leading to larger electrode/electrolyte contact areas and higher energy density; enhanced mass transport due to the dominance of radial (3D) diffusion; the faster transport of electrons, ions and molecules resulting in higher electrical and ionic conductivity and the formation of porous networks; shorter diffusion pathways, leading to enhanced cycling performance and better structural stability/mechanical robustness that brings increased flexibility for volume change during charge/discharge; a potential for new reactions (not possible with bulk materials); improved mechanical strength and structural integrity; the redox potentials of electrode materials, modified by nanostructures, resulting in a change of cell voltage or energy density.

Several disadvantages also have to be considered (41) (42) (44) (45). Nanometre-sized particles tend to form agglomerates that are difficult to disperse, mix and bind to produce (densely packed) electrodes; agglomeration during cycling leads to quick capacity fading and thus low thermodynamic stability; a risk exists of secondary reactions causing a high level of irreversibility (low columbic efficiency) and poor cycle life, and also producing safety problems; exploiting the full potential of nanoelectrodes is currently constrained by

the quality and expense of fabrication of the technology; a better understanding of the preparation of devices and their electrochemical performance must be developed.

Nanomaterials may incur high fabrication costs due to complex synthetic processes, low volumetric energy density due to reduced packing density of nanoparticles and undesired side reactions between the electrode and electrolyte due to large surface areas.

3.3.2.2 Examples of applications

In general, three application areas apply (42) (46): physical electrochemistry (e.g. solar cells, lithium ion batteries), imaging science (e.g. scanning electrochemical microscopy (SECM)), and analytical science (e.g. biological investigation such as single-cell studies, microchip fabrication, design of coordinated biosensors, addressable patterned electrodes).

Physical electrochemistry has been the main driving force for the establishment of reproducible and robust methods for the preparation of nanoelectrodes. Especially important is the field of storage (in particular lithium ion batteries, (super)capacitors), but energy conversion (organic solar cells, fuel cells) are also of relevance.

Lithium ion batteries

Characteristics of the technology (43) (44) (45): lithium ion batteries represent the state-of-the-art in small rechargeable batteries with relatively high voltages, energy densities and long cycle lives. They normally consist of a negative electrode (anode, e.g. graphite), a positive electrode (cathode, e.g. LiCoO_2), a lithium ion-conducting electrolyte and certain membranes. Nanometre-sized electrode materials increase electrical activity through lithium insertion and enhance the high rate capability. Nanotechnology helps to improve the battery's capacity, energy density, power density, cycle life and safety. It allows for high charge/discharge rates and reduces the specific current density of active materials. It reduces the volumetric changes and lattice stresses. For anodes, nanostructured (nanowires, nanorods, nanotubes and 3D porous particles) as well as nanocomposite materials (e.g. Si- or Sn-based nanomaterials dispersed in a carbon-based matrix) exist or are being investigated. For cathodes, nanostructures are investigated often as transition metal oxides or polyanion-based compounds. Nanostructured cathode electrodes offer improved energy storage capacity and charge/discharge kinetics, better cyclic stabilities because of their huge surface area for Faradaic reaction, short distances for mass and charge diffusion, added freedom for volume change accompanied by lithium intercalation and discharge.

Technical challenges (43) (44) (45) (47): further work is required to achieve controlled and large-scale synthesis of nanostructures; understand mechanisms of lithium storage in nanomaterials and kinetic transport on the interface be-

tween electrode and electrolyte; understand the impact of nanomaterials on the performance of lithium ion batteries and the mechanisms; develop different types of batteries for certain applications, such as high-energy lithium ion batteries for modern communication devices, high-power lithium ion batteries for HEVs, EVs, and power tools, or long-cycle-life lithium ion batteries for UPS and SSBs; develop new nanomaterials that address challenges such as high capacity, high cycling rate, rate capability, energy efficiency or improved safety. Challenges mainly stem from four sources: morphology and microstructure change, volume change of active electrode materials, structural change (or phase transformation), formation of insulating phases. Nanoelectrodes are difficult to prepare, and their dimensions and morphologies are hard to control. It is urgent and important to find cheap, environmentally friendly (positive) electrode materials to replace LiCoO_2 .

Technical opportunities (45) (47) (48): lithium ion batteries are and will be the most practical solution for a variety of electrical storage applications. However, it is unlikely that existing batteries will be able to meet the increasing demands of emerging technologies. Properly designed nanostructure and fabrication processes are needed in order to significantly improve battery performance. Opportunities for R&D are to unravel mechanisms of electrochemical performance enhancement by nanostructures with different microscopic features, more extensive studies of novel architectures of electrodes, development of large-scale, low-cost fabrication strategies for nanomaterials with desirable performance, develop an understanding of bio-inspired nanostructures, develop high-voltage electrode materials and new electrolytes of wider potential ranges, and develop a fundamental understanding of surface and interfacial processes that accompany the charge-discharge operation. Novel architectures deserve more attention because different geometry can display dramatically different behaviour.

Besides the established use of lithium ion batteries in portable electronics (e.g. digital cameras), emerging markets are large-scale batteries for electric mobility as well as stationary storage applications (e.g. in combination with renewable energy generation such as solar energy).

Super or ultra-capacitors

Characteristics of the technology (49) (50) (51) (52) (53) (54): electrochemical (super) capacitors (ES) consist of two electrodes, an electrolyte and a separator electrically isolating the two electrodes. Differing from batteries and fuel cells which store energy through chemical processes, ES utilize electrostatic separation between electrolyte ions and the electrodes. The electrode material is of very high importance for the efficiency, a high surface area and high porosity are key properties of the electrode. There is an attempt to combine the properties of dielectric capacitors (high power output) and batteries/fuel cells (high energy storage). There are two types of capacitive behaviour: electrical double layer capacitors (EDLC) show

no electrochemical reaction on the electrode material (→ pure physical charge) and pseudo capacitor/faradaic super capacitors (FS) have an electrochemically active electrode material (→ it can store charges). In an ES, the two mechanisms usually function together; therefore they have a higher specific capacitance and energy density.

The state-of-the-art materials used as electrodes are carbon particles, due to their high surface area for charge storage. By adding electrochemically active materials the energy density can be increased in EDLC. For FS/hybrid capacitors, metal oxides have shown good properties. Besides the electrodes, the electrolyte is a key component and has to fulfil the following requirements: wide voltage window, high electrochemical stability, high ionic concentration and low solvated ionic radius, low resistivity, low viscosity, low volatility, low toxicity, low cost as well as availability at high purity. Nanotechnology helps to improve capacitance, cyclic stability, energy density and power density. Relevant nanomaterials for future developments are still carbon-based materials, such as nanotubes (SWCNTs, MWCNTs) and nanocomposites (e.g. CNT/polymers, CNT/metal oxides).

Technical challenges (49) (50) (51) (55) are to achieve high surface areas and optimum pore sizes, to reduce the difficulty in purification, to reduce the costs of production (costs are much higher compared with other energy devices), to reduce the internal resistance to provide a high power density, and the design of electrode materials which combine EDL- and pseudo-capacitance.

Technical opportunities: due to their high efficiency, high power and high level of reliability, ES can complement or even replace batteries in some applications. Advantages compared to batteries (49) (51) are higher power densities, long life expectancies, long shelf life, high efficiency, a wide range of operating temperatures, environmentally friendly materials and safety. Disadvantages compared to batteries (49) (51), however, are low energy densities, high costs and high self-discharging rates.

Examples of applications (50) (55) are stop-and-go applications in electric mobility (EV, HEV, metro trains), e.g. to boost the battery or fuel cell in a HEV, stationary energy storage, and consumer electronics (e.g. digital communication devices, digital cameras, mobile phones).

Solar cells

Besides the use of electrodes in energy storage, electrodes are used also in photovoltaics in the solar energy sector. Here, a number of nanoscale materials (e.g. metal oxide nanoparticles, CNT, graphene) have the potential to substitute for indium tin oxide (ITO) as used for transparent electrodes. ITO has the advantage that it can be used as transparent as well as conductive material in solar cells, flat screens in consumer electronics, etc. However, indium is regarded as a critical raw material and the high-technology industry is intensively researching materials for ITO replacement.

3.3.2.3 Technology lifecycle

Nanoelectrodes have already started to leave their status as a pacemaker technology behind, and are beginning fully to exploit their potential as a key technology for most of the areas of application mentioned above. However, it is important to consider the concrete material used for a given application. High growth is to be expected for the next few years, until the technology reaches maturity. Maturity is about to be reached for nanoelectrodes in current and next-generation lithium ion batteries, where they are already being deployed on a regular basis. Large growth is expected for the application of nanoelectrodes in solar cells and capacitors, where they are expected to reach maturity in the years 2015 and 2020, respectively.

3.3.2.4 Technical challenges

Technical challenges for nanoelectrodes in general remain as follows (44) (47): understanding of nanosize effects and development of new theories, investigation of fine details of surface features, design of optimized nano/micro structures and surface modification, search for new synthetic routes and new material systems, developing nanostructured materials via more sustainable and greener strategies in manufacturing, achieving controlled and large-scale synthesis of nanostructures in order to realize widespread commercial application, and developing predictive theoretical tools for a better fundamental understanding of the relationships between nanostructures and electrochemical characteristics.

There are also technical opportunities (44): nanosized electrode materials are favourable in terms of kinetics and capacity, while their practical applications suffer from low thermodynamic stability and high activity towards surface reactions, in addition to handling problems (“kinetically stabilized” nanomaterials have to be considered). Electrode materials with nano/micro hierarchical structures are the systems of choice, combining negligible diffusion times and possible new lithium storage mechanisms with good stability and easy fabrication. Surface coatings are of great importance to the performance of nanoelectrodes, especially considering the high surface area. Efforts are underway to understand all the fine details of the surface chemistry. Carbon coating is one of the most widely used coating techniques for anodes (e.g. metal oxides) and cathodes (e.g. LiFePO_4) – enhancing the electronic conductivity of electrode materials, and resulting in improved rate and cycling performance, for example.

3.3.2.5 Impact on other energy sectors

Besides electrodes for storage technologies (e.g. batteries, capacitors) and solar power (in particular solar cells), nanoelectrodes influence other energy sectors as well, such as fuel cell technologies. The use of these energy storage and conversion technologies is also likely to influence other energy sectors and applications, e.g. combined heat and

power (CHP), solar home (storage and PV), storage connected to wind generation, or smart grids.

3.3.2.6 Key Players

There are many key players in nanoelectrodes; some examples are (56):

- Nanobattery “Nixelion” by Sony Corp. with tin-based nanoalloy anode commercialised in 2009 (consumer batteries, camcorder)
- Nanobattery “SCiB” by Toshiba Corp. with titanate anode and cobalt cathode developed in 2008 (consumer batteries, laptop)
- Altair Nanotechnologies Inc. with similar nanobattery to Toshiba’s, incorporated into the Lightning GT electric vehicle in 2008
- LIB-manufacturing companies: Panasonic Sanyo, ENAX, Mitsubishi Chemicals, NEC (JP), Samsung SDI, SK Innovation, LG Chem (KR), Johnson Controls (USA), Lishen, BAK, BYD (CN), Evonik Degussa, Li-Tec Battery, Varta Microbattery (GER), Leclanché (CH), Saft (FRA) (among others)
- Suppliers for the automotive industry in Germany: Robert Bosch, Behr, Continental, Manz, BASF (among others)
- Capacitor manufacturing: Maxwell Technologies, KEMET, DURACAP INTL., Evan’s Capacitor, Cornell Dubilier Electronics (USA), WIMA Berlin, Condensator Dornit (GER) (among others)
- Solar-cell manufacturing in Germany: Solar-Fabrik, SCHOTT Solar, Q-Cells, SOLON, Sunfilm, Bosch Solar Energy (among others).

3.3.2.7 Key drivers (market perspective)

Climate change and the necessity to lower CO₂ emissions drive the emergence of renewable energies. Advances in the field of energy conversion and storage become highly important. The increasing need for energy transmission and decentralized energy storage (e.g. smart grids) is another driver to be mentioned. Nanoelectrodes are used in energy storage and solar power technologies (e.g. batteries, solar cells, super-capacitors) and are among the most important components in terms of technical improvements and costs. The key drivers result in an increasing need for these technologies for electric mobility and large electric storage systems (e.g. in combination with solar power generation).

3.7.2.8 Developments to watch

Lithium ion batteries for consumer applications are mainly manufactured in Asia (China, Japan, South Korea). New generations in battery technology and emerging large applications may see this change.

Capacitors are mainly manufactured in the US (with some exceptions in Europe). As their market expands to new applications, Asian competitors may start attacking the incumbents.

In solar cells, European manufacturers are already experiencing harsh cost-related pressure (especially from China) and a market concentration.

Companies that are already active in the research and development of nanoelectrodes have a natural head start. Innovative small and middle-sized enterprises may break this barrier, and mergers and acquisitions may occur. Joint ventures play a vital role when it comes to getting new technologies applicable for products ready for market introduction (e.g. for electric mobility, tier-one supplier and battery manufacturers).

3.3.2.9 Key barriers

Key barriers are the high research and development investments necessary in order to develop nanoelectrodes, and the small market size in the short and medium term since the growth process has just started. There are only a small number of experienced experts in nanoelectrodes, electrode manufacturing experience cannot be bought, and the financial power of the market incumbents puts the activity of small and middle-sized enterprises at risk.

3.3.2.10 Expected market relevance

End user acceptance is key to market development and may take time to develop. The challenges lie in performance and cost, which together are very difficult to satisfy. Competition is harsh, and market concentration yet to take place. Technological challenges have to be overcome repeatedly through more investment in research and development or more expensive materials, thus increasing cost. Competitive factors are low cost, high performance, quality and reliability, and a rapid innovation cycle (time from research and development to market introduction). The competitive situation is the following: power of suppliers (low), power of customers (high), threat of substitutes (low), difficulty for new entrants (high), intensity of rivalry (high). The market relevance of nanoelectrodes is expected to reach a high level, for both solar energy and storage.

3.3.3 Nanocoatings

Nanocoatings are used in several applications, thus it is worth analyzing their relevance for the solar energy and storage sectors. In a first step, the basic characteristics of nanocoatings will be explained and a brief overview given of current manufacturing processes. Secondly, examples of possible applications will be listed. Technical challenges and opportunities will then be illustrated in

order to give an overview of the current problems and opportunities in applying nanocoatings. From these elements the likely focus for future research on nanocoatings will be identified. Next the maturity of the technology and its phase in the typical technology lifecycle will be presented. A market analysis will follow, with a focus on market drivers, challenges, opportunities, developments, key barriers and the relevance of the technology in the market. Finally, key players in research and industry will be listed.

3.3.3.1 Description of the technology

Nanocoatings refer to nanoscale thin films or coatings of a thickness and/or internal structure of 100 nm or less (57). The classification used for nanocoatings identifies three types of nanostructures, namely nano-structured multilayer coatings, functionally graded coatings and nanocomposite coatings (58). The choice of coating methods strongly depends on the functional dimensionality of the nanostructures needed (59): 1D nanocoatings (filamentary) present advantages in vapour deposition and electrodeposition, whereas 2D nanocoatings (layered, lamellar) are mainly used to increase chemical vapour deposition and gas condensation. 3D nanocoatings (crystallites, equiaxed) find usage in mechanical alloying and milling. A widely used type of nanocoating is nanostructured monolithics, due to their high dynamic-magnetic consolidation. Manufacturing processes used include field-assisted sintering and sinter forging, quasi-isostatic pressure processes, shockwave compaction and the sol-gel method (57). Other methods involve dip coating, spin coating, electrophoretic deposition (EPD), thermal spray coating, pulsed laser deposition, electro deposition and amorphous crystallization (57).

The following characteristics of nanocoatings favour their usage in PV applications (59). The multiple reflections achieved lead to an enlargement of the absorption path; there is decreased recombination loss as a result of the minimized absorber layer thickness; the energy band gap of solar cells may be tailored; and nanocoatings have useful self-cleaning characteristics (59) (60).

Nanocoatings also have characteristics useful for solar thermal systems (59): reduction of emittance, leading to decreased thermal radiative heat losses and a high absorptance over the solar spectrum (59); use for protection against corrosion (thermal and humid impact) (59); good coverage and adhesion characteristics, as well as the self-cleaning benefits already mentioned (59) (60); improved corrosion resistance, wear resistance, strength and hardness, especially in nano-structured monolithics and thermal sprays (57); with the help of nanocoatings, nanoporous solids can change physical properties (e.g. freezing point) as well as optical properties; and nanocoatings lead to an increase in reactive surface, have a low dielectric constant, high electrical conductivity and high thermal resistance (57).

3.3.3.2 Examples of application

Due to their characteristic benefits, nanocoatings are used in several energy market applications such as solar thermal devices and energy storage systems.

For example, photocatalytic coatings are used on self-cleaning tiles (titanium dioxide) and anti-fog surfaces (57), and nanocoatings (titanium dioxide nanoparticles, silicon nanorods) are used to enhance the efficiency and/or manufacturability of photovoltaic cells.

Looking at solar cells, nanocoatings are mainly used in DSSCs (dye-sensitized solar cells), for example on transparent electrodes (carbon nanotubes/graphene) (57) (61). Thermal spray coatings (alumina/titania nanoceramic, tungsten carbide, chrome oxide and yttria stabilized zirconia) are widely used in order to increase resistance to wear, erosion and corrosion while conserving ductility (57). Furthermore, Li-ion batteries with a titanium structure of nanonets are coated with silicon particles or SiO_2 to prevent TiVO_2 reacting with Ti^+ (62) (63). Nanostructure coatings with a metal matrix (containing nano-sized oxide particles) are used in ultra-black coatings and applied in solar thermal systems (58). Anti-reflective coatings are especially helpful for solar PV cells, since they reduce the reflectance from 40% to just 1% (64). Another application of nanocoatings is titanium-coated nanotubes used in hydrogen tanks (57).

3.3.3.3 Technical challenges

While nanocoatings embody several useful characteristics for the energy market, their extended integration is also limited by technical challenges. The main problem lies in the difficulty of large-scale production, a disadvantage many nanomaterial technologies share (65). Furthermore, quality assessment of nanocoatings with conventional assessment methods is complicated, and improved methods are still to be designed (65).

3.3.3.4 Technology maturity and lifecycle

Nanocoatings are generally relevant for both the solar power and storage markets. Thus they can be found in numerous applications in the energy sector. For example, nanocoatings for surfaces are already past market entry and currently in use. Focusing on the energy sector, solar thermal applications and batteries are on the verge of market entry, whereas for PV applications full technology maturity is not expected before 2020 (65).

The technology lifecycles of nanocoatings show similar results. Functional nanocoatings are already being used in the industry and are therefore in their growth period. In contrast, nanocoatings designed for PV applications are still in the emergence phase and will require more research to become a key technology in the solar sector (65).

3.3.3.5 Market analysis

In this section, recent market developments in nanocoating technologies will be analyzed. Additionally, an overview of future applications and opportunities for these technologies will be given.

Key drivers (market perspective)

Major advantages of nanocoatings are their unique combination of properties such as hardness and toughness and their unique capabilities such as impermeability and transparency (66). As a result, functional coatings bring added value and can even lead to new products in the energy industry (65). Another key driver of the technology is its potential to decrease manufacturing costs (65). Focusing on PV applications, nanocoatings bring more efficient materials and technologies. The current increase in available expertise with nanomaterials also supports the future use of nanocoating applications (65).

Opportunities (market perspective)

The market opportunities for nanocoatings strongly depend on the field of application. For example, the future market relevance of surface coating technologies is expected to be relatively high. The same applies to nanocoatings used in batteries. In contrast, the success of nanocoatings in photovoltaics strongly depends on the developments in this sector. Only if nanotechnologies in general become the key technology in the industry will nanocoatings become highly relevant. In summary, new products and more effective products can be realized using nanocoatings, so they hold the potential to shape the energy industry of the future (66).

Developments to watch

The success of nanocoating technologies depends on several factors; for example, regulations to cope with as yet unknown health risks could be introduced in the near future (65). As discussed before, the use of nanocoat-

ings in the PV sector also highly depends on the pending development where DSSCs become a key technology in this sector (65).

Key barriers

As shown above, nanocoating technologies have the potential to lead to crucial improvements in the energy sector. However, important barriers should not be neglected: the market is very cost-sensitive and only a few "must have" applications exist (66); unknown health risks of nanomaterials and known health risks in the production and processing of nanomaterials (especially powders) can limit the usage of nanocoating technologies (65); production is still relatively expensive (57); and the difficulty of integrating nanocoatings into existing technologies is also a key barrier to their use (66).

Economic challenges

A crucial short-term economic challenge is the competitive disadvantage of nanocoatings due to high costs (66). As discussed above, further challenges such as the importance of nanotechnology in general need to be considered as well.

3.3.3.6 Key Players

Research and development in nanocoatings for PV applications are carried out by alliances such as the FOM (Fundamental Research on Matter) Institute AMOLF and Philips Research (65). The key industrial players for nanocoatings are subdivided into the different fields of application. For example, Nanovere Technologies offer protective coatings. As shown in the table below, further categories are lubricants, functional and safety coatings as well as nanocoatings used in paint (58) (64).

Type of coating	Company or institution
Lubricant coatings	TuffTek
Protective coatings	AS&M in Hampton, Virginia
Protective and dirt repelling	Buehler AG in Uzwil, Switzerland
Paint	Cetelon Nanotechnik GmbH
Protective Coatings	Nanovere Technologies
Protective Coatings	Diamon-Fusion International Inc. (DFI)
Functional coatings	TopChim (Belgium)
Safety Coatings	Hyperion Catalysis International
PV-coatings (Alliance)	Arizona State University and Advent Solar
PV-coatings (Alliance)	FOM (Fundamental Research on Matter) Institute AMOLF and Philips Research

3.3.4 Carbon nanomaterials

Another nanotechnology that has the potential to critically influence the sectors of solar energy and energy storage is the technology of carbon nanomaterials. The following technology profile describes the characteristics of carbon nanomaterials as well as possible applications, technical challenges and the maturity and status of the technology within the technology lifecycle. Important players in terms of research and industry activities are identified, along with other sectors that may be impacted by carbon nanomaterials. Adopting a market perspective, the technology profile gives an overview of critical drivers, opportunities and developments to be watched on the market. It gives an idea of what economic challenges and key barriers the technology has to overcome to become commercially usable in applications and successfully enter and impact the market.

3.3.4.1 Description of the technology

Carbon nanomaterials are molecules consisting entirely of carbon. Depending on their geometry they are called **graphene** (hexagonally arranged crystal layer), **fullerenes/buckyballs** (sphere, with polyhedral structure of pentagons and hexagons) or **carbon nanotubes** (tube). Unlike graphite or diamond, carbon nanostructures possess metallic or semiconductor properties (67).

Carbon nanotubes

Nanotubes are cylinders made of strips of hexagonal graphite sheets shaped as tubes with a diameter on the nanometre scale. One distinguishes between single-walled carbon nanotubes (SWCNT) and multiwalled carbon nanotubes (MWCNT). Other geometries such as nanotori, nanobuds, peapods and stacked-cup carbon nanotubes (SCCNT) can occur, but they are recent discoveries and thus less common (68) (67).

As the names indicate, single-walled carbon nanotubes consist of one single tubular carbon layer only, whereas multiwalled carbon nanotubes consist of multiple layers. Since they can be produced by a simpler production process multiwalled carbon nanotubes are cheaper and thus preferred in the industry (68).

Depending on the direction in which a nanotube is rolled it can have either metal-like or semiconductor-like properties (68). Moreover nanotubes have very high values of the elastic modulus and very high tensile strength. Another property is the excellent thermal conductance due to their one-dimensional electronic structure, which guarantees electrical transmission without any heating (68) (67).

The common synthesis techniques used to produce carbon nanotubes are laser ablation for multiwalled nanotubes, arc discharge for single-walled nanotubes and chemical vapour deposition (CVD) for both kinds (68).

Fullerenes

Fullerenes possess high electrochemical stability and a high surface area. Moreover they exhibit rich photochemistry and thus can act as an electron shuttle. It is also possible to engineer a carbon nanostructured donor-acceptor assembly to mimic photosynthesis.

Graphene

Graphene is a 2D hexagonally-arranged crystal with the highest potential mechanical stiffness, strength, elasticity and electrical and thermal conductivity ever observed. Moreover it is optically active, transparent, chemically inert and impermeable to gases. Since graphene can be produced in different qualities the effectively observed properties of a particular flake of graphene depend on the quality of the material. Graphene can be combined with other 2D crystals to obtain additional properties (69) (70).

The dominant production technique for graphene is mechanical exfoliation by using an adhesive tape to produce graphene flakes for energy storage and solar cells (70). Although the CVD process enables roll-to-roll production and can produce quality graphene, it is not the most used technique since it is very energy-intensive and hence a costlier production process. Further production methods are liquid phase exfoliation and epitaxial growth on SiC or metal substrates (70) (69).

3.3.4.2 Examples of applications

Carbon nanomaterials are extremely promising for use in a variety of applications. Regarding consumer products, they will be applicable for example in displays, sensors and memory devices (68). Regarding energy storage, carbon nanomaterials may be used for electrodes in batteries and for catalyst support or membranes in fuel cells (68) (71) (72). In the solar energy sector it is imaginable to use carbon nanotube films as transparent electronic materials and to use nanotube composites for (organic) solar cell applications (68) (72). Moreover carbon nanomaterials could be utilized to produce conductive ink for printed solar cells (71). Another application possibility in the energy sector in general is coatings for wind turbine blades (71).

3.3.4.3 Technology lifecycle

The technology of carbon nanomaterials is still in the emergence phase of its lifecycle and thus can, in its current state, be regarded as a pacemaker technology. Thus it is in an early R&D phase still, but is expected to have a high impact on future developments in the industry.

3.3.4.4 Technical challenges

Though they are already promising, there are various technical challenges that carbon nanomaterials have to

overcome to be applicable and gain importance in the industry. Some of the most important issues that have to be dealt with are listed below.

Reproducibility

It is necessary to improve existing production techniques so as to be able reliably to produce nanotubes of specific types, and especially of specific diameter sizes, in large quantities (68).

Separation and sorting

To use carbon nanotubes in specific applications it is necessary to be able to separate nanotubes with semiconductor-like properties from nanotubes with metal-like properties and sort them by specific values of diameter, length and chirality (68).

Pure tubes

To make use of carbon nanotubes in certain applications it is necessary to find a way to remove metallic catalysts from the production process so that pure nanotubes with undistorted properties can be produced (68).

Agglomeration of nanotubes

One current problem is that, due to their tendency to agglomerate or bundle up, carbon nanotubes have to be broken down by mechanical size reduction or by adding dispersing agents in order to be usable – a problem currently lacking a solution (68).

Alignment of nanotubes

To obtain specific performance properties needed for specific applications, it is necessary to be able to induce an alignment of the nanotubes in a polymer matrix. Therefore a satisfactory method to achieve such an alignment needs to be found and made applicable for industrial use (68).

Functionalization

Functionalization is a processing technique that enables existing nanotubes to attach molecules or functional groups to their sidewalls and thereby improve their dispersibility in solvents. Functionalizing nanotubes is critical to achieving a uniform dispersion of the nanotubes, which is needed for better nanocomposites (68).

3.3.4.5 Impact on other energy sectors

In addition to their promising impact on solar energy, carbon nanomaterials may also have a non-negligible influence on other energy sectors. These sectors are energy-saving technologies, wind power, manufacturing techniques for nanostructures, fuel cells and heat pumps.

3.3.4.6 Key players

Regarding R&D as well as current industrial activities, there are a number of key players dealing with carbon nanomaterials. Those key players we have identified are likely to play an important part in the future development of the technology and are listed in the table below.

R&D	Industry
Shinshu University (Japan)	XG Sciences, Targray. avanzare (72)
Lawrence Berkeley National Laboratory, USA	Samsung, Nokia, Vorbeck Materials (72)
University of Southern California, USA	Angstrom Materials, Graphene Laboratories, CVD Equipment Corporation (72)
Nanotube Research Center, AIST, Japan	Bayer MaterialScience GmbH
Oak Ridge National Laboratory (ORNL), USA	AMO GmbH (69)
School of Physics and Astronomy at the University of Manchester, UK (69)	Showa Denko, China
Chalmers University, Sweden	Nanocyl, Belgium
Lancaster University, UK (69)	Future Carbon, Germany
University of Cambridge, UK (69)	
Fraunhofer, Germany	
Catalan institute of nanotechnology, Spain	
MIT, USA	
Michigan State University, USA	
Fondation Européenne de la Science (69)	

3.3.4.7 Key drivers (market perspective)

Looking at carbon nanomaterials from the market perspective, certain key drivers can be identified that will be crucial for the effective impact of the technology on the market. From a technical point of view, one of these key drivers is the need to improve existing production techniques as well as novel synthesis techniques in addition to the arc method, CVD, laser ablation and electric arc discharge. In addition existing techniques for testing nanotube behaviour need to be improved. In general there is a trend towards miniaturization, light weight and environmental friendliness.

Carbon nanomaterials outperform most competing materials through superior properties but comparable prices. The simplicity of their dispersion into composites also enables easy value-added tailoring of other materials. Those advantageous features are very likely to lead to rapid market penetration (72).

Concerning the market impact of graphene, market research already done for other carbon materials could be useful and transferable to graphene applications. From a financial point of view the fact that the discovery of graphene was honoured with the Nobel Prize has boosted the funding available from governments and venture capitalists to promote the development of the technology in the industry (72).

3.3.4.8 Opportunities (market perspective)

Another important indicator determining the future success of carbon nanomaterials in the market is what opportunities they will be able to offer. For example, carbon nanomaterials may enable higher performance and cost savings in catalyst materials and batteries. This could allow the industry to produce cheaper, lighter and more efficient devices (e.g. photovoltaic cells) (68). Nanotube-based electrically conducting films could be used as a replacement for indium tin oxide (68) (72). Moreover, composites for structural materials or alternative raw materials for production may be developed based on carbon nanomaterials. This could lead to further promising opportunities to collaborate with product developers (72).

3.3.4.9 Developments to watch

There are certain developments concerning carbon nanomaterials that should be carefully observed in the future. One important development is general public concerns about environmental, health and safety issues that could in the worst case act as a roadblock to commercialization (68). Many changes in regulation should also be expected as knowledge is accumulated and out-of-date assumptions are corrected (68). From a technical point of view the development of CVD methods

for low-cost and less energy-intensive graphene production is an important issue to be followed. Another promising future development is research into the possibility of producing graphene from carbon dioxide (72).

3.3.4.10 Key barriers

The most important barrier the technology of carbon nanomaterials has to overcome to be successfully usable in commercial applications is the difficulty of large-scale production. So far it has not been possible to produce high-quality carbon nanomaterials with defined characteristics and properties in large quantities. Therefore the most critical issue to be solved is reliable, large-scale commercial production (68).

3.3.4.11 Expected market relevance

Carbon nanomaterials are expected to be market-relevant in both solar energy and energy storage sectors (72).

3.3.5 Printed electronics

A further technology relevant to the energy harvesting and storage market is the technology of the printing of electronic components on arbitrary substrates. First the technology of printed electronics, its manufacturing technologies and the various materials compounds will be described. Then the technical challenges will be presented, to give an idea of current problems and focus points in recent research. Examples of possible applications will be listed and the maturity of the technology and its phase in the typical technology lifecycle will be presented. There follows a brief market analysis with a focus on drivers, challenges, opportunities, developments, key barriers and the relevance of the technology for the market. Finally, some important players in research and industry in Europe, the US, Japan and the rest of the world will be listed.

3.3.5.1 Description of the technology

Printed electronics are electronic devices fabricated by printing special inks on different substrates. Since the ink normally consists of nanosized particles (10^{-9} m), this technology is categorised as a nanotechnology.

Printing methods

There is a large variety of printing methods which can be applied, depending on the characteristics and demands of the printed electronic item. The resolution of these printing methods usually ranges from 10 μm to 50 μm .

One low-cost mass printing method is flexography, where an inked plate rotates around a cylinder which transfers the image onto a substrate under high

pressure. Another, slightly costlier and higher-quality printing method is gravure printing technology. For this fabrication method, an etched image is filled with ink and also rotates on a cylinder in order to print on the substrate. The advantage is that the ink film thickness can be varied and, since printing is at low pressure, an organic solvent may be used. Offset printing is a very popular mass-production method, especially for large runs. The distinctive feature of this printing method is that the image is first transferred from the image plate to a rubber blank and then printed onto the substrate.

Sheet-feed techniques are applicable to nanoprinting for lower throughput volumes and offer lower resolution. Inkjet printing enables accurate drop placement on a large variety of substrates. The ability to print on different and uneven surfaces with varying thicknesses and ink formulae are great advantages of this method. With screen printing ink is pushed through a screen, which enables printing on arbitrarily shaped and sized substrates. The ability to print with varying ink thickness is a particularly important aspect for non-uniform-density requirements. Another advantage is good deposition control, which prevents stair-stepping or broken images.

Finally, there are some recently evaluated printing methods which are still at the laboratory stage. In stamping/nanoimprinting, ink is printed with a stamp directly onto the surface. UV lithography uses electron beam lithography to produce the stamping tool. This technology shows great promise for sub-50 nm patterns. Aerosol jet technology creates an aerosol mist which is focused aerodynamically by a second gas stream for printing. The small droplet size, good control of deposit thickness, good edge definition, low ink consumption and smooth transitions between material layers suggest a promising future for this technology. Finally, Atomic Layer Deposition (ALD) is a digitally controlled printing method where precursors react with the surface of a substrate and create an image. The film thickness can be controlled by the characteristic growth rate which depends on the processing temperature (73) (74).

Types of ink

There are three main types of ink for printed electronics. The first is a suspension of metal nanoparticles (NP) and is called nanoparticle ink. This type of ink has very good conductive properties and is widely available commercially. The second type is a metal-organic decomposition (MOD) ink. MOD inks have reduced nozzle clogging and do not require colloidal stabilisers. Examples of metals which are used for NP or MOD inks are silver, copper, aluminium and nickel (listed by decreasing conductivity and price). In order to enhance conductivity, the inks are often cured after the printing process. In MOD inks, the heat burns off the organic

components and precipitates the metal, whereas in NP inks the heat decomposes the organic stabiliser. Then the particles may be sintered together by an even higher temperature to form a conductive feature. The sintering process can be avoided by using evaporating solvents or reactive printing, which is still limited to laboratory scale. The third type of ink is based on metal oxides which have the great advantage of being transparent and having excellent oxygen stability. The most popular metal-oxide ink consists of doped zinc oxide. It can be used to print conducting and semiconducting patterns on substrates. After the printing process curing is necessary to drive off the ligand. In the case of semiconductors, the curing temperature has to be high enough to guarantee a high degree of purity in the product (75).

3.3.5.2 Technical challenges and opportunities

One major problem of printed electronics is the slow sintering process which renders the precursor compounds to increase conductivity. The high temperatures of more than 200 °C rule out the use of PET and PC foils, which leads to the application of expensive heat-resistant polymers. In addition, the long sintering process (>30 min) complicates roll-to-roll production. An alternative for these problems is room-temperature sintering, which still has the disadvantage of a very long sintering time, and reactive printing where the conductive material is created *in situ* on the substrate (75). Another challenge is the interaction between the ink and the substrate. To avoid “coffee-ring” drying, the final geometry and layout of the ink drops on the substrate has to be arrested in a short period after deposition (76).

Transistors for mass-market applications require a charge carrier mobility of about 1 cm²/Vs. Complex electronic devices on the other hand require a carrier mobility of up to 5-10 cm²/Vs. This requirement can be met by optimizing existing materials or developing new ones. Due to the expensive catalysts and other materials used in the printed electronics production process, reducing the processing steps presents a large potential for optimization. Another drawback of printed electronics is inadequate material stability. The requirements of prolonged use and resistance to environmental factors demand improvements in optical, chemical and electrical properties in order to guarantee a longer life for the products (77).

On the other hand, printed electronics offer great opportunities such as fast roll-to-roll production (75). Furthermore, printed electronics enable the production of flexible electronic components by printing on flexible substrates and they make the production of large-area components possible (78).

Finally, the low complexity and the low price of inks and substrates allow for simple and low-cost production (77).

3.3.5.3 Examples of applications

Examples of applications of printed electronics in the energy sector are energy harvesting and storage devices. Organic conductors and metals can be used for electrodes as a replacement for indium tin oxide (ITO) in some applications. For example, electrodes for displays or photovoltaic cells, which have to be transparent, could incorporate printed electrodes. Other examples of the application of printed electronics are photovoltaic cells and disposable batteries. Although such photovoltaic cells still have very low efficiency ($\eta_{\text{PCE}} < 10\%$ (79)) and limited life, they are nonetheless promising for the future as building-integrated cells or even power-grid-integrated power sources. Printed batteries still have very low capacity, but in the near future a rise in capacity and integration into systems is expected (80) (76) (74).

3.3.5.4 Technology maturity and lifecycle

Low-capacity batteries are already available, but the very low capacity is still a serious disadvantage compared to conventional products. In the near future high-capacity batteries are expected, and by 2020 there will be system-integrated batteries on the market. Printed batteries in general only play a minor role in power supply and are only interesting in the very long term or for niche applications (they are not discussed in the roadmap). Portable printed solar panels, however, already exist. By 2016 the first solar cells will be integrated into buildings and facades for energy harvesting. It will take until 2019 for the first printed solar panels to be integrated into the power grid. Their relevance for the market in the medium to long term is medium-high to high, and they will play a major role in the future (80) (74). These applications are listed and discussed in the roadmap.

Taking a look at the technology lifecycle of printing methods, it is obvious that all printing methods are still at a very early stage and research is still needed. Atomic Layer Deposition, nanoimprinting, UV lithography and aerosol printing in particular are still in basic research and thus in an emerging state. Flexography, gravure and screen/inkjet technologies are already in a more advanced state, since with these it is easier to modify conventional techniques to obtain nanoink printing methods (78) (80).

3.3.5.5 Market analysis

Factors spurring the growth of printed electronics, i.e. market drivers, currently include: the development of organic PV, flexible batteries and other innovative products; low manufacturing costs, low barriers for new entrants and reduced handling costs for manufacturers,

which result in a higher return on investments; versatile products made possible by the free choice of substrates; and a decreased time-to-market due to simple production technologies (75) (80).

Printed electronics also offer many new opportunities, such as the bypassing of expensive and inflexible traditional silicon-based electronics, and they may be able to replace ITO in the future. The possibility of a fast roll-to-roll production, good scalability and low complexity are great opportunities to overtake conventional technologies. New possibilities of manufacturing thin, lightweight products cost-efficiently with minimal wastage can create innovative electronic items. Finally, the availability of experience with conventional printing techniques leads to low entry costs into this fast-growing market (75) (80) (77).

On the other hand, there are some major short-term challenges in this developing technology. First, there is the unfamiliarity with and lack of awareness of printed electronics among end users. Performance and product lifetimes of printed electronics products are presently unsatisfactory when compared to conventional electronics. The instability of organic materials results in an increase in costs, and there are also other technical limitations which inhibit the growth of the market. Since economic conditions are currently limiting investments, new products have to be highly innovative and the quality and reliability have to be on a very high level to be able to compete on the market. Finally, the general competitive situation in this market is extremely unfavourable (80).

In the future, there are some important developments to watch, such as great price sensitivity resulting from severe competition, bringing much pressure to innovate and fast technological change. Currently Europe (especially Germany) leads the world market and the core research is mainly done in Europe and North America, whereas integrated manufacturing takes place in Asia; however, this situation can change quickly in such a dynamic market. A further angle to watch is how soon the market adapts to the new technology to integrate printed electronics into new areas such as toys and textiles, offering extensive possibilities for a variety of new products. Finally, alliances play a vital role in the market and could be of great value in terms of competitive advantage. Some of the most important alliances: Printed Electronics Korea, FlexTech Alliance, Organic and Printed Electronics Association (OE-A), Printed Electronics Arena (PEA), Japan Advanced Printed Electronics Technology Research Association (JAPER), ROPAS, COLAE (77) (80).

3.3.5.6 Key players

The most important players in the printed electronics market are listed in the table below.

R&D Key players	
Organization	Description
Europe	
Colae (and its members)	Project designed to simplify and speed up the commercialization and adoption of organic electronics technology through the creation of industry clusters
ROPAS	Wireless sensor device on paper
FLEXIBILITY	Multifunctional, ultra lightweight, ultra thin, bendable OLEA
Swiss Center for Electronics and Microtechnology	Printed OPV with high-efficiency architecture, high-performance photo active and passive materials cost effective flexible substrates, diffusion barriers and substrates
Accent Pro 2000	Automated digital radiography systems for inspection of plastic electronics
UK Technology Strategy Board	OLEA
Oxford Photovoltaics	Transparent, glass based screen printable photovoltaic technology, solid state dye sensitized solar cells
USA	
Magnolia Solar	Space solar cells
University of Texas	3D rapid prototyping technologies
Solicore Inc.	Imaging technologies and power
Plextronics Inc.	Polymer-based OLED and OPV
Innovalight Inc.	Solar industry
Bridgelux Inc.	GaN-on-Silicon LED
3M	Ultra Barrier Solar Film
Alien Technology Corp.	RFID-UHF
Universal Display Corp.	Large area PHOLED
SouthWest Nano Tech. Inc.	Semiconducting inks based on SWCNT
College of Nanoscale Engineering at the University of Albany	Creation of a solar science and manufacturing consortium
QD Vision Inc.	Quantum dot-based IR materials for electroluminescent and photoluminescent applications
Japan	
Tokyo Institute of Technology	Low cost quantum dot photovoltaics with silicon inks
Waseda University	High performance inkjet-printed electronics
Research Center for Organic Electronics, Yamagata University	Manufacturing process for flexible organic LED illumination devices by printing
Japan Advanced Printed Electronics Technology Research Association (JAPER)	Large area flexible devices
Chemical Materials Evaluation and Research Base (CEREBA)	Organic electronics materials, OLED
AIST Flexible Electronics Research Center (FLEC)	Flexible devices, Printable electronics technology
Department of Electrical and Electronic Engineering, The University of Tokyo	Organic semiconductors dot thin-film transistors
The Institute of scientific and industrial research, Osaka University	Printed electronics, nanocomposites, nanofibres

R&D Key players	
Organization	Description
Rest of the world	
Flexible Display Research Center at Konkuk University and VTT	Precise Engraving Technology for PE;PE using R2R gravure printing method
Intelligent Polymer Research Institute at University of Wollongong	Understanding of electrical charges under solar irradiation in organic materials
Ascent Solar Technologies Inc., USA	Joint development agreement with TFG Radiant to establish manufacturing facilities in East Asia
Anwell Technologies Limited, Hong Kong	Development of thin-film solar panel manufacturing base in Dongguan
Tera-Barrier Films Pte. Ltd Singapore	Commercialization of its proprietary, moisture resistant films for organic solar cells and flexible displays

3.3.6 Nanocatalysts

An important nanotechnology which is already in the mature phase of the technology lifecycle is that of nanocatalysts. The following technology profile describes the characteristics of nanocatalysts as well as possible applications, technical challenges and the position in the lifecycle. Important players in research and industry are identified, along with other sectors that may be impacted by nanocatalysts. Adopting a market perspective, the technology profile gives an overview of critical drivers, opportunities, and developments to be watched on the market. It gives an idea of what economic challenges and key barriers the technology has to overcome to become commercially usable in industry and successfully penetrate the market.

3.3.6.1 Description of the technology

Nanocatalysts are nanoscale materials that have at least one nanoscale dimension, or have been subjected to nanoscale structural modification, in order to enhance their catalytic activity. Catalysts have the ability to accelerate chemical reactions without undergoing any permanent changes themselves (81).

The most significant characteristic of nanocatalysts is that they provide a larger surface area to speed reactions; materials which are not catalytic in bulk become so at nanoscale. Nanotechnology potentially enables custom design of catalysts to achieve perfect selectivity in a catalytic reaction (81).

Nanocatalysts can be classified into the following four groups (81).

Nanoparticulate catalysts

Nanoparticulate catalysts are transition-metal particles ranging from 1 nm to 50 nm in size, synthesized mechanically (grinding of bulk metals), by a chemical reduction process of metal salts or by the controlled decomposi-

tion of metastable organometallic compounds. In production a variety of stabilizers are used to control the growth of the initially formed nanoclusters and to prevent them from agglomerating. Highly dispersed mono- and bimetallic colloids can be used as precursors for catalysts, with applicability both in the homogeneous and heterogeneous phases (81).

Nanoporous catalysts

Nanoporous catalysts are inorganic solids with pores which act as corridors for molecules to move in and out of the catalyst. Semiporous membranes are useful in separating components of a fluid, i.e. to separate pollutants from the pure substances. Hybrid nanoporous crystalline materials (e.g. acidic zeolite catalysts) are used in gas processing and hydrogen storage, for the catalytic cracking of petroleum naphtha into gasoline and the transformation of methanol into hydrocarbons (81).

Nanocrystalline catalysts

Nanocrystalline catalysts are nanoparticles with a structure that is mostly crystalline. Compared to other high-activity catalysts, nanocrystalline catalysts can produce a more powerful effect in catalyzing a chemical reaction (e.g. cobalt oxide catalysts). Applications are the control of emissions from liquid petroleum gas powered vehicles and of alkaline volatile organic emissions from stationary sources (81).

Supramolecular catalysts

Supramolecular chemistry deals with the weaker, reversible noncovalent interactions between molecules. Much of the development of supramolecular catalytic systems arose from experience with enzyme catalysis. Catalysis employing supramolecular catalysts aims to achieve rate enhancement of reactions in terms of the structure of reactants and the mechanism of the reaction (81).

General

Nanocatalysts have a number of special properties that make them extremely valuable. For example, nanocatalyst particles have a high surface-to-volume ratio and thus have a large surface area. Due to their chemical structures they have strong electrical properties. Magnetic nanomaterials coupled with semiconducting materials also exhibit improved magnetic properties (e.g. in hydrogen production for fuel cells). In terms of thermal properties, nanocatalysts in the form of nanocomposite materials can overcome the challenge of producing the desired results in varying ambient temperatures. Other important advantages are the optical and photocatalytic properties of nanocatalysts. By controlling the particle size and thickness based on the critical wavelength of light it is possible to produce nanowires and quantum dots (81).

3.3.6.2 Examples of application

Examples of applications of nanocatalysts can be found in different industry sectors.

In the oil and gas industry nanocatalysts are used for catalytic cracking, heavy-oil up-gradation, cleaning up oil spills, desulphurization, reformation, coal liquefaction and biodiesel/ethanol production (involving the removal of impurities such as sulphur, nitrogen and metals to reduce the emission of toxic gases; the improvement of the frictional properties and thermal stability of the oil and gas; the reduction of the octane and sulphur content in the oil to reduce pollution levels; and increasing the fluidity of heavy oil) (81).

Concerning fuel cells, nanocatalysts are used for the manufacture of compact fuel cells with enhanced durability. They are also able to induce high energy density and advantageous oxidation resistance and redox properties (81). Nanoscale platinum is used as a catalyst for producing hydrogen to be used in fuel cells.

In the renewable energy sector, nanocatalysts enable the conversion of liquid fuels into energy resources to fuel automobiles. They also help reduce storage degradation and induce better cold flow properties and cleaner combustion (for bioethanol, biodiesel and various other biofuels) (81).

In the chemical and polymer manufacturing sector, nanocatalysts help to increase the efficiency, selectivity and yield of certain chemical production processes, and are used in polymer solar cells and fuel cells. Polymer semiconductors, agrochemicals, industrial chemicals, cosmetics and dyes/pigments are additional examples of applications of nanocatalysts (81).

3.3.6.3 Technical challenges

Though nanocatalysts have already reached the status of a key technology, there are various technical challenges that

they have to overcome to become even more successful in the industry. One current one is to ensure nanocatalyst stability and activity over a longer period of time, since instability can lead to the formation of undesired by-products (81) (82). Another problem that needs to be solved is that in many cases a nonhomogeneous distribution of the nanocatalyst in the reactive solution leads to an agglomeration of the nanoparticles (81) (82). In general, the manufacture and control of specific nano-sized particles can be regarded as a technical challenge (81) (82). Moreover the production of catalysts with higher product selectivity, and the reusability of nanocatalysts, are important issues that need to be addressed by current R&D activities (81).

3.3.6.4 Technology lifecycle

Nanocatalysts have already reached the maturity phase of the technology lifecycle with respect to the examples described above, and thus can be regarded as a key technology with high development potential. For other applications, such as rechargeable post-lithium ion batteries, the potential use of nanocatalysts is still at a basic research stage.

3.3.6.5 Market analysis

Key drivers (market perspective)

Looking at nanocatalysts from the market perspective, certain key drivers can be identified that will be crucial for the impact of the technology on the industry and the market.

One current key driver is a green and nanoscale trend in general. Worldwide regulations have fuelled the need for cleaner and more resource-efficient technologies such as catalysts. Thus the increase in efficiency and selectivity and the reduction in costs for the production of catalysts due to the use of nanostructures are critical factors concerning future industry use (81) (82).

Concerning petrochemical refining, the reduction of costs for separation by avoiding the formation of unwanted by-products is a critical issue. Also the reduction of air pollution by removing sulphur, carbon monoxide and nitrogen for a clean and renewable source of oil products with enhanced efficiency will play an important role. Regulatory issues pertaining to the environment have propelled the use of nanocatalysts so far. More efficient upgrading of heavy oils may be another important factor influencing the oil and gas industry (81).

The key driver in the energy sector is the need to meet the increasing demand for cost-effective renewable energy resources. This is likely to lead to a boost in fuel cells due to their increasing ability to store and produce clean energy. From a technical point of view, using the steam reforming process can improve the capacity and speed of biofuel production. Regarding environmental protection, regulations concerning the emissions of toxic exhaust gases and the idea of "green chemistry" reducing the use of toxic chemical solvents in reaction processes are important issues (81).

Critical drivers in the chemical industry are the reduction of manufacturing costs through lower temperatures and less requirement for reactants; increased purity and thus durability of products; and faster chemical reactions, allowing faster and less expensive production (81).

Opportunities (market perspective)

Another important indicator of the future success of nanocatalysts in the market is the opportunities they will offer. For example, combining nanocatalysts with microreactor technology would enable cross-directional or even metabolic flow – this is likely to be realized in the medium term. The commercialization of nanotechnology for catalytic cracking and catalytic reforming is a second promising opportunity from the industry perspective. Catalytic converters can also be regarded as an interesting future opportunity, along with the use of nanocatalysts for SNG fuel and biofuel conversion. Large-scale production and use of portable power units is a further very important opportunity for the technology, and nanocatalysts may also be usable as biological catalysts (81).

Key barriers

A critical barrier that the technology of nanocatalysts has to overcome to be successfully usable in the industry is a lack of infrastructure for new energy systems such as fuel cells. The difficulties of handling hydrogen will also slow down fuel-cell market penetration (81) (82).

Economic challenges

In addition to the technical challenges described, a number of economic challenges must also be met by the technology if it is to become important in industry and on the market. An example is the slow speed at which new technologies are adopted in the petrochemical refining

industry; another is current and future regulations with economic consequences on the use of nanomaterials. Finally, the cost of producing and using nanocatalysts is at present too high in relation to their current performance (81) (82).

Developments to watch

There are certain developments concerning nanocatalysts that should be carefully watched in the future, such as current and future regulations on nanomaterials and especially nanocatalysts, or current research at Symyx Technologies on low-cost metal catalysts with enhanced performance in chemical processing (81).

Expected market relevance

Nanocatalysts are expected to be market-relevant in the oil and gas industry, green technology, alternative energy and polymer industry sectors (82).

3.3.6.6 Impact on other energy sectors

In addition to their promising impact on solar energy and energy storage, nanocatalysts may also have a non-negligible influence on other energy sectors such as energy-saving technologies, heat, fuel cells and heat pumps.

3.3.6.7 Key players

Regarding R&D as well as current industrial activities, there are a number of key players dealing with nanocatalysts. The key players we have identified are likely to play an important role in the future development and market success of the technology and are listed in the table below, ordered by type of catalyst (82).

Type of catalyst	Company or Institution
Oil refining processes	HeadwatersNanoKinetix
Oil refining processes	Oxonica nanomaterials in UK
Batteries, emissions reduction, fuel cells, and hydrogen generation	QuantumSphere Inc. (incl. Energetics Incorporated)
Regenerative fuel production	Avoyelles Renewable Fuels Group
Fuel cell catalysts	Antaira (formerly called Advanced Nanotechnology Limited)
Chemical and petrochemical applications	Symyx Technologies
Hydrogen production	Nanoptek
P-Cube (removing sulphur from crude oils)	ThalesNano
FlexDS (desulphuration of crude oil for vehicles)	Catalysts and Chemicals Co. Industries Ltd.
Biofuel conversion	Sasol, Dioxide Materials, Albemarle Corporation, Green Power Inc.
Hydrogen conversion	Ultracell LLC

3.3.7 Nanofluids

The final nanotechnology that has the potential to influence the solar energy sector is the technology of nanofluids. The following technology profile describes the characteristics of nanofluids as well as possible applications, technical challenges and the maturity and status of the technology within the technology lifecycle. Other sectors that may be impacted by nanofluids are identified, along with key players that are likely to play an important role in terms of research and industrial activities. Since the technology of nanofluids is at a very early stage of research, it is not possible so far to make any reliable predictions about the future development of nanofluids on the market, which is why we have omitted the market perspective in this technology profile.

Out of the energy sectors considered in this study, energy storage and solar power (including PV and solar thermal), it is clear that the main relevance of nanofluids is to solar thermal applications. In the roadmap they are listed under the solar thermal application technology layer.

3.3.7.1 Description of the technology

Nanofluids are colloidal suspensions of nanometre-sized materials (nanoparticles, nanofibres, nanotubes, nanowires, nanorods, nanosheets or droplets) in a base fluid. They consist of a solid-phase nanomaterial and a liquid-phase base material. They are used to increase thermal conductivity, thermal diffusivity, viscosity and the convective heat transfer coefficients (83). Furthermore they enhance the ability to absorb light by scattering. The magnetic properties of the solid-phase nanomaterial can be used for better control of the distribution of the fluid or to modify the physical properties of the fluid (for example the freezing or melting point temperature) (84) (85) (86).

The most widely used preparation process is to disperse nano-sized powder in a fluid. The powder is first mixed with a surfactant to avoid aggregation of the nanomaterial caused by its high surface area. Homogeneous dispersion of the nanomaterial in the base fluid is achieved by magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing or ball milling (83).

Other methods to produce nanofluids are physical vapour condensation and the vacuum-SANSS (submerged arc nanoparticle synthesis system), in which the nanomaterial is made and dispersed in the fluid simultaneously to avoid agglomeration. Although drying, storage and transportation of the nanomaterial are thus avoided, these methods are not applicable for large-scale production and their costs are also very high. The costs can be reduced by using the one-step chemical method, but residual reactants in the nanofluids then constitute a major disadvantage (83).

The optical properties of the absorption fluid depend on the shape and particle size of the nanoparticles as well as on the optical properties of the base fluid (84).

3.3.7.2 Examples of application

In solar thermal collectors of concentrated solar power plants (CSP) nanofluids are used to enhance the absorption of sunlight by scattering the incident radiation. Common base heat transfer fluids are water, ethylene glycol, propylene glycol and therminol VP-1 (84) (85). The nanoparticles added to the base fluid may be copper, copper oxide, aluminium, aluminium oxide, zinc oxide, titanium dioxide, silver, nickel, or carbon-based nanostructures (e.g. graphite, fullerenes, single-walled carbon nanotubes (SWNTs), multi-walled carbon nanotubes (MWNTs), nanodiamond, graphene or single-walled carbon nanohorns (SWCNH)). Among these nanoparticles, carbon nanotubes seem to be preferred due to their very high thermal conductivity (maximum enhancement of thermal conductivity of 14.8%) (87) (88).

In photobioreactors, nanoparticles are used to enhance the performance of algae such as *Chlamydomonas reinhardtii*, *Cyanothece* and *Synechococcus elongatus* SA 66539 to increase the production of hydrogen or isobutanol by controlling the way light is delivered to the micro-organisms. This effect is achieved by plasmonic nanoparticles, which have certain wavelength-specific back-scattering characteristics to ensure a higher light density and hence a better light delivery to the organisms (86).

Another application of nanoparticle-enriched fluids is nano-modified insulating vegetable oil. By adding Fe_3O_4 nanoparticles to insulating rapeseed oil, the AC breakdown voltage and lightning impulse breakdown voltage can be increased by 20% and 14% respectively. The volume resistivity and the relative permittivity are also increased by this type of nanomodification (89). The breakdown strength of insulating mineral oils and synthetic ester liquids can also be increased by magnetic nano- Fe_3O_4 -particles (90).

Other fields of application are the use of nanoparticles in phase-changing materials in thermal energy storage systems to enhance the thermal conductivity (91), and the enhancement of the heat conductivity of cooling liquids by the addition of nanoparticles. Important examples where size, weight, efficiency or complexity can be reduced with nanofluids are chip, space, aircraft, military, automotive engine and heavy-duty cooling systems. The use of nanofluids in closed-loop cooling cycles in industrial systems results in more efficient and thus more economic operation of production facilities including (nuclear) energy plants. In the heating systems of very large buildings, nanofluids can help to reduce pollution by reducing energy consumption (83) (92).

In mechanical applications ionic multiwalled carbon nanotubes or ultrafine tungsten disulphide can help to reduce friction and thereby improve resistance to wear. Nanofluids with magnetic Fe_3O_4 nanoparticles have self-healing characteristics in case of leakages (83).

3.3.7.3 Technical challenges

Though promising for many potential applications there are various technical challenges that nanofluids have to overcome to be applicable and gain importance in the industry. Some of the most important issues that have to be dealt with are explained below.

Because of the aggregation of nanoparticles, the preparation of a homogeneous suspension at reasonable cost still remains the most important technical challenge to enable successful use of nanofluids in commercial applications (92). The surfactant used to avoid aggregation of the nanomaterials within the fluid represents a large challenge for industrial applications because of its physical properties under high temperature, and because most surfactants change the properties of the nanoparticles and remaining impurities can deteriorate the functionality of the fluid (83) (92).

Another important technical problem to be solved is the poor stability of nanofluids during their lifecycle, which results in decreasing functionality. Agglomeration of the nanoparticles leads to clogging of channels and also means decreased functionality; this can be avoided by surfactants and functionalized nanoparticles (83).

An additional technical challenge is the fact that one side-effect of the addition of nanoparticles to fluids is increased viscosity and density of the fluid, which may require more pumping power for circulation (83).

3.3.7.4 Technology lifecycle

The technology of nanofluids is at the very beginning of the emergence phase of the technology lifecycle. Thus in their current state nanofluids should be regarded as an emerging technology, which is still in basic research.

3.3.7.5 Impact on other energy sectors

In addition to their promise for solar energy, nanofluids may also have a non-negligible influence on other energy sectors such as nuclear power, energy-saving technologies, and in particular heat energy applications.

3.3.7.6 Key players

Due to the early stage of development, no key players have been identified.

3.3.7.7 Market perspective

Again, the technology is in such an early stage of research that no studies on market perspectives have been identified. One thing seems clear: overcoming the identified technical challenges will be critical for nanofluids to become commercially usable in applications and successfully enter and impact the market.

3.4 Manufacturing perspective

Without doubt nanotechnology has proved to be a promising field of research to overcome the global challenges in the field of resource and energy efficiency – as a matter of fact it is deemed to be the key enabler in this respect, as shown in the technology profiles above. Yet nanotechnology-based product concepts are but one necessary element in exploiting existing market potential and meeting societal needs. A major breakthrough of nanotechnology in terms of market impact and relevance also requires these products to be

- ◆ producible, distributable as well as recyclable
- ◆ on an industrial scale, and
- ◆ at reasonable cost and risk to business and society.

Thus, in order to understand the potentials but also risks and challenges that nanotechnology faces in manufacturing – not only in the energy sector – it is necessary to consider a holistic concept of value (93) (94). Consequently, for the purposes of this report all issues related to the manufacturing of nanotechnology-based products will be discussed and evaluated along the following three problem domains (see Figure 34):

1. Nanotechnology in manufacturing
2. Nanotechnology for manufacturing
3. Nanotechnology beyond manufacturing.

Their general description follows.

Problem domain 1: nanotechnology in manufacturing

In order to deal with nanotechnology in manufacturing one has to consider first of all the production, processing and handling of *nanomaterials* and *nanoproducts* in an industrial environment. Nanomaterials may be divided into *basic nanomaterials* and *nanocomposites*. Whereas basic nanomaterials are most often one-phase solids that have at least one nanoscale dimension, nanocomposites typically incorporate at least one basic nanomaterial. Nanoproducts are produced by applying at least one nanomaterial in the manufacturing process. Based on that, nanoproducts may be divided into (1) products that *incorporate* nanomaterials in order to feature some of their special properties, leading to superior

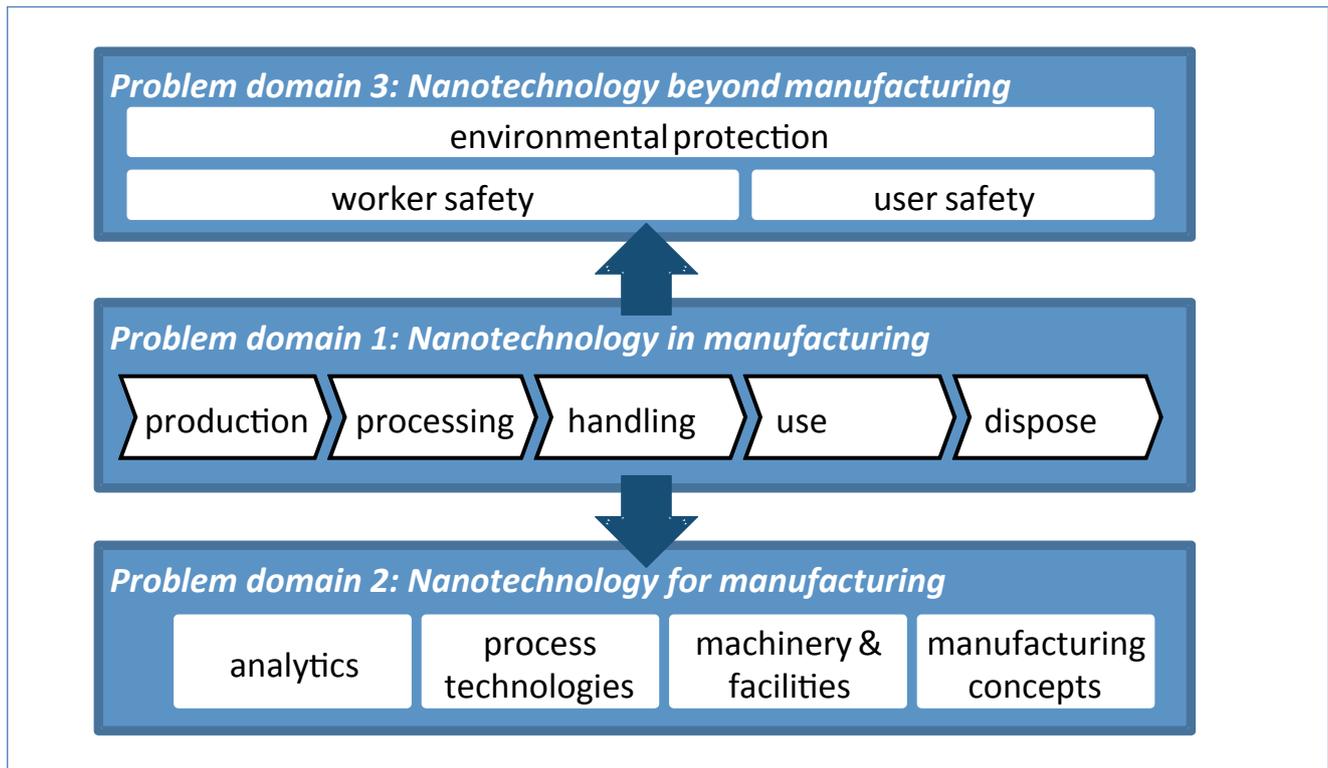


Figure 34 – Problem domains for nanotechnology in manufacturing

product performance/quality, and/or (2) products that are produced by *applying* nanomaterials or that *have a nanostate* during the process in order to achieve superior performance/quality but which do not incorporate nanomaterials or have a nanoscale dimension in their final state.

Nanomaterials are produced and processed *top-down* and/or *bottom-up* (40). The essence of top-down processes is the extraction of nanomaterials by processing non-nanomaterials, e.g. by extreme plastic deformation. In contrast, bottom-up processes rely on the growth/assembly of molecular building blocks into structures of a higher-dimensional order (\rightarrow nanoscale), by organic/inorganic chemical synthesis or nanolithography for instance.

Although some basic nanomaterials such as soot, pigments or SiO_2 have been applied in industrial processes for some decades and have occasionally led to some advanced nanoproducts in nearly every industry, nanotechnology is still a technological niche in manufacturing. There are still significant gaps in available manufacturing processes that lead from working prototypes to mature products for the consumer and industrial goods markets (93). Besides costs and financing, which appear to be the most significant challenge today, it is also the *scaling up* and *scalability* of production processes as well as *process stability* in terms of product quality and quantity that constitute major challenges for a large-

scale breakthrough of nanotechnology (see Figure 35). Although this appears to be true for any application in/of nanotechnology, it seems that these issues are even more valid for the applications in the energy sector as discussed in this report.

Problem domain 2: nanotechnology for manufacturing

Based on the above, it is clear that the production, processing and handling of nanomaterials not only requires more advanced analytical tools and machinery as a means to achieve the necessary precision and process stability, but it may call for new processing technologies or even manufacturing concepts in order to provide the basis for large-scale and profitable production of nanoproducts. Consequently, even if research into the application of nanotechnology to products in the energy sector leads to technologically sound product designs, their diffusion may still suffer from the lack of available process technologies and equipment.

Fortunately, nanotechnology also drives the development in this domain and has already been identified as promising. In some cases even the use of nanotechnology in mature applications may lead to new processes and equipment that will enable the production of other nanoproducts (see Table 2). These manufacturing processes have a broad influence on all nanotechnologies shown in the technology profiles.

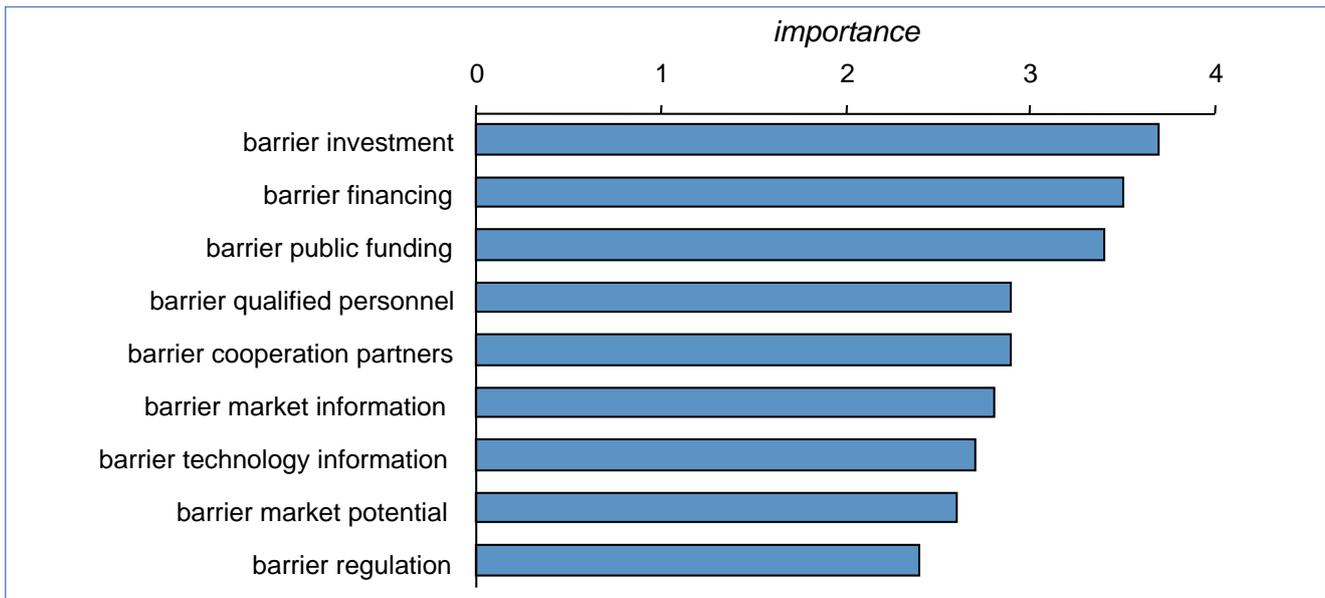


Figure 35 – Barriers for nanotechnology applications (survey of 107 German companies in the field of nanotechnology) (95)

Table 2 – Selected application possibilities of nanotechnology in mechanical engineering

Application possibility	Advantages by applying nanotechnology	Field of application	Examples for nanomaterials
Transparent hard-material layers	High hardness, transparency	Production technology, coatings	Aluminium oxide
Chemical mechanical planarization (CMP)	Ultrasmooth surfaces	Production technology (semiconductor industry)	CeO ₂ , SiO ₂ and others
Abrasion-resistant layers with low friction coefficient	Thin layers with good compromise of adhesion, hardness and friction	Production technology	Diamond like carbon, boron carbide, boron nitride
Friction-reducing coatings	Friction reduction through low-wear and, at the same time, low friction surfaces	Combustion engines	Iron carbide
Nanodiamond for low-wear tools	Extreme hardness and service life	Coating technology	Nanodiamond
Mechanical enhancement of polymers	Transparency and good viscosity/E-module ratio	Lightweight construction	Layer silicates
Plastic modifications	Wear resistance at low rolling resistance	Materials handling, drive technology	Carbon black, carbon nanotubes
Position systems	Precise positioning	Automation engineering, measuring technology	Piezoelectric crystals

Problem domain 3: nanotechnology beyond manufacturing

However, even if the problems directly linked to the manufacturing of nanomaterials and nanoproducts are solved, there are still some overarching issues related to the nanotechnology value chain that may represent major challenges or impose major risks for the breakthrough of nanotechnology. These are in particular societal concerns on the impact of nanotechnology on the

environment, workers and users. Most important in this regards is that these not only cover the production of nanomaterials and nanoproducts but also extend to the consumption/use and disposal of nanoproducts. None of these questions have been convincingly answered yet (93). In fact, some experts state that *societal feasibility* may be even more important than technological feasibility. The latter point is interesting as it implies that there may never be such a thing as a technology push in the domain of nanotechnology.

3.5 Roadmap Layer 1 – Nanotechnologies

In this section, the blue layers of the Roadmap will be described in detail. These layers describe nanotechnology developments which are expected to reach market readiness in the corresponding years. Market readiness means that the nanomaterial, component or technology has passed the pilot phase and is ready for use in commercial products (e.g. in first small series). However, broader market diffusion has not taken place. The same definition for market readiness also applies to the second and third layers of the roadmap.

The nanotechnologies described in the first layer enable or improve concrete application technologies in the fields of solar energy and energy storage, in the sense that a nanomaterial, component, or technology improves technical (e.g. efficiency, power, lifetime, safety) or non-technical parameters (e.g. costs, substitution of critical materials). This does not mean that nanotechnologies are the only influencing developments to improve or enable application technologies, but rather that, here, it is specifically the contributions of nanotechnology which are being pointed out. The layers are shown in Figure 36 and Figure 37. Most of the developments have been described at a general level in the technology profiles in the context of their relevance to application technologies and markets. Here, developments identified from the literature, existing roadmaps as well as expected future developments based on the roadmapping workshop II and additional expert interviews after the workshop are shown in the time frame from 2012 to 2030 and beyond.

It should be emphasized that this “meta-roadmap” has to be understood as a document that systematically maps different roadmaps, expert views and further literature into a single format which allows comparisons. The intention has been to identify main current and future developments. Thus not necessarily all possible developments to be found in the literature are shown in the roadmap, as there might not have been adequate information about a topic, the source might have been too old (e.g. older than 5 years) or not citable, the developments might not link to nanotechnologies or not be essential to outline the main R&D path in the energy sectors considered, etc. Also a roadmap, and a meta-roadmap as well, are always “living documents”, in the sense that regular updates and validation are necessary.

In the following, the entries in the nanotechnologies layer as shown in the roadmap are listed, explained, and linked to relevant application technologies where possible.

3.5.1 Nanotechnologies for solar energy

Nanoelectrodes

SE1 Metal oxide nanoparticles for transparent electrodes (other than ITO, e.g. based on ZnO, MoO₃, SnO₂) Metal oxide nanoparticles for trans-

parent electrodes are already in use today (different metal oxides in different solar cell types). They are expected to substitute for ITO in the medium to long term. The market entry phase is expected by 2015 (96) (97) (98).

SE2 Nanoparticles for recombination layers (metal oxides) Nanoparticles for recombination layers are already used today and expected to firm up their use in solar cells by 2015 (96) (97).

SE3 CNT for transparent electrodes in PV cells (ITO replacement) In addition to other organic or inorganic transparent conductors, carbon nanotubes are seen as the future successors to transparent films for PV cells from 2017 on (replacing ITO films) (98).

SE4 Graphene for transparent electrodes in PV cells (ITO replacement) Graphene is considered a good replacement for ITO films acting as electrodes, due to its characteristics including low sheet resistance, high optical transparency and excellent mechanical properties. The application of graphene in PV cells is not expected before 2020 (98).

Nanocarbon materials

SE5 Fullerenes (C₆₀, C₇₀, ...) for OPV Fullerenes are already extensively used as electron acceptors in OPV (III Generation). In the coming years (2013-2017), novel fullerene acceptors (including others in addition to C₆₀) as well as other organic acceptor materials are expected to be used to reach higher efficiencies (96).

SE6 Nanocarbon materials for counter electrodes in DSSC In the coming years (2013- 2017), nanocarbon materials (e.g. graphene, carbon nanotubes) are expected to be used to improve the counter electrodes in DSSC by replacing platinum (III Generation) (96) (98).

Nanocomposites

SE7 III-V semiconductor QD for intermediate band solar cells The efficiency of PV cells can be improved radically by the use of an intermediate band between the valence band and the conduction band in the semiconductor. This way energy levels which don't fit in the band gap can still be absorbed and converted into current. These energy levels of the semiconductor may be manipulated by quantum dots after 2018 to achieve the desired characteristics (98).

SE8 Gold nanoparticles as “hot spots” in PV cells By using gold nanoparticles, the efficiency of PV cells can be increased. The estimated time of implementation is the future after 2020 in emerging photovoltaic applications (III Generation) (98).

SE9 Core-shell composite materials for PV (QD Solar) are materials with a core of an inorganic material and a shell of another material in order to achieve certain characteristics in the material. These materials are expected to be applied between 2013 and 2016 to emerging photovoltaic applications (III Generation) (98).

SE10 III-V semiconductor QDs for tandem solar cells For III-V semiconductor PV cells, the band gap may be tailored by creating quantum dots for use in tandem solar cells after 2018 (98).

SE11 II-VI semiconductor QDs and wires for hybrid solar cells (ZnO, nanorods) Hybrid solar cells, which consist of organic-inorganic cell architectures, make use of ZnO nanostructures as electron acceptors. This technology is not expected to be applied before 2015-2019 (98).

SE12 Gold nanoparticles for plasmonic layers in solar cells The problem of bad light absorption by the thin absorption layers in thin-film solar cells (Generation II and III) can be solved by a light-scattering and absorption-enhancing layer of plasmonic metal nanoparticles. In the near future (2013-2015), solar cells with gold nanoparticles in a plasmonic layer are expected to enhance the absorption and hence the efficiency of the cell (98).

SE13 Si-QDs (hot carrier) In order to reduce the hot-carrier relaxation rate and thus energy losses, semiconductor quantum dots will be used to slow down energy cooling and thus enhance efficiency of solar cells. Market entry is expected after 2015 (98).

SE14 Nanocomposite QDs for single/multijunction PV (e.g. Si, II-IV, ...) In order to enhance the efficiency of solar cells, silicon quantum dot cells for example can be used in single/multijunction PV cells to tailor the band gap. Market readiness is expected for 2017-2020 (96).

SE15 Ti-O₂ Nanoparticles for DSSC are already extensively used in dye-sensitized solar cells (III Generation) (2008-2015). The time frame to 2015 points to the fact that the technology is still waiting to be taken up by the market. Other TiO₂ structures such as nanorods are expected to reach the market later (98).

SE16 ZnO Nanoparticles as substrate material in DSSC ZnO or other metal oxide nanoparticles (e.g. tin oxide) are expected to be ready for use as a substrate for dye-sensitized solar cells (III Generation) between 2015 and 2020 or even later (98).

Nanocoatings

SE17 Improved H₂O and air protection coatings for organic PV are foreseen for 2015 and were

discussed in workshop II. These coatings are expected to increase the protection of solar cells. Material performance inside solar cells is not expected to be improved by novel coatings (99).

SE18 Improved UV-resistant coatings for increased life time were discussed in workshop II and are also estimated for 2015. These coatings are expected to increase the protection of solar cells. Material performance inside solar cells is not expected to be improved by novel coatings (99).

Printed electronics

SE19 Printed inorganic nano-particulate PV (e.g. CIGS, CuZnSnSSe) Besides organic PV, nanoparticles are also expected to play an important role in the technology of printed inorganic PV from today to 2030. Nanoparticles are already used in roll-to-roll printing of thin film CIGS (II Generation). Further improvements as well as application to new technologies that avoid the use of indium, such as the CuZnSnSSe System, are expected in the future (96).

SE20 Nano-Silver as ink for printed electronics This technology refers to suspended metal nanoparticles (NP), which are already used today in printed electronics (98).

SE21 Dendritic polymers for organic photovoltaics (OPV) to improve morphology are polymers consisting of repetitively branched molecules, which are expected to be used in the foreseeable future (2017-2025) in emerging photovoltaic applications (III Generation) to improve the morphology. Similar advances are to be expected with cross-linkable polymers and block copolymers (98) (97).

Nanofluids

- **New heat transfer fluids** are mentioned in the context of solar thermal applications to be developed within the next decade. Common base fluids for heat transfer today are water, ethylene glycol, propylene glycol and therminol VP-1. If nanoparticles are added to the base fluid (e.g. metallic particles, metal-oxide particles or carbon-based nanostructures) the thermal conductivity of such a nanofluid can be enhanced. As stated in the technology profile on nanofluids, the development of nanofluids is still in its infancy and may become relevant further out.

Nanocatalysts

- With respect to the solar energy sector, no significant developments in nanocatalysts have been identified from the literature, and hence no nanotechnology is mentioned in the roadmap. However, nanocatalysts play a large role in hydrogen storage, for example.

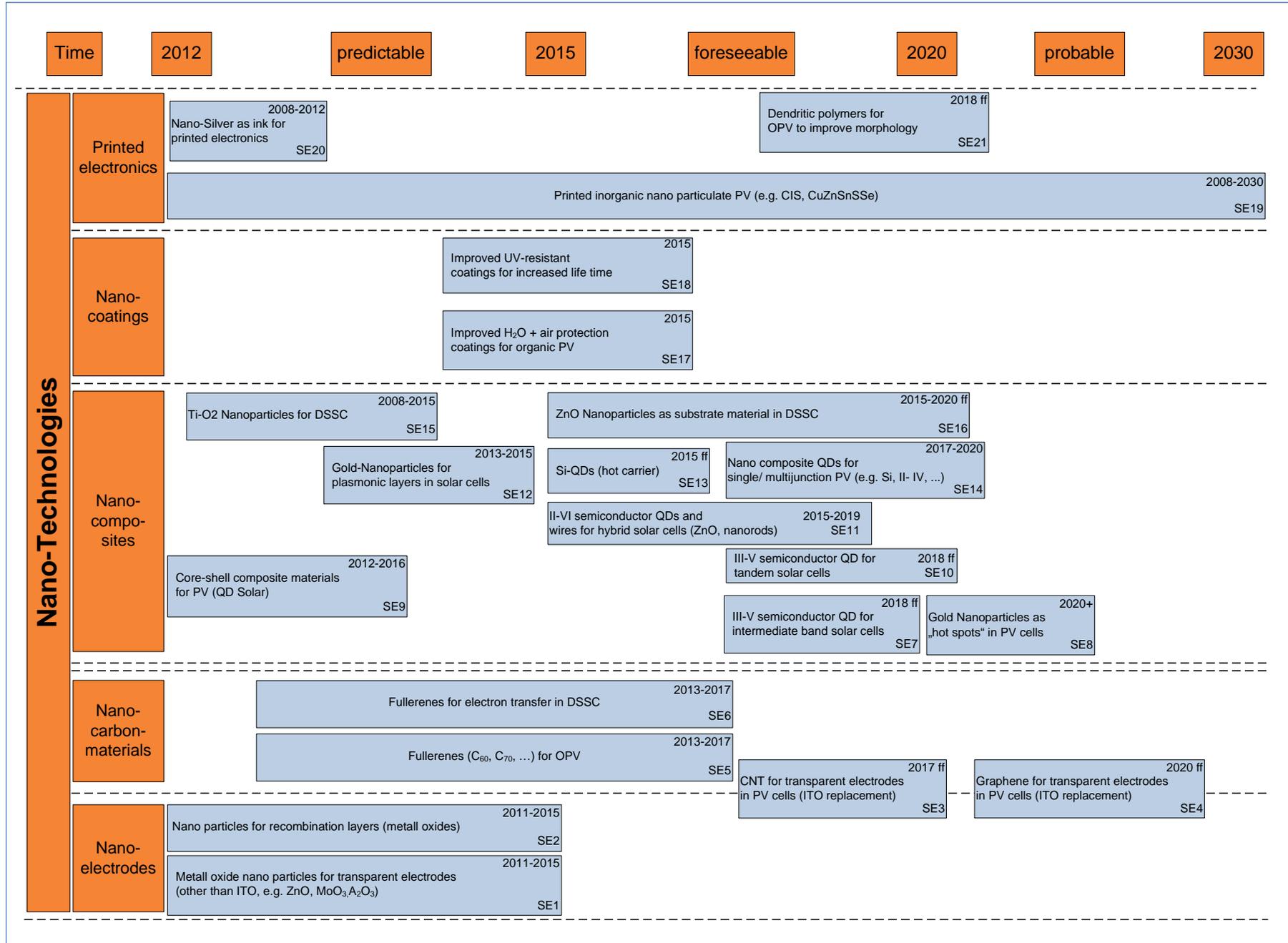


Figure 36 – Nanotechnologies for solar energy

3.5.2 Nanotechnologies for energy storage

Nanocarbon materials

- ST1 Carbon aerogels with nanometre-sized pores for supercaps** Nanoporous carbon is already broadly used in supercapacitors today, due to their high surface area and their good conductivity. Carbon aerogels with nanosized pores could be developed by 2015-2019 with precise control over the pore size. This could lead to very high electric conductivity of the electrodes in supercapacitors (98).
- ST2 Use of advanced carbons (graphene, CNT) in supercapacitors** After 2020 other advanced nanotechnology-based carbons, besides carbon aerogels, could also enter the market (e.g. graphene, CNT) (99).
- ST3 Carbon fibres for flywheels** With long-length carbon-fibre systems for rotors, the energy capacity of flywheels could be increased (analogously to ST8) (99) (100).
- ST4 Improved carbon nanotube materials for rotors** Flywheels with advanced carbon-based or other materials for the rotors (e.g. carbon nanotubes, lower-cost composites) can achieve higher storage densities. This could also translate into lower costs and be realized by 2015-2019 (99) (101).
- ST5 Nanocarbon for Pb batteries** Although a well-established technology, Pb batteries still have potential for further improvements, e.g. by using nanoscale carbon materials. Pb batteries are used as starter batteries or in stationary applications (99).
- ST6 Improved CNT composites for CAES (small)** Lower-cost CNT composites could be developed for small Compressed Air Energy Storage (CAES) by 2015-2019 for above-ground high-pressure tanks (101).
- ST7 CNT supercaps: five times higher energy density** With CNT-based supercaps, not only higher power densities but higher energy densities are also possible, up to a factor of five (99) (100).
- ST8 Long-length CNT for rotors of flywheels** With long-length carbon nanotube systems for rotors, the energy capacity of flywheels could be increased to about 10 kWh/kg in the long term (e.g. around 2025 or later) (99) (100).
- ST9 Graphite nanoparticles for H₂ storage** In the coming years (2012-2016) nano-structured graph-

ite is expected to be able to store hydrogen efficiently by absorption/desorption (98).

- ST10 Nanotubes for H₂ storage** Although metal hydrides are the today's choice for chemical hydrogen storage and CNT have not fulfilled past promises (today there is a broad consensus within the scientific community that the current stage of research in CNT for hydrogen storage makes their commercialization unlikely in the near future), in the more distant future (e.g. 2020 or beyond) CNT-based hydrogen storage could be realized (although not with pure CNT) (100).

Nanocatalysts

- ST11 Nano-Pt for H₂ catalysis** Platinum is known as a good catalyst and for improved catalytic reactions a large surface of platinum is important. Platinum nanoparticles are therefore used and available as catalysts already today for energy-efficient oxidation of hydrogen (e.g. for fuel cells). In the medium to long term, platinum-reduced catalysts may be developed (98).
- ST12 Distributed nanoparticles as catalysts (metal-air, rechargeable)** In the far future (beyond 2030) distributed nanoparticles could be used as catalysts in rechargeable (e.g. metal-air) batteries (99).

Nanoelectrodes

- ST13 CNT for FC electrodes and flow batteries** Due to their high electrical conductivity, carbon nanotubes are expected to be used as an electrode material in fuel cells or flow batteries in the near future (2013-2017). The advantages in their use in supercaps have been described above. In contrast, the use of pure CNT as electrode material in other batteries, in particular lithium ion batteries, is regarded more critically, although it is described in some documents (e.g. roadmaps older than 2-3 years)² (99) (98).
- ST14 Nanotitanates and large-scale/cost-optimized material** Lithium titanate batteries use lithium titanate nanocrystals or "nanotitanates" on the surface of the anode instead of carbon. The surface

² There was a discussion among the experts in roadmapping workshop II regarding the promises of the last decade concerning the potential of nanocarbons (in particular CNT) that did not translate into technical achievements and performance improvements. Today, other materials than pure nanocarbons are the subject of research. Thus nanocarbons such as CNT might still need longer development times, might need to be combined with other materials (e.g. within composites) or might just not be suitable for improving the performance of some of the applications (e.g. electrodes for LIB or use in hydrogen storage).

area can be greatly increased, allowing electrons to enter and leave the anode quickly. Faster recharging becomes possible and provides high currents when needed. However, lithium titanate batteries have a lower inherent voltage, leading to a lower energy density than conventional lithium ion batteries. Nanotitanates produced on a large scale and as cost-optimized material could be available around 2020 (99).

ST15 Solvents with nanoparticles are already available today (99).

ST16 Large-scale production of nano-LiMnPO₄ for high-voltage LIB The nanostructured olivine lithium manganese phosphate (LiMnPO₄) is known as a cathode material with a high voltage potential of about 5 volts and is hence a suitable choice for high-voltage lithium ion batteries. Large scale production of nano-LiMnPO₄ is expected around 2015. By then, the material could be applied to large-scale LIB (e.g. for electric vehicles) (99).

ST17 Nanosilica/fumed silica Fumed silica or fumed nanosilica (nanoparticles based on SiO₂) consists of microscopic droplets of amorphous silica fused into branched, three-dimensional secondary particles which then agglomerate into tertiary particles. Fumed silica has a strong thickening or gelling effect and helps improve the safety of batteries. Fumed silica is made using flame pyrolysis of silicon tetrachloride or from quartz sand vaporized in a 3000 °C electric arc. Major global producers are Evonik (Aerosil®), Cabot Corporation (Cab-O-Sil®) and Wacker Chemie-Dow Corning (99).

ST18 Nano-Si/Sn for Carbon as anodes for LIB (few% nano-Si) Whereas carbon materials have the advantage of possessing stable structures and very good electrical conductivity, their capacity is much lower compared to materials like silicon. At present, silicon shows the largest theoretical capacity as an anode material in lithium ion batteries. This capacity however fades drastically during electrochemical cycling, as a result of excessive volume expansion. Carbon materials can thus be used as an ideal "buffering matrix" for the silicon anode, combining the advantages and eliminating the disadvantages of both materials in one nanocomposite. Si/C nanocomposites with a small percentage of nanoparticulate Si inserted in a carbon matrix (not nanoscale) lead to higher capacities and good cycling properties. Besides Si/C, Sn/C nanocomposites may also be used,

since tin has a very high capacity as well.³ The commercial availability of such composites with a few percent of Si or Sn is expected for 2015-2020 (99).

ST19 Nano-Si/Sn for Carbon as anodes for LIB (~10% nano-Si) Si/C or Sn/C nanocomposites with a larger percentage of Si or Sn are expected beyond 2020. The goal is to maximize the Si/Sn content, leading to the development of lithium ion batteries with high capacity and high energy (e.g. suitable for the use in electric vehicles with longer ranges) (99).

Nanocomposites

ST20 Nanocomposite layers for solid electrolytes (Me-ceramics) are solid electrolyte materials (e.g. for Lithium solid-state batteries) based on metal-ceramic nanocomposite layers. They exhibit exceptionally high values of ionic conductivity. They are about or should soon be ready for the market (referring to the literature cited in the roadmap) (98).

ST21 Carbon black; polymer-nanocarbon composites for batteries; added small amounts of CNT Polymers with carbon nanoparticles inserted, e.g. small amounts of CNT, are expected to be ready for the market between 2012 and 2016 for use in batteries (99).

ST22 Nanocomposite layers for supercaps for hybrid capacitors With layers made of nanocomposites very high capacities can be achieved. They are about or should soon be ready for the market (referring to the literature cited in the roadmap) (98).

ST23 Core-shell composite materials for batteries (cheaper, thinner, one-step process) Core-shell composite materials for the use in batteries are available today, but should be technically improved by developing one-step production processes or producing thinner materials. Also, costs should be reduced in coming years (2012-2016) (98).

Nanocoatings, particles, alloys

ST24 Amorphous carbon coatings for LFP/graphites Amorphous carbon coating is one of the most widely used coating techniques for anodes

³ Pure Sn or Si-based nanostructures (e.g. Si-nanowires as anode materials) are relevant research topics but were discarded by the experts in roadmapping workshop II, since their commercialization is not foreseeable in the near future. This is due to the disadvantages of using these materials alone (such as volume expansions).

(e.g. metal oxides, graphites) and cathodes (e.g. LiFePO_4). It enhances the electrical conductivity of the electrode materials, and results e.g. in improved rate and cycling performance (99).

ST25 Nanostructured metal hydrides for NiMH batteries are estimated for the near future (2012-2016). NiMH batteries are still relevant e.g. for hybrid cars and other portable or consumer applications. (NiMH can be regarded in some sense as a bridging technology and will not compete with the lithium ion battery or other battery developments in the long term. NiMH has not been considered in the second layer of the "Application technologies" roadmap.) They still have some potential for improvement. Nanostructured metal hydrides could improve the performance of NiMH batteries in coming years (98).

ST26 Nanostructured metal hydrides for H_2 storage are expected to improve hydrogen storage between 2012 and 2016. For today's applications (e.g. in fuel-cell cars), hydrogen is still stored physically in tanks in the form of compressed or liquid hydrogen. Nanostructured or nanoparticulate metal hydrides (e.g. Mg, Al, Ni powders or alloys) have the advantage of improving the storage density through an improved surface-to-volume ratio. Another advantage is safety, as the process

of hydrogen release is endothermic and hydrogen is not released in an uncontrolled way. In the future, hydrogen could thus be stored chemically and e.g. applied to fuel-cell cars or other storage applications (98).

ST27 Stabilizing nanocoating for high-voltage materials Nanocoatings could improve other performance parameters as well, in particular the safety of batteries (such as lithium ion batteries, LIB), when developing high-voltage materials (tending towards 5 V) for next-generation LIB. Market readiness for such new coatings is expected beyond 2020 (99).

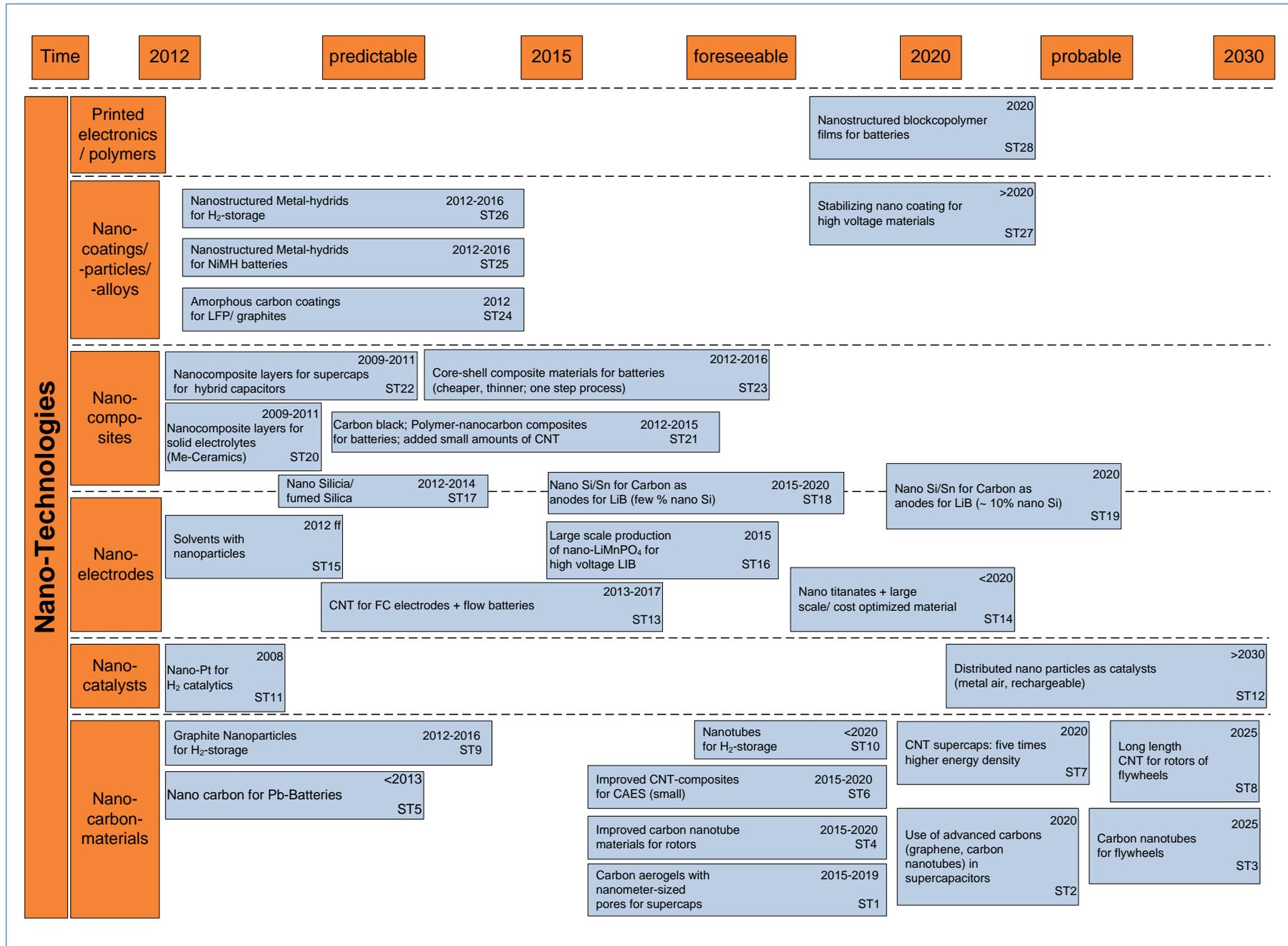
Printed electronics, polymers

ST28 Nanostructured block copolymer films for batteries are made up of chemically different blocks of polymerized monomers and are expected to improve solid thin-film batteries (Li-Polymer) beyond 2020 (99).

Nanofluids

- With respect to the energy storage sector, no significant developments in nanofluids have been identified from the literature and hence no nanotechnology is mentioned in the roadmap. Nanofluids play a role e.g. as heat transfer fluids in the solar thermal sector.

Figure 37 – Nanotechnologies for energy storage



3.6 Roadmap Layer 2 – Application technologies

The second, green layer, “application technologies”, describes the main applications and their development in the solar energy and energy storage sectors. These may be enabled by the nanotechnologies presented in section 3.5, or nanotechnologies may help improve performance parameters of these applications and finally lead to improved products, as explained later on in the third layer, “products”. Generally, the development of the application technologies is thus expected later in time (after the development of nanomaterials, structures and components), or nanotechnologies might substitute for existing materials and improve the performance of an existing application technology. Again, the market readiness of the technologies is considered (after pilot but before market diffusion). For their later application to products and markets (e.g. consumer products, mobile, stationary) they still might compete among each other or with energy application technologies from other sectors.

3.6.1 Application technologies in solar energy

Solar energy possesses great potential in the group of renewable energy sources. Among the renewable energy technologies, photovoltaics are especially interesting, for their supply pattern matches the demand profiles quite well. Also, besides large power plants, smaller decentralized photovoltaic units can be applied (e.g. to home solar or other applications). Although a fluctuating energy source, in sunny countries the energy production from solar energy can be predicted properly, whereas sources like wind are more difficult to handle in these terms. The critical issue with solar energy is to develop devices that will convert the solar irradiation into electricity efficiently and at the same time be cost-effective. Currently, conversion of solar energy into electricity is mainly achieved through photovoltaic (PV) cell technology (102).

Photovoltaics

The issues with the deployment of PV are efficiency and cost. Current energy conversion efficiency is about 25%-30% in a PV cell when it is made of crystalline silicon (Si). Crystalline silicon is an excellent conduction material; however, it is very expensive to produce. Cost of production of Si is reflected in the high cost of current PV cells and modules. Alternative cell materials such as titanium oxide are cheaper to produce. However, they have even lower conversion efficiencies compared to crystalline silicon as a so-called first-generation PV technology (102).

Nanotechnology can be used to develop alternative materials and manufacturing methods to produce cells with customized absorption characteristics, while retain-

ing acceptable conversion efficiency (10%-15%) and reduced cost simultaneously. Examples are crystalline materials with a controlled conductivity band gap to optimize energy absorption, and highly managed thin films (second-generation PV technology). An increase in solar irradiation absorption rates can also be achieved using multi-junction solar cells (an example of a fourth-generation solar cell), i.e. a layer of thin-film semiconductors with band gaps of variable energies, and a sensitized semiconductor, where surface attachment techniques are utilized to connect another strongly absorbing material, such as a dye. These types of advanced solar cells are called dye-sensitized cells (102). Other so-called emerging or third-generation PV technologies are organic solar cells and quantum dot solar cells. Nanotechnology is assumed to play by far the largest role in emerging PV, although improvements of the other technology generations by nanotechnologies and advanced nanomaterials are possible and relevant as well (e.g. nanoinks, nanoparticles for thin-film printing technologies or nanomaterials for transparent electrodes in all technology generations). An important role for nanotechnology in PV is to improve the energy or light management in the cells and hence their efficiencies.

Solar thermal energy

Solar energy can also be utilized as a heating source to generate hot water and space heating. Since the sun is a variable source that produces diffuse energy, managing the incident solar radiation is difficult because of its changing position. Here, nanotechnology can be helpful to manufacture complex nanostructured mirrors and lenses to optimize solar energy collection, as well as aerogels with nanopores to be applied as a transparent and thermally insulating material for the cover material of solar collectors (102). Nanofluids may also improve heat transfer in the heat transfer fluids of solar thermal power plants.

In the following, the entries in the Application technologies layer of the roadmap are listed, explained and linked back to relevant nanotechnologies or products, where possible.

Solar thermal

SE22 New heat transfer fluids New, improved fluids leading to better heat transfer have already been implemented and are expected to continue to have a significant role to 2020 and beyond (103). Adding nanoparticles can help to improve the heat transfer properties of these fluids (103).

SE23 Supercritical steam cycle Solar power towers are transitioned to supercritical steam cycles, which operate at a high temperature and can therefore convert solar heat at high efficiency (2015-2030) (103).

SE24 Laser, plasma, ultrasonic welding for collector is expected to be used for solar thermal collector production with improved properties by 2015 (104).

SE25 Nano-coated surfaces for reduced friction losses in fluid flow might be available by 2015. Thermal properties are improved and the flow of heat transfer fluids can also be optimized to increase the efficiency of the power plant (104).

SE26 Solar thermal – improve heat transfer to the liquid working temperature Nanotechnology may offer the possibility of improving heat transfer to the liquid working temperature as soon as 2016 (105).

SE27 Solar thermal – protect surface of collectors with nanocoatings (dirt, abrasion) Nanocoatings also offer the promise of protecting the surface of solar collectors against dirt and abrasion. As discussed in workshop I, this technology may develop by 2020 (105).

SE28 Improved reduced-emissivity coating for receiver In workshop II it was judged that by 2015 it will be possible to create improved reduced-emissivity coatings for receivers with the use of nanomaterials (99).

SE29 Generation of process heat <100 °C for industrial production As discussed in workshop I, nanotechnology already plays an important role in the reduction of process heat for industrial production (105).

SE30 New glazing materials, e.g. polycarbonate as well as new coating materials for collectors (e.g. titanium nitride oxide (TiNOX)) are expected to improve solar thermal collectors (104).

SE31 Develop PV + thermal (PVT) collector (R&D) Similar to the “hybridization” trend observed for PV technologies, the combined use of PV and solar thermal technologies is expected to be realized starting around 2015. This should be a long-term trend to 2020 and beyond (104).

SE32 Advanced coating materials for nano-coated surfaces are expected to further improve the efficiencies of solar thermal collectors to 2020 and beyond (104).

Concentrating photovoltaics (Generation IV)

SE33 Formulation of multi-layer systems is expected between 2013 and 2015 (104).

SE34 Highly ordered structures for novel thin-film multi-junction solar cells are expected to be de-

veloped around 2020 (compare with Generation II thin-film technology developments). Again, a tendency can be observed towards multi-junction and/or hybrid PV technologies to improve efficiencies and reduce costs (104).

Emerging technologies (Generation III)

SE35 Increasing markets for emerging PV at a low level, breakthroughs with respect to low cost/high efficiency (need to compete with Generation I/II PV) New market possibilities are likely to develop from 2020 onwards if emerging PV technologies can achieve cost savings or increase efficiency (106).

SE36 Breakthroughs in printable photovoltaic cells (printing of PV cells onto paper substrates that can be bent multiple times without a great loss in performance) Breakthroughs in printable PV cells could occur around 2015, increasing the potential and impact of this technology (compare with item SE39: mass production may be enhanced by breakthroughs in printable photovoltaic cells) (105).

SE37 High-efficiency compound semiconductor PV (multi-junction technology) Semiconductor PVs are expected to reach high efficiencies around 2020 (107).

SE38 Quantum wire solar PV In this approach, the intermediate band gap is realized with a stack of quantum wires; it may be expected around 2030 (108).

SE39 Mass production of printed solar cells The mass production of printed solar cells is already possible today, and will play an important role in the coming years (109). Linking to the “Nanotechnologies” layer: not only organic PV, but also inorganic and printed PV (thin film), making use of nanoparticles, could reach broader markets in the medium to long term. However, there are ongoing challenges in increasing efficiency and lifetime and reducing costs (109).

SE40 New electrodes and semiconductor materials, e.g. transparent electrodes based on nanoparticulate metal oxides (ITO replacement) or materials for QD solar cells, are expected to improve third-generation emerging PV in the next few years (2013-2015) and beyond (104).

SE41 New structure of dye-sensitized solar cells, QD + DSSC = full spectrum absorption New structures of dye-sensitized solar cells are expected to increase the absorption spectrum, around 2016. There is a clear ongoing trend towards hybrid PV architectures (110).

SE42 Advanced inorganic thin-film technologies (e.g. Indium replacement) or printing Advanced inorganic thin-film or printing technologies are expected to bring benefits around 2020, e.g. the replacement of Indium by metal oxides, CNT or graphene (96).

SE43 Quantum wells: photonics, thermo-photovoltaics; multi-photon-down converter; intermediate band gaps The goal in the use of quantum wells is additionally to use the energy of charge carriers that are found at the intermediate band gaps. This approach is expected to have a high impact between 2020 and 2030 (110).

Thin-film technology (Generation II)

SE44 Highly efficient organic solar cells made of colloidal quantum-dot precursor Precursors made of colloidal quantum dots (CQDs) are today highly efficient for inorganic solar cells. Quantum dots are particles of semiconductor material with discrete energy levels, defined by their size, and the energy levels determine the band gaps. The dots can be grown to any required size, allowing them to be tuned across a wide variety of band gaps without changing the underlying material or construction techniques. The ability to tune the band gap (even in the infrared) is what makes them desirable for solar cell use. CQD solar cells have already achieved promising efficiencies (96).

SE45 Si-based thin-film solar cells, cheaper production techniques (amorphous silicon thin films) The development of cheaper production techniques for amorphous silicon thin films increases their potential and is expected to play a significant role from now on until 2016, as discussed in workshop II (99).

SE46 Efficiencies in the range of 18%-22% with pin structures on flexible substrates, stable back-contact BSF materials to increase the efficiency could subsequently be realized between 2016 and 2020 (104).

SE47 Hetero intrinsic a-Si and micro nanocrystalline film (104) and

SE48 In situ long-distance power supply for tools and products by enhanced thin-film solar cells This application, discussed in workshop I and expected in 2015, is an example of how thin-film solar cells improved by nanotechnology could be used in the industry (104).

SE49 Triple- and quad-junction thin-film a-Si solar cells, solar concentrator techniques RF-

PECVD, MWCVD and MOCVD deposition systems In the periods 2013-2015 and 2016-2020 respectively, single and multi-junction thin-film solar cells may be realized with higher efficiencies (11% eff. for single junction a-Si solar cells; 24% eff. for single junction with hetero intrinsic a-Si layer; triple junction efficiency at 15% initial and 13% for stabilized cells). The goal is to explore novel thin-film multijunction solar cells (hybrid, multichannel) with highly ordered structures to achieve higher efficiencies by 2020 (104).

SE50 Thin-film solar cells based on carbon nanotubes (SWCNT) are a promising application of nanotechnology in the solar energy sector and are already at an advanced stage of research and development (104).

SE51 Thin-film full-spectrum solar cells with low concentration ratio are an already existing application (refers to highly efficient ultra-thin c-Si) (104).

SE52 15%-18% efficiency with BSF with a new window layer A back surface field (BSF) consists of a more highly doped region at the rear surface of the solar cell. It helps reduce surface recombination, leading to higher efficiencies for thin-film PV (e.g. c-Si) expected 2013-2015. As a result, back contact panels, solar integrated roofing and window glass could become available as products (104).

Crystalline silicon technology (Generation I)

SE53 Incorporation of back reflectors in solar cells could help further increase efficiency, conserve materials and reduce costs (104).

SE54 Develop new passivation technique (Plasma ion implantation) This is another process improvement which may lead to cost reductions around 2013 to 2015 (104).

SE55 Move to all-dry texturing processes (free of chemicals, safer, faster) This improvement in process technologies for crystalline silicon does not necessarily have to be based on nanotechnology. The hope in the medium to long term is to increase efficiencies of solar cells and to reduce manufacturing costs. This may be achieved around 2013 to 2015 or beyond (104).

SE56 Bifacial solar cell Light entering the PV device from both sides can be captured by a bifacial solar cell (BSC) structure that leads to an improved current output. BSCs could improve efficiencies and further reduce costs of existing

PV cells around 2016 to 2020, which should lead to the commercialization of the technology to the industrial level and subsequent mass production (104).

SE57 PV efficiency goes down with rising temperature → improve panel cooling with nanomaterials with high electrical conductivity By 2020 nanomaterials could be used to improve the panel cooling process of PV cells and thus enable higher PV efficiency (105).

Photovoltaics (general – module and systems level)

SE58 Space-based solar energy generation and transmission Beyond 2030, solar energy may be used in outer space to collect energy that will be sent back to earth (105).

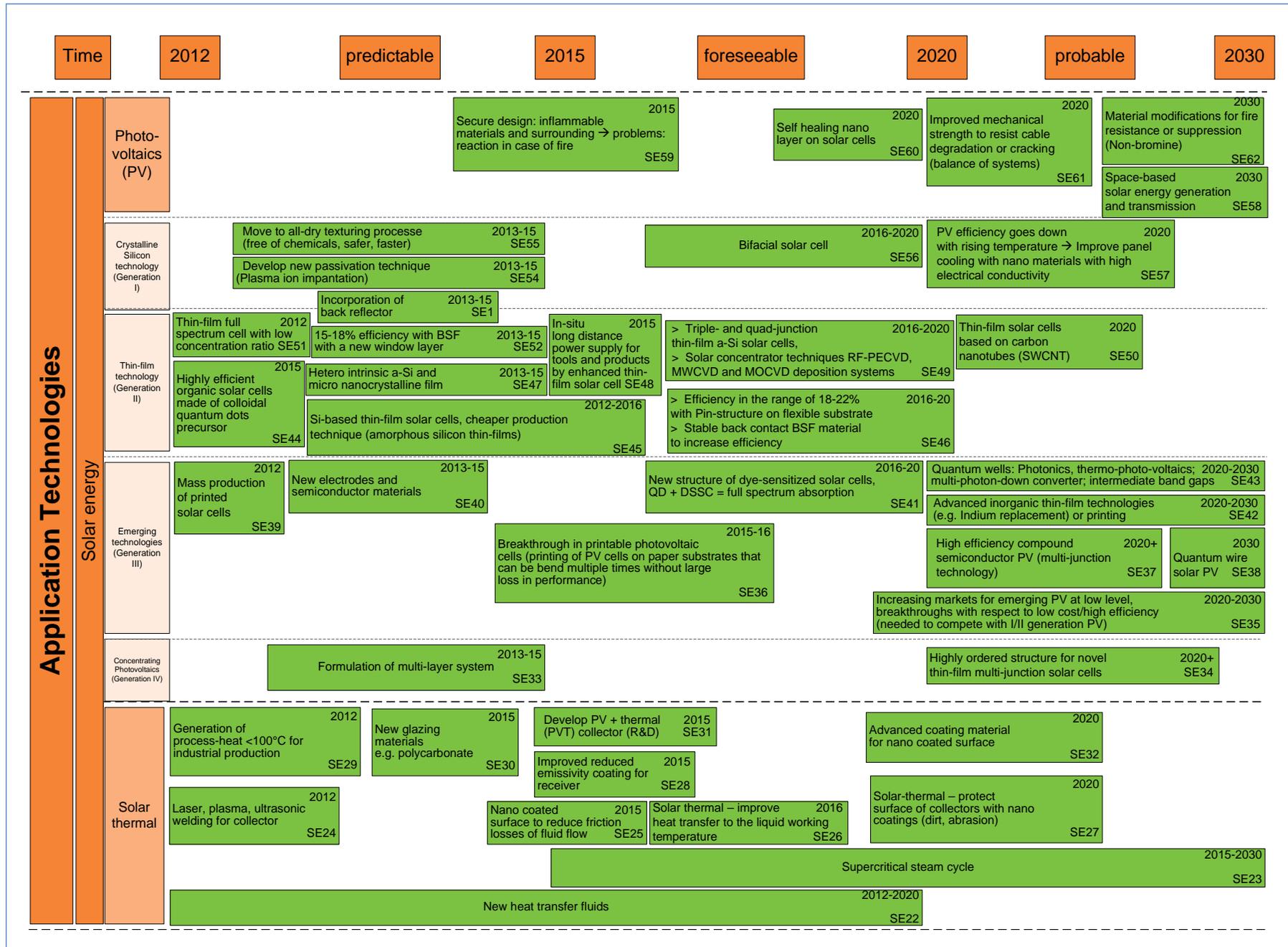
SE59 Secure design: inflammable materials and surroundings (→ reaction in case of fire) Together with the increasing use of photovoltaic modules comes an increased demand for modules suitable for use in demanding environments. PV modules are typically installed in outdoor locations such as on a roof, wall or other supporting structure. However, there are many (e.g. warm or dry) regions in the world where fire is of concern. PV modules in fire-prone areas may need to be fire resistant, for example when installed on building exteriors. According to a discussion in workshop II the application of new materials enabled by nanotechnology may help to decrease flammability. This development may happen around 2015 (99).

SE60 Self-healing nanolayers on solar cells could already be realized between 2017 and 2020, as discussed in workshop I. However, as in other domains, the potential of nanotechnology to contribute to the safety and environmental robustness of PV modules and systems (e.g. self-cleaning, self-healing and long life) should be considered a constant and long-term topic (105).

SE61 Improved mechanical strength to resist cable degradation or cracking (balance of systems) As discussed by the experts in workshop I, by 2020 nanomaterials could be used to improve the degradation and cracking resistance of cables and thus upgrade the overall balance of systems. Here as in other domains the motivations for the use of nanotechnology for PV systems are safety, lifetime and environmental aspects (105).

SE62 Material modifications for fire resistance or suppression (non-bromine) As the public and government agencies across the world are increasing pressure to phase out traditional bromine-based flame retardants, in the long term nanotechnology could help to develop fire-resistant or fire-suppressing materials. By 2030, for example, nanomaterials could be alloyed to other materials to improve the fire resistance of those materials (as discussed in workshop I). This potential development of PV modules/systems for fire and environmental protection should be considered together with the previous topic SE61, as a constant item of concern on the subject of safety (105).

Figure 38 – Application Technologies for solar energy



3.6.2 Application technologies in energy storage

Total electrical energy storage capacity installed worldwide was about 128 GW in 2010. Of this, over 99% is represented by pumped hydro energy storage (PHES). Only 440 MW of capacity is compressed air energy storage (CAES), 316 MW is sodium-sulphur batteries (NaS), 70 MW is lithium ion batteries, 35 MW is lead acid (Pb) batteries, 27 MW is nickel-cadmium (NiCd) batteries, 25 MW is flywheels and 3 MW is redox-flow batteries. (28) Storage was about 2%-6% of total installed capacity, depending on the region. This means that stationary energy storage has not been very significant in the past, and centralized mechanical energy storage has dominated electrochemical or other storage technologies.

However, the increasing global demand for environment-friendly or green (e.g. non-toxic, CO₂-reduced) and sustainable (e.g. recyclable, cost-effective) technologies, guided by corresponding policy, has in recent years prompted new, global trends towards electric mobility or smart energy generation and distribution (smart grids), for example.

This will probably cause a profound change in future demand for different energy storage applications, for products and markets in the mobile, stationary and even the consumer market. The quest for high-power large-scale energy storage in electric vehicles (e.g. lithium ion batteries or hydrogen-based fuel cells), or the increasing need for energy balancing with increasingly decentralized installations of fluctuating renewable energy sources like PV or wind energy, will potentially generate a large demand for novel and/or improved storage technologies. The example of lithium ion batteries (LIB) in particular, which were developed in the 1990s and have been dominant in portable electronics since then, shows the interdependencies of the consumer, mobile, and stationary markets. LIB in portable electronics have been the enabler and platform technology for mobile applications in electric vehicles, and as soon as costs for large LIB are reduced they are expected to become more attractive for stationary applications as well. The ongoing – and recently even increased – R&D activities will probably lead to high-power batteries of interest to the consumer market, which is looking for ever smaller, more compact, lightweight and powerful energy storage.

The application of nanotechnology to the improvement of LIB and other electrical energy storage technologies is potentially manifold.

Electrochemical energy storage

Lithium-ion technology is regarded as the most feasible variant of electrical energy storage, because of its high cell voltage and substantial energy and power density. Nanotechnology can enhance the safety and capacity

of lithium ion batteries greatly, for instance through new ceramic materials, heat-resistant and still flexible separators, and especially through high-performance electrode materials. This technology is expected to be deployed in future in hybrid and pure electric cars, as well as for stationary energy storage (here the cost factor is a key parameter). In the far future, rechargeable *Post-LIB* metal-air (e.g. Li-, Al-, Mg-air) batteries might provide significantly higher energy densities and greatly increase the range of electric vehicles. Today's hopes for high-energy Post-LIB focus strongly on the development of lithium-sulphur technology. *Redox-flow batteries (RFB)* and *high-temperature batteries* (such as NaS) are of interest in large-scale stationary applications. Here, nanofiltration membranes may for example improve RFB since, with better, layered, multi-functional membranes, electrolyte crossover and resistance can be reduced, stability increased and system cost lowered. The efficiency of flow batteries can be improved through identifying low-cost anti-catalysts and redox catalysts for negative electrodes based on nanotechnology, and developing non-aqueous flow battery systems with wider cell operating voltages. NaS technology has not been considered in more detail in this roadmap; these batteries have been demonstrated at more than 190 sites in Japan, totalling more than 270 MW in capacity. Worldwide, the Japanese company NGK Insulators dominates the market. Under *aqueous systems*, Pb batteries and Me-air batteries are discussed in the roadmap. Pb batteries still have potential for further improvement (e.g. by using fumed nanosilica to increase their safety). They are of interest, e.g. as starter batteries or for stationary applications, due to their low cost compared to alternative technologies.

Electrical energy storage

Electrical energy storage, using supercapacitors for example, offers high power densities and is suitable for use in stop-and-go applications in electric mobility or elsewhere, where energy is needed rapidly for a short time. However, the development of high-energy-density electrical or electrochemical capacitors is of interest as well, and would broaden the product or application portfolio. Advanced nanocarbons (e.g. CNT or graphene) could help achieve such goals in the future.

ST29 Supercapacitors with ultra-high power density through nanomaterial are expected to become available around 2015-2019. Nanoporous materials (e.g. carbon aerogels) and other carbon-based materials with large surfaces could help to achieve such high power densities (99).

ST30 CNT supercaps: five times higher energy density Nanocarbons, e.g. CNT, could help reach even higher energy densities by around 2020 (100).

ST31 Supercapacitors with higher energy density

Beyond 2020, supercaps may reach still higher energy densities with newly developed advanced materials (99).

Chemical energy storage

Nanotechnology has the potential to further improve hydrogen storage and production. Nanostructured metal hydrides are expected to improve hydrogen storage technology, whereas nano-Pt is used as a catalyst for hydrogen production. Today's applications, however, still strongly rely on physical rather than chemical hydrogen storage (e.g. tanks with compressed or liquid hydrogen for fuel-cell cars).

ST32 Use of low-cost catalysts for H₂ production As described in the nanotechnology layer, nano-Pt is used today as a catalyst for hydrogen production, and catalysts with reduced Pt are expected to be developed in the future. Low-cost catalysts may also be developed for H₂ production by 2020 (105) (99).

ST33 Nanoengineered 20%-by-weight H₂ storage is expected to be achieved by 2025. As described in the nanotechnology layer, nanostructured metal hydrides are today the subject of research intended to make these improvements. In the future nanocarbons other than pure CNT may also become relevant in this respect (100).

ST34 Efficient synthetic natural gas production (methanation) is expected to be realized around 2025 (99).

ST35 Development of H₂ storage materials with 6%-9% by weight (lower H₂ desorption, less degradation, optimized material composition) is expected around 2015 (111).

ST36 Improved H₂ storage by use of nanotubes (not only carbon-based) is thus expected around 2020 (compare with nanotechnology layer) (105) (99).

ST37 H₂ storage: large-scale electrolysis, H₂ turbine, gas grid (pipeline compression) At times when much energy is produced but consumption is low, energy may be stored in the form of hydrogen by using electrolysis ("power to gas"). The hydrogen can be stored, distributed via gas stations for H₂ vehicles or transformed to methane and distributed by local gas grids (99).

ST38 High-efficiency nanoporous H₂ storage (does not require low temperature) represents further developments expected around 2025 (105).

Flow batteries (high-temperature)

ST39 RFB: large size, large systems (MWh) Large RFB systems on the order of MWh are of even larger physical size and are only suitable for use in industry and similar applications with enough space available (99).

ST40 RFB: developed layered multi-functional membranes Concerning material improvements, nanotechnology among others is expected to help develop layered multi-functional membranes by around 2015-2020 (101).

ST41 RFB: upscale xWh, material improvements, smaller systems Scaling up, together with further material improvements and higher efficiencies as well as smaller system sizes, is expected to proceed for aqueous as well as non-aqueous RFB, to 2030 and beyond (99).

ST42 RFB: kW/kWh for stationary applications, non-aqueous Non-aqueous flow battery systems with wider cell operating voltages have improved efficiency and are expected to be available as kW/kWh systems around 2020 (101) (112).

ST43 RFB: MWh for stationary applications, non-aqueous For non-aqueous RFB, similarly to aqueous, scaling up to large-sized energy storage systems (MWh and beyond) is expected around 2020-2030 (113) (101).

ST44 RFB: kWh for stationary applications, aqueous (container-sized) RFBs for stationary applications are already available today as aqueous systems. At the kWh scale they are container-sized (113).

ST45 RFB: MWh for stationary applications, aqueous, at reasonable size RFBs at a reasonable size are expected to be realized around 2015-2020 in order to be applied in markets or areas with limited space but a need for large energy storage (112).

ST46 Me_x/O₂ RFB: electrode material in suspension (aqueous) In the longer term (i.e. 2030), metal oxide RFBs with electrode materials in suspension may be realized and further improve the RFB system (113).

LIB/post-LIB

ST47 Large-scale production of high-voltage Li-Batteries with nano-LiMnPO₄ for LIB In order to provide adequate nanostructured materials for the high-voltage batteries previously described, the electrodes and later on the whole system will

have to be produced on a large scale and with high throughput (compare with the nanotechnology layer) (99).

ST48 Use of metallic anodes for LIB (in portable electronics), small scale Small-scale LIB with metallic anodes to be used in portable electronics are expected to be available around 2020 (99).

ST49 LIB with long cycle life and low cost from nanomaterial: >5000 cycles at <240 \$/kWh, >10000 cycles at <480 \$/kWh Besides the energy density, the cycle life and cost reduction are key parameters for LIB development. Around 2020, conventional and current LIB technology should achieve significantly higher cycle lives at maintained or reduced costs or slightly increased cycle lives at significantly reduced costs. For both alternatives, different market perspectives arise (99).

ST50 Post-LIB (Li-S): >1000 cycles, high energy density, improved safety Around 2025, these batteries might be further improved and achieve higher cycles, energy densities and improved safety. For use in electric vehicles further time would be needed for Li-S development, and they may appear in EVs beyond 2030 (114).

ST51 Li-S with 2x energy density, ~200 cycles, small scale Post-LIB lithium-sulphur batteries may provide much higher energy densities (2-3 times are expected to be practically achievable) compared to current LIB systems. They could be available around 2020 with 2 times higher energy densities but with limited cyclability and at smaller scales (99).

ST52 Li-Polymer, Li-solid (non-polymer) These batteries have the advantage of safety through use of solid electrolytes. Li-Polymer and other solid-state batteries are expected to have improved energy densities (comparable to 5 V LIB) around 2020 (114).

ST53 Improved lithium ion batteries (2nd generation LIB): cathodes e.g. with NMC, NCA, LMO, LFP; anodes e.g. with LTO, modified C, soft C; electrolytes with additives; separators with nanocoatings First-generation lithium ion batteries based on lithium cobalt oxide (LCO) have been used in consumer electronics for many years, but are not suitable for use in electric vehicles due to safety concerns. Second-generation LIB based on the cathode, anode, electrolyte and separator materials mentioned are currently being further developed and are already used in electric vehicles. In the next few years

(i.e. before 2015), large-scale LIB with these materials will increasingly enter the market in electric vehicles, but also consumer or stationary applications (if inexpensive) are of interest in the future (101).

ST54 LIB 4: 4.4 V cells with advanced materials (NMC, NCA, ...) Compared with the 2nd and 3rd-generation LIB described above, the 4 V system can be considered as today's reference system. 4.4 V cells could be available around 2015 with advanced electrochemical materials (114).

ST55 Next-LIB: 5 V cells (cathodes with e.g. LMO, LiMPO₄ (5V); 5 V-electrolyte) By 2020 and beyond, 3rd-generation 5 V systems may be available. These could be based on nanostructured high voltage LiMPO₄, for example (114).

ST56 Next-LIB (high energy density): cathodes e.g. with composites, high-V (5 V); anodes e.g. with composites such as nanoSi @ C, high capacity Particularly driven by the race for high-energy batteries with longer ranges, 3rd-generation LIB with high (5 V) voltages are being developed, to be ready for the market around 2015-2025. Si/C or Sn/C nanocomposites for anodes as described in the "nanotechnology layer", together with high-voltage cathodes and electrolytes, could enable about 20% higher energy densities compared to today's LIB reference systems. This would correspondingly translate into higher ranges of electric vehicles. It should be mentioned here, however, that commercial availability of battery systems at a certain time would not mean that the batteries are already available within electric vehicles. Automotive industry representatives calculate that 5-8 years are needed for the implementation of new batteries into new EV concepts (114).

ST57 Post LIB: secondary Li-Air batteries are not expected to be realized before 2030. These batteries would allow for the highest energy densities batteries can achieve, and in the further future would be attractive for example for the production of electric vehicles with ranges comparable to today's cars and with a small battery size (114).

Aqueous systems

ST58 Carbon fibres and graphites for neg. electrodes in Pb-batteries in (micro) hybrid applications/cars Carbon fibres and graphites are expected to improve Pb-batteries in the short-term (2013-2014), making them more attractive for use in (micro) hybrid electric vehicle applications (99).

ST59 Pb-batteries with fumed silica (nano) Fumed silica is a highly effective gelling agent for the

sulphuric acid electrolyte in Pb-batteries. It increases service life and improves resistance to extreme temperatures, shock and vibration. Thus Pb-batteries with fumed silica entering the market today should become attractive for broader applications (e.g. off-road, sea) where extreme, harsh conditions exist (99).

ST60 Zn-Air, secondary battery The Zn-Air battery is expected to be realized as a secondary (i.e. rechargeable) battery around 2015-2020, first as a mechanically rechargeable system and later as an electrically rechargeable system. This is when Zn-Air batteries would gain attractiveness for application in electric vehicles (114).

ST61 Post-LIB: secondary Al-Air, Mg-Air Other secondary metal-air batteries such as Al- or Mg-air batteries are expected for later (e.g. around 2025-2030 or beyond). The role of nanotechnology in these Post-LIB could be the use of nanostructured metal oxides as catalysts (114).

Mechanical energy storage

For mechanical storage such as *flywheels (FWs)* or *compressed air energy storage (CAES)*, the role of nanotechnology is limited compared to the other storage technologies. However, carbon fibres or nanotubes could help increase the energy capacity of flywheels. Currently, FWs are used in many uninterruptable power supply and aerospace applications, including 2 kW / 6 kWh systems used in telecommunications. FW farms are being planned and built to store megawatts of electricity for short-duration regulation services. In CAES, carbon-based composites may improve advanced the adiabatic (heat-recuperating)

CAES of the future. The first commercial CAES plant was built in Germany in 1978 and has a 290 MW capacity. An additional plant with a 110 MW capacity was built in Alabama, US, 1991.

ST62 Stationary compressed air storage (ready for market, market development open) CAES systems are commercially available. However, advanced adiabatic CAES systems are currently being developed (101).

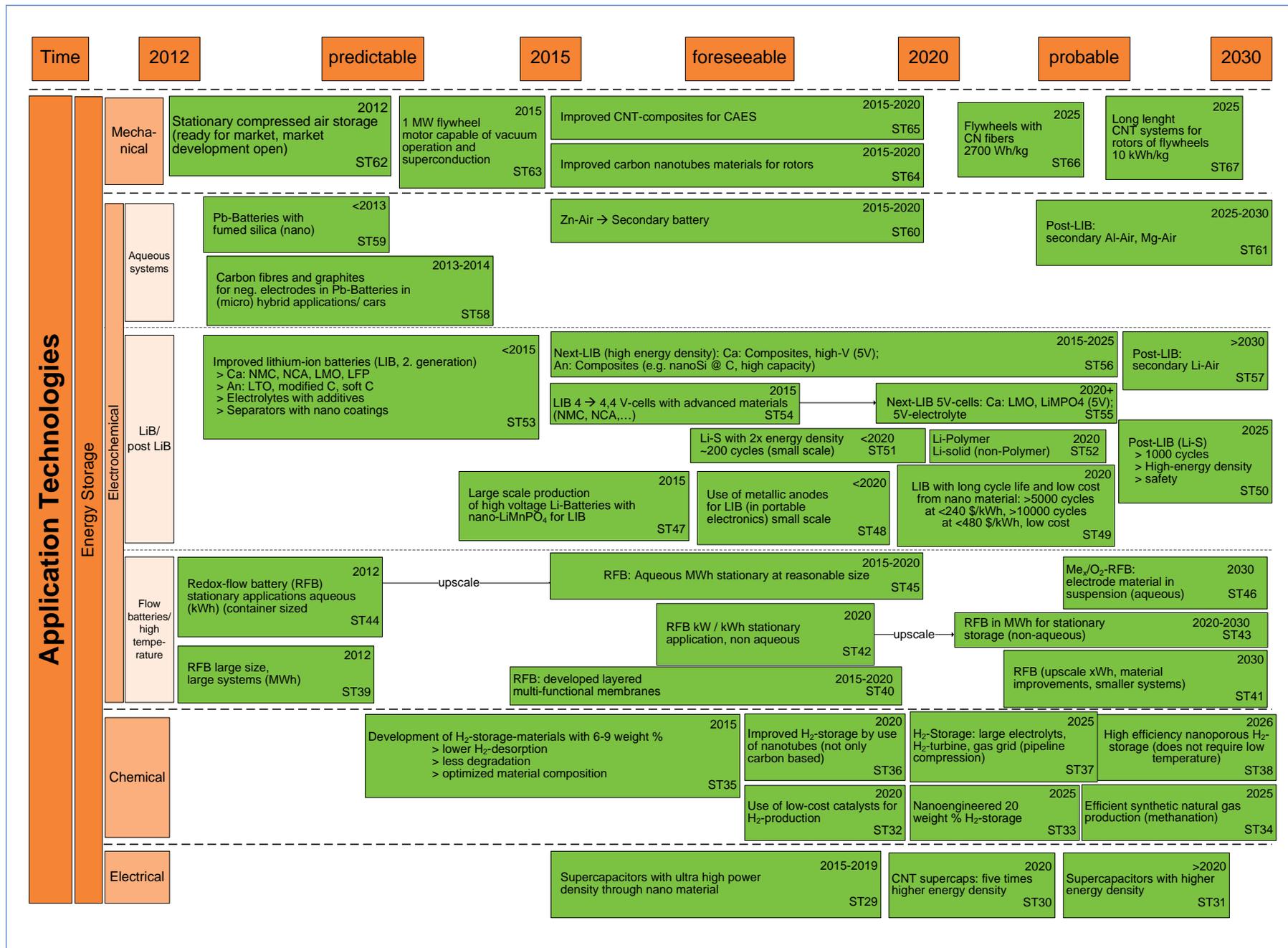
ST63 1 MW flywheel motor capable of vacuum operation and superconduction is expected to be realized in the next few years, e.g. by 2015. Challenges are to build magnets with higher mechanical strength or to initiate on-the-fly curing of composite flywheel rotor manufacturing (101).

ST64 Improved carbon nanotube materials for rotors could help to develop hubless flywheel rotors with four times higher energy, by around 2015-2020 (compare with the nanotechnology layer) (101).

ST65 Improved CNT composites for CAES Nanotube-enhanced composites for above-ground pressure tanks could support this development in the future, e.g. by 2015-2020 (compare with the nanotechnology layer) (101).

ST66 Flywheels with CN fibres 2700 Wh/kg
ST67 Long-length CNT systems for rotors of flywheels 10 kWh/kg Around 2025, high-speed flywheels are expected to be realized with improved energy densities based on nanocarbon fibres or nanotubes (100).

Figure 39 – Application Technologies for energy storage



3.7 Roadmap Layer 3 – Products

The third, red layer, “products”, describes the main application areas, products or markets for the previously described “nanotechnology-improved application technologies”. For both the solar energy and energy storage sectors the differentiation into consumer products, mobile, and stationary products/markets presents a suitable categorization to which relevant developments can be assigned. These products and markets are already closely connected to global developments and societal demands of clients and end-users. These needs are drivers for the design, demand and market success of new products.

In the following, the entries of the products layer as shown in the roadmap are listed, explained and linked to application technologies or global developments, where possible.

3.7.1 Products for solar energy

Consumer electronics containing low-cost but highly efficient photovoltaic cells or using other kinds of solar energy nowadays exist just in niche markets. Driven by the developments in the nanosector like printed electronics or developments in application technologies, these consumer electronics are expected to penetrate a broader market in the medium term (2015-2025) and potentially mass markets in the long-term perspective (2025-2030 and beyond) as soon as costs are notably reduced.

Mobility: wearable solar cells already exist today. These products contain mainly cheap photovoltaic cells with low efficiency for small applications. The combination of PV cells with optical elements forming a transparent PV unit is used at the moment in some automotive applications (large-scale systems). Emerging photovoltaics with high efficiency and low costs do not exist today, but are expected to reach niche markets in 2015-2020 and broader markets in the long term (2020-2030 and beyond).

Stationary: most products, however, might arise in the field of stationary/standalone power generators. Developments to 2030 are expected to lead from existing products like solar cells in roofing materials, through emergency power sources for disconnected areas (estimated in 2015), to power plants on the sea that can even be combined with tide or wave power plants (2020).

New models like reverse engineering to use solar reactors to produce methanol or gasoline out of carbon dioxide and water could be implemented on a timescale between 2020 and 2030.

In a long-term perspective (2030 and beyond), innovative concepts will enable totally different ways to use solar energy. One could be vertical farming, with low-cost mirrors and supporting structures. Nanotechnologies could

not only protect the mirrors from dirt (nanocoatings) but also mechanically enhance the supporting structures (carbon composites).

Consumer electronics (small scale, portables)

SE63 Printed solar on various surfaces (metal, plastics), PV on bent substrates This development includes for example PV on clothing and is expected to be realized around 2025 (as discussed in workshop I). It belongs to the general market evolution of emerging PV (105).

SE64 Niche market (low cost, high efficiency of emerging PV) Niche market development is expected for the consumer electronics sector from today onwards (depending on the development of emerging third-generation technologies regarding low cost and high efficiency) (109) (115).

SE65 Broader market (low cost, high efficiency of emerging PV) Once emerging PV enters niche markets and continues to improve its efficiency and cost, broader markets are expected to open up in the medium term (from around 2015 onwards) (109) (115).

SE66 Mass market (low cost, high efficiency of emerging PV) Following broader market penetration and together with new nanotechnology and emerging PV developments, mass markets are expected to open up in the long term (e.g. from 2020 to 2030 and beyond). Similarly to other market developments (e.g. for batteries), the market for emerging PV (in particular OPV) is expected to transfer from consumer to mobile and later to stationary markets (small to large scale while maintaining or increasing efficiencies and maintaining or reducing costs) (109) (115).

Mobility (cars, wearables)

SE67 Printable solar for low-cost, small application (smart packaging), wearable PV with printed electronics As discussed in workshop I, this technology is for example applied on solar bags, which allow the charging of cell phones (available today). A transfer to stationary markets is expected to occur in the medium to long term, as discussed above (105).

SE68 Combination of photovoltaic (PV) cells with optical elements to form a transparent PV unit These units are designed to replace conventional insulated glass units in curtain wall, window and skylight systems, where they simultaneously provide energy efficiency, solar energy generation and optimized daylight. The product is available today (110).

SE69 Niche market (low cost, high efficiency of emerging PV) Emerging PV developments and their consumer applications are also expected to transfer to new, niche markets in broader mobile applications in the medium term (compare with developments/scenarios across consumer/mobility/stationary products) (109).

SE70 Broader market (low cost, high efficiency of emerging PV) In the long term, broader markets are also expected to open up for Generation III PV systems (compare with developments/scenarios across consumer/mobility/stationary products) (109).

Stationary/Standalone

SE71 Solar in roofing materials, distributed rooftop PV The use of solar cells (mainly first and second-generation) and distributed PV on rooftops and in roofing materials is already an important issue in the solar energy sector today. In future, markets for decentralized private “home solar” or industrial systems are expected to expand further and spread from off-grid to on-grid markets as well (combining PV and stationary storage systems, for example) (105).

SE72 Low-cost and low-efficiency distributed PV: mobile → integrated stationary → large surfaces off-grid, organic PV in smart buildings Low-cost, low-efficiency PV products (in particular third-generation OPV) are expected to expand from mobile to integrated stationary products (e.g. Building Integrated PV – BIPV) and later (e.g. around 2020, see below) to large-surface (off-grid) products. This trend is beginning today and should continue in the medium to long term (compare with the market evolution described for consumer and mobility markets below) (105) (99).

SE73 Off-grid production facilities (→ ship container, e.g. in rural areas), independent power sources in intermediate areas (small town,...) are expected to be realizable by 2016 (105).

SE74 Power plant on sea (combined with tide or wave power plant) By the year 2020 it might be possible to build solar power plants on the sea and thus use the power of the sun and the power of the water simultaneously, as discussed in workshop I (99).

SE75 Niche market for large surfaces (low cost, high efficiency of emerging PV) A niche market development is expected for large-surface PV from 2020 on (depending on the development of emerging technologies regarding low cost and high efficiency). Comparing with consumer and

mobility market developments, it becomes clear, that Generation I/II PV systems are mainly relevant for stationary markets today and in the foreseeable future, whereas Generation III PV systems are expected to enter these markets in the long term after niche products in consumer and/or mobile applications have been implemented and improved. It should be noted, however, that this is a broad picture to describe general developments/scenarios (e.g. assuming that consumer to mobile to stationary applications would also mean to go from small to medium and large surfaces/areas of PV systems). More detailed market evolution scenarios will be feasible on the level of individual products, market segments or applications (116).

SE76 Vertical farming with low-cost mirror and supporting structures As discussed in workshop I, vertical farming is an extremely interesting possibility, especially for areas with little space and a high cost of land. It is estimated to be realized by 2030 (105).

SE77 Unglazed PV + thermal (PVT) collectors + heat pump refers to existing hybrid application technologies for stationary solar energy markets. They are expected to be further improved (in terms of efficiency and cost) in the coming years (compare with application technology layer) (104).

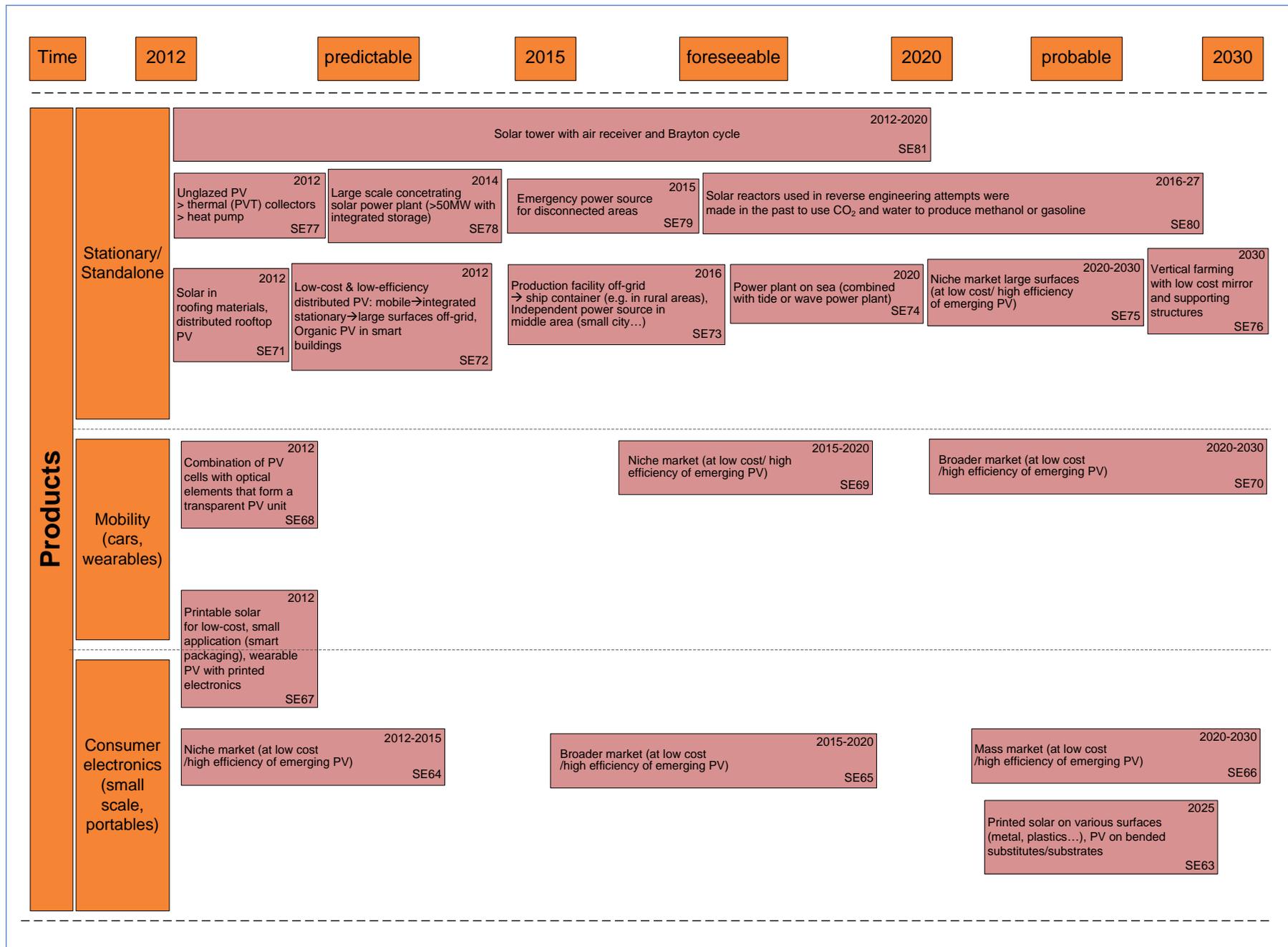
SE78 Large-scale concentrating solar power plant (>50 MW with integrated storage) The first large-scale concentrating solar power plants are expected to be realised around 2014 (105).

SE79 Emergency power source for disconnected areas When the connection of a specific area to its usual power supply breaks down, solar energy could potentially be used as an emergency power source for this area. This issue was discussed in workshop I and is expected to be practicable by 2015 (105).

SE80 Solar reactors used in reversed engineering to convert carbon dioxide (CO₂) and water into methanol or gasoline is an approach that is expected to be realized around 2016 as discussed in workshop I (105).

SE81 Solar tower with air receiver and Brayton cycle refers to a solar tower combined with a high temperature receiver that uses solar air turbines (Brayton cycle) to convert heat and pressure into electricity. This project started in 2010 and is planned to finish in 2020 (103).

Figure 40 – Products for solar energy



3.7.2 Products for energy storage

Stationary energy storage of electricity is of vital importance e.g. for establishing solar power as a primary power source (in particular for decentralized systems). The optimal place to provide electricity storage is locally, near the point of use. The critical issues when deciding on an energy storage system include the integration of renewable energy source generation which is temporally and geographically displaced from the point of consumption, balancing of hourly, daily and seasonal intermittency, grid stability and reliability, minimizing investments, minimizing environmental impact, demand-side management and the implementation of a smart distribution grid (117). In the ideal case, every business and every building should have its own local electric power storage equipment, which can supply power without interruption and satisfy the needs of households for 24 hours. With the technologies currently in place, such a unit for a common house capable of storing 100 kWh of electrical energy would require a small room and cost over US\$10 000. On the contrary, through developments in *nanotechnology*, it could be possible to reduce the size of energy storage batteries to the size of a washing machine and to reduce the cost to US\$1 000 (102).

For stationary storage applications, different *application technologies* are of interest and have more or less potential, depending on the intended use or business case and the technology that provides the best technical parameters for that use. For example, Pb-batteries are of interest for uninterruptable power supply (UPS) as they are cheap storage devices, but with unsatisfactory cyclability. For cyclic, i.e. regular charge and discharge applications, e.g. in connection with PV, LIB may have increasing market relevance in the future, as soon as LIB system costs are reduced to levels comparable to the Pb-battery. This may already happen in the next decade (by around 2020), and is strongly linked to the development and use of large-scale LIB in electric mobility. In contrast, as a large-scale storage technology LIB are likely to be competing with RFB (as they are scalable to large energy storage sizes, beyond the MWh range) or other mechanical or chemical, large-scale, centralized storage technologies.

Furthermore, *products and markets* in the stationary energy storage sector strongly depend on global developments such as CO₂-emission regulations – those for example which increase the attraction of environmentally friendly, low-carbon-footprint technologies, renewable energies, etc. – as well as on future private and industrial demand for stationary storage technologies. Recent studies and roadmaps (e.g. the EU Energy Roadmap 2050 or the German VDE study on the demand for energy storage in the transmission grid) show that the carbon footprint improves and the economic demand for energy storage technologies increases with the share

of fluctuating renewable energy sources (RES) such as PV and wind energy, since energy balancing becomes more difficult with a very high share of RES. This however is expected to be economical first for smaller and decentralized storage application (e.g. home solar) on the distribution grid level, and will only pay off on the transmission grid level in the farther future. Here, large transmission lines will still be more economical in the next decades, since they allow for energy balancing of locally-generated energy over long distances.

These general trends are described in the roadmap as follows.

ST90 Home solar The use of PV energy generation and storage in private households, called home solar, is already possible and implemented today. Increasing energy prices and reduced governmental subsidies for feeding the solar energy produced into the grid are factors which drive the use of such decentralized home solar applications (113).

ST91 Energy storage in isolated grids The storage of energy is or can become economical if countries, regions, areas or places with a need for energy are isolated from each other and balancing (for example) is not feasible. Energy storage technologies are already used today in such contexts, in isolated grids or on the distribution grid level (113).

ST92 RES (Renewable Energy Source) electricity integration (industrial, distribution, small-scale) Electricity integration on an industrial scale in connection with RES and energy storage technologies is expected in the short to medium term, e.g. around 2015-2020 on the distribution grid level. Here, much lower electricity prices for industries are still a high barrier to the demand for storage technologies compared to the private sector. However, on a small scale and with decreasing costs of energy storage systems, markets are expected to be established and expand in the future (113).

ST93 Peak shaving (industrial production) Peak shaving, i.e. shaving the demand from peak times (e.g. noon) to times with lower demand (e.g. night), is expected to be realized commercially with energy storage systems around 2020-2025 (113).

ST94 RES (Renewable Energy Source) electricity integration (transmission, large-scale) Around 2030 and beyond, the share of RES and demand for energy storage could have increased sufficiently that, together with reduced system prices,

large-scale storage technologies become economical and are integrated into the transmission grid (113).

Consumer electronics

Energy storage devices can be expected to benefit in the future from R&D activities in the mobile and stationary sector, as these sectors today rely on past developments (for example, on LIB as consumer batteries). Higher energy densities, smaller system sizes and reduced costs are always of interest for consumer markets as well, of course, with the everlasting demand for cheap, small, lightweight, integrated and long-lasting power sources.

ST68 MP3 players become more and more obsolete due to the emergence of smartphones that allow for extensive music consumption This trend may already be observed today and is expected to continue (118).

ST69 Smartphone shipments grow about 60%, huge growth worldwide is happening today (119).

ST70 Tablet sales rise as tablets become mobile computers is expected around 2020 (119).

ST71 Mobile internet devices (issues: costs, efficiency, off-grid) already exist today and will increasingly be in demand in the future. The same applies to the following trend (96):

ST72 Mobile phone shipments grow about 10% where particularly strong growth can be observed in regions such as Africa today (120) (119). Also,

ST73 MP3 player sales continue to fade towards 1 Mio shipments (118). In contrast,

ST74 Tablet sales grow towards a market of 200 Mio units (100% increase from 2012) This is expected by 2016 (119).

ST75 Mobile phone sales rise with market penetration and new business models in Africa/Asia The worldwide increase in sales is expected to continue until 2020 (120).

ST76 Smartphone sales rise as people worldwide want high mobile availability and functionality This is also expected to continue until 2020 (120).

ST77 Future developments are hard to foresee as technology changes very fast in consumer electronics It is therefore not possible reliably to sketch scenarios for developments involving electronic devices other than mobile phones, tablets, laptops, etc. going beyond 2020 to 2030. However, some general trends may still be assumed: small-

er, cheaper, lighter, more power, integrated, and increasingly ubiquitous communication (96).

Mobility

Products and markets for large-scale stationary storage, and storage in electric mobility, are not independent of each other. The development of small-scale batteries for consumer electronics in the 1990s was a favourable basis for the uptake of the technology for use in electric vehicles since around 2000, especially in LIB. Thus a technology reached maturity in consumer electronics in the past, and is now being further developed for large-scale application in the mobile sector. In a similar way, the technology is expected to become more attractive for stationary products in the future. For mobile applications – where supercaps for stop-and-go uses or hydrogen-based fuel cells for vehicles with long ranges are also relevant, in addition to batteries such as LIB, NiMH, Pb or future Post-LIB – the general trend in energy storage technologies can be described as follows.

From niche to broad mass markets

ST79 2 and 4-wheelers E-bikes are already established in broad markets, and e-cars are about to start exploitation – first markets now, with ramp-up within the next decade.

ST80 Other niche markets (e.g. further e-mobility concepts such as logistics vehicles, leisure vehicles, etc.) are emerging. In sum:

ST78 First markets for a broader range of applications are emerging and expected within the next decade for small and/or lightweight electric vehicles. These may still be high-premium and high-cost products for certain customer groups or for certain niche applications, where only small series will be bought (96).

ST81 After PHEV/BEV other products also reach the market (buses, boats, off-road vehicles, etc.) For larger electric vehicles (as for e-bikes), it is expected that niche markets and other, perhaps broader markets will develop once PHEV/BEV have been established and accepted (due to reduced costs, regulations that guide and support their distribution, etc.) (96).

From hybrid to pure xEV

ST83 E-mobility dominated by HEV/PHEV (BEV on a low level, first users) → market ramp-up Between today and 2020, the market ramp-up of xEV is expected to be dominated by hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Pure electric vehicles (BEV) are expected to reach a broader market after these transitional technologies. This should be well beyond 2030 (96).

ST86 Decreasing share of PHEV, increasing share of BEV → diffusion of BEV (HEV may decline or be replaced) The share of HEV and PHEV is expected to decrease in the long term (e.g. beyond 2030) and HEV may completely vanish from the market (96).

From short to long range

ST82 Short range for e-mobiles (e.g. 80 km-150 km BEV today) Today, BEVs typically have ranges of 80 km-150 km (given a certain suitable battery size and weight, cf. i-MiEV from Mitsubishi) (121) (122).

ST84 Longer range for e-mobiles (e.g. 200 km in 2020) In the medium term (around 2020), ranges of about 200 km are expected to become possible. This may be realized with third-generation high-energy LIB (121) (122).

ST85 Long range for e-mobiles (e.g. >400 km beyond 2030-2035+) Long ranges (comparable to those possible with today's combustion engines) are expected to become possible only beyond 2030 to 2035. New generations of Post-LIB (e.g. Li-S) batteries with significantly higher energy densities (order of magnitude 3 or more) would be needed to reach such levels with storage similar in weight and size to the batteries used in small, short-range BEVs today (121) (122).

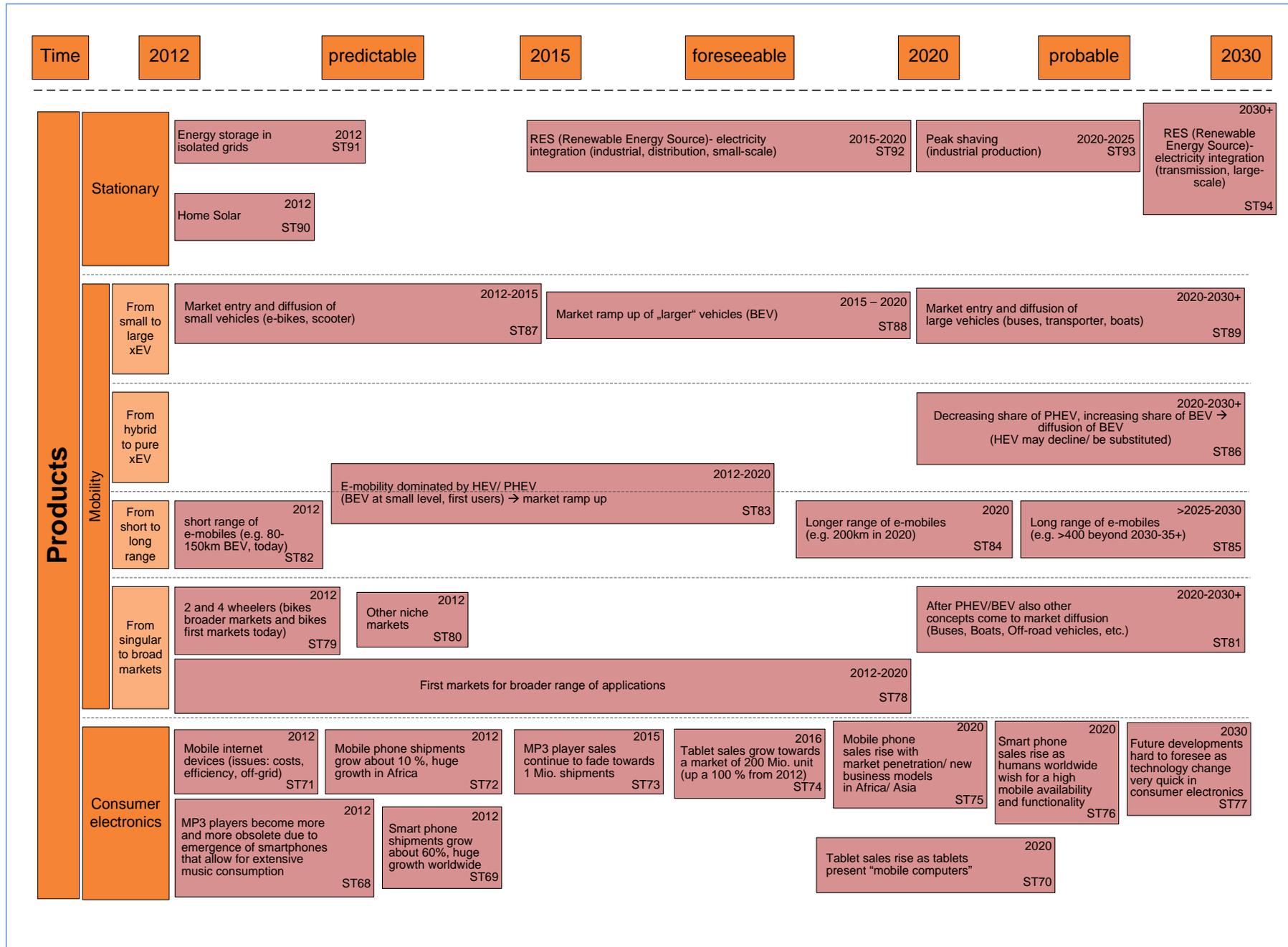
From small to large xEV

ST87 Market entry and diffusion of small vehicles (e-bikes, scooters) Small electric vehicles are already in the market today and expected to increase their market share in the short term. By 2015 or later, new niche markets for different kinds of 2-4 wheelers for leisure applications might arise (123).

ST88 Market ramp-up of 'larger' vehicles (BEV) Between 2015-2020, governments and the automotive industry worldwide have set the goal of bringing electric vehicles to market. The absolute numbers may be lower than promised, but the vehicles are available based e.g. on second-generation LIB technology; they will be offered at reduced prices and will therefore be affordable for broader customer groups (123).

ST89 Market entry and diffusion of large vehicles (buses, transporters, boats) Market diffusion of larger vehicles is expected to be realized from 2020 to 2030 or beyond. Procurement by local governments is happening today and may grow in the near future, but a market for broader customer groups will need improved and lower-cost vehicles (123).

Figure 41 – Products for energy storage



3.8 Roadmap Layer 4 – Global developments

The diffusion of energy storage and PV technologies is driven by global developments. In general, five categories of such developments may be distinguished:

- Politics, legal, society
- Growth of the economy
- Growth of population and demographic changes
- Resources
- Climate change.

The main global developments have been allocated to these categories and are briefly described in the following paragraphs.

3.8.1 Politics, legal, society

To limit the increase of global temperature to 2 °C, a reduction of CO₂ emissions from 32 Gt in 2020 to 21 Gt in 2035 is required (21). A promising way to achieve this goal is to increase the share of renewable energies. WEO-2011 (22) estimates that the renewable share in power generation will increase from 3 % 2009 to 15 % in 2035. To reach this increase, specific support schemes for renewables have been implemented in the EU. Promoting renewable energies and reducing CO₂ emissions are the major focus of current EU energy policy. Due to its success in Europe, similar support schemes are likely to be adopted in other countries. This is a major driver for the diffusion of PV.

The penetration of fluctuating electricity generation will increase the network load. To distribute the electricity from renewable sources and to maintain the current level of security of supply, grid extensions will be needed. In industrialized countries, grid operators have to face the problem of very low societal acceptance of grid extensions. Energy storage can be a viable alternative to grid extensions in certain cases. Therefore the political goal of increasing the share of renewables is a major driver for the diffusion of energy storage.

In developing countries, off-grid generation and isolated networks are very common. Increasing the security of supply is a major challenge here. This goal can also be achieved by the diffusion of energy storage.

In addition to these political drivers, social developments will drive the diffusion of PV and energy storage. An increasing demand for mobility, mobile information and interconnection requires storage technologies specifically designed for mobile applications.

GD1 Isolated networks/off-grid energy supply (e.g. for developing countries) (96)

GD2 Need to increase security of energy supply in developing countries (96)

GD3 Problems of acceptance of network expansion (industry) (96)

GD4 Demand for safety of new technologies as decentralization increases (96)

GD5 Need to create access to affordable energy in developing countries (96)

GD6 Increasing individual mobility (96)

GD7 Need to ensure security of energy supply in industrial countries (96)

GD8 Increasing demand for mobility (96)

GD9 Increasing demand for mobile information and interconnection (96)

GD10 Reduction of local emissions (e.g. dust, NO_x, noise) (96)

3.8.2 Growth of the economy

Growing economies will result in a 19 % increase in primary energy demand between 2010 and 2035 (21). In light of climate change, this increasing demand must not be satisfied by fossil fuels alone.

GD11 Energy demand will increase by 19 % from 2010 to 2035 (96) (124)

GD12 Energy demand will increase by 19 % from 2010 to 2035 (96) (124)

3.8.3 Growth of population and demographic changes

According to WEO-2011 (22), global population will increase by 3.5 % per year. Based on this growth rate, the world's population will exceed 8.5 billion people in 2035, which corresponds to an increase of 1.7 billion people compared to the year 2010. In addition, urban areas are expected to grow due to rural migration, forming megacities. As a result, the demand for energy and resources will increase significantly. To meet this demand, increased use of emission-free technologies will be required.

GD13 Importance of ICT, interaction of digitally connected objects in networks (96)

GD14 Urbanization: megacities (96)

GD15 Urbanization: smart cities, green cities (96)

GD16 Demographic change (not globally homogeneous) (96)

GD17 3.5% growth in population per year: 6.8 bio (2010) (96) (125)

GD18 3.5% growth in population per year: 8.5 bio (2035) (96) (125)

3.8.4 Resources

In the next decades, materials prices are likely to rise significantly due to an increasing demand for basic resources (e.g. copper). The volatility of materials prices is also expected to rise. As a result, the reduction, recycling and substitution of materials is becoming more and more important. The use of fossil fuels may decrease: WEO-2011 (22) estimates that the fossil fuel share in final energy consumption will decline from 81 % in 2010 to 75 % in 2035. Renewable energy sources have a great potential to fill the gap, especially biomass and solar and wind power. Increasing competition in the use of biomass (gas tank vs. food on the table) could be a driver for solar and wind power.

GD19 Increasing demand for resources for emerging technologies (demand 2030 versus production 2006, factors: Gallium 4.0, Indium 3.3, Scandium 2.3, Germanium 2.2) (126)

GD20 Competition in the use of biomass (food vs. fuel) (96)

GD21 Cooperation between industrial countries and developing countries to recycle critical materials (96)

GD22 Share of renewable energies: increase from 3 % (2009) to 15 % (2035) (96) (125)

GD23 Fossil fuels: decline from 81 % (2010) to 75 % (2035) (99) (125)

GD24 Competition in the use of biomass (food vs. fuel) made worse by shortage of oil (96)

GD25 Materials with high economic importance and high support risk: rare earth, PGM, Niobium, Germanium, Magnesium, Gallium, Antimony, Indium, Tungsten, Fluorspar, Beryllium (127)

GD26 Food/water shortage (96)

GD27 Food/water shortage (♦ energy demand for sea-water desalination) (96)

GD28 Fossil fuels: decline from 81 % (2010) to 75 % (2035) (99) (125)

GD29 Oil as feedstock (96)

GD30 Rising material prices and volatility of material prices (96)

GD31 Increasing demand for basic resources (e.g. Copper) (96)

GD32 Reduction, recycling, substitution of materials becomes more and more important (105)

3.8.5 Climate change

Based on the current state of knowledge the emission of greenhouse gases is the main cause of climate change. Energy-related CO₂ emissions make up a substantial share of these greenhouse gases. Over the coming years and even decades further increases in energy-related CO₂ emissions are expected (21). As a direct result, global temperature is expected to rise, increasing the probability of natural disasters. Due to melting pole caps, a rise in average and extreme sea levels is very likely (28).

To limit the effects of climate change, a reduction of greenhouse gases is required. This is a driver for (almost) emission-free electricity generation technologies such as PV.

GD33 Increase of global temperature: 50% chance of limiting the increase to 2 °C in the 450 ppm scenario (96) (124)

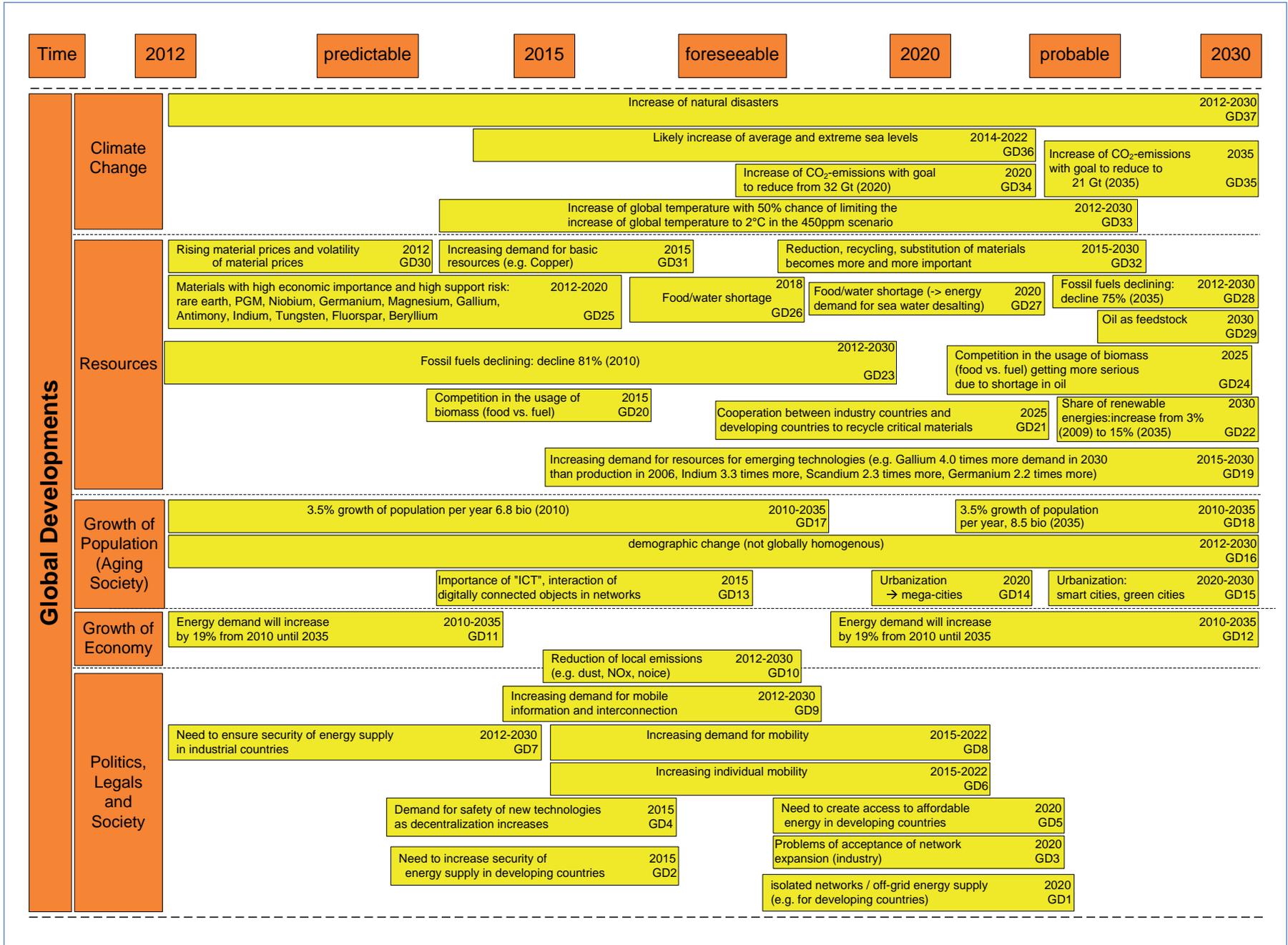
GD34 Increase of CO₂ emissions with goal to reduce from 32 Gt (2020) (96) (124)

GD35 Increase of CO₂ emissions with goal to reduce to 21 Gt (2035) (96) (124)

GD36 Likely rise in average and extreme sea levels (96) (128)

GD37 Increase of natural disasters (96)

Figure 42 – Global developments with an impact on the sectors energy storage and solar energy



4 Conclusions

The present Technology Report is the result of forward-looking research into the significance of nanotechnologies for solar energy and storage. It fits into the IEC's recent efforts to contribute to solving the "energy challenge", as exemplified in three White Papers published by the IEC Market Strategy Board (MSB)⁴. As a pilot this study has also served to investigate how the MSB may contribute to the IEC's duty to conduct a permanent technology and market watch, without which relevant and timely standards cannot be developed.

This report contains a wealth of information for those interested in the following topics:

- solar energy (both photovoltaic and thermal) or electricity storage,
- nanotechnologies,
- an educated but not commercial forecast of likely developments in these technologies and their uses and markets.

By a combination of measuring the research interest in these topics as it has developed over two decades, examining and describing the actual technologies and their potential improvements, and assessing a wide range of analyses and events as they will affect the use of the technologies into the future, this report has mapped out the developments which may be expected. It has shown:

- what applications are likely to prove the most useful and thus pull research and development along behind them,
- how the technical potential of the technologies themselves will condition the products which can be manufactured and the uses to which they will be put,
- the influence of global economic and political conditions, both favourable and unfavourable, and
- the likely result of all these forces on the market, with an idea of the shape and size of that market over the next fifteen years.

The conclusions it has reached show that many aspects of the techniques examined are being and will increasingly be influenced by nanoscale materials; in fact, for some of them nanotechnology may make the difference between success and failure. Consequently the report will be of great use for those planning the use of solar energy and storage, whether they make products, use those products

to generate and store electricity, or organize the use of the electricity produced. All three communities:

1. that of electricity generation, transmission and distribution,
2. that of equipment manufacture, and
3. that of investment in and regulation of electricity,

will thus benefit from the information provided.

In the IEC's own activities, two major directions may be distinguished where the current results will be used. Several of the IEC Technical Committees (TCs) will find in them an ideal basis for informing their work on future standards for products, systems and installations – we can cite TC 21, Secondary cells and batteries; TC 82, Solar photovoltaic energy systems; TC 117, Solar thermal electric plants; and the brand new TC 120, Electrical Energy Storage (EES) Systems; but there are others as well. For these, the quality and quantity of the information in the present report represents an enormous advantage when compared to the usual situation, where volunteer experts bring in this type of information but in a scattered, unsystematic and incomplete fashion. The second direction in which the current project – but this time more its methods than its specific results – may be useful to the IEC is in future technology and market watch projects. When a high-technology field has been identified as relevant to a market area of specific interest, the foreseeable effects of that technology may be similarly assessed and the IEC's work thus situated and guided so as to match market needs.

Finally, it is worth exploring – even in quite different areas – the gains to be realized for the IEC by learning from the approach adopted in this Technology Report, so as to build future roadmaps using four layers:

- Global developments
- Products
- Applications
- Technologies.

5 Recommendations

1. The MSB recommends the Standardization Management Board (SMB) to convey the present Technology Report to all National Committees (NCs) and relevant TCs, in particular TCs 8, 10, 21, 64, 82, 105, 111, 113, 117, 119 and 120, so that they may use the results directly in proposing and carrying out the development of standards.

- 1.1 The MSB recommends the SMB to encourage TC 113 to take the initiative, while cooperating closely with the TCs interested in relevant

⁴ 1. *Coping with the Energy Challenge: The IEC's role from 2010 to 2030 (2010)*
 2. *Electrical Energy Storage (2011)*
 3. *Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage (2012)*

nanotechnology applications, to develop the standards required for cost-effective and reduced-risk roll-out and market acceptance of nanotechnology solutions for electricity storage and solar energy.

- 1.2 The MSB recommends the SMB to request TCs 10, 21, 82, 105 and 117 in particular to identify gating factors and obstacles to the use of nanotechnology to improve applications for which they are responsible, using the information on “challenges” provided in this report. Obstacles may be related to societal attitudes, safety, the environment, cost, quality or a number of other factors. Insofar as standards and conformity assessment may contribute to removing such obstacles and thus achieving the advances promised in the report, the TCs and the IEC community should be encouraged to involve stakeholders in creating a consensus on the standards and other measures needed and to publish the results so as to guide the actors in the field.
- 1.3 The MSB recommends the IEC to help outside stakeholders such as regulators, research institutions and consumer organizations to be-

come involved with the TCs, to agree on identifying the relevant “challenges”, to decide how the IEC’s products and services may help to meet them, and to generate the usable contents of those products and services, so that the IEC may contribute to realizing nanotechnology’s benefits in the energy sector.

2. The IEC recommends organizations active in investment, product and system design and marketing, installation and regulation of solar energy production and electricity storage to take the present results into account.
3. The MSB intends to investigate how it may usefully apply the techniques demonstrated in the current report to future areas where the influence of a technology in a market of interest needs to be investigated.
4. The MSB recommends the IEC to study roadmapping in the four layers explained and applied in the present report, possibly in connection with the systems approach under development in the SMB and the Conformity Assessment Board (CAB).

6 Annex

6.1 List of abbreviations

ALD	Atomic layer deposition
BEV	Battery electric vehicle
CAB	Conformity Assessment Board of the IEC
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CHP	Combined heat and power
CIGS	Copper indium gallium (di)selenide
CNT	Carbon nanotube
CPCI-S	Conference proceedings citation index-science
CQD	Colloidal quantum dots
CZTS	Copper zinc tin sulphur
CVD	Chemical vapour deposition
DSSC	Dye-sensitized solar cell
EDLC	Electrical double-layer capacitors
EPD	Electrophoretic deposition
EES	Electrical energy storage
ES	Energy storage

EV	Electric vehicle
FS	Faradaic supercapacitors
FW	Flywheel
HEV	Hybrid electric vehicle
ITO	Indium tin oxide
LIB	Lithium ion battery
MOD	Metal-organic decomposition
MSB	Market Strategy Board of the IEC
MWCNT	Multi-walled carbon nanotube
NC	National Committee of the IEC
NP	Nanoparticles
OE-A	Organic and Printed Electronics Association
OLED	Organic light-emitting diode
OPV	Organic photovoltaic
PC	Polycarbonate
PEA	Printed Electronics Arena
PET	Polyethylene terephthalate

PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaics
QD-cell	Quantum dot solar-cell
QDSSC	Quantum dot-sensitized solar cell
R&D	Research and development
R2R	Roll-to-roll
RES	Renewable energy source
RFB	Redox flow battery
RFID	Radio-frequency identification
ROPAS	ROll-to-roll PAPER Sensors (EU research programme)
SCCNT	Silver coated carbon nanotubes

SCI	Science citation index
SMB	Standardization Management Board of the IEC
SMES	Superconducting magnetic energy storage
SNG	Synthetic natural gas
SWCNH	Single-walled carbon nanohorn
SWCNT	Single-walled carbon nanotube
SWNT	Single-walled nanotubes
TC	Technical Committee of the IEC
UPS	Uninterruptible power supply
w.r.t.	With respect to

6.2 Studies screened

No.	Author	Title	Year	Type	Institutions	Country	Focus
1	AGIT	Nanotechnologie pro Gesundheit: Chancen und Risiken	2004	Report	AGIT (Aachener Gesellschaft für Innovation und Technologietransfer)	Germany	Medical use of nanotechnology
2	Andersen, P.D. et al.	Technology Foresight on Danish nano-science and nano-technology	2005	Article	/	Denmark	Nanotechnology in Denmark
3	Antón, P. et al.	The Global Technology Revolution: Bio/Nano/Materials Trends and Their Synergies with Information Technology by 2015	2001	Report	RAND Corporation (Research AND Development)	USA	Nanotechnology
4	Arden, Wolfgang et al.	More-than-Moore	/	White Paper	International Technology roadmap for Semiconductors, provided by Semiconductor Industry Association	USA	MtM-Technologies
5	Battelle Memorial Institute and Foresight Nanotech Institute	Productive Nanosystems – A Technology Roadmap	2007	Roadmap	Battelle Memorial Institute	USA	Nanotechnology in general, APT, APPN, APM, call for cooperation
6	Bazito, F.; Torresi, R.	Cathodes for Lithium ion Batteries: The Benefits of Using Nanostructured Materials	2006	Article	Universidade de São Paulo	Brazil	Energy storage

No.	Author	Title	Year	Type	Institutions	Country	Focus
7	Benett, H.	Priorities for Standards and Measurements to Accelerate Innovations in Nano-Electrotechnologies: Analysis of the NIST-Energetics – IEC TC 113 Survey	2009	Paper	National Institute of Standards and Technology	USA	General
8	BMBF	nano.DE-Report 2011 – Status quo der Nanotechnologie in Deutschland	2011	Report	BMBF	Germany	Status quo in Germany
9	BMBF	Nanotechnology Conquers Markets	2004	Report	BMBF	Germany	Nanotechnology
10	BMWA	The Trend of Energy Markets up to the Year 2030	2005	Study	Institute of Energy Economics at the University of Cologne (EWI)		Market demand
11	Bruce, E.	Technology Roadmapping: Mapping a Future for integrated Photonics	/	Report	Massachusetts Institute of Technology	USA	Roadmapping
12	Bruce, P. et al.	Nanomaterials for Rechargeable Lithium Batteries	2008	Report	Angewandte Chemie	Germany	Energy storage
13	Chan, C. et al.	High Performance Lithium Battery anodes using silicon nanowires	2007	Report	Nature Publishing Group	USA	Energy storage
14	Chin-Long Wey	Nanoelectronics: Silicon Technology Roadmap and Emerging Nanoelectronics Technology in Taiwan	2005	Article	National Central University	Taiwan	Nanoelectronics
15	Clarkson University	Solar Thermal Roadmap	2010	Report	New York Solar Thermal Consortium, Clarkson University	USA	Solar
16	Compañó, R. et al.	Technology Roadmap for Nanoelectronics, 2. Edition	2001	Roadmap	IST	Belgium	Nanoelectronics, esp. CMOS
17	Compañó, R. et al.	Technology Roadmap for Nanoelectronics, 1. Edition	1999	Roadmap	Microelectronics Advanced Research Initiative / IST	Belgium	Nanoelectronics, esp. CMOS
18	Department of Trade and Industry (DTI)	New Dimensions for Manufacturing: A UK Strategy for Nanotechnology	2002	Report	Department of Trade and Industry (DTI)	UK	Nanotechnology

No.	Author	Title	Year	Type	Institutions	Country	Focus
19	Deutsche Solarthermie-Technologie Plattform (DSTTP)	Forschungsstrategie Niedertemperatur-Solarthermie 2030 für eine nachhaltige Wärme- und Kälteversorgung Deutschlands	2011	Report	Bundesverband Solarwirtschaft (BSW); itw; Fraunhofer ISE	Germany	Solar energy
20	Diczfalusy, B. et al.	Tracking Clean Energy Progress	2012	Paper	International Energy Agency (IEA)	France	Clean energy
21	Edkins, M. et al.	South Africa's renewable energy policy roadmap	2010	Report	Energy Research Centre, University of Capetown	South Africa	Renewable energy in general
22	Environmental Technologies Action Plan	Nanotechnology brings new Solutions for Carbon Capture	2007	Brochure	Environmental Technologies Action Plan	European Union	CO ₂ -Capture
23	European Commission	Nanosciences and nanotechnologies: An action plan for Europe 2005-2009	2005	Study	European Commission	European Union	Action Plan for Europe
24	European Commission	MONA: A European Roadmap for Photonics and Nanotechnologies Foresight Brief No. 158	2008	Paper	European Commission	European Union	Solar
25	Executive Office of the President	The National Nanotechnology Initiative. Strategic Plan	2007	Report	Executive Office of the President, Washington, DC	USA	Strategic Plan
26	Fabricius, N.	Standards for Nano-Enabled Applications of Electronics: Perspectives from IEC	/	Report	Karlsruhe Institute of Technology (KIT)	Germany	Standards in Nanotechnology
27	Fabricius, N.	Aktuelle Ergebnisse der Nano-Normung	2011	Presentation	Karlsruhe Institute of Technology (KIT)	Germany	Status Quo Nano-Standards
28	Fitch, J.	Nanoelectronics Standards Roadmap	2007	Roadmap	IEEE Nanotechnology Standards Roadmap Initiative	USA	Nanoelectronics
29	Fraunhofer ISI	Energietechnologien 2050	2010	Report	Fraunhofer ISI	Germany	General
30	Fraunhofer ISI	LIB 2015 Roadmapping: Stand, Ergebnisse und Ausblick	2011	Report	Fraunhofer ISI	Germany	Energy storage
31	Frost & Sullivan	Advances in Smart Grid-Technologies	2010	Report	Frost & Sullivan	USA	Smart Grid (inter alia energy storage)
32	Frost & Sullivan	Global Smart Grid Market	2011	Report	Frost & Sullivan	USA	Smart Grid (inter alia energy storage)

No.	Author	Title	Year	Type	Institutions	Country	Focus
33	Frost & Sullivan	Materials for Energy Storage – Research and Development Management	2010	Report	Frost & Sullivan	USA	Energy storage
34	Frost & Sullivan	Opportunities for Nanotechnologies in Electronics – Technology Market Penetration and Roadmapping	2011	Presentation	Frost & Sullivan	USA	Carbon Nanotubes, Nanowires, Nanoparticles, Graphene
35	Frost & Sullivan	Asian Pacific Secondary Lithium Battery Market	2011	Presentation	Frost & Sullivan	USA	Energy storage
36	Frost & Sullivan	Chinese Photovoltaic Market	2011	Presentation	Frost & Sullivan	USA	Photovoltaic
37	Frost & Sullivan	European Large Scale Energy Storage Market and Opportunities from Growth in Renewable Energy	2011	Presentation	Frost & Sullivan	USA	Energy storage
38	Frost & Sullivan	Global Materials Market for Alternative Energy Storage Mechanisms	2011	Presentation	Frost & Sullivan	USA	Energy storage
39	Frost & Sullivan	Global Solar Power Markets	2009	Presentation	Frost & Sullivan	USA	Solar energy
40	Frost & Sullivan	Building Integrated Photovoltaics: Technology Market Penetration and Roadmapping	2010	Presentation	Frost & Sullivan	USA	Photovoltaic
41	Frost & Sullivan	Materials Market for Photovoltaic Systems in Central and Eastern Europe – A Key Region for Renewable Systems	2011	Presentation	Frost & Sullivan	USA	Photovoltaic
42	Frost & Sullivan	Mega Trends and Impact on Chinese Energy Storage Market	2011	Presentation	Frost & Sullivan	USA	Energy storage
43	Frost & Sullivan	Nanotechnology for Automotive Applications	2010	Presentation	Frost & Sullivan	USA	Nanotechnology
44	Frost & Sullivan	Solar Cell Manufacturing Equipment Market	2011	Presentation	Frost & Sullivan	USA	Solar energy
45	Frost & Sullivan	South African Solar Water Heater market	2011	Presentation	Frost & Sullivan	USA	Solar energy
46	Frost & Sullivan	Electricity Storage Technologies: Market Penetration and Roadmapping	2011	Presentation	Frost & Sullivan	USA	Energy storage

No.	Author	Title	Year	Type	Institutions	Country	Focus
47	Frost & Sullivan	Awards for Nanomaterials Applications Roadmap: The 2030 Scenario	2009	Report	Frost & Sullivan	USA	Nanomaterials
48	Frost & Sullivan	Photovoltaics – Global Developments	2008	Report	Frost & Sullivan	USA	Photovoltaic
49	Frost & Sullivan	Smart Textiles – Assessment of Technology and Market Potential	2010	Report	Frost & Sullivan	USA	Nanotechnology
50	Frost & Sullivan	Advanced Coatings and Surface	2011	Series "Technical Insights"	Frost & Sullivan	USA	Coatings, Graphene Fabrication
51	Frost & Sullivan	Inside Research and Development	2011	Series "Technical Insights"	Frost & Sullivan	USA	Coatings (Antifog, Protection for living Cells, Graphene Fabrication, etc.)
52	Frost & Sullivan	Performance Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Performance Materials (Quantum Dots for Solar cells)
53	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Nanotech used in textiles, energy waste recycling, etc.
54	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Batteries, LED-Displays, Quantum Dots, etc.
55	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Carbon Nanotubes, solar cells, Nanoparticles, etc.
56	Frost & Sullivan	Performance Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Supercapacitor, Carbon capture, alloy, etc.
57	Frost & Sullivan	Hitech Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Textiles, semiconductors, solar reactors, etc.
58	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Capacitors, nanotubes in solar cells
59	Frost & Sullivan	Inside Research and Development	2011	Series "Technical Insights"	Frost & Sullivan	USA	Light harvesting complex out of spinach, etc.
60	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Carbon nanotubes, welding

No.	Author	Title	Year	Type	Institutions	Country	Focus
61	Frost & Sullivan	Performance Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Hydrogen storage, removing oil from tar sand, etc.
62	Frost & Sullivan	Advanced Coatings and Surface	2011	Series "Technical Insights"	Frost & Sullivan	USA	Anti-fog coating, food packaging, etc.
63	Frost & Sullivan	Inside Research and Development	2011	Series "Technical Insights"	Frost & Sullivan	USA	Hydrogen production, carbon sequestration
64	Frost & Sullivan	Inside Research and Development	2011	Series "Technical Insights"	Frost & Sullivan	USA	Nanomechanical devices, dye-sensitized solar cells
65	Frost & Sullivan	Advanced Coatings and Surface	2011	Series "Technical Insights"	Frost & Sullivan	USA	Corrosive protection through atomic layer, E-Beam lithography, etc.
66	Frost & Sullivan	Performance Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Highly efficient solar cells made of colloidal quantum dots
67	Frost & Sullivan	Hitech Materials	2011	Series "Technical Insights"	Frost & Sullivan	USA	Harvest Energy, Reduce Emission
68	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Energy Generation, Fuel Cell Technology
69	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Energy storage
70	Frost & Sullivan	Advanced Coatings and Surface	2010	Series "Technical Insights"	Frost & Sullivan	USA	Nanotechnology
71	Frost & Sullivan	Energy and Power Systems	2012	Series "Technical Insights"	Frost & Sullivan	USA	Energy
72	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Solar, energy storage
73	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Energy Harvesting, Lithium Batteries
74	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Nanotechnology, Photovoltaic
75	Frost & Sullivan	Energy and Power Systems	2011	Series "Technical Insights"	Frost & Sullivan	USA	Energy, Photovoltaic, Batteries

No.	Author	Title	Year	Type	Institutions	Country	Focus
76	Frost & Sullivan	Advanced Manufacturing	2011	Series "Technical Insights"	Frost & Sullivan	USA	Solar Cells
77	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Solar Cells
78	Frost & Sullivan	Nanotech	2010	Series "Technical Insights"	Frost & Sullivan	USA	Solar Cells
79	Frost & Sullivan	Environment and Building	2011	Series "Technical Insights"	Frost & Sullivan	USA	Solar Cells
80	Frost & Sullivan	Futuretech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Solar energy
81	Frost & Sullivan	Nanotech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Energy storage
82	Frost & Sullivan	Microelectronics	2010	Series "Technical Insights"	Frost & Sullivan	USA	Energy storage
83	Frost & Sullivan	Futuretech	2011	Series "Technical Insights"	Frost & Sullivan	USA	Quantum Dots
84	Fulbert, L.	A European roadmap for photonics and nanotechnologies	2008	Report / Roadmap	Merging Optics and Nanotechnologies	France	General
85	Goodenough, J. et al.	Basic Research Needs for Electrical Energy Storage	2007	Report	Department of Energy, USA	USA	Energy storage
86	Graetzel, M.	Nanocrystals and Energy, from batteries to solar cells	2005	Presentation	Swiss Federal Institute of Technology, Lausanne	Switzerland	Nanocrystalline junctions, high power lithium ion batteries, photovoltaic generation of electricity, solar hydrogen production
87	Gray, M. et al.	Surface Immobilization Nanotechnology for CO ₂ Capture	2009	Report	US Department of Energy	USA	Nanotechnology
88	Green, B. et al.	American Roadmap – Nanotechnology for Concrete	2010	Presentation	US Army Corps of Engineers	USA	Military usage of Nanotechnology in buildings etc.
89	Guy Carpenter & Company	Nanotechnology – The Plastics of the 21st Century?	2006	Report	Guy Carpenter & Company	USA	Future impact of nanotechnology on insurance

No.	Author	Title	Year	Type	Institutions	Country	Focus
90	Haegyeom, K. et al.	Nano-graphite platelet loaded with LiFePO ₄ nanoparticles used as the cathode in a high performance Li-ion battery	2011	Article	Department of Materials Science and Engineering, Seoul National University	Korea	Energy storage
91	Hessen Ministry of Economy, Transport, Urban and Regional Development	NanoNormung – Normung im Bereich der Nanotechnologien als Chance für hessische Unternehmen	2007	Report	Hessen Ministry of Economy, Transport, Urban and Regional Development	Germany	Standards in Nanotechnology
92	Hessen Ministry of Economy, Transport, Urban and Regional Development	Application of Nanotechnologies in the Energy Sector	2008	Report	Hessen Ministry of Economy, Transport, Urban and Regional Development	Germany	General
93	Hessen Ministry of Economy, Transport, Urban and Regional Development	Nanotechnologie in der Natur – Bionik im Betrieb	2011	Report	Hessen Ministry of Economy, Transport, Urban and Regional Development	Germany	Bionic
94	Horter, H. et al.	Roadmap “Nano-Mikro-Integration zur Messung physiologischer Parameter mittels textiler Sensoren“ MpPS	2008	Report	Institut für Textil und Verfahrenstechnik	Germany	Textile and medical applications
95	Horvarth, G.	Colorado nanotechnology roadmap 2006	2006	Roadmap	Leeds School of Business, University of Colorado	USA	Nanotechnology
96	Howell, D.	Vehicle Technologies Program	2011	Presentation	US Department of Energy	USA	Energy storage
97	Hullmann, A.	The Economic Development Of Nanotechnology – An Indicators Based Analysis	2006	Report	European Commission	European Union	Nanotechnology
98	Hunt, W.	Advanced Material and Devices for Stationary Electrical Energy Storage Applications	2010	Report	US Department of Energy, Sandia National Laboratories, Pacific Northwest National Laboratories, The Minerals, Metals and Materials Society	USA	Energy storage
99	Hutchby, J.	Extending the Road beyond CMOS	2001	Report	Electrocircuits and Devices Magazine	USA	CMOS
100	Hwand, Y.	Nano-enhanced Market perspectives in solar and li-ion batteries	2010	Presentation	Arthur D. Little	USA	Energy storage, solar energy

No.	Author	Title	Year	Type	Institutions	Country	Focus
101	IEA	Technology Roadmap – Solar Photovoltaic Energy	2010	Roadmap	International Energy Agency (IEA)	France	Solar energy
102	IEA	Technology Roadmap – Solar Photovoltaic Energy	2010	Report	OECD / IEA	France	Solar energy
103	Inage, S.	Prospects for Large-Scale Energy Storage in Decarbonised Power Grids	2009	Report	International Energy Agency (IEA)	France	Energy storage
104	iNEMI	2009 Roadmap	2009	Executive Summary	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
105	iNEMI	Roadmap and Research Priorities 2011	2011	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
106	iNEMI	Electronics and Solar Energy and New Technology	/	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology, solar energy
107	iNEMI	iNEMI Roadmap Process and Industry Collaboration Projects to Close Roadmap Gaps	2012	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
108	iNEMI	Flexible Electronics Roadmap – From Concept to Product	/	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
109	iNEMI	Mass Data Storage Roadmap	2010	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Data Storage
110	iNEMI	Future Challenges For Electronics Manufacturing	2011	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology, Electronics
111	iNEMI	FF02: iNEMI Technology Roadmap	2009	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
112	iNEMI	Challenges of Solar Manufacturing	2010	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology, Solar
113	iNEMI	iNEMI Roadmap Highlights	2010	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
114	iNEMI	iNEMI Roadmap Highlights	2011	Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology

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115	iNEMI	Technology Roadmaps: Driving Industry Collaboration	2006	Roadmap / Presentation	iNEMI (International Electronics manufacturing Initiative)	USA	Technology
116	Irish Council for Science, Technology and Innovation	ICSTI Statement on Nanotechnology	2004	Report	Irish Council for Science, Technology and Innovation	Ireland	Nanotechnology
117	Iversen, T.	A Nanotechnology Roadmap for the Forest Products Industry	2005	Presentation	STFI-Packforsk AB	Sweden	Forest Products
118	Iversen, T. et al.	A Nanotechnology Roadmap for the Forest Products Industry	2006	Report	STFI-Packforsk AB	Sweden	Forest Products
119	Kasavajjula, U. et al.	Nano- and bulk-silicon-based insertion anodes for lithium ion secondary cells	2006	Report	/	USA	Energy storage
120	King, G. et al.	Development of a Bio-nanobattery for Distributed Power Storage Systems	/	Report	NASA	USA	Energy storage
121	Klingeler, R.	Nanoskaligkeit und Grenzflächeneffekte in oxidischen Batteriematerialien	/	Presentation	Innovationsallianz Lithium Ionen Batterie, BMBF	Germany	Energy storage
122	Lamble, B.	Li-ion Battery and Nanotechnology	2008	Presentation	/	USA	Energy storage
123	Linton, J.; Walsh, S.	Integrating innovation and learning curve theory: an enabler for moving nanotechnologies and other emerging process technologies into production	2004	Report	Lally School of Management and Technology, Rensselaer Polytechnic Institute	USA	Nanotechnology
124	Lovegrove, K. et al.	Realising the Potential of Concentrating Solar Power in Australia	2012	Report	Australian Solar Institute	Australia	CSP
125	Luther, W. et al.	Innovations- und Technikanalyse – Nanotechnologie als wirtschaftlicher Wachstumsmarkt	2004	Report	VDI Technologiezentrum GmbH	Germany	Nanotechnology
126	Lyons, V. et al.	Draft – Space Power and Energy Storage Roadmap Technology Area 03	2010	Roadmap	NASA	USA	Energy storage
127	Maharey, H.	Nanoscience and Nanotechnologies	2006	Roadmap	Ministry of Research, Science and Technology, New Zealand	New Zealand	Development of the Energy Sector in NZ

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128	McWilliams, A.	Nanotechnology: A realistic market assessment	2010	Report	Frost & Sullivan	USA	Nanotechnology
129	Mendelsohn, M. et al.	Utility-Scale Concentrating Solar Power and Photovoltaics Projects: A Technology and Market Overview	2012	Paper	DOE	USA	Solar, PV
130	MiGHT	Identification of Business and R&D Opportunities in the Application of Nanotechnology in Malaysia	2007	Report	Malaysian Industry Group for High Technology (MiGHT)	Malaysia	Nanotechnology
131	MIMOS	Nanoelectronics Technology Roadmap For Malaysia	2008	Presentation	MIMOS (National R&D Centre in ICT)	Malaysia	Nanoelectronics
132	Nanoroadmap Project (NRM)	Roadmaps at 2015 on nanotechnology application in the sectors of: materials, health and medical systems, energy	2006	Report	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Nanotechnology in medical and health sector
133	Nanoroadmap Project (NRM)	Roadmap report on nanoparticles	2005	Report	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Nanoparticles
134	Nanoroadmap Project (NRM)	Roadmap report on dendrimers	2005	Report	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Dendrimer (Nanostructures)

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135	Nanoroadmap Project (NRM)	Road Maps for Nanotechnology in Energy	2006	Report	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Nanotechnology
136	Nanoroadmap Project (NRM)	Draft roadmap on solar cells	2005	Roadmap	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Solar Cells
137	Nanoroadmap Project (NRM)	Draft Roadmap Report on Nanoporous materials	2005	Roadmap	AIRI/Nanotec IT; Willems & van den Wildenberg (ES/NL); VDI/VDE-IT (DE); Institute of Nanotechnology (UK); MATIMOP (IL); Technology Centre (CZ); VTT (FI); Yole Développement (FR)	European Union	Nanomaterials
138	NanoRoadSME	Nanomaterial Roadmap 2015: Overview on Promising Nanomaterials for Industrial Applications	2005	Roadmap	European Commission	European Union	Nanomaterials
139	NanoRoadSME	Roadmap report concerning the use of nanomaterials in the aeronautics sector	2006	Roadmap	European Commission	European Union	Nanomaterials
140	NanoRoadSME	Roadmap report concerning the use of nanomaterials in the automotive sector	2006	Roadmap	European Commission	European Union	Nanomaterials
141	NanoRoadSME	Roadmap report concerning the use of nanomaterials in the energy sector	2006	Roadmap	European Commission	European Union	Nanomaterials
142	NanoRoadSME	Roadmap report concerning the use of nanomaterials in the medical and health sector	2006	Roadmap	European Commission	European Union	Nanomaterials

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143	NASA	Nanotechnology	/	Presentation	NASA	USA	Nanotechnology
144	NASA	DRAFT Nanotechnology Roadmap – Technology Area 10	2010	Roadmap	NASA	USA	Nanotechnology
145	Nedo	Battery Development 2006, 2008, 2010	2010	Roadmap	Nedo	Japan	Li-ion batteries
146	Organic Electronics Association (OE-A)	OE-A Roadmap for Organic and Printed Electronics, 4. Edition	2011	White Paper	VDMA	Germany	Nanotechnology in electronics
147	Pennsylvania Nanomaterials Commercialization Center	Technology Roadmap Overview	/	Mindmap	Pennsylvania Nanomaterials Commercialization Center	USA	Technology
148	Peterson, C.	Nanotechnology: From Feynman to the Grand Challenge of Molecular Manufacturing	2004	Report	Foresight Institute	USA	Molecular Manufacturing
149	Prakash, R. et al	A ferrocene-based carbon–iron lithium fluoride nanocomposite as a stable electrode material in lithium batteries	2010	Report	Karlsruhe Institute of Technology (KIT)	Germany	Energy storage
150	Priaulx, M.	Solar Cells and Nanotechnology	2005	Article	University of Wisconsin-Madison	USA	Solar Cells
151	Rae, A.	Nanotechnology is now starting to find Applications in Electronics	/	Article	TPF Enterprises LLC	USA	Nanotechnology
152	Rasmussen, B. et al.	Danish Nano-science and Nano-technology for 2025	2004	Article	The European Foresight Monitoring Network	Denmark	Nanotechnology
153	Reiss, T. et al.	Nanotechnology Research in Russia – An Analysis of Scientific Publications and Patent Applications	2010	Report	Fraunhofer ISI	Germany	Nanotechnology
154	Reiss, T. et al.	NANORUCER	2010	Working Paper	Fraunhofer ISI	Germany	Nanotechnology
155	Roco, M.	Societal Implications of Nanoscience and Nanotechnology	2001	Report	National Science Foundation (NSTC, NSET)	USA	Nanoscience and Nanotechnology
156	Sigrist, M.	Predicting the Future: Review of Public Perception Studies of Nanotechnology	2010	Report	Human and Ecological Risk Assessment	Switzerland	Nanotechnology

No.	Author	Title	Year	Type	Institutions	Country	Focus
157	Sopian, K.	Solar Energy Technology Roadmap, Malaysia	2010	Presentation	Solar Energy Research Institute Universiti Kebangsaan Malaysia	Malaysia	Solar energy
158	Steinfeld, M. et al	Nachhaltigkeitseffekte durch Herstellung und Anwendung nanotechnologischer Produkte	2004	Report	BMBF	Germany	Nanotechnology
159	Tanaka, N.	Technology Roadmap – Electric und plug-in hybrid electric vehicles	2011	Roadmap	International Energy Agency (IEA)	France	HEV, PHEV
160	Tanaka, N.	Technology Roadmap – Concentrating Solar Power	2010	Roadmap	International Energy Agency (IEA)	France	Solar
161	Tanaka, N.	Energy Technology Perspectives	2010	Report	International Energy Agency (IEA)	France	Energy
162	Textor, R.	Die Zukunft Österreichs – Chancen und Risiken im nanotechnologischen Zeitalter	2006	Report	Wien, 2006: Buchverlage Kremayr & Scheriau/Orac	Austria	Nanotechnology
163	The Institute of Nanotechnology	Roadmaps for Nanotechnology in Energy	2006	Report	Institute of Nanotechnology	European Union	Nanotechnology, energy
164	Thielmann, A.	Trends in Battery Technology Patents	2008	Article	Nanotechnology Law and Business	/	Energy storage
165	TWA Network	Korea's Nanotechnology Roadmap for the next ten years	2011	Roadmap	TWA Network	Korea	Nanotechnology
166	VDI	Meta-Roadmap Nanomaterialien – Zukünftige Entwicklungen und Anwendungen	2009	Meta-Roadmap	VDI	Germany	Nanomaterials
167	Volz, A.	The European landscape of Nanomaterials and Sustainable Energy technologies	/	Presentation	Projekträger Jülich	Germany	Nanotechnology
168	Vullum, F. et al.	Characterization of lithium nanobatteries and lithium battery nanoelectrode arrays that benefit from nanostructure and molecular self-assembly	2006	Article	/	USA	Energy storage
169	Wagner, L.	Nanotechnology in the clean tech sector	2008	Report	MORA Associates	/	Nanotechnology

No.	Author	Title	Year	Type	Institutions	Country	Focus
170	Waide, P.	Gadgets and Gigawatts: Policies for energy efficient electronics	2009	Presentation	International Energy Agency (IEA)	France	Electronics
171	Wang, C. et al.	Nanotechnology Prospect for Rechargeable Li-ion Batteries	/	Report	Materials Research Laboratories, Industrial Technology Research Institute	Taiwan	Energy storage
172	Yang, Y. et al.	New Nanostructured Li ₂ S/Silicon Rechargeable Battery with High Specific Energy	2010	Article	American Chemical Society	USA	Energy storage
173	Zhang, H. et al.	Urchin-like nano/micro hybrid anode materials for lithium ion battery	2006	Article	/	USA	Energy storage
174	Zhenhai, W. et al.	Binding Sn-based nanoparticles on graphene as the anode of rechargeable lithium ion batteries	2011	Article	Department of Mechanical Engineering, University of Wisconsin-Milwaukee; et al	USA	Energy storage
175	Ziebert, C. et al.	Lithium-Ionen-Batteriezellen auf Basis von neuartigen Nanokomposit-Materialien (LIB-NANO)	2009	Presentation	Karlsruhe Institute of Technology (KIT)	Germany	Energy storage

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