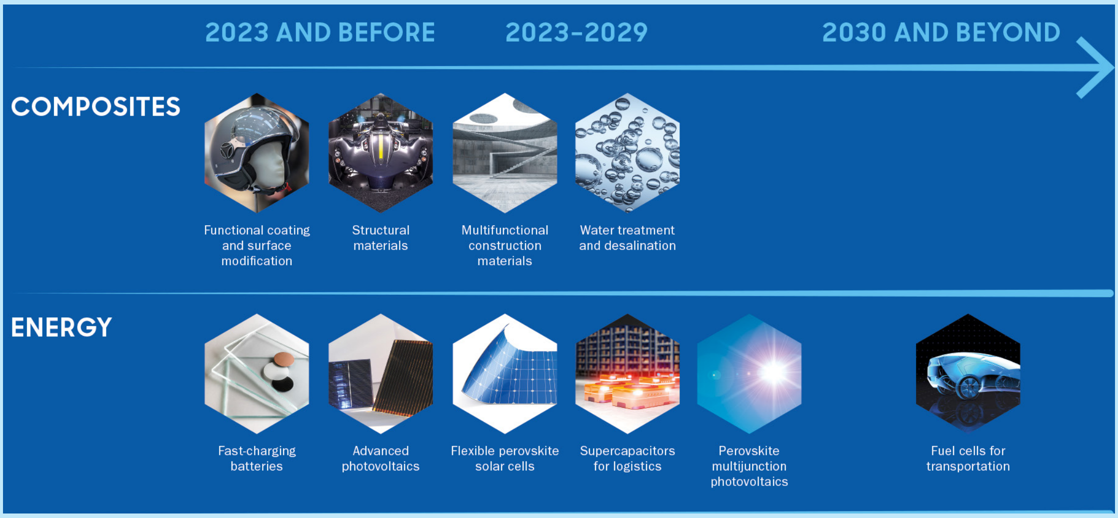
The Graphene Flagship Technology and Innovation Roadmap

Energy Storage and Generation

This chapter covers energy applications of graphene and related materials. Graphene applications in energy vary from fuel cells, hydrogen generation and (gas) storage, batteries, supercapacitors to photovoltaics.

The most interesting application areas from a European innovation perspective for graphene innovation are supercapacitors and fourth-generation batteries. Hydrogen production and storage as well as batteries are further interesting areas. In terms of photovoltaics, third generation PV is more likely to become interesting on a European level, with perovskites being the most promising application area for graphene.



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4 Energy generation and storage

4.1 Potential energy applications

This chapter covers energy applications of graphene/2D materials. The application areas are summarized in Figure 48.

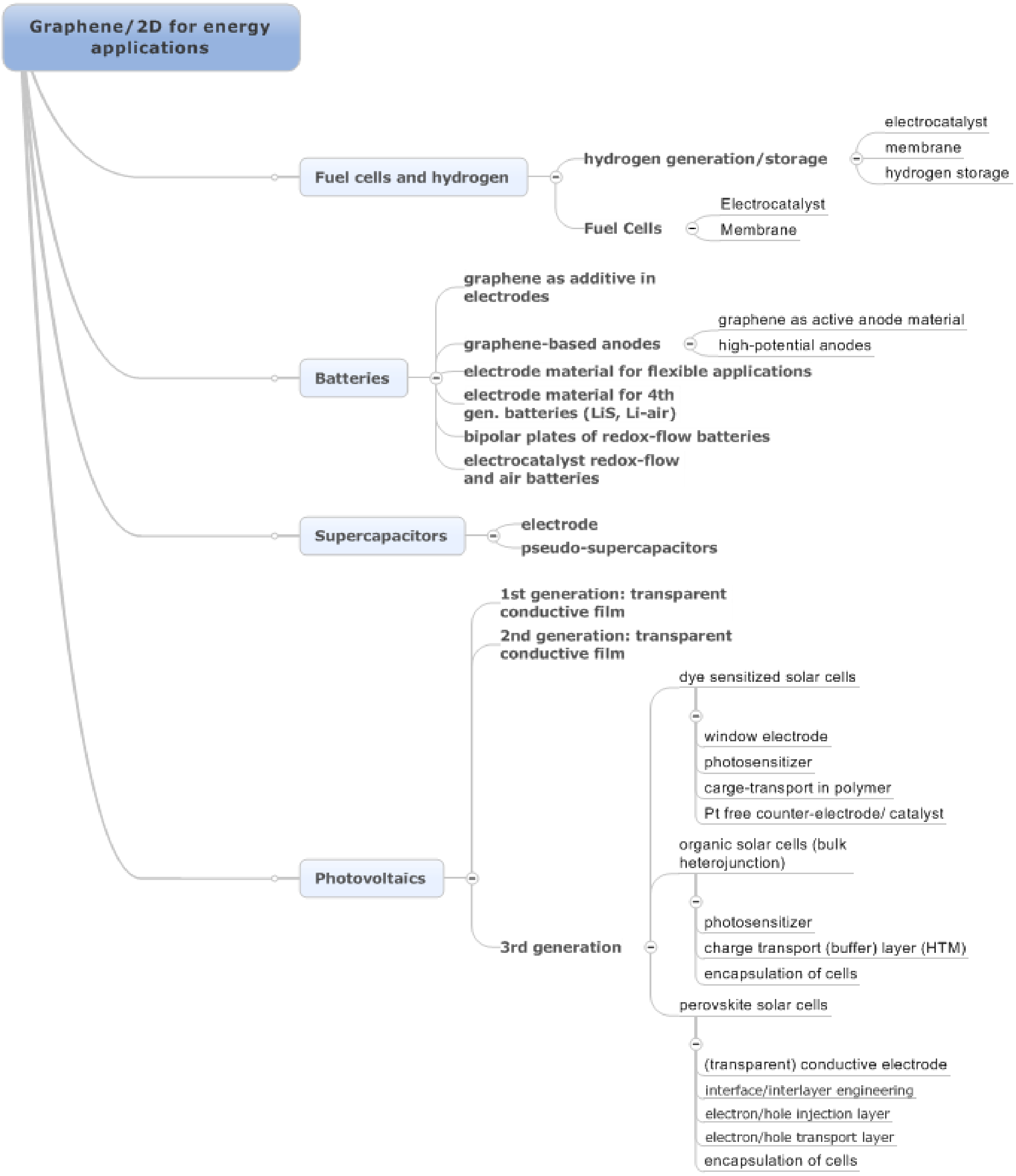


Figure 48: Energy related application areas of graphene/2D materials.

Some other energy related applications are covered in chapters 1.4 (electric field grading, electric conductivity) and 5 Electronics & Photonics (nanogenerators/micro-energy harvesters).

4.2 Fuel Cells and hydrogen economy

The following section is particularly focused on Proton Exchange Membrane Fuel Cells (PEM FC). This kind of fuel cells is prevailing in the most relevant application markets, as there are vehicles and stationary storage (s. Figure 49). Moreover, PEM FCs represent the most prominent focus of research. Graphene and other 2D materials are particularly expected to contribute to components for this type of fuel cells. In some special cases Direct Methanol Fuel Cells (DMFC) are also addressed, as graphene and other 2D materials might contribute to improvements in this technology as well. Explicitly excluded are high temperature fuel cells like Solid Oxide Fuel Cells (SOFC).

Fuel cells are energy converters. They transform chemically stored energy in electrical energy. Therefore, fuel cells alone cannot be seen as energy storage solution. But together with fuel tanks they can be used – like batteries and supercapacitors – for energy storage respectively power supply.

The chapter also looks at power to gas applications (electrolysers) in hydrogen generation, as well as hydrogen storage applications for graphene. These applications are assessed separately starting at chapter 4.2.4 Hydrogen generation and storage.

4.2.1 Market perspective: graphene/2D materials in fuel cells

Applications of PEM fuel cells cover a broad spectrum: The technology is used in stationary applications for power generation, particularly in combined heat and power (CHP) generation systems. The related devices are often implemented in residential applications; Fuel cell technology can be used for levelling peak power; and it is used to avoid grid reinforcement. In terms of fuel cells applications, PEMFC is expected to dominate smaller systems with less than 50 kW (relative to other fuel cell technologies), whereas SOFC and MCFC will dominate the high-power output-range (>300 kW). [241] Rather small systems are typically used in residential and small commercial buildings as well as in cell towers for telecommunications. Larger systems are often used in mixed-use buildings such as corporate campuses, hospitals or data centres. Sometimes FC systems are also as backup power.

Another key application-area is transport. In this case particularly bigger vehicles, including those for urban transport and long-distance applications are relevant. A minor part of fuel cell applications are mobile devices and the power supply of portable electronics.

From a global perspective, the market for PEM FC reached $340 million and $460 million in 2010 and 2014, respectively. This number is expected to reach $534 million by 2015 and $1.9 billion by 2020, registering a compound annual growth rate (CAGR) of 29.4% from 2015 to 2020 [242].

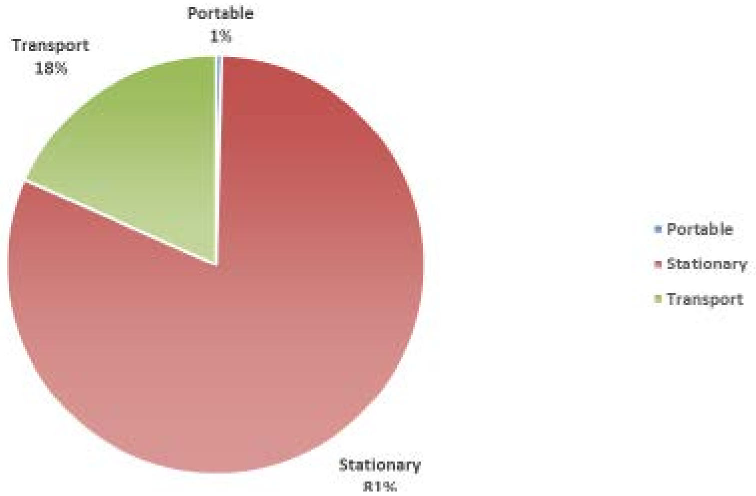


Figure 49: Global fuel cell shipments, broken out by MWS, 2014. Source: [243]

Among these application areas the main advantage of fuel cell technology is that it allows for fast fuelling compared to battery technology. Moreover, for automotive applications, the range of energy delivery is higher due to the higher energy density of 500 Wh/kg (today's lithium-ion batteries have an energy density of 150 Wh/kg). Another advantage is that fuel cell systems show high energy efficiency compared to common combustion technologies. The electric efficiency is up to 60% and the combined efficiency (including heat) reaches even more than 90% [244]. Moreover, it is beneficial for application that fuel cells do not produce poisonous emissions like NOx or SOx, they emit no noise, have no moving parts, the reliability is high, and they can work autonomously [243, 245].

One major technological challenge in fuel cell technology is the oxidant reduction reaction (ORR) at the cathode. The main aim is to increase simultaneously the power density and the durability. The prevalent technology is based on platinum or platinum alloys used as catalyst. An analysis revealed that 15 % of the patents in fuel cell technology are related to platinum based catalysts (s. Figure 50). A drawback of the technology related to PEM FC operation is that the carbon supports degrade during chemically aggressive fuel cycling conditions and that the platinum catalysts can become reduced in activity. For DMFC operations methanol crossover and CO poisoning effects can lead to poorer operational stability and limit lifetime. Moreover the platinum-metal catalysts are expensive and limited in long-term availability and so alternates are under investigation, including graphene-based solutions.

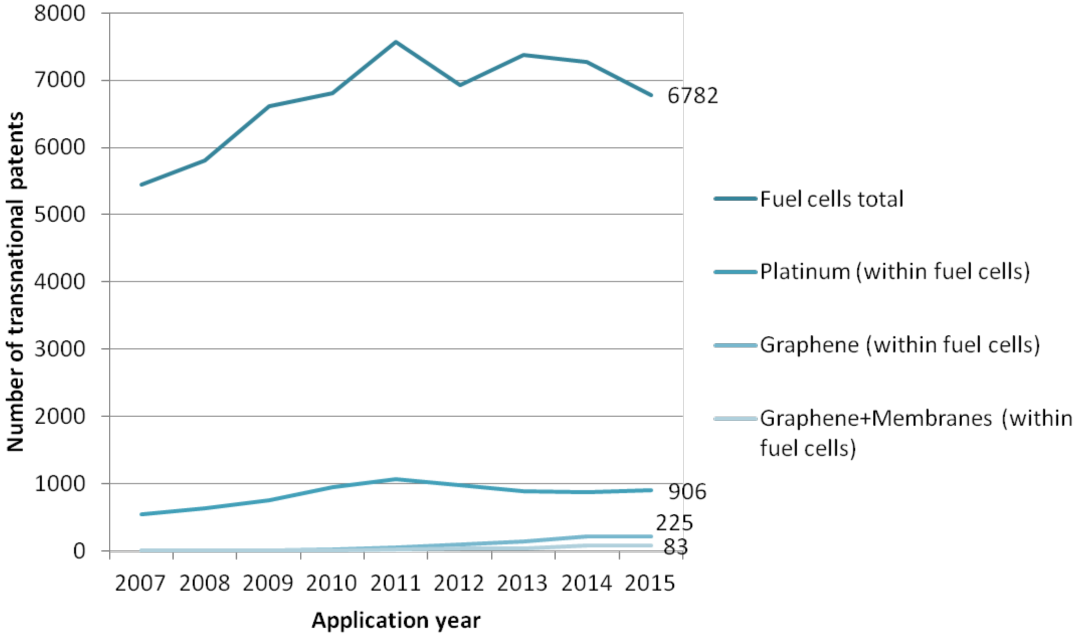


Figure 50: Patents in Fuel Cell technology. [137]

Within the fuel cell domain there is a visible increase of activities in the last few years: The shipping rose about 50% between 2014 and 2015 [243]. With regard to countries, major player in the fuel cell domain is Japan which pursues a vigorous hydrogen policy and intends to create a “hydrogen society” by 2020 [246, 247]. In the US the hydrogen technology gets awareness due to large scale pilot projects [248]. From an economic perspective, Europe already has a relevant role in the fuel cell value chain: 28% of direct jobs on fuel cell system level and even 33% of the companies working in the global fuel cell supply chains are located in Europe [243]. This role of hydrogen-technology is reflected in the research agenda of the European Commission: In Horizon 2020, €1.3 billion are foreseen for related research and demonstration (including the matched industry funding), mostly through the FCH2 initiative. [243]

The major relevance of fuel cell technology and hydrogen power generation is to be seen in a global concept of renewable energy generation. “Green hydrogen”, which means hydrogen generation from surplus peak power from renewables, is certainly not a standard today. But it will be a relevant pillar in the technology mix of a future sustainable energy supply system. Hydrogen technology can play a role with regard to both power supply and energy storage e.g. within power-to-gas concepts. It is assessed that reaching the 20%-CO_2 reduction objective in a global climatic change policy will only be possible with – among others – hydrogen technology.

Even though hydrogen technology will probably play a significant role in the future, today the economic situation is still difficult: In 2014 many fuel cell companies reported higher losses. Only a few were able to reach a growth of revenue [243]. There are still two major barriers for commercial fuel cell applications – even though both are not undisputed: One significant barrier is the hydrogen distribution from highly dispersed sources to the point of need [243, 248, 249]. This appears to generate a dead-lock-situation: Due to technology maturity issues the number of particularly fuel cell vehicles is very limited. Hence the refuelling infrastructure is not widespread. On the other hand, the missing refuelling infrastructure prevents the propagation of fuel cell vehicles, which is the reason for reluctant investments in R&D.

Many governments are tackling this issue with stimulus packages. Japan and South Korea are actively building hydrogen fueling stations. In Europe, UK has approved the Hydrogen Refueling Station Infrastructure Grant Scheme to provide £6.6 million ($9.7 million) in funding over two years for 12 hydrogen infrastructure projects. In Denmark FC vehicles are being encouraged via tax exemption [250]. In Germany, Shell will install a nationwide network of hydrogen fuelling pumps at retail sites [251].As another major barrier for commercial fuel cell applications high costs for the technology are reported. It is repeatedly mentioned that particular high effort for catalysts from platinum and platinum alloys are the reason for these high costs. But also costs for e.g. bipolar plates are playing a relevant role. This barrier, however, is not undisputed, and it is difficult to assess up to which extend this barrier can be overcome by scaling up.

Fuel Cell Vehicles

In vehicle applications, particularly the PEM fuel cell technology is used. Key issues in this area are power density and the reduction of prices [249]. Today, the prices for fuel cell vehicles are similar to battery-based electric vehicles: The price for a Tesla electric vehicles starts at about $57,000; in Japan fuel cell cars are available for about $60,000 [249].

With regard to markets, Japan and Korea are ahead of the US and the EU: In general, Japan focuses on fuel cell based passenger cars, whereas in the EU fuel cells are particularly discussed with regard to range extenders in electric vehicles [249]. Accordingly, in Japan the incentives for fuel cell cars in terms of subsidized bonus are three times higher than for battery-based electric vehicles [249] – Japanese government supports fuel cell vehicles with $20,000 subsidy and the Japanese government equipped its ministries and other offices with fuel cell cars as official vehicles. As leading market, Japan has the power to standardise the related technology. For example the standard for compressed hydrogen filling stations has been defined in Japan. But the Japanese vehicle marketed for fuel cells is more or less a closed-shop and hard to enter for companies from outside Japan [243]. Beside Japan, also Chinese OEMs started significant developments in fuel cell passenger car markets [249], whereas in the US the incentives for fuel cell passenger cars have already started to phase out [249].

From the company's perspective, major OEMs in the sector of fuel cell cars are [249]:

- Toyota (JP)
- Hyundai (KR)
- Honda (JP)
- Daimler (DE)
- BMW (DE)

Key players in the automotive fuel cell technology development are Toyota and Daimler. Daimler recently has announced the launch of a fuel cells based SUV in 2017. Other European car manufacturers appear to pursue rather an on-hold strategy with regard to fuel cell development. In general, the OEMs in the automotive industry often collaborate with fuel cell technology suppliers and do not have significant own R&D activities with regard to this technology. E.g. VW cooperates with the Canadian fuel cell company Ballard. Other leading manufacturers of fuel cells for the automotive sector are [249]:

- Nissan (JP)
- Suzuki (JP)
- Kia (KR)

Another market opportunity for fuel cell technology in the vehicle sector is public transport. Here the major benefit of fuel cells is the issue of non-hazardous emissions. This probably propagates the technology in regions where air pollution is a major issue. Today, already various pilot activities are implemented with hydrogen powered buses. So, it might be that public transport in the future is a relevant market for fuel cells. But with regard to technology development it has no specific relevance as the related technology is the same as in passenger cars – only with cascaded fuel cell stacks. Also in the area of material handling, forklifts, and trucks fuel cell technology has interesting advantages and European companies are involved in related activities. But, in general, these applications can be seen as niches.

The overall picture with regard to fuel cell vehicles can be assessed as follows: even though in 2015 Toyota has already launched the fuel cell based car Mirai and Hyundai the iX35 [249] a significant increase of fuel cell vehicles is not to be expected before 2025 [243].

Stationary Fuel Cells

Another major application for fuel cell technology is stationary systems. The largest share off shipments of fuel cells systems is still in the stationary sector [243]. They are, on the one hand, used for back-up power generation. In large power facilities (>300 kW), the prevailing technologies are SOFC, MCFC and AFC, all not relevant for graphene activities. PEM fuel cells might, however, play a relevant role for smaller scale systems in a decentralised and renewable-based energy system. In this case, electric peak power from renewables can be transferred to gas by electrolysis, the so called power-to-gas approach. The advantage is that the distribution can build on the existing infrastructure of the natural gas grids [245]. In residential PEM fuel cells the gas can then be re-transferred into electric energy and heat. Hence, hydrogen technology, can be used for grid balancing and by this it is a good opportunity to increase the flexibility of renewable-based energy systems [248].

The related stationary systems are used not only for energy generation, but also for co-generation of heat. Here the “waste-energy” can be also exploited and therefore the system reaches a higher efficiency [248]. The related technology is called combined heat and power (CHP) technology. These CHP systems have substantially less CO_2 emissions than boilers or grid power supply [245]. The public and policy is interested in the related technology, as it levers the efficiency of the overall energy system [243]. For this application predominantly PEM fuel cells are used. For residential applications increasingly micro-CHP are implemented with a capacity of 1 kW to 6 kW. Until 2020 the micro-CHP market is expected to be $4.44 bn [252].

A major barrier for the CHP technology is the very high costs for investment [248]. Nevertheless, in Japan, Korea, and the USA stationary fuel cells are already commercialized [245]. The related market is again dominated by Japan, which is about 6-8 years ahead [244]. Japanese government has already heavily and successfully subsidized the market introduction of residential fuel cells [243]. Accordingly, Japan has the lead in stationary applications with more than 120,000 devices [248], and 98% off shipments in the CHP area are in Asia [243].

Also for Europe a large market potential for stationary fuel cells can be assessed [245]. Today, the biggest hurdle is the price and accordingly the reduction of production costs. Only with relevant volumes competitive pricing and acceptable payback periods can be reached [245]. The EU-strategy with regard to stationary fuel cells is implemented in the so-called ene.field project [253], involving nine EU fuel cell system suppliers. This might spread the technology in the end. But, with regard to technology development, the European system suppliers collaborate with Asian fuel cell manufacturers. For example Viessmann (DE) integrates micro-CHP fuel cells from Panasonic (JP) and Vaillant (DE) from Honda (JP). BaxiInnotech (DE), just recently, closed its own technology development and now relies on Toshiba technology (JP). Key vendors of micro-CHP systems are [254]:

- BDR Thermea Group (NL)
- Honda Motors (JP)
- Vaillant (DE)
- Viessmann Group (DE)
- Panasonic (JP)

4.2.1.1 Role of graphene/2D materials in fuel cell technology

Graphene is mainly discussed as electro-catalyst or catalyst support material in e.g. PEM FCs cathodes for oxygen reduction reaction (ORR). Required characteristics of this electro-catalyst include:

- oxidation respectively corrosion resistant and high catalyst durability

- highly conductive
- specifically functionalizable in order to deposit catalysts as well as the ionomer ultra thin layer onto it

Graphene nano platelets (GnPs), in general, show exceptional characteristics of large specific surface area (SSA) combined with extraordinary electric conductivity. Graphene and related derivative 2D materials and nano-composites can be used:

- as catalysts for the electro-catalytic reaction itself
- as functionalised material where active sites are occupied with other active materials
- doped graphene
- graphene / metal or metal oxide composites

Graphene oxide (GO) and related carbon nitrides (gCN) have the advantage that they show many functional groups on their surface. These can act as chemically active sites in catalytic reactions or as anchoring sites for metal-particles. However, functionalized graphene shows decreased electric conductivity.

A major challenge is durability in both the anode and cathode of fuel cells. This is where graphene and related 2D materials have the most potential by providing corrosion resistant catalyst supports [255].

New applications can be envisaged. For example, flexible graphene-based fuel cells could be integrated in smart textiles. An advantage of graphene in this application might be that flexible electrodes for portable fuel cell systems could be realized in the future [256].

From a regional perspective, particularly in China there is an increase of activities on fuel cell catalyst related research with focus on graphene. An analysis of scientific publications revealed that today China is the leading country in this respect (s. Figure 51). But in general, compared to other application areas in energy storage and generation, the scientific activities with regard to graphene in fuel cell technology are rather limited: the total number of publications from 2009-2014 was less than 600, compared to e.g. about 2000 in each of the other application areas: battery technology, photovoltaic and supercapacitors.

Also from a patenting and thus application perspective, graphene and its 2D derivatives appear a little less appealing for fuel cell technology compared to other areas: in the mentioned period of six years worldwide all together 77 transnational patents were filed. For comparison, in photovoltaic application there were almost 400 patent applications with regard to graphene in the same period.

Recent reviews are summarized in Table 24.

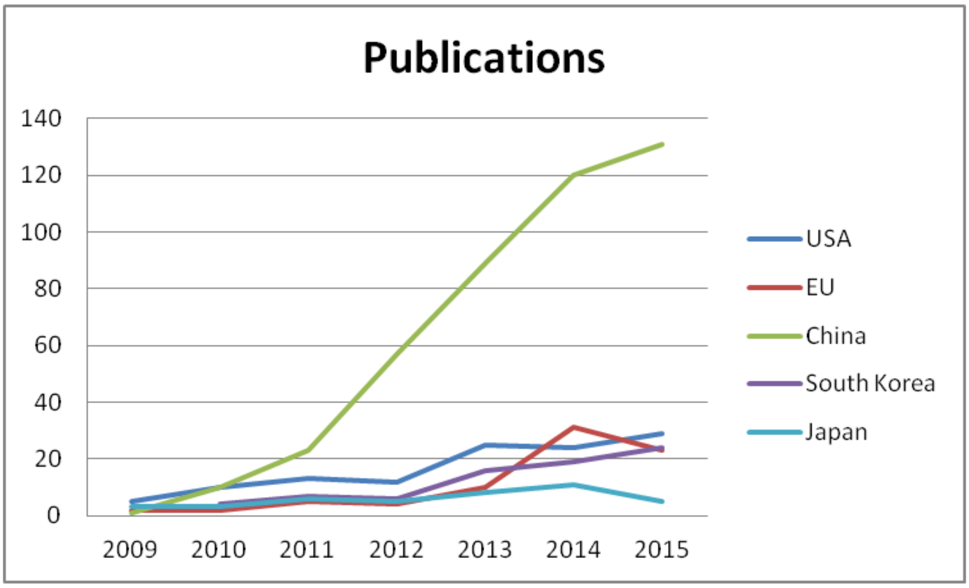


Figure 51: Publications on fuel cell catalyst with regard to graphene. [257]

Table 24: Recent reviews related to fuel cells and hydrogen applications of graphene/2D materials.

Topic	Reference
Fuel cell catalysts	[258]
Catalysis with two-dimensional materials and their heterostructures	[236]
Energy applications	[256]

4.2.1.2 Market Opportunities for graphene in fuel cell technology

4.2.1.2.1 Pt-reduction key target of fuel cell development

Today the quantity of platinum used in fuel cells for car applications has already dropped by two thirds [249]. That leads to current costs for noble materials in car fuel cells of 1000-1500 € per system [259]. The reduction of platinum amount is assessed to have a high impact on cost reduction [249]. The US Department of Energy has set the aim of 0.15 g Pt/kW, which means about 500 € for a 100 kW-vehicle or even less. These ambitious targets will require further research and development on noble metal reduced concepts. The key challenge is to maintain a high level of performance and durability compared to fuel cells with a higher platinum loading.

4.2.1.2.2 Pt-free electrocatalyst issue for automotive applications after 2030

Particularly, when/if the fuel cell technology will boom in the automotive sector, costs for platinum will become relevant for the price of the overall system. One expert, consulted for this report, assessed very roughly that platinum costs will cause 25% of the fuel cell system (at a production quantity of 500,000 FC cars). Even though, platinum-free electrocatalyst are expected not to be an issue in the next 10 years – although it might become relevant after 2030. Then it is to be expected, however, that various concepts for noble-metal-free electrocatalysts will be available.

4.2.1.2.3 Carbon species enjoy trust in automotive sector

Scepticism against noble-metal-free electrocatalysts in the automotive sector is high (s. 4.2.1.3.1). But, as one industry expert stated, at least, an advantage for graphene based concepts is that there is a high confidentiality in carbon species with regard to electrode materials, e.g. because of corrosion properties. Therefore, the introduction of graphene might encounter lower barriers, especially when these are offered as "drop-in" replacements for existing Pt/C FC electrodes. Moreover, it is said that there are only a very few materials available to replace activated carbon.

4.2.1.2.4 Different opportunities for graphene in FC technology

A key issue for success of fuel cell technology – particularly in mass applications like vehicles – are power density and costs [249]. Cost drivers for fuel cell technology (PEM FC) are (among others):

- platinum and other noble materials
- membranes
- bipolar plates
- tanks (composites, see also chapter 3.2 Additive to bulk solids/composites)

In all these components graphene or GRM might contribute to an improvement of performance and a cost reduction. Endplates also increase costs in fuel cell technology. But, today it is unclear if graphene can play a role in this area. Another challenge that can be addressed by graphene is durability in both the anode and cathode of fuel cells.

4.2.1.2.5 Fuel cells in automotive sector at a turning point

Currently, the fuel cell technology in the automotive sector is at a critical point: In 2015 two Asian car manufacturers have launched first commercial fuel cell cars (Toyota: Mirai; Hyundai: iX35). The development of the whole technology will decisively dependent on the market success of the new fuel cell series.

Worldwide the discussion on the dominant technology for future transport is still ongoing. Particularly, Japan backs fuel cells. The Japanese policy and society gave a very clear commitment towards hydrogen technology as future backbone of their power system [260]. Nevertheless, not only Toyota but also Daimler as a European company can be seen as technology leader with regard to fuel cells in cars.

4.2.1.3 Market threats affecting graphene in fuel cell sector

4.2.1.3.1 Controversial: Relevance of platinum reduction

The reduction or replacement of platinum in fuel cell electrocatalysts is often discussed in academic publications – not only with regard to graphene. Practically, by 2020 the limit of 15 g platinum per vehicle is expected. And by 2025, when large scale commercialization is implemented, less than 10 g platinum per vehicle should be reached [259]. However, from an application perspective the relevance of platinum reduction is not undisputed:

- Platinum shows a very good recyclability. The US Department of Energy sets the target of 98 % recycling ratio. In case of a significant market increase, recycling might play a relevant role for availability of platinum. Hence, the price for the raw material might decrease some years after a fuel cell technology has been established [243].
- The share of platinum used for fuel cell applications is about 0.1 % of the global demand [243].
- Moreover, it has to be stressed that high overall costs of fuel cell systems are due to various items – like e.g. the compressor, membranes and bipolar plates –, not only due to noble material content of the electrocatalyst [259].
- And last but not least, as crucial barrier for the development of fuel cell technology the insufficient infrastructure for dissemination and hydrogen supply is mentioned – which is not at all related to material costs/costs of fuel cells [243, 248, 261].
- Metal-free catalysts including those based on graphene have not shown equivalent performance. However, Pt-free metal catalysts are entering the market (e.g. Amalyst) and graphene-based GO, gCN nanocomposites could support that by leading to more durable supports.

According to some experts interviewed within this study, platinum-free electrocatalysts will not be an issue for automotive applications before 2030: Particularly, when/if the fuel cell technology will boom in the automotive sector, costs for platinum will become relevant for the price of the overall system. In the midterm and at a given production quantity of 500,000 FC cars, platinum costs will cause 25 % of the fuel cell system. Even though, platinum-free electrocatalysts are expected not to play a role then. After 2030 – when platinum-free electrocatalysts might become relevant – it is to be expected, however, that various concepts for noble-metal-free electrocatalyst will available.

4.2.1.3.2 No relevant European technology development in combined heat and power (CHP)

Micro-combined heat and power (micro-CHP) is an attractive stationary application area for PEM fuel cell technology to use waste heat and to increase overall energy efficiency [245, 248]. Today, in Japan this technology is already widespread for residential applications [248, 262]. There are, however, also relevant system integrators for micro-CHP in Europe (e.g. Viessmann, Vaillant, Bosch, BaxiInnotech, Buderus) [253]. But, as for the related technology development, there is no relevant player in Europe anymore, since also BaxiInnotech has closed down its in-house development. Today, all of the mentioned system integrators use technology from Japan. Some European stakeholders are active in developing FCs for stationary applications, but they need to close the gap to the Japanese manufacturers, which already supply the integrators.

4.2.1.3.3 Niche markets in logistics and transport: weak position for European PEM FC manufacturers

In principle, advantages of fuel cell-based power generation are [243, 245]:

- no hazardous emissions (like NOx or SOx)
- no noise
- high reliability

This suggests the technology for several applications like forklifts for material handling and buses. Indeed, these applications can be seen as attractive and developing niche markets for fuel cells – particularly in Europe [262]. But, though there are some smaller stakeholders in Europe, material handling is already very much dominated by Ballard (Canada). And busses – from a FC technology perspective – cannot be seen as specific field of application, as it is directly linked to the automotive sector: Here, the major strategy of European players is just to redouble automotive fuel cell systems.

4.2.1.3.4 Long lasting development phase threatens reputation

The development phase of fuel cell technology has been on-going for decades. Worldwide, there have been several market incentive programs fostering the technology uptake. In the USA, incentives for fuel cell based passenger cars have been phased out [249]. The number of fuel cell vehicles on the road, however, is not expected to increase substantially before 2025 [243]. It is perceivable that this very long time to market has an impact on the image of the technology in general, threatening the overall reputation. . In one fuel cell expert assessment from 2009 (i.e. 7-8 years ago) it was stated: “For the last 50 years success has always been 10 years away” [263].

4.2.1.3.5 Unclear policy strategy

The fuel cell community complains that in the last years the commitment from European policy makers and industry towards fuel cell technology has been unclear or inconsistent. Compared with the clearly expressed Japanese strategy towards implementation of the "hydrogen society" [243, 249, 260], this impression can be supported. One exception to this is EU measures in research and demonstration: In Horizon 2020 a significant budget will be directed at fuel cell and hydrogen-related energy calls, especially channelled by the FCH2 initiative [243].

4.2.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in fuel cells

4.2.2.1 Current strengths for graphene/2D materials use in fuel cells

4.2.2.1.1 Potential to reduce amount of platinum in fuel cell electrocatalysts

There is a market opportunity to investigate Pt-free catalysts and combinations with graphene-based support systems that offer reduced corrosion and improved durability – especially when these are offered as "drop-in" replacements for existing platinum/carbon FC electrodes. There are several approaches reported where graphene materials contribute to the reduction of platinum as a limited resource key metal used in fuel cell electrocatalysts. Some alternatives based on functionalized graphene derivatives are beginning to show first promising results regarding electrocatalytic activity and robustness or potential cost efficiency – also applications as electrolyzers or in alkaline fuel cells [264, 265].

Reduction of platinum by graphene and graphene related materials can be reached by different means. Graphene related materials are discussed as simple support, active support or active materials. Some examples are:

- Nitrogen-graphene composites have shown promising results as a strategy to reduce platinum in electrocatalysts. E.g. platinum-nano-particles can be encapsulated with a nitrogenated graphene layer [266]
- Today, 70% of the platinum in a fuel cell electrode is not used in the reaction. Graphene can improve the usage of platinum on the electrode [267].
- Graphene oxides (GO) have many functional groups/defects which can be used as chemically active sites on the surface. They can act as anchoring sites for doping with metal nano-particles to foster catalytic reactions. This functionalized graphene can lead to improvements of electrocatalysts in fuel cells [268].
- Graphene can increase resistance of the electrolyte layer against oxidation. This reduces material loss.
- Graphene can increase the efficiency of methanol/ethanol electro-oxidation [269].

4.2.2.1.2 Increased robustness of fuel cells

Graphene can contribute to increase the robustness of fuel cells. Graphene nano-particle (GnP) based electrocatalysts show a reduced inclination to be poisoned by carbon monoxide [270], which is an often reported problem of fuel cell electrocatalysts. In methanol fuel cells graphene-based electrocatalysts decrease cross-over of methanol, which often reduces efficiency of these systems [271]. Moreover, graphene electrocatalysts are reported to be more resistant against corrosion [272]. Used as a catalyst support in both the anode and cathode of fuel cells, the durability can be enhanced [255]. All this can contribute to the long-term cycle stability of the fuel cell system, which is besides cost and power density still a major challenge.

4.2.2.1.3 Reduce costs of manufacturing due to improved processing

Graphene-based electrocatalytic materials can, on the one hand, contribute to reduce material costs by replacing platinum. But another – maybe even more relevant – contribution of graphene to overall price reduction of fuel cells can be the manufacturing. Graphene is reported to be easier to process compared to platinum-based electrocatalysts. This can lead to a cost reduction in the manufacturing of fuel cell bipolar plates.

4.2.2.1.4 Special applications in functional layers, membranes and flexible fuel cells

Graphene and graphene related materials might play a role in further applications in the hydrogen and fuel cell technology:

- Graphene can be also used on the gas diffusion layers or within the microporous layers to control the water management in operating fuel cells..
- Membranes are another relevant costs factor in fuel cells. Results indicate graphene could improve their properties. Accordingly, the patent analysis revealed an increase in patenting in this area (s. Figure 50). In 2015, about one third of the graphene related patents in fuel cell technology are dealing with membranes.
- Fuel cell technology is establishing as opportunity for power supply in portable electronic applications, e.g. in smart textiles or mobile phones [243, 262]. For these applications graphene might contribute with flexible electrodes.

4.2.2.2 Current weaknesses and challenges for graphene/2D materials use in fuel cells

4.2.2.2.1 Competition with established standards

The introduction of graphene-based materials in fuel cell electrocatalysts are hampered, because the new material has to prove its catalytic advantages, a high durability, and an industry-compatible processability – and all that at the same time. As there are already competing materials on the market, all aspects have to at least reach the state of the art. In general, common platinum/activated carbon electrocatalyst are well established and mastered in the fuel cell technology. The willingness to change electrocatalyst material is limited. Particularly in the automotive industry, concepts have to pass tough accelerated testing, before they are taken into consideration at all.

4.2.2.2.2 Dead-lock situation: production capacity versus attractive orders

Even though graphene appears to have at least some potential for electrocatalyst applications, the industry is reluctant to use it in fuel cells. Repeatedly it is mentioned commercial available graphene materials do not live up to the requirements. That appears to be a result of a typical dead-lock situation: On the one hand, the investment for graphene material and process development is only justified, if relevant market volumes are tangible. On the other hand, realistic market volumes cannot be assessed without data on performance, availability, and prices of the new material – which, however, requires detailed material development and process implementation. The often reported lack of production capacity and insufficient data on the quality of commercial graphene prevent the application industry from commitment towards graphene.

4.2.2.2.3 Graphene-materials not optimized to fuel cell-applications

Graphene-based electrocatalyst structures are often not optimised to fuel cell-applications. In the past, the industry and applied research has purchased commercial available graphene and applied it more or less in their standard processes. The resulting performance with regard to catalytic activities and system's performance was poor. Therefore, the reputation of graphene suffered. On the other hand, highly specialized graphene is available at best at lab scale.

Besides, functionalized graphene can be used as catalytically active area but at the same time, the electrical conductivity should remain high. This trade off of high catalytic activity (high funtionalisation) with lower conductivity must be managed to maintain the electrochemical performance in FC applications.

4.2.3 KPIs for Fuel Cells

Table 25: Typical KPIs for fuel cells.

	Unit	Description	Literature
	µA/cm²	**Specific Activity** Pt on high surface area carbon: 445-535 $\mu A/cm^2_{PT}$	

	Unit	Description	Literature
		platinum group metal-free current status: 24mA/cm² (@0.9V$_{IR\text{-}free}$) 2020 target: >44mA/cm² (target is lower due to lower expected cost of platinum group metal free catalyst)	[273]
	A/mg	Mass Activity @ 0.90 V vs RHE for both rotating disk electrode and fuel cells Pt on high surface area carbon 0.43 – 0.52	
		Single-cell polarisation curves (voltage vs current density) along with following KPIs: - **maximum power density** (mW/cm²) - **current density at 0.8 V** (in mA/cm²) - voltage at 500 mA/cm²	
 810 **240**	 mW/cm² mA/cm²	Pt on high surface area carbon Maximum power density (at 150 kPa) Current density at 0.8V	
	V	Half-wave potential of oxygen reduction (ORR half-wave potential) (E1/2) KPI for the Performance of electrocatalytic activity of catalyst material (for oxygen reduction reaction):	
	Wh/kg	**Specific/gravimetric energy density** characterizes potential capacity of a storage system, weight related	
150	Wh/kg	Today's battery systems	[274]
500	Wh/kg	FC system based on a hydrogen tank at 700 bars (storage capacity around 5% by weight) and an electric yield for the PEMFC system around 60 % http://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf So for a little more than 200 kg and 100 000 kWh, we found 500 Wh/kg	[250]

	Unit	Description	Litera-ture
1100	Wh/kg	Today's Fuel cell systems (including hydrogen storage)	[275]
	Wh/L	**Volumetric energy density** characterizes potential capacity of a storage system, size related	
450-500	Wh/L	Today's Fuel cell systems (including hydrogen storage)	[275]
	W/L	**Volumetric power density** characterizes maximum power output of a storage system, size related	
>3	kW net/L	Fuel cell for automotive applications	[249]
	€/kW $/kW	**Price**	
75	€/kW	in 2023	[276]
150	€/kW	in 2017	[276]
100-200	$/kW	2022 Fuel cell for automotive applications	[249]
200-300	$/kW	2018 Fuel cell for automotive applications	[249]
>500	€/kW	Today	[276]
600-800	$/kW	2014 Fuel cell for automotive applications	[249]
<1500	$/kW	Long term: PEM/SOFC-based fuel cell system	[243]
1500-3800	$/kW	Today's PEM electrolyser	[248]
2300	$/kW	2014 SOFC-based fuel cell system	[243]
5000	$/kW	2014 MCFC-based fuel cell system	[243]
5000	$/kW	2014 PEM-based fuel cell system	[243]
	€/kWh	Price	
150	€/kWh	Fuel cell system	
450	€/kWh	Battery system	

	Unit	Description	Literature
	€/g	Price material	
34	€/g	Platinum	
		Durability Electrocatalyst stability under dynamic and stationary operation of fuel cells Performance and component degradation via diverse methods and for accelerated degradation, routines have been developed. For instance, operation at open circuit voltage (OCV) Also ex-situ screening of durability, e.g. with rotating disc accelerated testing of catalysts and support [277], is interesting (before going in-situ, does not replace later in-situ testing)	
	h	**Durability**	
5,000 - 6,000	h	Fuel cell for automotive applications	[249]
10,000	h	Fuel cell for automotive applications	Expert

4.2.4 Hydrogen generation and storage

In the field of hydrogen storage, the main field of application regarding graphene is graphene-based hosting material for H_2 fuel storage. Sate of the art of hydrogen storage technology is compressed gas storage, particularly for automotive applications. The gas is stored at a pressure of 700 bar. Disadvantage of the existing technology is that already the compression consumes 12 % of the energy stored in the hydrogen; moreover the fuelling equipment and tanks have to be designed to sustain these high pressures; and last but not least, there are relevant safety concerns.

As for graphene-based storage, already at some 10-100 bar significant absorption of hydrogen on the surface of the graphene sheets can be observed. An increase of pressure makes only sense up to a specific level, i.e. until the whole surface is covered by H_2. Advantage of this so-called absorptive storage is that either a lower storage pressure or an increased capacity is possible, compared to compressed gas storage systems. The lower pressure of the whole system might lead to a higher acceptance of hydrogen fuelling in general, due to safety issues.

Besides, graphene is also discussed to be used as membrane for hydrogen production/filtering. For a more general assessment of the membrane properties, please refer to chapter 3.5 Special application: Filtering, desalination/deionization and membrane applications.

4.2.4.1 Opportunities for graphene in hydrogen storage sector

4.2.4.1.1 Low pressure gas storage might become relevant in the long-term

The high pressures used in today's hydrogen storage require huge investments in infrastructure of the fuelling equipment and have a negative impact on the acceptance of fuel cell technology due to safety reasons. Hence, low pressure solutions are discussed as promising for the long-term perspective. Graphene-based storage systems might play a role, as they can be operated at lower pressure. But this issue is also discussed with regard to other storage concepts like metal hydrated solid storage (s. 4.2.4.2.2).

4.2.4.1.2 Graphene based storage in various applications

Specific advantage of graphene in gas storage is that the material is highly robust and therefore most suitable – not only for transportation applications. Besides applications in the automotive sector, graphene-based hydrogen storage might be interesting for further applications in other sectors, e.g. mobile applications are becoming increasingly attractive, particularly for military applications. Also the electrification of the aerospace sector might be a soaring application area for hydrogen storage and fuel cells. As for hydrogen storage, graphene related activities are not only restricted to PEM fuel cells and DMFCs – like in the area of fuel cell technology as such – but it can also play a role e.g. in SOFC technology which is particularly interesting for all kind of stationary power supply.

Moreover, the further development of hydrogen storage might also enable improved gas storage in general and expand the applications to gases like methane, propane, butane, and even CO_2.

4.2.4.1.3 Hydrogen generation: power to gas

Grid balancing is a relevant issue for the implementation of a power system based on renewables. Hydrogen appears to be an interesting candidate for large-scale energy storage. From a technological perspective, the major issue in this case is the electrolysis with platinum as electrocatalyst. The very high voltages, typical for these application, require highest robustness against corrosion. Graphene related materials (MoS2/WS2) are reported to be used to foster the hydrogen evolution reaction (HER) by delivering active catalytic sites [278, 279].

4.2.4.2 Threats to graphene in hydrogen storage sector

4.2.4.2.1 700 bar standard locked in for coming years

Today in the automotive sector the operating pressure for compressed gas hydrogen storage systems is standardised at 700 bar. This settled standard is a high barrier for new storage concepts as all the equipment is now designed to come up to these requirements. Currently, particularly in Asia relevant investments are made to install fuelling infrastructure, based on 700 bar standard. A parallel standard with lower pressure is not probable. Hence, experts underline, the hydrogen storage technology in mobile applications is more or less locked in for the coming years. A potential matter of discussion, however, is to keep the 700 bar standard for fuelling infrastructure but at least reduce pressure in the mobile tanks of the vehicles. By doing this, the costs and weight for the tanks might be reduced and safety might be increased.

4.2.4.2.2 Alternative technologies discussed for hydrogen storage

To increase the capacity by using highly porous materials is exploited not only in graphene based storage technology, but also in others like graphite- or metal hydrate-based storage systems. Currently, there are some technologies strongly discussed for hydrogen storage – even though, they are, like graphene-based approaches, still in a research stage:

- Particularly for solid storage, **metal hydride-based** storage systems are researched. These systems are particularly dedicated for stationary applications due to their high weight. Advantage of metal hydride storage systems are safety issues, as the process of hydrogen dissolution stops immediately after an incident. Disadvantages are the high effort required for charge/discharge, the relatively low capacity of 2-3 % W at low pressure (could be increased up to 6-8 % W at high pressure), and high costs for the system.
- **Graphite or carbon nanotubes** can also be used for hydrogen storage. As for graphite flakes, a specific surface area of up to 3000 m^2/g is reported. Advantage of these systems is a theoretical increase of capacity up to 3-5 % W. But a problem can be the required cryogenic temperatures of 50-80 K, respectively high pressures. Another problem can be the fast dissolution of the hydrogen with related safety concerns [280].
- Best figures ever reached for absorption-based storage systems were based on **metal-organic frameworks**. They are particularly interesting, as they have both a huge internal surfaces area and many active sites. The capacity reached about 6-7 % W. The metal organic frameworks were integrated in pressure tanks. The activities were pursued e.g. by GM and partially financed by the US DoD. Until now the maturity has reached a level of about TRL 3-4.
- An expert reported **polymer-based** storage systems with polyanilin and polypyrrol already reaches 8 % W.

4.2.4.3 Strength of graphene in hydrogen storage sector

4.2.4.3.1 High specific surface area of graphene increase capacity of gas storage

The advantage of graphene for gas storage in general, respectively hydrogen storage in particular, is the high specific surface area of the material. Theoretically, this allows, first and foremost, an increased storage capacity. The related figure of merit is percentage by weight (% W) which is a measure for the weight of hydrogen in relation to the material or whole system. In principle, 6-7 % W is possible for the pure material, resulting in 3-4 % W for the whole storage system.

The aim of the Graphene Flagship activities is to lower the required pressures for hydrogen tanks (120-300 bar) at same capacity and to increase capacity in general. Reference point for the activities is the hydrogen storage system of Toyota, which reaches 0.04 kg/L at 700 bar. The dedicated research focus of the flagship is on material design to increase the surface area and porous networks.

4.2.4.3.2 More design opportunities as chemi- and physisorption possible

Gases can be absorbed on the surface of solids by physisorption or chemisorption. As for graphene, both ways of binding are possible.

In case of physisorption the gas molecules are attached at the surface by e.g. van der Waals forces. The binding energy in this case is low. That allows the fast loading, respectively fuelling of the storage system. Moreover, theoretically the high surface area leads to high gravimetric density of the storage system, whereas in the related systems the volumetric density is rather low. That means the final systems are relatively light but rather large-sized. As for graphene, the volume depends decisively on compacting of the material.

In case of chemisorption, the gas is bound on the surface of the storage material by atomic bonding. For release the bonding has to be dissociated by additional energy effort. Advantage is that the storage is quite stable. The chemisorption based storage material is expected to reach highest gravimetric density of up to 8.3 % W if the graphene sheet is completely saturated with hydrogen molecules [281]. That means by using graphene, lighter hydrogen storage systems might be viable.

- Within the Graphene Flagship improvements of the gravimetric density are intended for both: chemisorptions (0.8% W are reached in an experimental stage) and physisorption (1% W @ room temperature and 120 bar). Also research is aiming at reducing the sorption and desorption activation energy by doping with Nb_2O_2.
- A new approach for hydrogen storage based on graphene tries to combine the advantages of the physisorption and chemisorption: the local curvature of the graphene sheet determines which kind of carbon hydrogen bonding prevails. As the graphene

sheets are mechanically flexible and the curvature can be manipulated, this characteristic can be exploited to implement new charging respectively discharging strategies – also at room temperature [282].

- Another focus of research is porous mesostructures with irreversible amine linkages between the graphene layers. This leads to a functionalization which allows dynamic change, specific distances and the change of curvature under light irradiation (WP12).

4.2.4.3.3 Graphene to increase volumetric energy density of high-pressure tanks

Before a transition phase from high to low pressure storage, graphene might be used to enhance high-pressure storage systems. A high pressure tank could be filled with graphene to enhance the tank-system, make it more stable and increase capacity. The approach has a couple of benefits: It has the potential to increase the volumetric energy density of the system (even if it might not decrease the weight related storage capacity greatly H_2/kg of the system). By this, it would decrease the volume of the tank, which is very valuable for the automotive industry. And finally, the system is less explosive. Hence, an option for graphene in the mid-term might be to use it within existing storage concepts as high-surface-area material to increase storage density.

4.2.4.3.4 Graphene (membranes) for hydrogen generation

Graphene is impermeable for gases and liquids, but not for protons. This property can be used for hydrogen generation. By employing these highly selective graphene-based membranes, hydrogen can be extracted from air and used in fuel cell applications, as demonstrated by the Manchester University [283, 284]. This approach, however, is in a very early stage as today the required single-layer graphene sheets can be produced just in the size of some millimetres. For further membrane applications please refer to chapter 3.5 Special application: Filtering, desalination/deionization and membrane applications.

Besides and as mentioned above, Graphene related materials (MoS_2/WS_2) are reported to be used to foster the hydrogen evolution reaction (HER) by delivering active catalytic sites [278, 279].

4.2.5 KPIs for hydrogen generation

Gravimetric density GD, mass percent, percentage by weight [% W; w/w]: to compare weight of hydrogen storage systems (percentage of the weight of the hydrogen related to the weight of the storage system)

The figure of merit in the hydrogen storage is the gravimetric density. It can be related to the pure material or the storage system. Even though, the weight of the storage system is unclear until it is finally developed, an average estimation is: the system will have half of the gravimetric density the material has.

Table 26: KPIs for hydrogen storage.

	Unit	Description	Literature
	% W, (also w/w)	**Gravimetric density GD, mass percent, percentage by weight**	
3	% W	Solid storage of hybrids	
5.5	% W	System @ room temperature Definition of Department of Energy DoE of the USA of a “good” storage system	
7	% W	gasoline system	[285]
8.3	% W	chemisorption based storage with graphene material (if graphene sheet is completely saturated with H_2	[281]
8.8	% W	pure gasoline	[285]
	kWh/kg	**Gravimetric/specific energy density** to compare weight of energy storage systems	
1.8	kWh/kg	System, Definition of Department of Energy DoE of the USA of a “good” storage system	
1.8	kWh/kg	System, State of the art of hydrogen storage (Compressed gas storage [GH2] @ 700 bar)	[285]
8	kWh/kg	System, gasoline	[285]
11.5	kWh/kg	Pure material, gasoline	[285]
33.3	kWh/kg	Pure material, State of the art of hydrogen storage (Compressed gas storage [GH2] @ 700 bar))	[285]
	kWh/L	**Volumetric energy density** to compare size of energy storage systems, indicator for the range of an energy storage system	
0.9	kWh/L	System, state of the art of hydrogen storage (Compressed gas storage [GH2] @ 700 bar)	[285]
1.3	kWh/L	Pure material, state of the art of hydrogen storage (Compressed gas storage [GH2] @ 700 bar))	[285]

	Unit	Description	Literature
7	kWh/L	System, gasoline	[285]
8.8	kWh/L	Pure material, gasoline	[285]
	m²/g	**Specific surface area SSA** KPI for porous materials	
540-650	m²/g	Commercial Graphite	[286]
500-1000	m²/g	Commercial Graphene	[286]

4.2.6 Roadmap for Fuel Cells and hydrogen storage

4.2.6.1 Current maturity: 'Mostly lab scale'

Most of the developments are currently at lab scale and low TRL levels. Electrocatalyst (Pt reduction) are at a higher TRL level (TRL2-3), whereas membrane related and other fuel cell related technologies are rather at TRL1/2. Storage applications are at best at applied research stage, but the optimized configurations are not fully known yet. Therefore, the overall rating of graphene in fuel cells and hydrogen production is rather at lower TRL.

4.2.6.2 Barriers/challenges (summarized)

Fuel Cells

- Most PEM fuel cell technology integrators are not based in Europe, especially for CHP
- Fuel cell technology itself is at a turning point and the future direction in Europe is not yet clear; also the policy is not clear enough.
- Reputation of non-metallic catalysts is not good; platinum could work and cost reduction potential when avoiding platinum is only limited
- Competition with established standards (low willingness to change)
- Low maturity at the moment (test in actual fuel cells needed)
- Graphene supply: dead-lock situation between demand and supply (investment is only justified through larger markets, markets only start existing if larger scale testing and assessment is possible)
- Commercially available graphene materials not tailored to fuel cell use (as electrocatalyst). Existing materials perform not well enough with existing processes.
- Some promises/ideas (e.g. for end plates, flexible fuel cells) are still only ideas or theoretical

Hydrogen storage and production

- Membrane technology is only at fundamental research level
- 700 bar technology locked-in for coming years, no change foreseeable
- Benchmarking with alternative technologies missing

- Viability of some storage solutions based on graphene are interesting, but need to be proven in application (e.g. combination of physisorption and chemisorptions)

4.2.6.3 Potential actions

If the area of graphene/2D in fuel cells and/or hydrogen storage is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

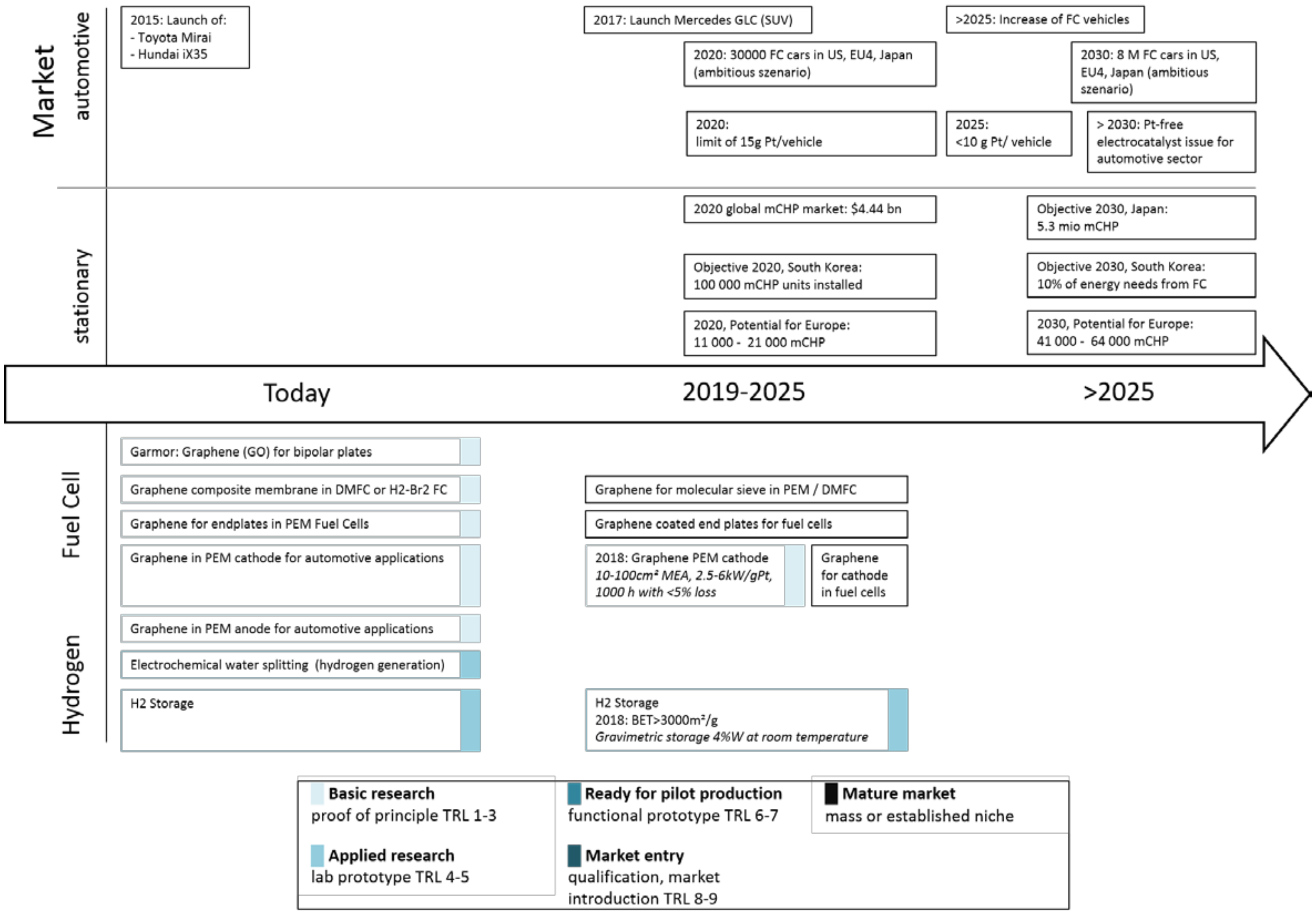
Fuel Cells

- Engage with fuel cell research community to allow realistic testing and benchmarking with competing technologies and metal catalysts
- Further investigate functionalization (with e.g. metals)
- Investigate standard processes compatible with existing ones for integration into fuel cells
- Large scale functionalization and preparation of porous networks/curved graphene
- Repeatability and degradation
- Live up to very high performance expectations and fulfil industrial standards with regard to quality and quantity to reach at least the level of well established platinum

Hydrogen storage and production

- Explore possibilities to improve storage at 700 bar
- Check if low pressure tanks in vehicles are feasible despite 700 bar standard
- Explore market opportunities for storage of other gases
- Benchmark with competing technologies
- Increase surface area and porosity
- Further investigate physisorption and chemisorptions to optimize sorption and desorption (e.g. with functionalization)

4.2.6.4 Roadmap



4.2.7 Conclusion fuel cells and hydrogen economy

Graphene shows a potential to reduce or even replace noble metals in fuel cell electrocatalysts. Moreover, it has beneficial properties regarding durability of electrocatalysts. It can be in principal used as a simple drop in for conventional catalyst support, as active catalyst support, or even as an active material (when functionalized). But the relevance of particularly platinum reduction is disputed in the fuel cell community: on the one hand it contributes to costs; on the other hand it has a very good recyclability and platinum-free fuel cells are sometimes even assessed to be not viable. In any case, all kinds of new concepts have to come up to very high performance expectations and fulfil industrial standards with regard to quality and quantity to reach at least the level of well established platinum. In general, platinum-free electrocatalyst is rather an issue for fuel cells beyond 2030. Besides electrocatalyst applications, in the future graphene might be interesting for membranes, functional layers, or portable applications. Even fully new fuel cell architectures are thinkable e.g. based on printed circuit boards (PCB).

For hydrogen storage, graphene has the advantage to be highly efficient due to its large specific surface area which allows low pressure and higher volumetric capacity. When it comes to applications, a decrease of pressure in the storage system is no short term opportunity, as high pressure tanks are already an established standard. But a short to medium term opportunity could be to exploit it to decrease tank volume of 700 bar systems.

As for the fuel cell market, residential technology is increasingly dominated by Japanese companies. In automotive applications fuel cell technology is at a turning point: the future role of the technology will be decided shortly, because soon strategic decisions of relevant car manufacturers are expected. Europe, however, has given no clear commitment towards fuel cells anyhow. For graphene, it appears reasonable to primarily observe the strategic decisions in the fuel cell market very properly and to assess if there is further technology development in Europe to be expected.

Table 27: Assessment of market and technological potential of graphene/2D materials use in fuel cells and hydrogen storage and generation on a scale - -, -, 0, +, ++.

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
Reduction of noble metals in electrocatalysts	+	-
Replacement of noble metals in electrocatalysts	+	0 (long-term)
Membrane	+	0

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
Endplate	?	?
Increased volumetric capacity of high pressure tanks	+	+
Low pressure tanks	+	+ (automotive: long-term ?)
Hydrogen generation (membrane)	+ ?	0 ?
Hydrogen generation (electrocatalyst)	+ ?	++ ?

4.3 FOCUS: Lithium-ion batteries for mobile and motive applications

This chapter deals with the use of graphene in batteries. The focus is on rechargeable lithium ion batteries particularly with graphene-enhanced anodes. Flexible batteries are particularly investigated in chapter 5.6 Flexible and/or printed electronics.

The promises and challenges of Si incorporation in anodes for lithium-ion batteries (LIBs) are widely discussed, and present LIB anodes may already contain minute percentages. In general, the production of silicon is an established business dominated by larger companies. These Si producers already identified battery materials as a major and rapidly expanding market; therefore, they dedicate significant efforts and resources towards developing specialized solutions. The use of graphene can help improve the performance of Si-based anodes.

4.3.1 Lithium-ion cells and electrode materials

Li-ion batteries currently represent the electrochemical storage technology of highest energy densities. At the same time LIBs are technologically mature and feature good commercial availability. Many recent developments of electronic consumer products are strongly coupled to advances in LIBs. The technology is considered to be an enabler for electro-mobility and the transition towards renewable energies.

Current LIBs are based on intercalation compounds, serving as host structure for Li-ions on the anode and cathode and a liquid electrolyte, enabling the shuttling of ions between both electrodes. Commonly, layered oxide materials are used as cathode materials. The first generations of LIBs were realized using $LiCoO_2$. To increase capacity and electronic conductivity, substituted mixed transition metal oxides $Li(Ni,Mn,Co)O_2$ (NMC) are used today. State of the art NMC materials with a ratio of 6:2:2 with respect to Ni:Mn:Co feature a gravimetric capacity of 180 mAh/g vs. Li/Li^+.

At the anode side, graphite is the standard material for most LIBs (see section 4.3.1.3). With the increasing Li-storage capacity of novel cathode materials, the necessity to also introduce new technologies on the anode side is growing in order to increase the capacity on cell level, but also to improve the fast charging capability of cells, which still remains limited by the intercalation kinetics of graphite.

4.3.1.1.1 Key performance indicators for anode materials and LIBs

The most often used key performance indicator for battery electrodes is the specific or gravimetric capacity [mAh/g]. Any material concept reaching 1000 mAh/g and above can be seen as interesting. The specific energy density [Wh/kg] is one of the most important figures of merit to compare battery cells and systems.

Table 28: Battery KPIs.

Value	Unit	Description	Literature
	mAh/g	**Specific/gravimetric capacity** To compare electrode technologies	
372	mAh/g	Graphite (theoretically)	[287]
800	mAh/g	High-capacity anodes (Si-graphene)	[287]
1100	mAh/g	GO-Si-nanoparticle (flexible)	[34]
3600	mAh/g	Silicon (theoretically)	[34]
	€/kWh	**Cost energy storage**	
150-400	€/kWh	Battery cell for electric vehicles (2018)	[288]
<80	€/kWh	Battery cell for electric vehicles (2030)	[289]
	Wh/kg	**Gravimetric energy density**	
150-270	Wh/kg	Battery cell for electric vehicles (2018)	[289]
250-350	Wh/kg	Battery cell for electric vehicles (2030)	[289]

4.3.1.2 Market situation for cell manufacturing and LIB production

LIB markets are strongly growing. In 2017, the world production of LIBs almost reached the 100 GWh mark and an ongoing yearly growth of more than 20 % in terms of produced capacity is expected to persist until 2025 or even beyond. Production capacities are concentrated on China and Korea followed by Japan and the US. China is expected to host more than 60 % of the global production capacities by 2025. According to numerous announcements, production capacities in the range of two-digit GWh/year will be build up in other regions of the world, including Europe, in the near future.

China has significantly increased research in the last few years. Compared to this, the other regions show significantly lower engagement in lithium-ion battery technology (see Figure 52). Due to this role as first mover in the 1990s, Japan is leading in terms of patents although its market shore has been decreasing over the past years.

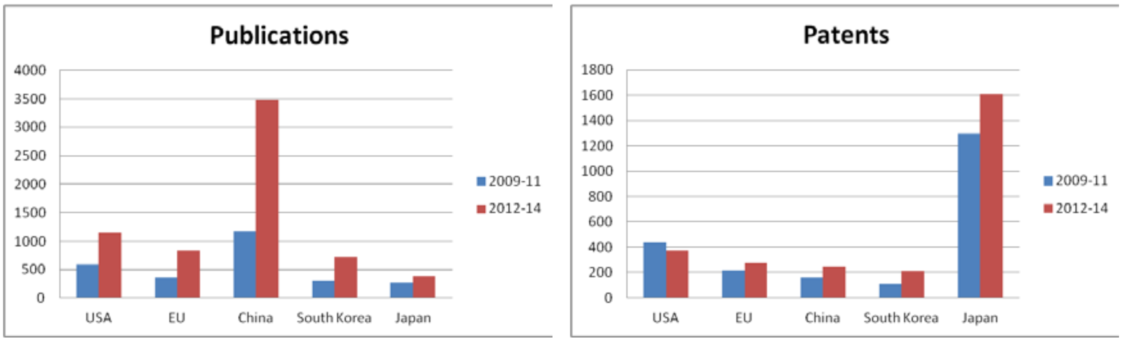


Figure 52: Publications and transnational patents on lithium-ion batteries. [137, 257]

Due to the complexity of LIBs and their components, the value chains include several steps from raw materials extraction, materials synthesis and component and cell manufacturing up to battery integration and production of battery management systems. Complete value chains (comprising all these intermediate steps) can only be found in few countries. From an industrial perspective, Europe is still lacking behind in provision of many necessary materials and components.

4.3.1.2.1 Resource availability

Several of the resources necessary for the production of current Li-based batteries are scarce, e.g. cobalt and potentially lithium / graphite. Besides the availability of respective raw-materials, the geographic distribution of reserves is unfavourable for European supply. While Co-mining is concentrated on the Republic of Kongo, the market of many other minerals and raw materials is controlled by China. The access to resources and their price for smaller European customers is currently not good and there is a high dependence on supply from abroad. With respect to the availability of Li-, Mn-, Co- or Ni-sources, Europe strongly depends on the world market. This can in general be a threat for the manufacturing and use of LIBs in Europe.

4.3.1.2.2 R&D-perspective

From R&D perspective, competitive activities can be found in Europe, particularly in the fields of many next generation or post-LIB technologies. Besides research and technology focused organizations, many European companies are also significantly involved in the R&D activities. Players from the European Union are holding more than 20 % of the world's LIB patents[14], taking a position in between the US and Japan. The translation towards commercialization and value creation however lags behind. This might - to some extent - be a result of the industrial structure of European enterprises involved in LIBs. In contrast to Asia, the majority of European companies that are active in the field of LIBs are small or medium sized, making it difficult for them to raise the necessary investment resources to scale up and become competitive with their large counterparts in Asia or the US.

4.3.1.3 Next generation anode materials

Current LIB anodes are based on graphite, since the material features a low potential vs. Li/Li^+, has relatively good resource availability and a fair gravimetric capacity of 320 mAh/g. The low volumetric capacity of the material is however less advantageous for LIBs. The mechanism of Li-storage is based on Li-intercalation between the carbon-mono-layers of graphite, inducing only small structural changes during cycling (volume change of about 10 %).

4.3.1.3.1 Mechanism and challenges of the Li-Si alloying reaction

Among several approaches to utilize conversion materials or metallic lithium as anode, the use of alloying materials like silicon can offer high specific capacities. Pure Si-electrodes would offer a theoretical gravimetric capacity of 3578 mAh/g, equivalent to a stoichiometry of $Li_{15}Si_4$ in the battery's charged condition. The high specific capacity however comes at the cost of a large volume change of the anode's particles (up to 300 %) leading to mechanical stress inside electrodes and instabilities in the electrode/electrolyte system.

The utilization of silicon/carbon composites can reduce the volume expansion of a Si-based electrode as whole, if a porous carbon structure is used, which can accommodate the volume change of the Si-particles during alloying. In order to overcome the issues of Si/electrolyte instabilities, associated to the repeated breaking of the solid electrolyte interface (SEI) during cycling, more specific requirements to the carbon structure are called for. Following several models proposed in literature [290], a flexible and adaptive carbon wrapping around Si-particles might be a means to form a protective intermediate layer

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14 (recent data from 2017)

between electrolyte and Si-active material, thereby ensuring a stable SEI, but also sufficient electronic and ionic conductivity necessary for the Li-Si alloying reaction. These requirements call for carbon particles with lateral dimensions comparable to those of the Si-particles (typically few 100 nm). Graphitic particles with many carbon-layers would however not facilitate Li-diffusion to the surface of Si-particles, since Li-transport perpendicular to the layers is inhibited. Few-layer graphene nano platelets (GNPs) could meet the requirements for both, lateral size and electronic and ionic conductivity. Due to the high aspect ratio and mechanical stability, graphene is of high promise to accommodate structural changes inside the electrode (volume change compensation) and at the same time serve as effective and protective intermediate layer between Si-particles and the electrolyte (chemical "shielding") [291]. In order to function as anode material, Si-particles must however not be completely shielded. Good electronic and ionic linkage to the current collector and electrolyte respectively are necessary to provide for adequate reaction kinetics during the charge / discharge process. Graphene can - in principle - provide both, electronic as well as ionic conductivity. Therefore, its thickness should not exceed 4 to 10 layers. A narrow size distribution is necessary in any case. Si/C or Si/G composites with a silicon content of up to 20 % would feature a specific capacity of >1000 mAh/g.

While thin graphene flakes can be beneficial for the electronic and ionic conductivities of graphene containing composites, the resulting high surface area also leads to disadvantages. When used at the anode side, carbon compounds undergo SEI formation in the first electrochemical cycle. The build-up of this passivating layer is a one-time process for carbon materials. The associated consumption of electrolyte and Lithium is directly proportional to the interfacial area between anode material and electrolyte (hence particularly high for high surface area graphenes). If no pre-treatment like anode pre-lithiation is applied, the loss of Li (SEI build-up) would necessitate the strong overcompensation with additional amounts of cathode material to introduce more Li in the cell. In practice, this might countervail any improvements in energy density on cell level, introduced by graphene enhanced high capacity materials.

4.3.1.4 Market opportunities and threats for next generation anode materials

Graphene is considered to be an enabling material for many new applications in almost all fields of technology. Up to now, the material has found commercial application as additive in electrodes, bulk composites, coatings or paints where it is being utilized for its mechanical strength or high conductivity. Although production is rapidly growing, a significant market penetration has not taken place in any field yet. For most applications, graphene will remain in a research and prototyping phase for the next years. The low level of commercialization is also reflected by the low global production volume, which is of the order of 1000 tons/year [4]. Production facilities are located in China and the US mainly.

The market price of graphene powder therefore significantly depends on its quality and ranges between 100 and 10000 €/kg [7]. Prices are expected to significantly drop in the next years due to the ramp up of production capacities and establishment of large scale production techniques. Despite the typical association of CVD graphene being way too expensive for high volume and rather low cost applications such as batteries, some graphene providers work on appropriate production schemes.

The battery market currently demands Si particles in a wide range of sizes and properties. However, our consultations showed a consensus among silicon providers active in Europe that the major share of the value creation will not lie in providing Si powders, but in supplying aggregated electrode materials. The benchmark in terms of cost/mAh is graphite, which also defines the price-window for any Si/C or Si/G based composites.

The industrial structure in Europe is heavily fragmented by small graphene producers and larger existing anode material producers, who are currently focussing on graphite. The collaboration between both at present is rather limited.

4.3.1.5 Applications and downstream markets for advanced LIBs for automotive and mobile electronics

At present, many applications already rely on either primary or secondary batteries as power source and can be found in all fields of consumer, transport and industrial equipment. Particularly mobile electronic devices only exist due to the availability of high energy batteries. In other segments like automotive or industrial applications a side by side of electric powered and fuel powered devices can be found. Due to improvements in technology (e.g. higher energy density) or reduction of cost, the share of battery powered equipment has increased during the last years. Established energy storage technologies are more and more replaced by rechargeable batteries, particularly LIBs.

On the other hand, completely new applications arise, e.g. stationary energy storage driven by the transformation of the energy economy towards de-centralized and timely fluctuating energy generation. In these cases, only few alternatives to electrochemical storage exist and batteries can be considered an enabler for these applications.

4.3.1.5.1 Influence of policy and regulation

With regard to future developments of the rechargeable lithium-ion battery market, legislation, consumers, and global competitors pose three strong drivers. The market positioning and further technical development of electrically powered cars is supported with current and expected regulations on European and (inter-)national level, most of them of a subsidy nature.[15]

The various subsidy schemes, however, do not support the further technology and infrastructure development of automotive batteries alone. Government subsidies and several European automotive manufacturers are involved in further development of other technologies, e.g. fuel-cells.

Global competition poses another relevant driver for the European lithium-ion battery market development. This is especially apparent in the cost-sensitive automotive and portable headphones and speaker sector, while the hearing aid sector with its ties to the European health care systems underlies special dynamics.

4.3.1.5.2 xEV and consumer markets

The global battery electric vehicle (BEV) market was valued at 1.2 million sold units in the end of 2015, as compared to 77 million sold automotive vehicles worldwide in 2015 [292, 293]. As passenger cars and industrial vehicles are currently amongst the largest market segments of the global vehicle market, these market segments are likely drivers of future BEV market developments [294, 295]. Europe is amongst the strongest players in global passenger car sales with an estimated 20 to 25 % in 2015, however, can still improve its market share in BEV and hybrid vehicle sales [292].

As to consumer products, the consumer electronics market has a size of 155 billion € in 2015 and 160 billion € in 2017, with an expected compound annual growth rate (CAGR) of 0.9 % until 2020 [296]. The worldwide headphone industry revenue was at 3.5 billion € in 2014 [297], which is estimated to consist to 60 % of wireless products [296, 298]. Asia and the US are the largest manufacturers of and markets for portable electronics and wearables, followed by Europe. Hearing aides as medical devices pose a special case in the portable electronics and wearables field, but have comparable technical features. The European hearing aid market size was of approximately 250 million € in 2014 [299].

Contrary to the automotive and vehicle market, rechargeable lithium-ion batteries are the established standard technology for the consumer and health market or in the process of becoming so. Recent developments show increasing sales numbers for portable speakers and wireless on- and in-ear-headphones [300]. These products usually feature

[15] Regulations meaning temporary government incentives for industry to develop the needed charging infrastructure, state subsidies and fiscal incentives for private automotive buyers in Norway, the Netherlands, Belgium and other European countries. Further relevant are climate protection legislations and plans, such as the German climate protection plan that aims to significantly reduce the production of combustion engine based vehicles altogether by 2050, while French government is discussing a sales prohibition of combustion engine vehicle by 2040.

rechargeable lithium-ion batteries in the form of hard- and soft-packs as well as coin cells. While non-rechargeable coin cells are the current standard in the hearing aides sector, first products featuring rechargeable energy storage technology are already available on the European market. Currently the yearly battery capacity used for hearing aides amounts to about 0.5 GWh corresponding to 2 - 2.5 billion coin cells per year.

4.3.2 Direct innovation interface: Graphene enhanced anode materials in LIBs

The interface between the innovation spheres along the value chain from graphene production to application in LIBs can be characterized by a set of requirements, initially determined by the application. The main requirements in terms of energy and power density, cost, safety, lifetime and cyclability are commonly visualized as so called "spider diagrams" (see Figure 53). Typically, these parameters are strongly correlated and can not be adjusted independently. Any design decisions upstream the value chain are basically oriented on this set of requirements and need to be translated into specific requirements on electrode materials, electrolytes and passive components by the cell manufacturer. On the one hand this leaves a certain degree of freedom of choice for the design of cells. On the other hand, trade-offs, e.g. between cost and energy density (as might be the case for graphene enhanced batteries) are limited due to the specifications of the end-user.

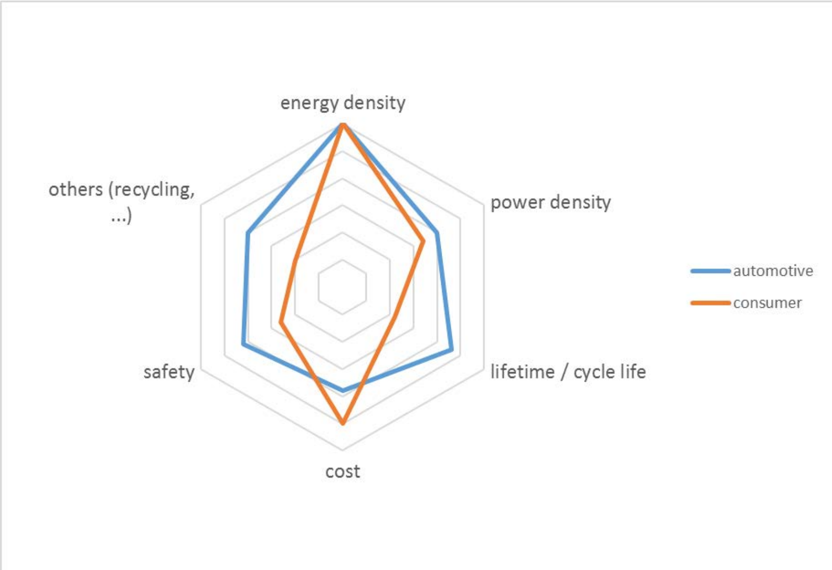

Figure 53: Generic spider diagram showing the requirements determined by different applications. A higher radius in the diagram means higher/stricter requirements

New anode materials are interesting for cell manufacturers, if an overall increase of the area covered by the spider diagram is possible. However, certain parameters within the requirements are fixed and should not decline due to the introduction of new materials.

Particularly the target of decreasing cost to a value of 85 €/kWh for LIBs[16] appears to be a priority for end-customers (see section 4.3.1.5). Due to its multi-functionality, graphene enhanced materials might yield a better performance in all parameters but cost.

Besides the properties of new materials, the issue of standardization and product qualification is important. At present, no standards for graphene as well as for graphene enhanced composites exist, which producers could refer to. Furthermore, qualification and test procedures are not known to the graphene industry and probably need to be developed based on specific application scenarios.

4.3.2.1 Technological strengths and weaknesses for the use of graphene enhanced anode materials in LIBs

Graphene is a multi-functional material, with several of its intrinsic properties being valuable for the application in LIBs, namely its high conductivity, mechanical strength and storage capacity (see section 2.1). The unique selling proposition of graphene enhanced anodes arises from the simultaneous utilization of the multi functionality of graphene and high specific capacity of Si. Graphene must be used as a multi-purpose material and not as a component having only one function.

4.3.2.1.1 Properties of graphene enhanced materials

The strong volume changes which advanced anode materials exhibit during cycling must not be translated to cell level. The overall volume change inside a cell must not exceed 5 %. Hence, there is a limit to the use of Si in anodes. Current anode composites feature a porosity of about 70 % which can be utilized for the accommodation of Li_xSi_y particle growth. With a similar porosity of Si/C or Si/G composites, a maximum of about 15 % Si would be feasible. Increasing the porosity beyond this value would again lead to a decrease of volumetric capacity since a high porosity means low density of active materials.

Other factors also need to be considered for cell construction, if a new material is applied. For example, a certain mechanical strength of the electrode must be ensured to withstand coiling and other manufacturing procedures. To provide the necessary mechanical support, special binders or enclosing structures might be needed, which again decrease the energy density. The potential of graphene to enhance the structural integrity of electrodes is not yet clarified.

Besides serving as enabler for Si-based anodes, G / rGO or GO materials can also be utilized as host materials for Li-ions themselves. Depending on defects and their chemical composition or surface groups, the experimentally observed capacity can even exceed the intercalation capacity of graphite [301]. At present, no industrial activities are known where pure graphene would be tested as active material.

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[16] 100 $/kWh target, e.g. [289]

4.3.2.1.2 Properties as passive component or additive

More generally, graphene or rGO is also discussed as an additive in battery anodes as well as cathodes due to its high electronic and thermal conductivity. The addition of graphene could increase the electrodes conductivity and hence power density. Furthermore, the high conductivity of graphene might allow to reduce the amount of electrochemically inactive components in electrodes (e.g. other conductive additives), thereby also increasing the energy density of cells. Graphenes might also support heat transport in the cell and reduce cell aging due to decreasing local hot-spots.

4.3.2.1.3 Production and handling of materials

The nano properties of graphene might pose certain challenges during manufacturing of electrodes. In any case, the secondary particle size of any new composite should be above 1 µm in order to be processable on existing equipment. In general, the generation of dust needs to be avoided for safety reasons. Due to the low density of the material and relatively easy electrostatic charging of particles, powder handling particularly of graphene is difficult to manage and extensive safety precautions must be taken. Similar issues are known for CNTs. EHS regulations hence are considered to be a threat for any nano-materials. At present, there are only few studies about the toxicity of graphene containing materials. It is certain, that manufacturers would not be able to handle materials, which are toxic in terms of lung cancer or other illnesses.

On the other hand, handling as dispersion might be an option. The low solid content of graphene dispersions can be unfavourable for slurry preparation. In order to avoid restacking of graphene platelets, surfactants have to be introduced. Separation of these surfactants is difficult. As inactive components, their presence is undesirable in electrodes.

Regarding general manufacturing of materials and electrodes, there are no short term drop-in solution for the preparation and processing of graphene enhanced electrode materials. It is however important for anode material producers to provide a product which is processable on already existing equipment.

4.3.2.2 Market opportunities and threats for the use of graphene enhanced anode materials in LIBs

As discussed in the previous section, the properties of graphene open up several opportunities for its future use in battery technologies, like Si/C-anodes. In the field of LIBs, there is a strong market pull and demand for improved materials, which can help to meet the increasing customer demands. Particularly the simultaneous increase of energy and power density in LIBs might lead to successful application of graphene. The combination of both properties is useful e.g. in power tools.

4.3.2.2.1 Graphene for future technologies

Beyond established LIBs, other opportunities for graphene in post-LIB battery technologies might exist, e.g. Li-S and Li-air. The materials deployed in these systems require the use of special membranes and conductive additives and can benefit from the use of graphene. Respective fields of application are however future and higher risk prospects, since these technologies will not be market ready within the next 10 years.

4.3.2.2.2 LIB-market volume and large-scale production

Compared to many other fields of a potential application of graphene, the LIB material market is rather huge and also strongly growing. If a commercialization of graphene enhanced materials is possible, it will be a strong driver for the graphene market in general. The market size can however also be a threat for graphene producers. Providing the high quantities needed in LIBs can be challenging for small and medium sized companies. A market introduction will only happen, if cell manufacturers are guaranteed reliability of supply. Product quality and consistency on the other hand are issues that graphene producers have to struggle with already today, although production volumes are rather low. With respect to the use and recycling of expensive and toxic solvents, industrial efficient ways need to be developed for production.

4.3.2.2.3 Cost and competing technologies

Cost competitiveness will be the main issue for the application of graphene in LIBs. Improving a batteries performance does only allow for a limited increase in material costs. There are alternative and established technologies available, which enable the use of Si/C composites even without applying graphene. Present approaches focus on the utilization of silicon/graphite composites. Natural graphite is available at a price of 5-10 €/kg. Suitable graphene platelets currently cost several 100 €/kg.

In order to improve the conductivity of electrodes, carbon black with a price of 5-10 €/kg is commonly added to electrode material mixtures. Carbon nanotubes (MWCNT: 40-125 €/kg, SWCNT: 1700 €/kg) are also successfully used to optimize the porosity and morphology of electrodes and increase conductivity at the same time.

With respect to other battery technologies, the time window for the introduction of graphene in Si/C composites might also be limited. Particularly for automotive application, a gradual transition towards Li-anodes and all solid state batteries from is predicted once the technology has reached the required maturity (2030+). This would again reduce the demand for Si/graphene anode materials.

4.3.2.2.4 Resource availability

For all top-down approaches on graphene production, graphites are mandatory raw-materials. The availability and cost of graphite at present is quite good. Due to increasing demands for anodes in LIBs, prices might however rise. The reserves of natural graphite are predicted to become exhausted within the next 50 years, if the accelerated growth of LIB production continues [302]. On the other hand, synthetic graphites, synthesized by petrochemical processing, are comparably expensive at present, but may become cheaper in the future.

4.3.2.2.5 International competition

From the market point of view, graphene enhanced materials can be an opportunity for Europe. The conditions for innovations in the EU are relatively good, since there is a good availability of public funding for related activities. It is however necessary to also establish materials suppliers (graphene, Si) and cell manufacturing in Europe in order to cover the whole value chain for LIBs. At present, electrodes and cells are seldom manufactured in Europe, only the assemblage of battery packs and systems is taking place here. Particularly the limited amount of anode manufacturers in the EU might be a threat for local graphene production and value creation. In turn, from the perspective of materials supplier in general, the establishment of a cell manufacturing industry would yield the highest potential for their growth.

In general, it can be assumed that graphene will play a role in lithium-ion technology, as all main lithium-ion cell manufacturers are said to have graphene-activities. Indirectly, indeed the European OEMs which are active in the field of xEV might benefit from this development – as they strongly rely on and are strategically linked to Asian cell producers like LG Chem, SDI, and Panasonic. But there will be no competitive advantage for the European industry, because the related companies will also sell their batteries to other OEMs.

4.3.3 Indirect innovation interface: LIBs in automotive and mobile electronics

For many electric and electronic applications depending on a mobile power source, LIBs are the technology of choice. At present, they are unmatched in terms of volumetric and gravimetric energy density, also featuring a fair cycle life. Although subject to continuous improvement, the basic design and constituents of LIBs will remain the same for at least the next 10 years.

Hence, many applications powered by mature technologies like lead-acid batteries or nickel metal hydride batteries are currently adapted towards the implementation of LIBs (e.g. electric forklift trucks or consumer electronics). In other cases, LIBs are expected to allow for an even more disruptive technological transition. Although still having a significantly higher energy density, primary batteries (powering smaller electronic devices) are progressively replaced by secondary LIBs. The transition from combustion engines to battery electric vehicles can be considered as an even more profound change. It can be expected that most present and future mobile electric applications as well as some of the stationary storage applications will be tailored for the deployment of LIBs.

4.3.3.1 Technological strengths and weaknesses for the use of LIBs in automotive and mobile electronics

4.3.3.1.1 LIBs for automotive use

Electric vehicles are still not competitive with combustion powered cars in terms of performance and cost. Still, the xEV-market is projected to experience a strong growth due to legislation and demand for "green"-transport by users.

In practice, the limited range and the high acquisition costs of electric cars are major bottlenecks for their usability, with the main reason being the high cost-share of energy storage. In order to make xEVs more competitive, prices below 85 €/kWh are required by car manufacturers.

Furthermore, a time of >1 h is necessary for the re-charging of an automotive battery. Besides the charge acceptance capability of the batteries themselves, there is also a lack of suitable charging infrastructures similar to petrol stations for combustion cars, which would allow for fast charging (>1 h).

In terms of cyclability, a similar lifetime of battery and car would be desirable. If an average usage of 200000 – 300000 km is estimated, 1000 cycles of a battery providing for 300 km of range would be necessary before its capacity drops below 70 % of its initial value. At present, LIBs have a cyclability of around 300 full cycles, clearly missing the stated aim. The overall energy throughput can be increased if the capacity is not fully utilized (e.g. 70-90 % DoD). This would however come at the cost of an even lower range per charging cycle. Typical usage scenarios in automotive feature 1500 cycles, thus seldomly utilizing the full capacity / range of a car.

For the automotive and industrial vehicle market, increasing driving range and charging speed of lithium-ion battery technology is of the essence. Herein lie opportunities for introducing new technologies such as graphene-enhanced lithium-ion batteries.

In practice, both volume and weight available for the accommodation of a car-battery are limited. The increase, particularly of the volumetric energy density of LIBs, would allow for the transition of xEVs from presently serving as city- or short distant commuting-cars towards long distance cars suitable for travel. Another approach would be to keep the stored capacity of car-batteries at a constant level, but significantly increase their charge acceptance to allow re-charge durations similar to present residence times at petrol stations.

Besides the battery chemistry, the energy density of the energy storage system is largely determined by cell and pack design as well as external components like cooling and battery management systems. Currently, a strong R&D-focus lies on the cell format for automotive batteries and which significantly affects the energy density.

4.3.3.1.2 LIBs for miniaturized wearables

Many wearable electronic devices offer limited space for their power sources. Batteries need to fit into functionalized designs geared towards physiological circumstances like the wearing convenience of headphones, electronic bracelets or watches. The energy usage of in-ear and on-ear headphones is influenced by the applied sound-level and features like noise-cancelling. In addition, customers require better usability of their portable electronics[17], which in turn requires better processor performance and longer battery life time [303]. This translates to an increasing demand for energy, while maintaining or preferably decreasing the volume of the power source. Providing the necessary energy density is tough for LIBs, particularly if very small cell formats are chosen. The ratio of active to passive components in a battery impairs with decreasing size, since the thickness of casings and other components can not be downscaled arbitrarily. This demands for very high energy density active-materials.

Hearing aides:

Hearing aides are currently transitioning from a classical medical device towards multi-purpose gadgets, also realizing lifestyle features and smart services. Many new functions might become available when a constant data-connection to e.g. a smart phone could be established. Possible advancements are the tracking of vital signs and automated triggering of distress calls, the use of the hearing aid for the transmission of directions or as universal translator for barrier free communication across different languages.

All these services and a blue-tooth connection between hearing-aid and smart-phone in particular are very power demanding. In order to provide a certain usage comfort, the battery lifetime still needs to be reasonably long. Fast charging does not have the highest priority, since sufficiently long time periods (e.g. during sleep) for re-charging are available.

[17] Such as controlling their portable electronic product with their smartphone, charging it inductively and within shorter timeframes than currently possible.

Other wearables / headphones

In principle, similar trends and arguments as stated for hearing aides also apply to other wearables like smart-watches and headphones. Particularly the trend towards cordless in-ear headphones leads to very high demands on battery miniaturization and increase of energy density. In general however, the requirements in terms of battery lifetime and cyclability in the consumer branch are not as high as in automotive or industrial applications. An increase of capacity at the cost of cycle life therefore seems to be acceptable.

4.3.3.1.3 Safety concerns of new batteries / LIBs

In addition to offering a better performance, LIBs and particularly new battery technologies will have to comply with safety requirements in terms of thermal management and long-term stability [304]. This might pose a bottleneck to the introduction of new battery technologies in products. Particularly for medical devices or devices that are carried close to the body, safety is of outmost importance.

4.3.3.2 Market opportunities and threats for the use of LIBs in automotive and mobile electronics

4.3.3.2.1 Cost situation

From a market perspective, the cost of LIBs is still the biggest obstacle for their broader diffusion into applications. The cost situation may be different for certain consumer applications, where even a higher cost for energy storage might be acceptable since the cost of the battery is small compared to other components of electronic products. For the automotive industry however, prices clearly need to go down.

4.3.3.2.2 Innovation perspective

Currently, the lack of cell production capacities and a closed value chain in Europe is also a bottleneck for innovations in the application sector. Due to the dominance of Asian cell manufacturers, it is more difficult for end users to find collaboration partners who are willing to provide tailor made LIBs, suitable for the specific application. Particularly smaller customers of LIBs have to take what is available on the market.

Due to the strong market power as customer of LIBs, the European automotive industry could set standards for new batteries and also for the use of new materials, e.g. graphene enhanced anodes. Furthermore, certain standards could reach beyond performance oriented specification and also focus on a truly low carbon supply chain and manufacturing way of LIBs, which would render electric transportation even greener.

The use of graphene enhanced batteries might also bring benefits on a non-technological level. The role of graphene, as hot scientific topic and subject to Nobel prices, is beneficial for marketing of end-products.

4.3.3.2.3 Legislation and markets beyond automotive / 3C

A further diffusion of LIB-technology to applications is also seen in other industrial sectors beyond automotive and 3C, like industrial transport, military applications and aerospace. With respect to new materials and technologies, these markets might however have relatively high requirements in terms of safety and stability. A market entry, e.g. of Si/graphene-based LIBs might thus be more likely for consumer electronics, since the requirements for cycle life are not as high. The use of smaller cells and lower power densities in consumer applications also means lower safety risks.

The European legislation on low carbon economization is an important driver for the use of LIBs. As demonstrated by China, a strong growth of xEV markets can be stimulated by legislative measures. Similar approaches might be successful in Europe on the basis of locally subsidized electric transport (e.g. busses) or stationary power storage.

4.3.4 Innovation roadmaps

An explorative roadmap for a lithium-ion battery with graphene enhanced silicon anode is presented below.

4.3.4.1 Graphene enhanced anode materials

4.3.4.1.1 Graphene production and types of graphene / price

The search for suitable types of graphenes for battery applications is still ongoing. With respect to materials, the use of the term graphene may be justified as long as it is a nano material with clear benefits as compared to conventional and already known graphite based materials. The cost of respective materials strongly depends on what kind of process and raw-material is used, as well as on the targeted number of layers. Currently the price range for GNPs is between 100 - 400 €/kg, depending on properties and manufacturing technique. The price target for 2020 is to go below 40 €/kg. In 2030, a price of 25 €/kg could become possible. It is however unclear whether this price will be cheap enough to enable an implementation of graphene in applications. The example of CNTs, which were successfully commercialized in several applications, however shows, that a higher price as compared to standard materials is economically feasible, if a high technological benefit is provided.

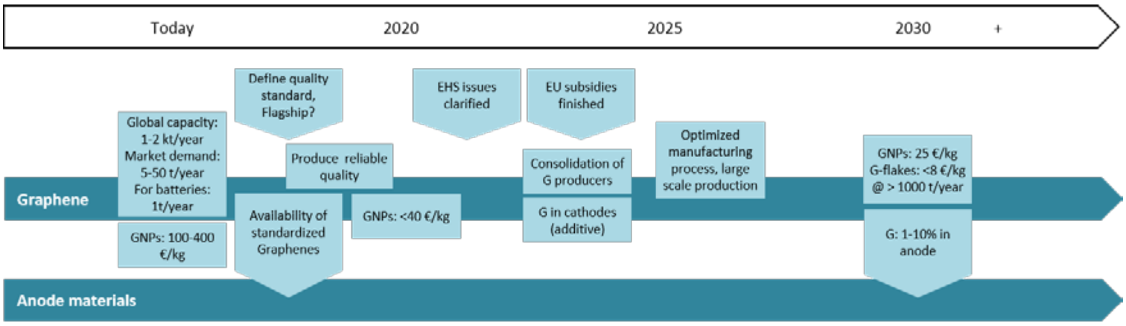


Figure 54: Roadmap for graphene-enhanced anode materials.

In terms of production volume, a huge global overcapacity can be observed at the moment. Particularly for materials produced in Europe, there are currently no significant markets, since most of the graphene used for end-products is produced in Asia. Optimized synthesis routes and equipment for large scale production of graphene might be available around 2025. Due to the limited time-frame of public funding programs like the Graphene Flagship, a consolidation of graphene producers and market shakeout is expected to happen after funding in Europe runs out.

4.3.4.1.2 Quality standards and regulation

Product consistency and comparability of producers is still a major issue for European graphene manufacturers, particularly if large quantities are required. The establishment of quality standards is considered to be of utmost importance for the further development of any graphene markets. The actual standardization of graphene will however take a long time (see section 2.1.2).

Besides standards, requirements of safety regulations also need to be addressed quickly. Volume production in Europe strongly depends on a successful REACH registration. The production of GNPs might already be possible under the label of graphite. However with respect to powder handling, compliance with and safety regulations of downstream customers need to be addressed.

The development of Si/graphene anode materials is one of the most promising applications for graphene and will be focused on by a Spearhead-project within the Graphene Flagship. Still, the right type of graphene for this application needs to be found and anode material design as well as production processes need to be developed and optimized. A time scale of 15 years from a working lab-model to larger scale production is realistic.

Every type of production technique gives a different material and the functioning in Si-composites will strongly depend on the material's parameters (see section 4.3.1.3). For any prototyping, a consistent supply of graphene with consistent quality is mandatory. Besides particle morphology and properties, the delivery form of graphene is important, if it is supposed to be processed on existing equipment. An optimized manufacturing process has to be developed, preferably with low output of waste, which is suitable for fabrication of Si-compounds and anode production.

4.3.4.2 Further development of LIBs

A strong growth of LIB markets can be expected. Technical improvements will be introduced on all levels of lithium-ion cells and for all active as well as passive components in the next years. Particularly for larger cell formats (cylindrical 21700, pouch or prismatic) a strong growth in terms of production/year is to be expected due to the clear application perspective in cars (see below). Current KPI in 2017 for 18650 cylindrical cells are 270 Wh/kg, 750 Wh/l for cells based on NMC cathodes and graphite based anodes with small additions of SiO.

With respect to currently available anode materials, a continuous increase of Si-content is aimed on. Around 5 % Si in Si/C-composites could be achieved before 2020. The increase of Si content will continue until a specific anode capacity of about 1000 mAh/g and a good balance between the thickness of cathode and anode is reached. The prototyping phase for respective anode material compositions is typically of a duration of 3-4 years.

The implementation of up to 15-20 % could be possible by 2025 if enabling developments, particularly in the field of electrolytes and electrolyte additives can be made. A respective cell would feature an energy density of about 350 Wh/kg and 850 Wh/l.

It is unwanted to loose cycle life due to this increase of energy density. The target is to have capacity retention for at least 300 cycles at a DOD of 80 %. Particularly for high contents of Si, formation losses during the first cycle are an issue. Pre-lithiation could help to reduce these effects and the commercial application of this complex procedure might become possible around 2030.

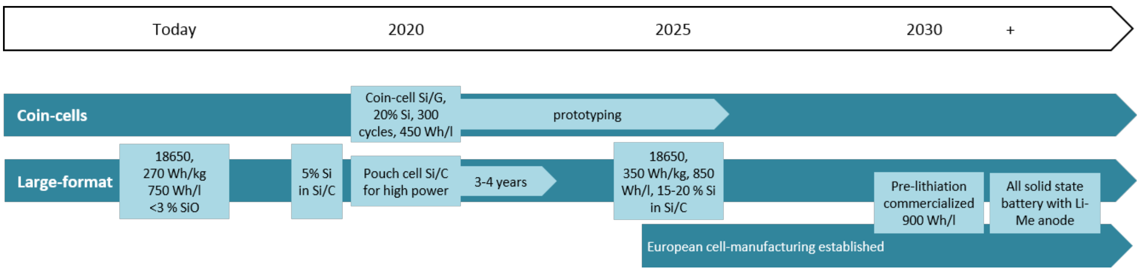


Figure 55: Roadmap for the further development of LIBs.

In the long-term, a transition from state of the art liquid electrolyte based LIBs to all-solid-state batteries might happen. This could allow the use of metallic lithium as anode and is considered to be a game changing technology, particularly for applications requiring highest volumetric energy densities on system level. While this technology is yet far from commercial maturity, a market entry might happen around 2030 or beyond.

Based on several announcements (e.g. TerraE, NorthVolt) it can be expected that a European cell manufacturing, which would close the value chain from materials to end products, will be established latest 2025. In addition to initiatives driven by European companies, several established foreign cell manufacturers (e.g. SK Innovations, Tesla) are also planning to build-up production capacities in Europe.

4.3.4.3 xEVs and mobile electronics

Out of the broad portfolio of LIB utilization, two specific application cases are discussed:

4.3.4.3.1 Automotive:

A strong trend towards xEVs is expected in the next 10 years. Most car manufacturers already have several xEV models in their portfolio. The offer will be further expanded leading to a higher market share of xEVs. From a technological point of view, several challenges need to be overcome in order for car manufacturers to provide adequate electric substitutes for combustion powered cars. The range of battery electric vehicles needs to be increased. At present, most models feature a range between 100 and 300 km. Depending on the type of car, a range beyond 500 km is aimed on for the future. Furthermore, the cost of xEVs needs to decrease. This will be achieved by scaling up the production of cars and components, but also by technological improvements, which can enable a higher cost efficiency.

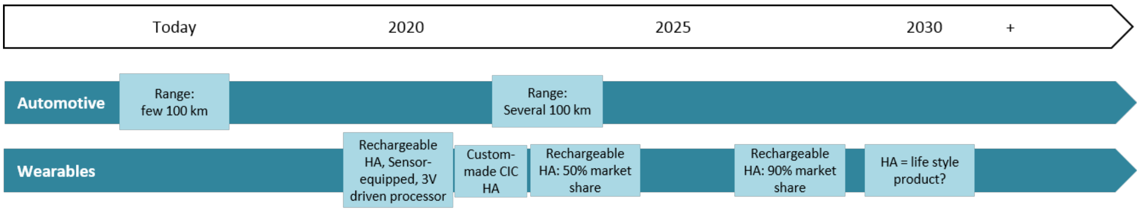


Figure 56: Roadmap for the further development of xEVs and hearing aides.

4.3.4.3.2 Wearables / hearing aides:

Several developments are going to be introduced in hearing aides in the next years. Primary batteries as established power sources will be substituted by secondary batteries. Most manufacturers focus on lithium-ion technology. A certain re-design of hearing aides is however necessary in order to adapt to LIBs. At present, hearing aid processors are based on 1.4 V technology. The electronics need to be replaced by 3 V compatible systems. By 2022 a market share of 50 % of rechargeable devices is projected which will extend towards 90 % by 2025. Considering an average lifetime of 7-10 years this means, that most hearing aides will be powered by LIBs by 2030.

With respect to functionality and usage, the development until 2030 is hard to predict. However, the aim is to implement more and more medical functionalities as well as lifestyle features into hearing aides. Similar to the transition from cell-phones with a battery life time of several days to smart-phones with battery cycles of one day, it is expected that hearing aid users will adapt to more frequent charging cycles, if the device functionality improves and consumption of primary cells can be reduced.

4.3.4.4 Joint interface roadmap

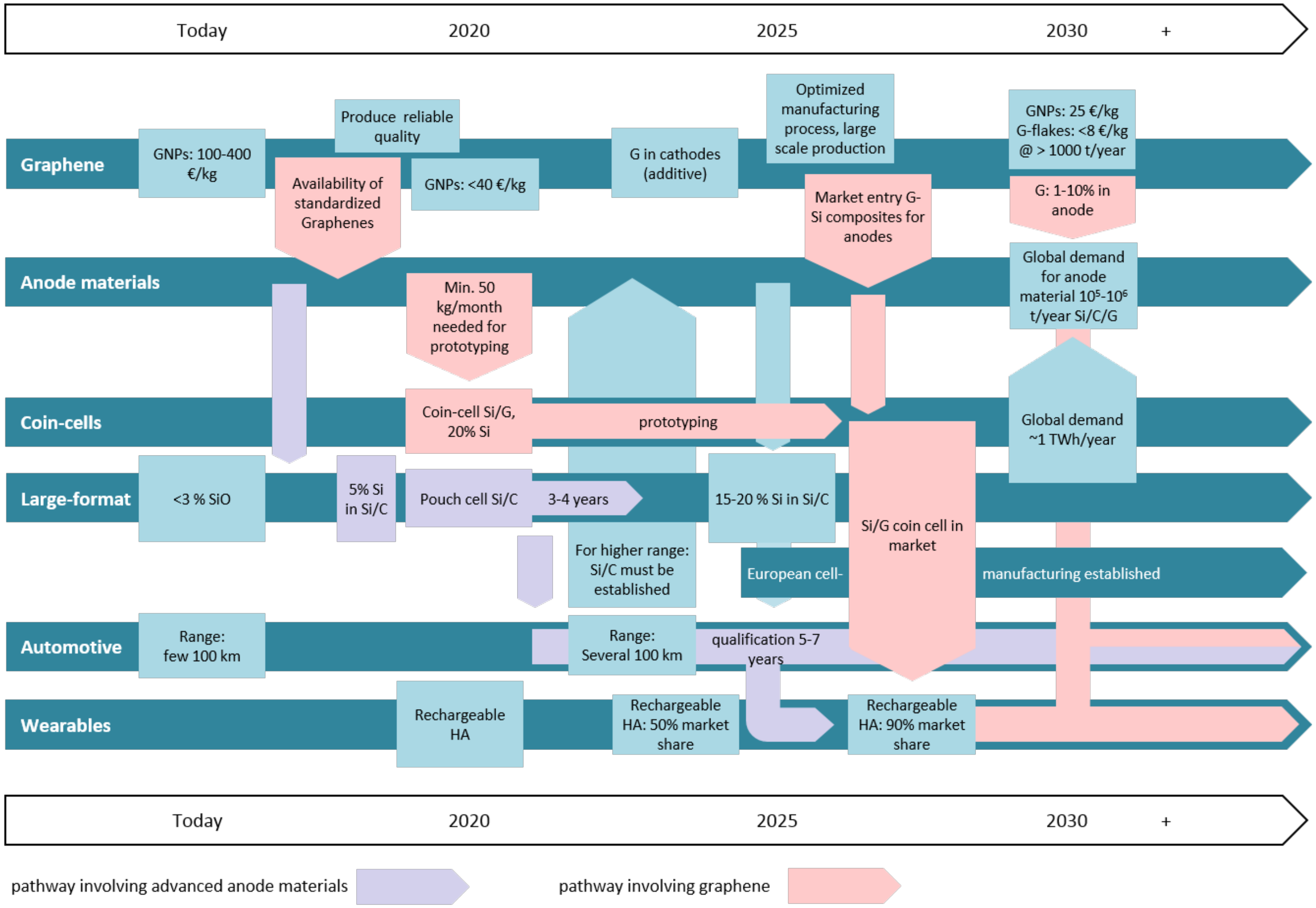


Figure 57: Interface roadmap for the introduction of graphene enhanced Si-anodes in LIBs for application in cars and wearables.

4.3.4.4.1 Standardization and qualification as necessary milestones

The establishment of graphene standards and the development of a stable and consistent supply chain are necessary for any implementation of graphene in downstream applications like LIBs. In order to find a fast solution to the current lack of graphene standards, a backwards approach could be followed and quality standards could be defined for a given application e.g. Si/graphene-compounds based on a type of graphene that proofs to be working well in experiments. This kind of standard should be established in the next few years (<2020) in order to enable downstream markets to test graphene in their applications. A large initiative like the Graphene Flagship could define these standards and at the same time provide a quality label to help manufacturers qualify and market their product to customers. Typically a period of about 2 years is necessary for manufacturers to qualify any existing but slightly adapted materials (e.g. new type of graphite) to their customers. This period can be significantly longer (5 to 10 years) for a completely new material.

4.3.4.4.2 Spearhead activities and cell manufacturing

The Spearhead-project on Si/G anodes within the Graphene Flagship is recognized as important activity to bridge the gap between materials production and cell integration. The aim is to have a functioning proof-of-concept prototype in 2020. To further develop this prototype on relevant production equipment, a constant supply of material (about 50 kg/month) will be necessary. Already small deviations or batch to batch changes might cause problems if commercial production equipment is used. To fully develop all steps of large scale production of cells and test the material, a prototyping phase of 3-4 years is necessary. The market entry of Si/graphene-based cells could happen between 2025 and 2030. Initially, the format could be coin cells, but the aim is to also develop larger pouch cells.

Regarding the situation of a European cell manufacturing industry, the implementation of new technologies in batteries is a big opportunity to gain competitive advantages over established players. Any green field production lines in Europe can be equipped with technologies suitable to process the latest materials and battery chemistries. Hence, a new European cell manufacturing plant would be a chance for European material producers, particularly of advanced anode materials potentially containing graphene, to enter the market. Issues regarding handling and processability of nano-materials could be addressed already in the design of production lines. This might be more challenging for already existing facilities in other regions of the world.

4.3.4.4.3 Applications of LIBs

European automotive industries are a driver for the incorporation of Si in battery anodes, due to their high demand for more range and a higher volumetric energy density of cells. So far, no concrete activities of incorporating graphene into automotive batteries are planned under the involvement of car companies. The topic is not yet popular in the industry. Considering the so far limited production capacity of European graphene producers, automotive batteries might not be the best entry point for the material, since the clear need for high volume production might overextend current capabilities of the industry.

From a product perspective, potential gains in cell performance are only one parameter of many, which is important for car batteries. The significant price pressure for energy storage and distinct safety requirements could be obstacles for the implementation of newest technologies. Due to the rather complex qualification procedures in the car industry, market ready product would take another 3 to 4 years until ready to be utilized in xEVs.

The first adopters of graphene enhanced batteries might be manufacturers of consumer applications. Respective cells might be more costly in the beginning of their production. Lifestyle applications with high margins might be able to absorb the higher cost of energy storage and on the other hand benefit from marketing effects of graphene enhancement. Consumer products are often however not manufactured in Europe. The strong anchoring in Asian countries could be a threat for European anode material providers if cells as well as end products are manufactured in Asia.

From a global perspective, it is projected, that the demand of LIBs might reach 1 TWh/year in 2030, which would translate to a demand of 100 kt/year - 1 Mt/year of anode material with a specific capacity of 500-1000 mAh/g. If graphene proves to be useful in batteries and suitable production and processing techniques can be developed, a great potential for the material could arise from this application. The use of 1-10 % of graphene in anodes would generate a demand of 1-100 kt/year, exceeding the current demand by at least a factor of 1000.

4.3.5 Conclusions on graphene-enhanced LIBs

At present, LIB markets are strongly growing. Advanced LIBs with high (volumetric and gravimetric) energy density are a necessary enabler for electro mobility. In addition, the development of wearables and "smart" devices also relies on high performance and high energy batteries to allow for bluetooth connectivity and other features. A high energy density is particularly problematic for small cell formats. New technologies are needed to make rechargeable batteries competitive to "throw away" solutions.

From a cell-production point of view, capacities for established LIBs are concentrated on Asia and the US. European industries are still looking for possible entry points to LIB markets (TerraE, Northvolt, ...).

With respect to the use of graphene in batteries, the initially poor graphene supply and value chain characterized by a low production quantity, high price and limited processability on downstream equipment lead to a poor reputation of graphene in the battery community ("spoilt expectations"). There is a poor acknowledgement in/exchange with the battery community. The graphene community is said to be not aware enough of all requirements of applications – particularly to meet the demand of the automotive industry.

In order to be able to fulfil the growing technical requirements of applications, a development of new components on all levels of LIB-cells (anode, cathode, electrolyte, passive components) will happen **in the future**. The growth of LIB markets is expected to remain strong with annual rates > 20 % in terms of production capacity. Si/C composites are likely to find use in Li-based batteries. The requirements for a C-matrix supporting the utilization of Silicon as active material are close to the properties of GNPs.

This leads to particular **opportunities for graphene.** The material might be implemented as one component of an advanced anode material: Si/C/G composites with high capacity and good fast charging performance. The global demand of 10^2-10^3 kt/year of anode material in 2030 would lead to a high market potential for graphene. For a successful implementation in batteries for automotive, a graphene enhanced material needs to meet the high cost target of <80 €/kWh for energy storage. In addition, the industry requires long and demanding qualification procedure. It is hence unlikely that automotive could become the first adopter of graphene enhanced LIBs. In consumer applications however, a higher price is possible if a better performance can be achieved.

Several **requirements** need to be met for a successful market entry:

- Technical: Finding the right Si/G/C mixture and composite manufacturing technique: Solution to Li-loss in first cycle (SEI formation, high surface area of graphene); Processing of nano-powders in industrial environment (existing equipment).
- Market: Reasonable price of Si/C/G-composite. Benchmark graphite (20-30 €/Ah).
- Interface: Availability of standardized types of graphene; Continuity of quality; Development of application specific test procedures.

Table 29: Assessment of market and technological potential of graphene/2D materials use in batteries on a scale - -, -, 0, +, ++.

Role of graphene in batteries	**Current technological potential (USP)**	**Market potential (EU perspective)**
conductive additive in electrodes	+	-
Stand-alone anode material	0	--
(multi-functional) component in high-capacity anodes	+	+

4.4 FOCUS: Supercapacitors for industrial applications

In supercapacitors (also: ultracapacitors, electrochemical double layer capacitor EDLC) energy storage is based on electrostatic interactions, while batteries rely on chemical reactions. Thus, supercapacitors feature shorter charging times, the ability to provide higher power in short time (so-called burst energy) and significantly more charging cycles as compared to batteries. Hybrid supercapacitors use both, electrochemical and electrostatic energy storage. Sometimes they include the so-called pseudo-supercapacitors, or the hybrid battery (which incorporate in bulky form both battery and supercapacitor materials).

4.4.1 Supercapacitors and electrode materials

Commercial supercapacitors consist of two or more carbon-covered electrodes separated by an electrolyte solution. The storage mechanism relies on electric double layer formation in the electrolyte solution in direct vicinity to the electrode's surface. Typically, the use of activated carbon powder as electrode material enables a significantly enlarged electric surface area (compared to traditional capacitors). Both, further increased active electric surface area and further reduction of the distance between the electrodes may increase energy storage capacity while retaining high power capability. Moreover, the optimization of the pore structure of the electrode material may make the internal surface area more accessible to the electrolyte, also leading to an increase of capacity.

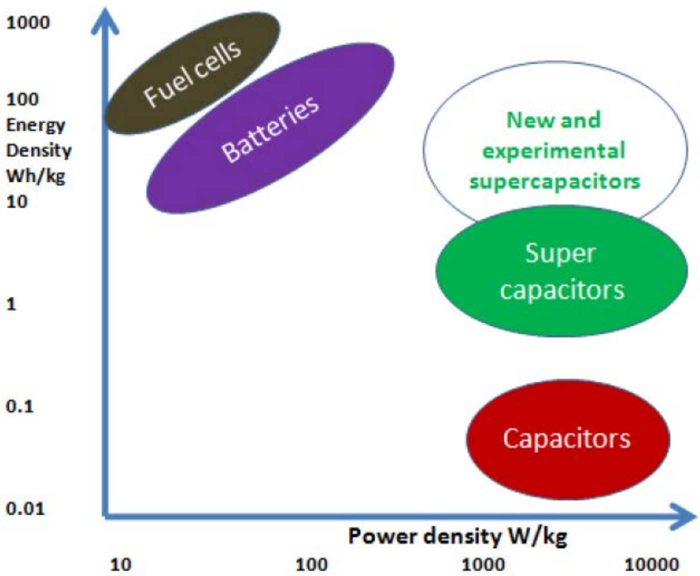


Figure 58: Energy density vs. power density for energy storage devices. [305]

In general, charge and discharge of supercapacitors is not limited by slow redox reactions, qualifying their use for fast storage and delivery of power[18]. Simultaneously, systems may provide advanced lifetime and endure more charging cycles than comparable battery systems, where intercalation-induced stresses can cause material swelling and subsequent electrode failure. Indeed, while current lithium-ion batteries (LIBs) endure several hundred full cycles, supercapacitors may charge and discharge way more often (up to the order of a million cycles). The durability and the number of charge and discharge cycles is not limited by the electrode material but by the stability of the electrolyte. Moreover, the operating voltage depends decisively on the stability of the electrolyte. That means in order to exploit the performance increase of a supercapacitor, a significant effort is necessary to further develop the electrolyte.

The performance of supercapacitor systems usually is tailored to the respective application with a trade-off between key performance measures. In particular: life time of supercapacitor cell or module (number of charging cycles or years), its power density (W/kg or W/l), its energy density (Wh/kg or Wh/l), and production cost (€/Wh). If, for instance, an application requires 5-8 Wh/kg, the respective supercapacitor may feature about one million charging cycles and cost about 10 €/Wh. In contrast, other extreme examples might require a much higher power density and peak power, but accepts a lifetime of only 48 h.

Table 30: KPIs for supercapacitors.

Value	Unit	Description	Literature
	Wh/kg	**Specific energy density**	
5-9	Wh/kg	Commercially available supercapacitors	
150-270	Wh/kg	Batteries for battery electric vehicles (today)	[289]
200-300	Wh/kg	Batteries for electric vehicles (2020)	[289]
	W/kg	**Specific power density**	
10,000-14,000	W/kg	Current commercial lithium-hybrid supercapacitors (18-25 Wh/L)	[287]
100,000	W/kg	Record: commercially available supercapacitors	

18 A state-of-the-art supercapacitor cell of approx. 3400 F can provide a maximum peak current in the order of 2,000 to 3,000 A.

Value	Unit	Description	Literature
	V	**Operating voltage**	
>2.5	V	Today	[306]
3.0	V	Barrier, difficult to overcome	[306]
3.3	V	Future, (1.5 fold energy density)	[306]
		Lifetime	
500,000-1 m	cycles	Common supercapacitor	
		Costs	
<0.01	$/F	Classical figure of merit for supercapacitors (e.g. 20$ / 3000 F cell @ production quantity >1m/a)	
8-20	€/Wh	Today: Supercapacitors	
150-400	€/kWh	Today: Li-ion battery	[288]
		Material costs	
<15	€/kg	Today: activated carbon	
50	$/kg	carbon nanotubes used in supercapacitors	[34]
>200	€/kg	graphene species, relevant for supercapacitors	[307]

Another advantage of supercapacitors as compared to lithium-ion and lead acid batteries (LABs) is, is that they can be used in rougher environments and have a higher temperature tolerance [34]. Supercapacitors perform in the range of -40 to +85 °C[19] as compared to a typical range of 0 to +45 °C (charge) for lithium-ion batteries. Moreover, the systems have fewer thermal heating issues [305], also there is a lower risk of thermal runaway and catching fire. That means, supercapacitors are distinguished by higher safety and reliability, long lifetime of up to 10 years and, deduced from that, very low maintenance costs [305]. The disadvantage of supercapacitors is, first of all, the significantly lower energy density, leading to up to 20 times lower storage capacity than in batteries [34, 305, 308]. Therefore, today the systems are bulky. Moreover they have a higher inclination to self-discharge in comparison to batteries [305].

Batteries show superior performance for applications that require consistent energy delivery such as electric vehicles (xEVs). Hybrid (or asymmetric) supercapacitors promise

19 This range can be extended to -50 to +100 °C.

to combine advantages of traditional supercapacitors and batteries: they charge almost as quickly as traditional supercapacitors, but self-discharge more slowly, and approach the energy storage capacities of batteries, while enduring more charging cycles [309]. There is also an increasing interest to utilize hybrid energy storage systems (i.e. batteries + supercaparcitors) in xEVs which would offer efficient regenerative braking, battery safety, and improved vehicle acceleration.

4.4.1.1 Graphene as electrode material in supercapacitors

Graphene materials are used in supercapacitors for electrodes. The huge advantage of the material is the high accessible specific surface area (SSA) of 2630 m^2/g. Indeed, state-of-the-art material activated carbon has even a higher SSA (up to 3000 m^2/g), but the usable surface for the electrolyte is lower due to unfavourable mesoporous properties [310]. Moreover, the conductivity of graphene is higher [311]. Another advantage of graphene-based supercapacitors compared to existing concepts is the higher mechanical and thermal stability of the electrodes [256].

It is worth noting that the mesoporosity of activated carbon typically limits the access of the electrolyte to the internal surface area. In fact, activated carbons have a wide pore size distribution, including internal mesopores (2-50 nm), which partially hinder the double layer formation. Graphene-based materials, owing different structural properties in comparison to active carbon, are designed to overcome the aforementioned drawback.

Currently, there are different kinds of graphene used for supercapacitor electrodes. Some examples are:

- Reduced graphene oxide (rGO) [256, 287]
- Graphene-based platelets (GNPs) with different spacer materials CNT [287, 310]
- Aerosol spray dried Graphene Oxide with a hierarchical 3D structure (GO) [256]
- GO decorated with chemicals, e.g. KOH [256]
- Microwave expanded graphite oxide (a-MEGrO) [256]

To decrease the size of the supercapacitor systems, research activities aim at raising the fill factor and by that improving packaging density [287]. This leads to storage systems with higher energy density.

The power density determines speed of charging and discharging. A limiting factor for the charging speed of a supercapacitor system, however, is the ionic conductivity of the electrolyte, which is not influenced by graphene electrodes.

4.4.1.2 Market situation for supercapacitors

Market studies [34] claim the market volume for supercapacitors approximates to five percent of the battery market, however, with higher growth rates. In particular, > $ 850 million are estimated for 2016, and expectations for 2020 reach > $ 3 billion [34]. The market appears less consolidated and the dominance of Asian companies is far less pronounced as in other energy related application areas, at least from an R&D point of view. Accordingly, the number of patents in supercapacitor technology shows that the USA is in the lead position and Europe on the second place (s. Figure 59).

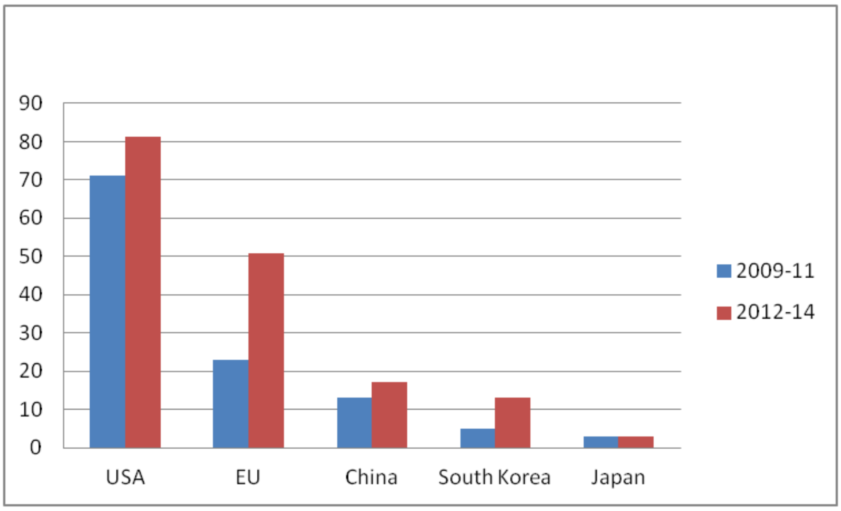


Figure 59: Number of transnational patents in supercapacitor technology. [136]

The supercapacitor technology still bears a lot of potential and is less dominated from Asian regions – even though China, Korea, Japan, and Taiwan are already in a starting position [310]. Many supercapacitor production sites are located in North America (CA, US), Asia (China, Korea, Japan, Taiwan), and Australia [312]. The market leaders are also located in these regions, namely American MaxWell Technologies Inc., Japanese electronics corporation Panasonic, Nippon Chemi-Con and Maxwell subsidiary NessCap Ltd., Korea [312]. In fact, European supercapacitor manufacturers are few in number and mostly small-sized.

Offering a relatively mature technology, supercapacitor manufacturers are pushing for mass applications. Therefore, they are improving manufacturing processes in terms of cost and environmental friendliness, increasing energy density of their products, and communicating what their products have to offer. Less established players are additionally concerned with proving the reliability of their products for increasing their attractiveness to potential buyers.

The ability of fast capturing and delivery of power (pulse power) makes supercapacitors ideal for higher power and highly dynamic applications. Today, supercapacitors are standard particularly for motor start up in large engine tanks, submarines, missiles, diesel trucks, and railroad locomotives. So, the predominant markets are heavy engineering, automotive, and military [305]. Supercapacitors are also interesting for specific applications where fast delivery of stored energy is required, like electro-forming of metals.

Moreover, peak power for robotics and actuators are relevant areas and supercapacitors might play a role for back-up power in electric utilities and factories. Hence, relevant drivers for supercapacitor technology are industrial machinery and transportation [34]. In transportation, applications like mass transit and load cranes are relevant [287]. In the professional sector, additional drivers for supercapacitors are electronic instruments like power tools and communication devices [34].

The characteristics of fast delivery of power puts supercapacitors also forward for electromobility applications, as they might solve the problem of fast fcharging of electric cars. But as the energy density is still significantly too low, this application is not viable today. In the short term, applications like energy recuperation from braking processes are rather probable. This can contribute to a decrease of fuel consumption from 15 % up to 20 % [313, 314]. In the long run, transportation is expected to be the largest market and it is sometimes speculated that supercapacitors might even completely replace batteries [310]. But today the systems are not competitive with regard to both energy density and price. In fuel cell technology they might be used for augmentation in order to increase dynamics of the system.

In general, supercapacitors can be used as bridge power for uninterrupted power supply (UPS) [305]. Particularly in the renewable energy sector, supercapacitors might be interesting for short term grid stabilization of voltage. Both bridging and peak power can be provided [315]. The “energy smoothing” and momentary-load devices might generate a totally new market [305].

Another main growth driver for supercapacitors is consumer electronics [34]. Today, in these applications supercapacitors are suffering from being too bulky, due to low volumetric densities [34]. In the long-term, they might be used in combination with energy harvesting, e.g. to be used in wireless sensors systems for monitoring purposes [305]. Apart from their potential of being used as energy storage devices, small supercapacitors could play an important role in further downscaling of electronic circuits. At present, their response times are rather long as compared to other types of capacitors. Hence, their use in higher frequency applications is rather limited.

4.4.1.3 Market opportunities and threats for the European supercapacitor industry

As very few companies are early adopters and willing to take the risk of installing an energy/power storage system of non-established market players, European supercapacitor manufacturers are in the process of establishing trust by the means of accelerated testing. Testing their products in different applications would be further beneficial to that purpose, for results from accelerated testing have only limited conclusiveness. This is however rather difficult to realise with the limited financial resources of smaller companies. Further contributing to the limited financial leeway of European supercapacitor companies is the lack of European production infrastructure. For instance, electrode materials or electrodes themselves have to be imported and are not seldom of limited reliability.

In the last couple of years, the battery technology has been a more visible research focus in the field of energy storage than the supercapacitor technology. Even though supercapacitors show a reasonable potential, the technology was less matter of public research funding and industrial research and development [308, 316]. Publication analysis reveals that particularly in Europe and the USA the engagement in battery technology was significantly higher (s. Figure 60). Even though, some companies like Skeleton Technologies were quite successful in acquiring funding for graphene-based supercapacitor development and ramp-up [317, 318], patent intensity in supercapacitor technology suggests low interest of industry in this area (s. Figure 60). Certainly, this is due to the fact that batteries have a broader application spectrum and a significantly higher level of maturity. But, supercapacitors might provide attractive solutions for high-value niche applications, what is particularly interesting for US and European economy. And in the long run they might even become an alternative to batteries – or the two technologies merge.

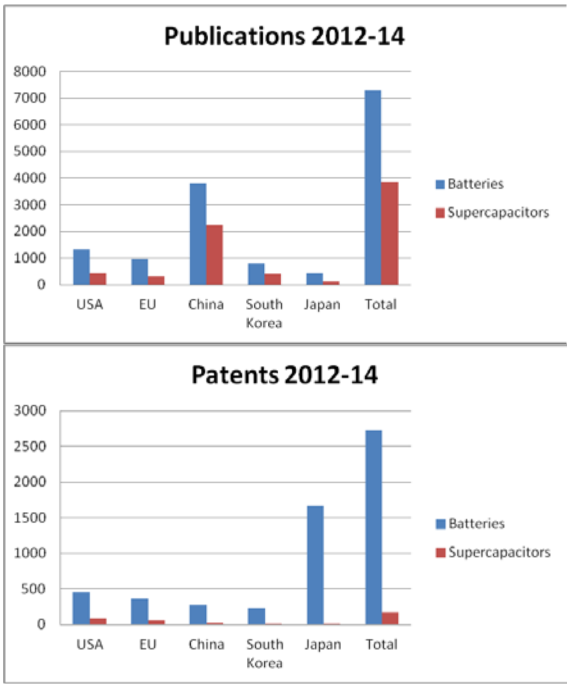


Figure 60: Publications and transnational patents in battery and supercapacitor technology (2012-2014). [137, 257]

4.4.1.3.1 Macroeconomic value of a cell production

At least in the high volume automotive market, for both batteries and supercapacitors there is no major cell manufacturer located in Europe. But lower steps of the value chain will most certainly not generate relevant macroeconomic value added for Europe. Moreover, both materials and electrodes have to be seen as commodities, suffering from high price competition. Only in case of high volume applications, companies can generate relevant revenue by materials. But even then, the macroeconomic role will be negligible compared to the revenues created with systems and from OEMs. That leads to the conclusion that the economic impact of graphene research in the area of energy storage depends decisively on the creation of a European cell manufacturing – which does not depend on success in electrode technology but particularly on economic and political considerations.

Currently, there is no major supercapacitor manufacturer located in Europe. There is a risk for Europe of missing the opportunity and slide into a situation like in other energy application technologies, where the technology value chain is already very much settled particularly in Asia, and partially in North America. There are, however, first supercapacitor manufacturers and related material producers in Europe. It appears highly necessary to support the development of a European eco-system and value chain in order to seize the opportunity of this less established technology.

A joint European effort towards next-generation energy storage might lead to a specific ecosystem, entailing the creation of regional manufacturing capacities. To achieve that, it is necessary that the related competences enclose not only technology development, but also integration, scale up, commercialization and market expansion activities. It has to be stressed that the set up of a new production and subsequent market expansion requires huge investments. Private investors will reject from financing an activity which is isolated and just based on material related competences. Besides material research, demonstration is crucial. The development of a whole value chain with orchestrated innovation activities will be necessary to stir a cell production in Europe.

4.4.1.4 Applications for supercapacitors in forklift and material handling markets

Electric forklift trucks feature several competitive advantages over internal combustion (IC)-powered ones: lower operation cost per hour, less maintenance requirements, no on-site emissions, no need for fuel-storage infrastructure. State of the art electric equipment, however, often comes with a higher initial cost, limited load capacity (< 5 t) and acceleration capacity and the disadvantages of time-consuming charging processes. Hence, electrical devices are particularly applied for indoor use or emission sensitive environments. Lead acid battery systems are still most widely used as power source in electric forklifts. With a typical charging time of 8 hours, followed by a cool-down time of another 8 hours, users need to hold more than one battery per vehicle, each amounting to about 3000 to 5000 €. The average lifespan in these operations is around 3 to 5 years, leading to significant cost for the user.

While lithium-ion batteries have become the standard energy source in consumer electronics and electric cars, there is still controversial discussion about their advantage in forklift trucks. In current business models, forklift users often consider their higher initial cost as compared to lead-acid battery cells a disadvantage and choose the cheaper lead-acid option in 9 of 10 cases. This is likely to change with the trend to industry 4.0, as new business models such as renting out whole forklift truck fleets shift the focus from initial component cost to product reliability. Another point of discussion relates to their comparably lower weight per energy density. Particularly in counter balance trucks, which make up more than 50 % of the total lift truck market, heavy energy storage components provide counter weight to heavy loads. Lighter energy storage components can, however, always be accompanied by low-cost steel weights.

Besides, the ability of lithium-ion battery systems to fast charging and their high rate capability, absence of cool-down intervals, gassing and equalization charging and higher lifespan has led to their market entry in the last few years. They will be utilized especially in small- and medium-sized devices that are used in (partly) automated warehouses, such as pallet jacks, stacker trucks, order pickers or tow tractors. The displacement of lead-acid type batteries as the major power source in electric forklift is, however, not expected to happen before 2020.

Forklift trucks and related equipment are one of the most widely used tools in logistics, materials handling, food, automotive and retail industry. Driven by the fast growing e-commerce sector, the world market for forklifts of about 36 billion € [319] is expected to grow by a CAGR of 5 to 7 % until 2022. The European market, being the second largest after Asia-Pacific, has a projected CAGR of 4 to 5 % particularly pushed by retail, wholesale and logistics [320]. Among the available forklift truck designs, the demand for warehouse trucks with small to medium load capacities shows a comparably high growth. This development is likely related to the industry 4.0 trend and therewith related automation of warehouses and manufacturing processes. As many warehouses have yet to be adapted accordingly, the demand for small to medium-sized forklift truck designs is likely to continue.

While particularly in the Asia-Pacific region IC-powered trucks are still predominant, the market share of electrically powered drives (about 40 %) [321] is strongly increasing. In contrast, Europe may serve as a lead market due to the much higher penetration of electric forklifts based on established regulation and public environmental concerns.

4.4.2 Direct innovation interface: Graphene in supercapacitors

At present, the application scenario lacks a unique selling proposition – a tough challenge for the Graphene industry to qualify and promote their products.

4.4.2.1 Technological strengths and weaknesses for the use of graphene in supercapacitors

With regard to commercial utilization of graphene materials for supercapacitor electrodes, the most relevant output parameters are cost per mass, specific surface area (capacitance), purity and conductivity, and last but not least consistent quality and availability. Additionally, as activated carbon is the current supercapacitor electrode material of choice, graphene materials will have to show better performance.

Firstly, a supercapacitor surface electrode material should be in the range of 20 €/kg. Only at that price and below, a large and stable production becomes feasible.

Conductivity and specific capacitance of supercapacitor electrode materials are, amongst others, related to the accessible surface area and pore size distribution. The higher the accessible surface area and the narrower the pore size distribution, the better for the application in supercapacitor systems. Due to restrictions in size, the volume of an electrode material is more relevant in supercapacitor systems than weight. Graphene material producers should hence indicate the accessible surface area of their product in m^2/g. Additionally, pore size distribution of the product should be communicated in unit nm.

4.4.2.1.1 State-of-the-art electrode material activated carbon

The state-of-the-art material is activated carbon for both electrodes. The activated carbon has a specific surface area SSA of 3000 m^2/g. On the one hand it is important for electrode materials to have a high specific surface area. But moreover, it is important to have a meso- to nano-porous structure in order to ensure access of the electrolyte to the surface of the solid material [287]. The activated carbon is, indeed, designed as a nanoporous material [322]. But, the distribution of the pores is insufficient [34]. As a result, a major problem with activated carbon in supercapacitors is particularly low energy density [34]. Hence, one of the major objectives in supercapacitor development is the electrode material improvement to overcome this problem. And graphene has the potential to be a key technology for this task [34].

Further relevant to conductivity and capacitance of electrode materials is their interplay with other components in the actual application. For instance, the electric resistance of the electrode material can differ depending on the thickness of the electrode material, hence influence (dis)charging speed or power density. This interplay can also be described as internal resistance of a supercapacitor system. So far, no reliable testing data on internal resistance and long-term performance of graphene-enhanced supercapacitors is available.

4.4.2.1.2 Supply of consistent material quality

Speaking of reliability, both graphene producers and raw electrode material purchasers stressed the need for higher purity of and consistent quality of graphene materials. Achieving that will require improved production processes as well as industry standardization of measurement procedures and units. Currently, performance values and quality provided by graphene producers vary greatly and make it difficult for potential buyers to rely on and compare the data, which, in turn, hinders increasing the market share in any application. Improved production processes could also increase accessible surface area of graphene. For instance, developing a non-aqueous exfoliation production process of graphene suitable for mass production could reduce the use of non-conducting surfactants, as currently utilized aqueous-based exfoliation processes. However, any changes in graphene production processes will need clear financial incentives, such as mid-term prospects of increased market shares or subsidies.

In the first production testing it has become apparent that there are no principle problems with graphene-based materials in processing. Also some industry friendly processes appear feasible for graphene processing like spray gun deposition and 3-D printing. These processes are standard, easy to handle and very versatile [323].

Another development approach is to use laser induced graphene (LIG) to improve the production process [324].

4.4.2.2 Market opportunities and threats for the use of graphene in supercapacitors

Due to the lack of a large-scale European graphene production infrastructure, lack of industry standards, strong international competition, and comparatively high costs, the threshold for introducing graphene into supercapacitors is very high at present.

In order to become competitive, graphene-enhanced supercapacitors would need to perform at least 10 per cent better in one parameter than supercapacitors with activated carbon as electrode material. Volumetric energy density and cost are the parameters of highest priority to improve.

4.4.2.2.1 Suitability of available materials to industrial requirements

Today, commercially available graphene materials with sufficient properties are still quite expensive compared to carbon black, activated carbon (<12 €/kg), and other nano-materials (CNT: 40 €/kg). Indeed, there are very small quantities of graphene necessary in process materials like inks, and based on this, already relevant improvement in supercapacitor applications can be reached. But, if the whole electrode consists of graphene, the total amount of material becomes more substantial. The commercially available volume of graphene-based materials, however, is not undisputed: even though there is already a delivery capacity of tons per year [34], representatives from the industry complain of insufficient reliable production volumes. Moreover, it appears the manner of provision does not come up to the typical purchase standards in manufacturing industry.

However, improving these parameters would require testing the materials' performance in the supercapacitor system. This will prove difficult as long as no standardized validation procedures exist, which would allow producers to reliably test their type of graphene. As small supercapacitor manufacturers experience particular difficulties to show long term testing results of their products, European companies are most unlikely to introduce another variable to their test procedures in the course of the next five to ten years.

Also the quality of the delivered material, especially from batch to batch and supplier to supplier, appears improvable. The processing of graphene powder is still very difficult. Due to strong van der Waals forces, aggregation occurs, which affects both the surface area and the number of electrochemically active sides [34]. Graphene in dissolved forms like in inks is easier to process.

Future Markets estimate a potential market size of $500 m up to $1 bn [34] for graphene-enhanced supercapacitors. Today, there are some supercapacitors based on graphene available on the market. Some companies engaged in the development and manufacturing of graphene-based supercapacitors are [34]:

- Sunvault Energy (USA)
- Skeleton Technologies (EST)
- Graphenex (UK)
- Graphene ESD (USA)
- AdvEN Solutions (CA)
- Angstron Materials (USA)
- BASF (printable supercaps) (DE)
- Bluevine Graphene (roll-to-roll) (USA)
- Zapgocharger (UK)

Only two of the European companies (Skeleton Technologies, Zapgocharger) are really producing supercapacitors [310].

4.4.3 Indirect innovation interface: Supercapacitors in forklifts

Future materials handling markets create a window of opportunity for collaborative product innovations – possibly driven by supercapacitor literacy and customer-oriented product specification.

4.4.3.1 Technological strength and weaknesses for the use of supercapacitors in forklifts

Limited load capacity and long downtimes for charging are considered the two major disadvantages of electric forklifts. Both route back to the low power density of lead acid batteries. The application of supercapacitors in forklifts has great potential to overcome this limitation and to enable shorter charging times, better performance and an overall decrease in energy consumption due to techniques like recuperation. In particular, two scenarios appear conceivable: hybrid solutions combining batteries and supercapacitors as well as equipment solely based on supercapacitors.

The combination of batteries and supercapacitors enables the separation of energy and power supply capability of a system. While supercapacitors can deliver the high power needed for the extremely dynamic and demanding forklift duty cycles (~seconds), the battery brings the high energy density needed to continuously recharge the supercapacitor during the forklift operation time (8 hours - day). This distribution of tasks can increase the systems efficiency and reduce operating stress of the battery thereby leading to a prolonged lifetime. Due to the fundamental differences of the dependence of potential *vs.* state of charge (SoC) between batteries and supercapacitors, DC/DC converters are needed for hybrid power sources. Combinations with both lithium-ion and lead-acid batteries appear conceivable, with the latter holding most promise for conventional forklift trucks: utilizing well-established and low-cost lead-acid batteries with upgraded power enabled by supercapacitor modules. Such a hybrid forklift truck powered by a battery/supercapacitor system would largely gain in operating performance, but the overall downtime required for charging would not improve significantly. One has however to note, that the cost of hybrid devices is rather high as compared to systems based on one power source only. It is thus unclear whether hybrid devices can compete in terms of cost, although they might show a promising performance.

4.4.3.2 Market opportunities and threats for the use of supercapacitors in forklifts

Mass application markets such as logistic and automotive vehicles cater to a cost-sensitive client base and require large quantities of components. Supercapacitor manufactures intend to improve the efficiency of their manufacturing processes, in particular by reducing the number of production steps and increasing the output volume. Environmentally friendly production and product life cycles potentially enables cost reduction and certainly provides an additional sales pitch, particularly for European end-customers. Several supercapacitor manufacturers already market their products as environmentally friendly. Anticipation of potential restrictive environmental legislation poses a convenient side effect of these efforts. European supercapacitor manufacturers agree to require more customer oriented product specification standards throughout their industry to attract new customer groups and enhance sales figures. For potential clients, the competing lithium-ion battery technology often provides sufficient charging speed at significantly higher energy density and comparable lifetime. As especially large potential clients apply high standards to their component suppliers, adhering to and developing relevant industry standards constitutes a key step towards higher market penetration. The process should certainly include a joint understanding of wording, units, and measurement procedures.

4.4.3.2.1 Role of (small) European supercapacitor producers

While private investors and R&D engineers of established industries may acknowledge the potential benefits of the supercapacitor technology in different application areas, demonstration of long-term reliability remains crucial. In the forklift and logistics sector, There is a strong interest towards integrating functioning and tested supercapacitor technology. However, it remains questionable whether products of European supercapacitor manufacturers will be the first to be introduced into mass applications. Larger players can invest more resources into product optimization and quality management, and are thus more likely to become suppliers of choice for the logistics industry and others. Forklifts end users are cost driven. The main reason for the slow introduction of LIBs in forklifts (below 5 % total market share) is their price. Hence, the strategy to bring supercapacitors to market would be to target a price lower than LIBs.

Some new European supercapacitor manufacturers (especially start-ups) have both an interesting technology (higher energy density, higher power density, while comparable lifetime) and especially an industrial roadmap and a technology that have the potential to disrupt the unit cost of supercaps (in large quantity), thanks to new manufacturing process compared with traditional players (especially North American).

4.4.3.2.2 Opportunities opening up due to digitization of production processes

The shift towards industry 4.0 and the related miniaturisation of vehicles and automation of manufacturing processes poses opportunities for supercapacitors in small to medium-sized forklift trucks and manufacturing robots. Although logistic and manufacturing processes could become more efficient with fast-charging energy storage components, the infrastructure of production plants, warehouses, and overall energy grid infrastructure will need to be adapted accordingly. Current infrastructures are not suitable for fast-charging, meaning comparably more automated vehicles or robots are in use for longer periods of time. On the plant level, traditional charging rooms will need to be substituted with more dispersed charging stations across the whole plant or an inductive charging infrastructure. The resulting elevated peak energy demand may require a further developed energy grid in Europe. While the described infrastructure adaptations are complex and at the same time essential to the comprehensive introduction of supercapacitors in forklift trucks and manufacturing robots, they are by no means unlikely. The ongoing development of charging stations for BEVs is much more demanding as compared to forklifts energy/power needs. In average, forklifts have a lower battery capacity as BEVs and are used in a much smaller radius. If European industry is to stay competitive, its infrastructure will have to comply with the demands of Industry 4.0 developments sooner or later.

High-value applications like in forklifts, cranes, and other load lifting applications may constitute key drivers for a wide spread market penetration of supercapacitors before this technology can qualify for a wider range of energy storage demands. Global industries experience a strong trend towards automated manufacturing and logistic processes and robotics. Small to medium-sized automated guided vehicles (AGVs) need smaller energy storage options and thus more frequent charging. In automotive manufacturing plants, where AGVs are already widely spread, it is not unusual to find operative times of only about 50 % due to charging and waiting times. Hence, the use of supercaps would greatly improve CAPEX by cutting the number of AGVs needed.

4.4.4 Innovation roadmaps

For graphene applications in energy, supercapacitors appear to be one of the most advanced and mature technologies. First commercial activities, also in Europe, could be observed and graphene is an enabler to allow addressing new applications for supercapacitors.

4.4.4.1 Graphene as electrode material in supercapacitors

Several larger technological developments appear necessary before graphene can become interesting as an electrode material in supercapacitor systems. Many of the current technical issues are related to inconsistent properties of graphene (e.g. batch to batch differences) and resulting inconsistent test-results in supercapacitors. In order to successfully implement graphene in electrode materials, industry standards for testing need to be developed and harmonized, based on defining and agreeing on application relevant key performance indicators (KPI). Meanwhile, the graphene industry continuously improves their production processes with the aim to provide reliable supply to any downstream markets.

With respect to electrode materials for supercapacitors, a purely graphene-based material might not offer the required performance. Composites of graphene and other carbon materials might be the best way to improve performance and meet cost requirements at the same time. A second step, after establishing a reliable and consistent graphene supply, would thus be the development and optimization of suitable graphene containing composites.

Current prices of relevant graphene species range between 200 to 700 €/kg. Experts expect that a price reduction to the range of 20-50 €/kg might be possible before 2020. However, the price of alternative and state-of-the-art electrode materials (e.g. activated carbon) currently applied in supercapacitors is below 15 €/kg. The price for a graphene containing composite designed to serve as electrode material certainly must at least be in close reach to this benchmark. Only very significant performance advances may justify substantial additional costs. The benchmark material will likely advance in both cost and quality over time, too.

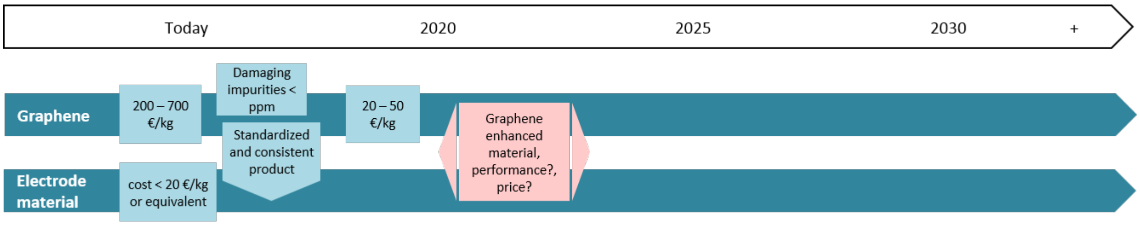


Figure 61: Roadmap for the further development of graphene-enhanced electrode materials for supercapacitors.

4.4.4.2 Further development of supercapacitors

At present, supercapacitors utilization is limited to few niche applications. However, the industry strongly desires wide-spread penetration of initial mass markets. Hence, the further development of supercapacitors in terms of performance and price is strongly coupled to its successful implementation in downstream products. At present, state-of-the-art devices typically offer an energy density of 9 Wh/kg (or 11 Wh/l) at a price of 8-20 €/Wh at cell level. The temperature window for the use of supercapacitors is -45 to 85 °C. The superior power density of supercapacitors strongly benefits application scenarios requiring high current and short response-time, while they are less competitive when high energy densities is demanded.

Experts expect a wide variety of supercapacitor applications. Uniform testing standards and KPI communication to potential customers were identified as crucial steps to promote the technology in prospective markets. Performance tests should align with specific application cases, including accelerated testing protocols complemented with long-term tests (e.g. in current forklift trucks). Industry experts expect that the volumetric and gravimetric energy densities may roughly double within the next five years, with significant cost reductions to be achieved simultaneously. Important milestone for the technology include the development of electrolytes allowing for a voltage above 3V (expected by 2019), and the emergence of new technologies like Li-Caps.

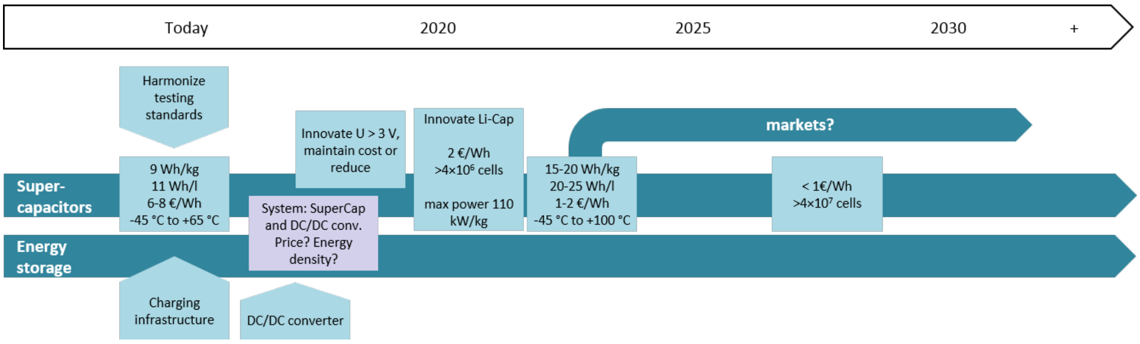


Figure 62: Roadmap for the further development of supercapacitors as storage devices in energy storage systems.

Strong expansion of supercapacitor sales constitutes a key requisite for achieving the set price-targets. Manufacturers aim at selling more than four million cells per annum in 2021, which may enable cost reductions towards a range of 1-2 €/Wh. Within the following five years, a tenfold increase of that sales numbers would be needed to bring watt hours costs below 1 €. For their utilization as energy storage devices with levelled voltage, supercapacitors will require the use of DC/DC-converters to constitute integrated systems, which can easily be incorporated in current and future applications. Experts identified a remaining lack of detailed knowledge about supercapacitor performance and capabilities in downstream engineering communities as bottleneck hampering their widespread implementation in energy storage solutions. Establishing design standards enabling developers to choose between different energy storage technologies (e.g. LIBs, LABs, or supercapacitors) could certainly benefit a faster diffusion of these innovations. Once first successful applications both draw attention and result in transferrable experience, the knowledge gap about the potential and implementation of supercapacitors may quickly resolve.

4.4.4.3 Development of new forklifts and AGVs

The growth of the industry continues in line with the expansion of the logistics sector. Electrified equipment further gains importance as stricter legislation will likely further restrict fuel-driven forklifts and demand reductions of CO_2 emission. The trends towards industry 4.0 and automated warehouse systems creates a demand for automatic guided vehicles and their integration in warehouse system possibly linked to order fulfilment and sales infrastructures. However, new concepts like small AGVs require a completely different infrastructure and are no drop-in solution for existing warehouse-systems. Requisites include: guidance systems, full coverage radio connection for data exchange, and automated charging infrastructure within the warehouse. Prototypes and small scale series production already exist today.

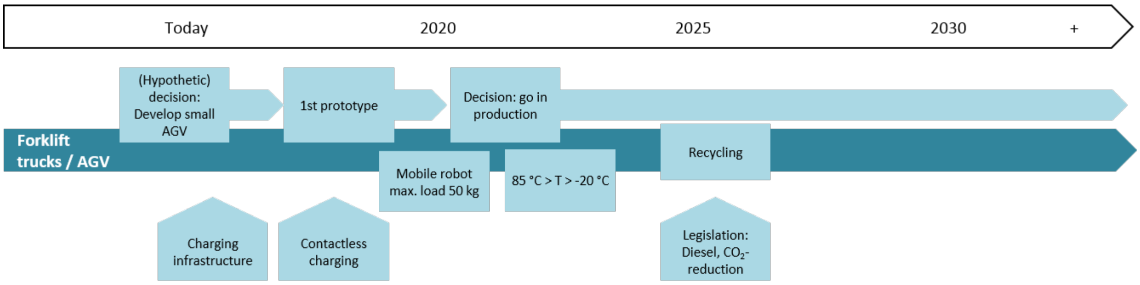


Figure 63: Roadmap for the development of an AGV.

A hypothetic innovation cycle for next-generation products would likely evolve in the following fashion: In case a forklift company made the decision to develop a small AGV solution including novel energy storage technology such as supercapacitors in mid-2017, a first prototype could be developed by 2018-2019. After a testing phase of 2 to 3 years, the company would have to decide about going into production 2021-2022. A desired AGV load capacity of at least 50 kg by 2020 will require an alternative power source, as LAB-based systems probably will not be capable of delivering the necessary currents. Beyond energy storage performance, other factors will influence the choice of technology, including safety requirements also for elevated temperatures of up to 85 °C, and good recycling properties.

4.4.4.4 Joint interface roadmap

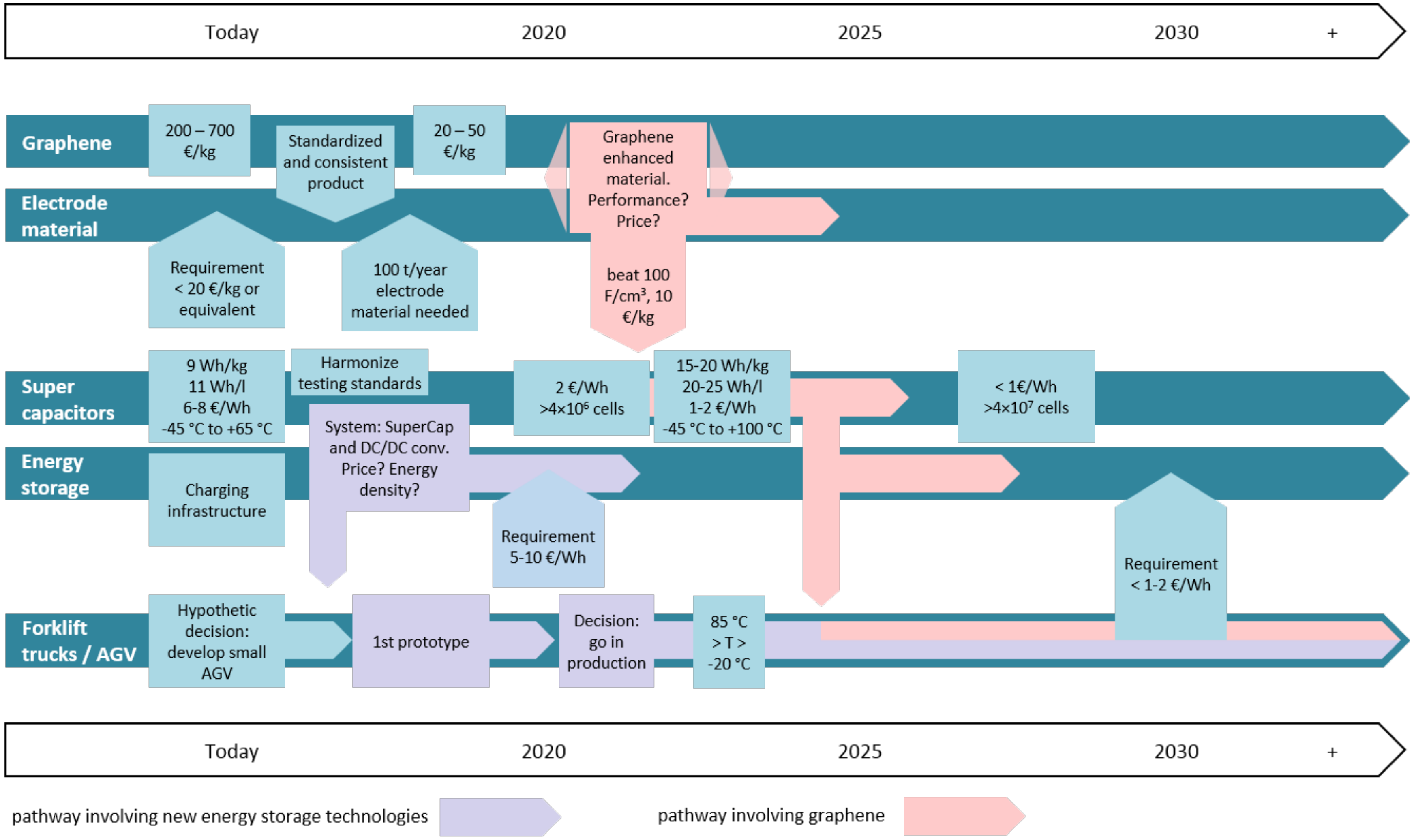


Figure 64: Interface roadmap for the implementation of graphene-enhanced materials in supercapacitors for forklift applications.

A successful innovation involving new technologies relies on the establishment of interfaces to intermediaries and down-stream markets. Once a unique selling proposition of the technology is found, several non-technological steps of an innovation process must be addressed, firstly by informing down-stream industries about the technological potential, but also by gathering information about application relevant requirements. The successful adoption of technology heavily depends on trust in this new technology and the reliable compliance of all frame conditions like supply chains and quality management with the requirements of this particular industry. The innovation interfaces can only be developed and strengthened, if the upstream product is sufficiently standardized by suitable characterization methods. The establishment of application relevant test procedures and the subsequent supply of consistent product quality, which is particularly important and challenging for the graphene industry are pre-requisites for any further development. According to experts, efforts regarding standardization and product comparability should be made as soon as possible, potentially with the support of public authorities or in the frame of initiatives like the Graphene Flagship.

With respect to the envisioned value chain spanning from graphene and supercapacitor production to forklift applications, the further development of the supercapacitor industry might generate a demand of 100 t/year of carbon-based electrode materials in 2018/2019. If graphene producers want to enter this market, e.g. as part of a composite of carbon-based materials, a window of opportunity exists for a material price below 10 €/kg, if a specific capacity of 100 F/cm^3 can be achieved until 2022. This would require significant research and investment efforts. Due to continuous improvements of competing materials in terms of performance and price, the given KPI for 2022 must be considered a moving target and will change according to the duration which graphene and electrode material producers need, to develop a graphene enhanced composite. It is important, to progress from isolated lab-scale experiments to industrial-scale-prototyping and testing. This step would be requisite for a serious assessment whether and when graphene may find commercial application in supercapacitors.

Graphene based supercapacitor development can benefit from graphene material sciences as such. But, in addition to that, the graphene deployment can profit from further development in nanotechnology – as it certainly is a nanotechnology as such. E.g. the mastering of processes, equipment and nano-architecturing of the materials might contribute to improvements in graphene deployment. Therefore, a systematic collaboration between and within the subjects might be beneficial. This is probably not only related to supercapacitor development, but it might be particularly beneficial in this area as it might increase opportunities on the further way towards commercialization.

The supercapacitor technology itself is more advanced than most activities regarding graphene. Products are commercially available. Due to performance restrictions, initially the supercapacitor production will not be for the automotive sector. But, there are various high-value applications viable for (graphene-based) supercapacitors, like in cranes, forklifts, and other kinds of load levering applications, which might allow the creation of business opportunities in the nearer future. System integration was already successfully accomplished for first applications. For example the use of supercapacitors in combination with batteries in forklifts was already addressed by a feasibility study and the construction of few prototypes. Experts judge it very likely that prototyping activities assessing the potential of supercapacitors as energy storage technology for forklifts and related AGVs will continue and expand in the next few years.

4.4.5 Conclusions on graphene-enhanced supercapacitors

Supercapacitors are advantageous as compared to LIBs in terms of power density and cycle-life. They lack the energy density necessary for common mobile applications. Current costs of devices are still high due to low quantity production. Producers of supercapacitors are located in Europe, Asia and the US. There is no dominant market position of any region yet due to the newness of the supercapacitor technology and production. Patenting activities are concentrated on the US and Europe. Producers in Europe are often small companies as compared to their counterparts in Asia and the US.

Graphen has proven useful on lab-scale. At present, industrialization is inhibited by the poor graphene supply and incomplete value chain, low production quantity, high price and its limited processability on downstream equipment.

In the future, digitization and automation of production processes call for new and high-performance mobile energy storage devices. The up-scaling of supercapacitor production will decrease costs and render the technology suitable for larger scale applications. The energy density of supercapacitors will increase due to innovations in the fields of electrolytes (→ higher cell voltage) and electrode materials (→ higher capacity). The **opportunities for graphene** particularly arise from the novelty of the supercapacitor industry, which renders players quite open to innovations. Also, there is a need for new high-performance electrode materials. The implementation of graphene in supercapacitors as composite material (graphene, CNTs, activated carbons, …) could increase the power, energy density and thermal robustness of the devices. New technologies, e.g. hybrid capacitors, may open up new possibilities for the implementation of graphene-related materials (e.g. functionalized graphene).

Several **requirements** need to be met for a successful market entry:

- Technical: Finding the right graphene / CNT / activated carbon composition and composite manufacturing technique; Tailoring and specific design of porosity to improve performance (e.g. graphene foams, aerogels, composites); Processing of nano-powders in industrial environment.
- Market: Reasonable price of graphene-based composites. Benchmark activated carbon (<12 €/kg).

- Interface: Availability of high quality and sufficient quantity of graphene; No batch-to-batch deviations of material properties and quality. Development of application specific test procedures.

Table 31: Assessment of market and technological potential of graphene/2D materials use in batteries on a scale - -, -, 0, +, ++.

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
Stand-alone supercapacitor electrode material	0	0
Part of composite as supercapacitor electrode material	+	+
Pseudo-supercapacitor electrode material	+	+

4.5 Photovoltaics

The photovoltaics (PV) technology is divided in three different technology generations:

1st generation is particularly based on crystalline-silicon (c-Si) solar cells. This technology generation dominates the photovoltaics market with about 90% market share [325]. One of the most relevant key figures of PV technology is energy conversion efficiency. Today, 1st generation solar cells reach the highest efficiencies with 25 % of all the three technology generations [326]. In 2014, the costs for the related PV systems were < € 1/Wp [327]. Even costs of $ 0.59/Wp are reported [325]. Even though the prices have already dropped significantly, the trend in the PV market towards reduction of costs continues. But it is not only about module and system related costs, also cost drivers like installation and maintenance play a significant role [328]. This has to be taken into account when the different technologies are compared.

2nd generation photovoltaics is based on thin-film technologies. Particularly, CdTe solar cells represent this technology with an overall market share of 5-15 % [325, 329]. The aim of 2nd generation solar technology is the reduction of material costs, because smaller amounts of materials are needed. Moreover, the technology aims at decreasing the production costs. Low cost deposition techniques like printing and electro deposition are feasible. Today, CIGS, a specific 2nd generation technology, reaches already a production cost level of < € 0.5/Wp. A drawback of 2nd generation technology is a lower efficiency than 1st generation, reaching about 22 % [330]. The long term perspective of 2nd generation PV is unclear as the International Energy Agency reported the market share shrank from 15 % in 2009 to 10 % in 2013 [325]. But besides today's classical roof-top applications, 2nd generations might play a role for flexible and light weight solutions as well as in building integrated PV.

3rd generation photovoltaic encompass:

- dye sensitised solar cells (DSSC)
- organic photovoltaics (OPV)
- quantum dot photovoltaics (QDPV)
- perovskite photovoltaics

3rd generation photovoltaics is driven by further cost reduction trends and use of more abundant materials. Production processes should be industry friendly and materials should be low cost. In addition to that, new applications are possible as e.g. some 3rd generation technologies allow flexible devices. Moreover, dim lighting and indoor applications can be implemented as these types of solar cells usually perform better under indirect/diffuse and low light conditions. That recommends 3rd generation for consumer electronics. A promising new field of applications are off-grid applications, e.g. in the internet of things (IoT). As most 3rd generation solar cells can be made (semi-) transparent, also new building integrated photovoltaic concepts might be realised in the future [331]. Today, 3rd generation photovoltaic technologies are in an early stage and still show low efficiencies with <15 %. Only perovskite PV has reached efficiencies of > 20 % [326]. But this young technology is far from being used commercially.

4.5.1 Market perspective: graphene/2D materials in photovoltaics

In 2013, the global photovoltaic market was about $ 96 billion [325]. A further increase up to $ 137 billion is expected for 2020 [328]. Frost & Sullivan even calculates for 2020 with $ 179 billion [332]. Until then, there will be a two digit annual growth rate for this sector [328]. Even though Europe still represents one fifth of the global photovoltaic market (s. Figure 65), for the future it is expected that lead markets will be in China and India due to beneficial solar irradiation in these regions [327, 328].

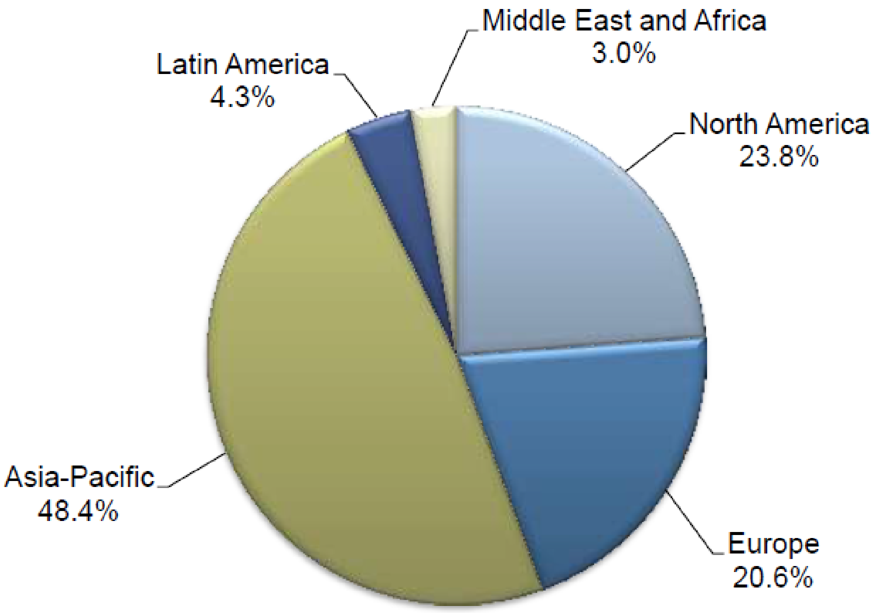


Figure 65: Total Solar Power Market: Per Cent of Revenue by Region, Global, 2015 (source: [332])

In addition to that, manufacturing has already shifted towards China, due to lower production costs and also unfair pricing advantages of Chinese companies. Therefore, between 2008 and 2014 several US and European manufacturers have declared bankruptcy [333]. Today, according to analysts, all of the top ten PV manufacturers are located in China or Taiwan [334]. Frost & Sullivan also mentions for the major market participants of the solar power market some companies from other regions [332]:

- Trina Solar (CN)
- Canadian Solar (CA)
- Jinko Solar (CN)
- JA Solar Holdings (CN)
- Hanwha Q Cells (KR)
- First Solar (USA)
- Sharp Solar (JP)
- Yingli Green Energy (CN)

Even though major industrial players are located in China, the engagement in transnational patenting of next generation solar technologies is low in that region (s. Figure 66 and Figure 67). The data underpins the conclusion that China challenges the field by increasing scientific activities: The number of Chinese publications has more than doubled in recent years and today the country shows the worldwide highest amount of publications for 3rd generation PV.

Patent and publication data allow another relevant clue with regard to the interest of industry in 2nd and 3rd generation PV: Initially, the technologies stirred a lot of attention in the industry, indicated by an extraordinary high transnational patenting activity – in Japan and the USA the number of transnational patents even exceeded significantly the number of publications. This is no surprise as the related technologies particularly aim at cost reduction, a very relevant issue for industry. But the high engagement of industry and the patenting has dropped significantly. This is particularly the case for 2nd generation PV in the USA and Japan (Figure 66). A reason for that might be the decreasing economic engagement in solar technology in these countries.

Despite the decreasing engagement of industry-oriented stakeholders, the academic attention on the issue of next generation solar technology is still unabated – not only in China. With more than 25,000 publications between 2012 and 2014 the amount has surged by 55 % compared to the period before.

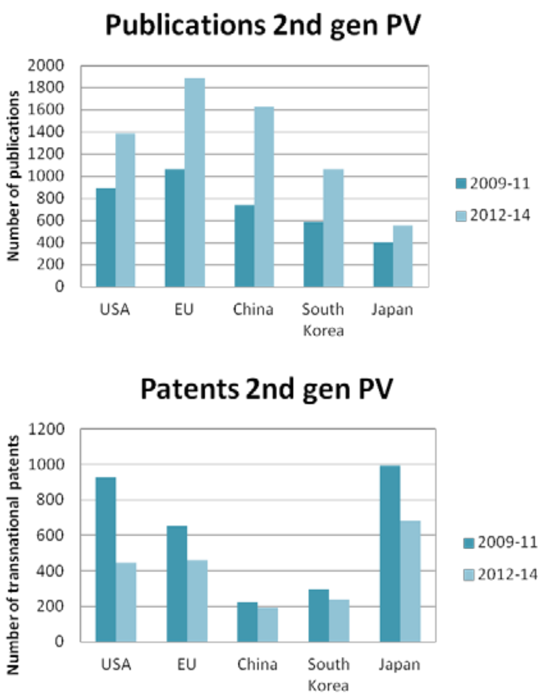


Figure 66: Publications and transnational patents in 2nd generation solar technology. [137, 257]

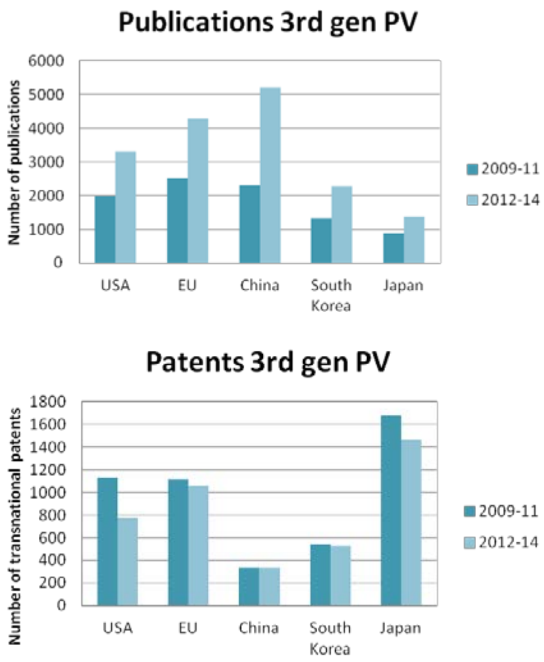


Figure 67: Publications and transnational patents in 3rd generation solar technology. [137, 257]

4.5.1.1 Role of graphene/2D materials in photovoltaics

The theoretical advantages of graphene for solar cells are particularly the transparency and high conductivity , combined with its universal applicability, originating from the tuning of the optoelectronic properties through functionalization. Hence, in all generations of solar cells graphene might be taken into consideration as transparent conductive electrode. For building integrated solar cell applications, (semi-) transparency is relevant for both electrodes. Hence, it can be also used as platinum free counter-electrode in 2nd and 3rd generation solar cells. Perovskite solar cells, integrating transparent conductive electrodes based on graphene, reached an efficiency of 12 % [335].

In dye sensitized solar cells and organic PV graphene can play a role as photosensitizer for light harvesting. Graphene with tunable work function can be used as a universal buffer layer in OPVs [336] and perovskite solar cells (PeSCs) [337] for charge transport. and can replace e.g. PEDOT:PSS [338]. In perovskite solar cells it can be used for charge collection and transport. Related graphene-based perovskite solar cells reach an efficiency of >18% at lab scale [339], and 12.6% on 50cm^2 active area, [340] and are produced by low temperature processing (< 150 °C). This allows cost reduction in the manufacturing process [341].

- In dye sensitized solar cells graphene can be used as counter-electrode instead of platinum. In this case the high specific surface area (SSA) of graphene is beneficial.
- Moreover, graphene can build a barrier for moisture. As for perovskite solar cells, a monolayer of graphene might be used for encapsulation.

- Even though the scientific community is very much engaged in next generation PV (s. 4.5.1), graphene is not in the centre of research interest: In 2nd generation PV graphene plays a role in 4 % of the publications; in 3rd generation PV it is almost 7 %, after all (for comparison: in supercapacitor technology about 50 % of all publications are related to graphene).
- The use as power bars/connectors in 1st generation PV (conductive inks) is highly debatable, as the used inks already perform well and graphene inks currently do not perform well enough. For further considerations on conductive inks please refer to chapter 5.6 Flexible and/or printed electronics.

Table 32: Recent reviews related to photovoltaics applications of graphene/2D materials.

Topic	Reference
Graphene/2D materials for energy conversion and storage	[287]
Graphene/2D materials for dye sensitized solar cells	[342]
Graphene/2D materials for solution processed solar cells	[338]

4.5.1.2 Market Opportunities

4.5.1.2.1 Potential of price reduction by 2nd and 3rd generation PV

The prices for PV power generation are expected to decrease continually. Frost & Sullivan expect a price of $ 0.5/kW [334] in 2020. This steady price fall will support technology concepts with potential for cost reduction. Both 2nd and 3rd generation solar cells are particularly developed to decrease module costs. Beside material costs and material consumption – as for 2nd generation PV –, the production process is vital for the overall costs. Therefore, for 2nd and 3rd generation PV it is crucial that the production process is industry friendly. Making e.g. easy roll-to-roll processes available for PV manufacturing is an attractive advantage of 3rd-generation PV. Graphene might contribute to these improvements.

4.5.1.2.2 Perovskite solar cells with high efficiency and new properties

Because of high efficiency, perovskite solar cells enjoy a high attention recently. Within the family of 3rd generation solar cells, in 2014 this new technology concept has caused a leap in efficiency up to 22.1% [330] – and there is still room for advancements. These cell efficiencies are already comparable to 2nd generation photovoltaics. The high-efficiency can be reached despite cheap materials and manufacturing processes [329]. The perovskite solar cells can be produced in wet chemistry processes and at low temperature, therefore they are usable for roll-to-roll processes. The final costs, announced for semi-transparent perovskite solar cells are $ 0.06/W, which is 50 % lower than the one for Si solar cells [343]. Moreover, the cells allow new application areas, similarly to other 3rd generation cells, due to [329]:

- flexibility
- semi-transparency
- tailored form factors
- thin-film
- light-weight

4.5.1.2.3 New application areas for PV beyond classical roof-top modules

2nd and particularly 3rd generation PV is suitable for light weight, wearable, and flexible solutions. This opens the field for new off-grid applications. Moreover, 3rd generation PV allows the exploitation of dim lighting and indoor conditions, because these cells do not lose power dramatically under shade and variable light conditions [344]. These characteristics are making 3rd generation PV suitable for consumer applications and new Internet-of-things (IoT) related tasks (see also chapter 5.6 Flexible and/or printed electronics for further considerations on flexible applications).

4.5.1.2.4 Building integrated PV

The 2nd and 3rd generation of solar cells allows new ways of adapted integration of PV technology in buildings. This so-called building integrated photovoltaic (BIPV) is different to c-Si-based photovoltaics. With the modified modules it is possible to integrate photovoltaics in the facade, the roof tiles [345] and even in windows – as semi-transparent solar cells are concerned. Even though, the efficiency today does not reach the level of Si-based solar cells, the BIPV approach promises a relevant contribution to European energy supply. The boom of BIPV has been expected for a while but still has not taken off [346]. However, the BIPV concept might open up an opportunity for relevant revenues in Europe [347]: It allows new architectural design concepts, which require customisation. That offers new opportunities for different parts of the value chain and it can be expected that relevant parts of value creation will remain near the point of use.

4.5.1.3 Market Threats

4.5.1.3.1 Potential cool down of perovskite PV-hype

The technology readiness level of particularly the perovskite technology is still very low, as it is still very young. The technology is expected to be commercialised not before 2020. The current hype, based on the very promising properties of the perovskite cells, is in danger to cool down when major implementation problems occur. Already now, major issues are under investigation on larger scale: Perovskite solar cells are criticized due to their lead contend; the long-term stability is an issue; and scaling up shows significant problems [329]. In the worst case graphene activities might be affected, regarding both lost research investments and image. However, the recent developments in terms of stability of perovskite cells are promising and these advancements mitigate this threat. [348, 349]

As graphene addresses several of these issues (e.g. stability and manufacturability), it can become an enabler and mitigate this threat or even turn it into an opportunity for graphene as a potential large scale application. But there are also other technologies/materials addressing these issues, such as in above mentioned references (e.g. fluoropolmers and rubidium cations).

4.5.1.3.2 Continuous cost reduction in 1st generation PV

Costs are the most relevant issue for 1st generation solar cell market. The global market share is more or less directly related to costs. The price of c-Si-based PV has experienced a significant decrease in the recent years. And it is expected that this crumbling of prices will continue in the coming years – not particularly because of 2nd and 3rd generation PV, but because of improvements in c-Si-based PV. Hence, the price advantage of second and third generation solar cells – with and without graphene – shrinks. Therefore, a purely price driven approach will not be feasible but applications need to be targeted where the USPs towards c-Si are high.

4.5.1.3.3 Scepticism against solar technology investment due to the “trauma” of lost Si-PV production

From 2009 to 2014, 1st generation PV has experienced a rapid shift of manufacturing capacities from Europe and the US to particularly China [334]. Today, the manufacturing is highly dominated by Chinese and Taiwanese companies [325]. This devastating loss of production capacity in the area of solar cells has caused scepticism against supporting next generations of photovoltaic technologies. To make bad things worse, particularly China and India are the most promising markets for photovoltaics due to beneficial solar irradiation [328] – and it is often reported, that production follows markets.

4.5.1.3.4 Low efficiencies of dye sensitized solar cells and organic PV

Dye sensitised solar cells (DSSC) and organic PV (OPV) are suffering from low efficiencies (OPV: 11.1 %; DSSC: 11.9 % [326]). As for dye sensitised solar cells, it is expected that the figures will not improve significantly any more. The low efficiency combined with the disadvantage of liquid electrolytes turned relevant industry stakeholders to abandon the technology and recently change over to particularly perovskite technology.

Better low light efficiency and building integrated PV, however, is still a valid business case for this technology, which might be even pushed by internet of things developments.

4.5.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in photovoltaics

4.5.2.1 Current strengths for graphene/2D materials use in photovoltaics

4.5.2.1.1 Transparent conductive electrode for flexible PV

Basically, graphene can be used in transparent conductive electrodes (TCE) of solar cells in all three generations. Today, fluorinated tin oxide (FTO) or indium tin oxide (ITO) are state of the art for the related applications. But, because the former is brittle and the latter is based on rare materials, potentially expensive in the future and also not very mechanically flexible, there is pretty much research done to replace them [350]. Graphene is discussed as one candidate among others – like metal meshes and silver nano-wires – for future transparent conductive electrodes. In the end also combinations of graphene and silver nano-wires might replace ITO [351]. In general, graphene-based TCEs have some generic advantages:

- A particular advantage of graphene as TCE is that the material can be used in flexible applications – in contrast to FTO.
- Graphene based TCEs show good optical transmission properties. Hence, they might be used in (semi-) transparent solar cells.
- Particularly, for 2nd-generation PV, graphene based TCEs are interesting because they can be implemented in high temperature thin-film processes.
- As for dye sensitised solar cells, graphene might be an interesting alternative to silver nano-wires as TCE because it is resistant against corrosion caused by halides, commonly used in the technology approach.

For further information on transparent conductive films, please refer also to chapter 3.3 and for flexible TCFs particularly to chapter 5.6 Flexible and/or printed electronics.

4.5.2.1.2 Good results for charge collection layers in perovskite solar cells

Graphene shows very good charge collecting properties in perovskite solar cells. Graphene nanoparticles (GnP) can increase the efficiency of related solar cells [341]. Also, few-layer graphene (FLG) flakes incorporated in titanium dioxide-nanoparticles can be used as electron collection layer [287]. The related perovskite solar cells show – for 3rd generation PV – a remarkable efficiency of 19.5% [352]. Graphene oxide exhibits an even better performance regarding charge collection and is more transparent than graphene, but it is less conductive [350]. Interface engineering performed with Graphene and 2D related materials shows a viable role in improving both the performance and stability of perovskite solar cells. In particular, n-rGO was demonstrated as additive into the perovskite layer of perovskite solar cells (reaching PCE of 18.7%). [353] rGO was demonstrated as an additive in the PCBM electron transport layer of planar inverted perovskite cells, resulting in a PCE of 14.5% [354]. rGO also showed improvements in the TiO_2 of mesoscopic perovskite cells resulting in PCE of 19.5% [352].

As graphene addresses some of the current issues of perovskite solar cells, it can be seen as a potential enabler of this technology, making it more feasible for commercialisation. In proof of that, GRMs were used to "on-demand" tune the interface properties of perovskite solar cells, enabling the realization of large area (active area 50.6 cm^2) perovskite-based solar modules achieving the highest efficiency PCE of 12.6% for a perovskite solar module with >30 cm^2 active area to date. [340]

4.5.2.1.3 Hole transport layer in OPV with tolerance to moisture and good processability

As hole transport material (HTM) in organic photovoltaics graphene can replace PEDOT:PSS. Compared with PEDOT:PSS, graphene is not hygroscopic [287]. Like PEDOT:PSS, graphene-based materials are compatible to roll-to-roll processes and do not require vacuum techniques for deposition, as inorganic hole transport layers do. Graphene can also be deployed as electron transport layer (ETL).

However, best film qualities are only realized with high quality films, which need to be transferred to the substrate. Thus, the assessment of wafer scale integration applies (5.2 Electronics: Cross-cutting issues), although the requirements are potentially lower.

4.5.2.1.4 Increased durability of perovskite solar cells by graphene/2D materials

Due to the inert properties, graphene/2D materials are distinguished by a high resistance against corrosion. This together with the tunable work function recommends the material for being a universal and protecting buffer-layer. In perovskite solar cells graphene and other 2D materials and composites thereof have been used for this purpose increasing stability and efficiency of the cell [339, 355, 356]. This prevents the entrance of moisture and reduces internal degradation through heating and, by this, increases the durability of the system. Therefore graphene and 2D materials can enable a better stability as one of a few potential options, addressing a major barrier of perovskite technology.

4.5.2.1.5 Industry friendly processability of graphene-based materials

The processability of graphene materials fits to standard processes used in 2^{nd} and 3^{rd} generation PV. The materials are processable in cheap procedures, no cleanroom is necessary and rather simple wet chemistry technologies can be used. Also it is suitable for roll-to-roll processes. Solution-based techniques or vapour-deposition, suitable for graphene-based materials, have the advantage that they are more or less easy to scale up. Printed and graphene flake based processes are easier to scale up as higher quality

CVD films that need to be transferred. Indeed, the development of graphene-based PV is in a very early stage, but until now, the available graphene quality appears high enough.

4.5.2.2 Current weaknesses and challenges for graphene/2D materials use in photovoltaics

4.5.2.2.1 High resistivity of graphene-based transparent conductive electrodes

Even though some properties of graphene as transparent conductive electrode are superstitious than the incumbent ITO (see also chapters 4.5.2.1.1 and 5.6), and graphene materials have the advantage of being highly transparent, the insufficient conductivity of the today's graphene materials is a relevant drawback. The sheet resistance of ITO is <20 Ω/m² and solution processable graphene material are said to be far from that (at similar transparency). Even if the conductivity is increased by using more graphene layers, this would have a negative effect on the transmission. Other alternative approaches, for instance doping, need to be controlled and endurable. Hence, it is disputed if the conductivity and transparency, combined with manufacturability, stability, economical feasibility and compatibility can in principle reach required levels.

Moreover, silver nanowires and metal meshes are discussed as current technologies of choice for ITO-replacement. The related technologies already show high technology readiness levels. The only drawback for silver nano-wires is applications where halides are used, like in dye sensitised solar cells, as they are inclined to corrode.

4.5.2.2.2 Very early stage of 3rd generation PV: weaknesses still veiled

3rd generation PV development is still partially in an early stage – particularly in the perovskite solar cell technology. Even though graphene materials have shown interesting properties for related technology concepts, the production implementation – or even the commercialization – is not broadly addressed yet. Therefore relevant weaknesses are still unclear and might come up during the implementation phase. For example, in process developments of second-generation PV, the production of large surfaces with graphene materials has caused degradation of electric properties. It is to be expected that comparable problems might occur in 3rd generation process development too, when they are transferred to pilot production and mass manufacturing.

4.5.2.2.3 R&D focus on other issues than graphene

As mentioned, the basic technologies with regard to 3rd generation PV are in an early stage of development. The main research effort is put in basic problems of the technology as such, e.g. in dye sensitised solar cells rather the redox couple is a fundamental issue of industrial research. If any, these fundamental tasks are in the focus of the research budgets of companies engaged in the 3rd generation technology deployment. Graphene related research appears to have a low priority in PV industry. Accordingly, less than 4 % of transnational patents in 2nd and 3rd generation PV are related to graphene.

4.5.3 KPIs for photovoltaics

Most often used KPI for photovoltaics technologies is the energy conversion efficiency [%]. Moreover the price per peak power [$/Wp] plays a relevant role.

For indoor energy harvesting or at low light conditions (application areas like Internet of Things (IoT) or Wireless Sensor Networks (WSN)) – additional criteria are relevant for the performance assessment of photovoltaic technologies:

- life-time
- size in relation to performance (form factor advantage)
- flexible, wearable
- light weight

Table 33: Typical KPIs for photovoltaics applications.

	Unit	Description	Literature
	Ω/□	**Sheet resistance (R_S)** KPI for transparent conductive electrodes Always with regard to transmittance (TR)	
< 10	Ω/□	Requirement for transparent conductive window in PV systems	[287]
~30	Ω/□	Graphene-based TCE (via doping) (@TR ~90%)	[287]
~20	Ω/□	Graphene-metal grid TCE (@TR ~90%)	[287]
	%	**Transmittance (TR)** KPI for transparent conductive electrodes Always with regard to sheet resistance (R_S)	
> 90	%	Requirement for transparent conductive window in PV systems	[287]
	%	**Energy conversion efficiency**	

	Unit	Description	Literature
		KPI to compare photovoltaic technologies	
~25	%	1st generation PV (c-Si)	[330]
22-23	%	2rd generation PV (CdTe, CIGS)	[330]
		3rd generation PV	[330]
11.5	%	Organic PV (OPV)	
11.9	%	Dye sensitized solar cells (DSSC)	
22.1	%	Perovskite solar cells	
12	%	Perovskite solar cells with graphene based TCE	[335]
13.5	%	2nd generation (CIGS, 45 mm² cell with graphene TCE)	[357]
18.2-19.5	%	Perovskite solar cells with graphene material interlayer and/or doping	[339, 352]
	$/W$_{DC}$	**Costs**	
		CIGS (@14% module efficiency)	[358]
0.56	$/W$_{DC}$	Manufacturing costs	
0.72	$/W$_{DC}$	Sustainable price	
< 0.4	$/W$_{DC}$	Potential for cost reduction (long term)	
	$/W$_p$ €/W$_p$		
0.59	$/W$_p$	PV system	[325]
0.48–0.56	$/W$_p$	silicon heterojunction (SHJ) solar cells	[359]
0.50	$/W$_p$	conventional c-Si module	[359]
< 0.5	€/W$_p$	2nd generation solar cells (CIGS) (= < 0.55 $/W$_p$)	
0.38	$/W$_p$	Target for solar PV modules (according to Frost&Sullivan)	[332]

4.5.4 Roadmap for photovoltaics

4.5.4.1 Current maturity: 'Mostly lab stage research'

Graphene use in photovoltaics is currently mostly at the lab stage. Some applications already are in the applied research stage, such as transparent conductive electrodes. However, despite the advancements in recent years, there is still no actual application close to market and not much advancement has been reported in recent years. As regards to 3rd generation photovoltaics, graphene has some advantages when it comes to corrosion resistance and flexibility. However these types of solar cells are themselves not yet commercialized or are currently at the pilot production scale. In the most commercially advanced 3rd generation PV applications, graphene plays no role so far. The focus is rather on improving existing and already used materials. Still chances are there that graphene might play a role in 3rd generation PV in the future, especially as some lab scale demonstrations are promising (e.g. use in perovskite cells). Moreover, graphene and 2D materials could enable or support hybridization of various 3rd generation PV (especially OPVs with perovskite PV) in tandem and integrated structures.

4.5.4.2 Barriers/challenges (summarized)

2nd generation PV

- Drastically downturn in 2nd generation PV production
- Integration as TCE and elaboration of actual USP compared to other upcoming technologies and the incumbent ITO
- Cost reduction as major argument for 2nd and 3rd generation PV while cost of 1st generation PV decreases continuously and is hardly beatable

3rd generation PV

- Reduce cost to compete with 1st and 2nd generation
- Low power conversion efficiency or reliability/long term stability
- USPs compared to 1st generation PV
- Actually industry friendly and scalable processes
- European value chain?

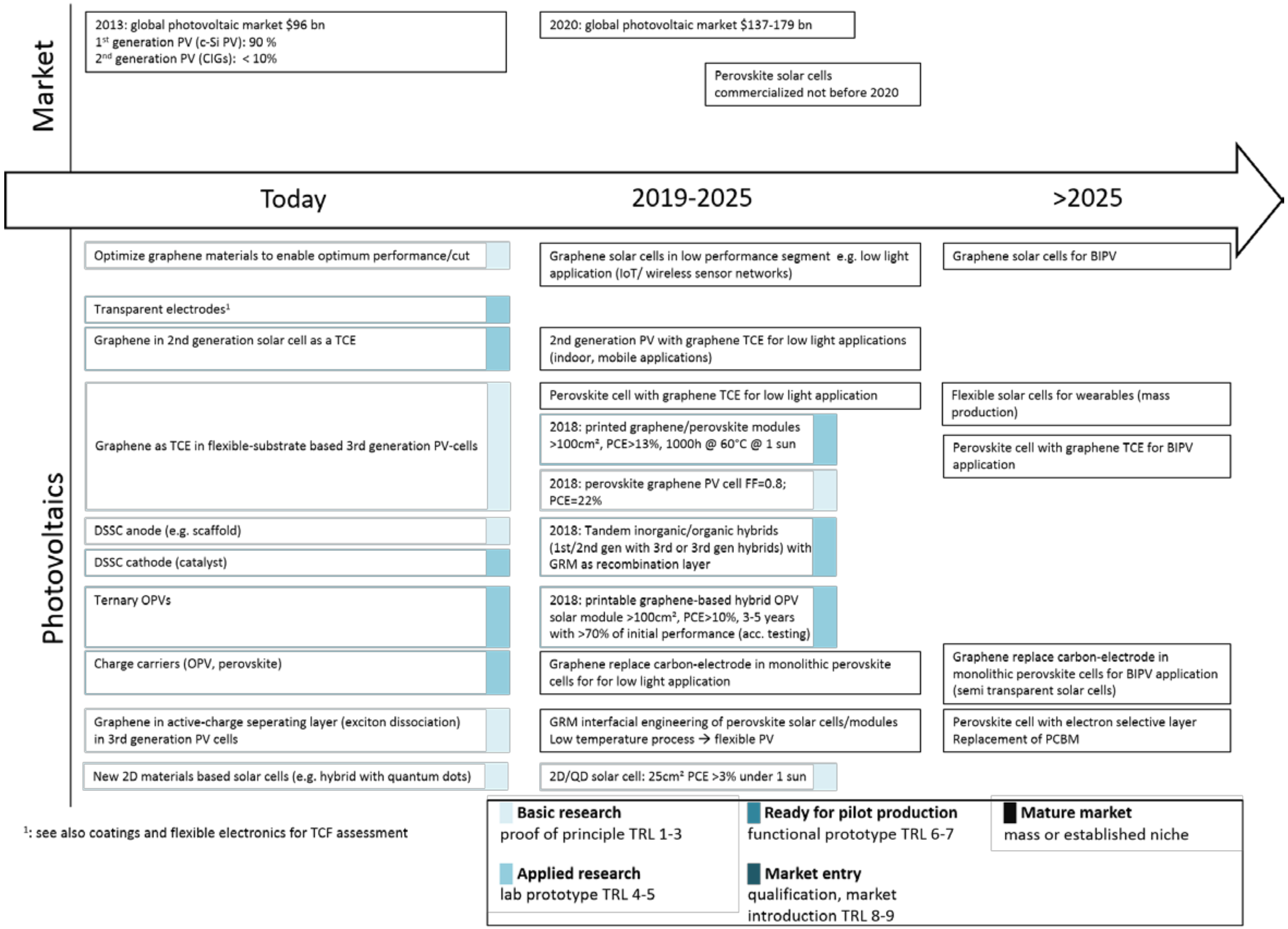
4.5.4.3 Potential actions

If the area of graphene/2D in PV applications is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

- Continuous monitoring of European economic potential and role in photovoltaics manufacturing
- Continuous monitoring of performance in alternative technologies (e.g. silver nanowires, metal mesh)
- Engage with PV community and test under industrially relevant conditions
- Elaborate value added and USPs of 2nd and 3rd generation photovoltaic solutions compared to 1st generation PV (new application areas, building integrated PV)

- Address feasible processes for integration compatible with common production techniques
- Investigate graphene's influence on long terms stability and other deficiencies of 3rd generation PV
- Upscaling of 3rd generation PVs, utilizing GRM inks for large area/throughput, when feasible
- Explore GRM as cross-linking layer (intermediate recombination layer) for hybrid tandem and integrated structures to reach higher efficiencies

4.5.4.4 Roadmap



4.5.5 Conclusion photovoltaics

Graphene is discussed as transparent conductive electrode TCE for all generations of photovoltaics (see also 3.3 for further considerations regarding TCF) as alternative to fluorine tin oxide (FTO) or indium tin oxide (ITO). The assessment of graphene-based TCE is ambiguous: Either the conductivity or the transmittance has shown to be not sufficient. Moreover, there are more mature alternative candidates like metal meshes and silver nano-wires to replace ITO. Only with regard to robustness graphene shows a better performance than silver nano-wires. Graphene-based TCE, however, might be advantageous in niches like flexible and semi-transparent photovoltaics.

Today, the major players for the production of 1st generation photovoltaics (silicon-technology) are located in China. Graphene is not expected to cause a technological step change in this technology. That means neither from an economic nor from a technological perspective strong engagement in this area make sense. 2nd and 3rd generation photovoltaics are particularly developed to lower module prices by decreasing production costs. In some tasks graphene can make a difference in these technologies. But the market perspective of the younger PV technology generations is still unclear: the price distance to 1st generation PV shrinks. Hence, particularly, 2nd generation has lately shown a step backwards with regard to market shares. Moreover, particularly western industry rather back down from the next generation PV technologies. In academia, 3rd generation perovskite solar cells are highly valued as future photovoltaic technology, due to promising results regarding efficiency. As for market attractiveness, the related technology might be used in the future for building integrated PV, wearable and moblile applications, windscreens for automotive industry, self-powered devices for IoT, etc.. It is important to focus on the USPs of the technology and not only claim that it will be cheaper than Silicon photovoltaics. The latter can be doubted anyways, especially for a new technology, and interesting areas are the ones where Silicon cannot be used. This might bear an industrial potential for Europe, as some of the main academic and industrial actors on perovskite solar cell and 3rd generation PV commercialisation are located here.

From a technological perspective, graphene shows promising properties for charge collection in perovskite modules. Accordingly the concentration on 3rd generation, and particularly perovskite solar cells appears reasonable.

Table 34: Assessment of market and technological potential of graphene/2D materials used in photovoltaics on a scale - -, -, 0, +, ++.

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
Transparent conductive electrode	-	-
2nd generation	0	-
organic solar cells (bulk heterojunction)	+	0/+
dye sensitized solar cells	+	--
perovskite solar cells interface engineering and protection	+	+

4.6 Summary Energy

Graphene applications in energy vary from fuel cells, hydrogen generation and (gas) storage, batteries, supercapacitors to photovoltaics.

The fuel cell market is dominated by Japanese companies and the future role of fuel cells in Europe, be it stationary or mobile, is not clear yet. One of the main barriers for fuel cells for transportation is the missing fuelling infrastructure. This unclear market situation for Europe and the missing integrators reduces the macroeconomic potential of graphene research for fuel cells. Graphene can be used to reduce the Pt catalyst content, e.g. as catalyst support or as active material. It is also discussed as membrane, but this technology is still at early the lab stage and less mature as the use as catalyst support. From a European innovation perspective it is not the most interesting energy application. Hydrogen storage and generation on the other hand are more interesting, as the integration into storage systems is more promising and the market prospects and vision for a Europe with an energy system based on renewables is clearer.

The current lithium ion battery cell production, i.e. potential integrators of graphene technologies, is dominated by non-European companies. The European perspective on graphene innovation for this type of batteries is not so attractive, as European actors are only active in niche markets. Although the European automotive industry will need batteries and can benefit from graphene innovation, the graphene integration occurs in the battery cell production. In lithium ion batteries, graphene can be for instance used as an additive to electrodes. The usage of graphene in that area poses a low technological barrier, but also no large improvements. It appears that graphene has a somewhat negative image in the European battery community. A more promising field for European graphene innovation is in 4th generation batteries (lithium-sulphur, lithium-air, and redox-flow batteries) and flexible batteries, which are expected to enter the market beyond 2030. Because these markets and the related battery production is not yet existing on large scale or dominated by a country, there is still a chance to enter.

The area of supercapacitors is the energy application area where graphene enabled innovations are closest to the market. It is one of the most interesting fields for graphene innovation for energy due to the strong added value and ease of integration. The results are promising and there is still room for improvement. However, the mass market for supercapacitors does not exist yet, because the technology is not competitive with batteries in terms of storage capacity. There are some special applications and first markets in special areas. From the integrator perspective, there is no dominating industry yet and Europe is still in the race. Therefore, further research, development and ecosystem development is highly recommendable. This could also become a real success case and advertisement for graphene.

The area of photovoltaics is strongly dominated by silicon-based 1st generation PV from China, with low and still declining prices. The 2nd generation PV market share is declining, although the technology never really took off. From a European macroeconomic perspective it is less favourable to address 1st and 2nd generation PV with graphene developments. The 3rd generation is currently entering the market (e.g. OPV) in niche markets with some European players. Perovskites are currently under strong investigation and appear to be promising. The market perspective for 3rd generation PV is still unclear and despite the expectations of large building integrated PV markets, it has not reached beyond large scale demonstration and niche applications yet. It is important to strengthen the USPs of 3rd generation PV with graphene developments in applications where Si cannot be used. Cost reduction alone is no argument for 3rd generation PV, because cost only will become competitive (if ever) with 1st generation PV after a large scale production is established. Potential graphene applications for all PV generations are graphene as transparent electrode but other solutions appear to be better. Only in flexible areas some advantages are possible. Besides the use as TCE, for perovskite and other 3rd generation PV, graphene can address some of the current drawbacks and appears therefore particularly interesting, e.g by interfacial engineering in hybrid and perovskite solar cells to improve efficiency and stability.

In summary, the most interesting application areas from a European innovation perspective for graphene innovation are supercapacitors and 4th generation batteries. Hydrogen production and storage are further interesting areas. In terms of photovoltaics, 3rd generation PV is more likely to become interesting on European level, with perovskites being the most promising application area for graphene.

Table 35: Summarized assessment table of all energy application areas primarily sorted by European market potential and secondary sorted by USP.

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
Supercapacitor electrodes	++	++
Pseudo-supercapacitor electrodes	++	++
Battery: electrode material for 4th generation batteries (e.g. LiS, Li-air)	++	++
Hydrogen/gas: Hydrogen generation (electrocatalyst)	+ ?	++ ?
Hydrogen/gas: Increased volumetric capacity of high pressure tanks	+	+
Battery: high-potential anodes	+	+
PV: perovskite solar cells interface engineering and protection	+	+
Hydrogen/gas: Low pressure tanks	+	+ (automotive: long-term ?)
PV: organic solar cells (bulk heterojunction)	+	0/+
Fuel Cells: Membrane	+	0
Fuel Cells: Replacement of noble metals in electrocatalysts	+	0 (long-term)
Hydrogen/gas: Hydrogen generation (membrane)	+ ?	0 ?
Fuel Cells: Reduction of noble metals in electrocatalysts	+	-
Battery: additive in electrodes	+	-

Role of graphene	Current technological potential (USP)	Market potential (EU perspective)
PV: 2nd generation	0	-
PV: Transparent conductive electrode	-	-
PV: dye sensitized solar cells	+	--
Battery: active anode material	0	--
Battery: bipolar plates of re-dox-flow batteries	+	?
Fuel Cells: Endplate	?	?