Vegdirektoratet
Trafikksikkerhet, miljø- og teknologiavdelingen
FoU Stab
26.01.2015

Statens vegvesen

Graphene feasibility study

and foresight study for transport infrastructures

STATENS VEGVESENS RAPPORTER Nr. 448

Statens vegvesens rapporter

Tittel
Graphene feasibility study

Undertittel
and foresight study for transport infrastructures

Forfatter
Farzan A. Ghavanini and Helena Theander

Avdeling
Trafikksikkerhet, miljø- og teknologiavdelingen

Seksjon
FoU Stab

Prosjektnummer
603360

Rapportnummer
Nr. 448

Prosjektleder
Mohammed Hoseini

Godkjent av

Emneord

Sammendrag

Antall sider 53

Dato

NPRA reports

Norwegian Public Roads Administration

Title
Graphene feasibility study

Subtitle
and foresight study for transport infrastructures

Author
Farzan A. Ghavanini and Helena Theander

Department
Traffic Safety, Environment and Technology Department

Section
FoU Stab

Project number
603360

Report number
No. 448

Project manager
Mohammed Hoseini

Approved by

Key words

Summary

Pages 53

Date

Graphene feasibility and foresight study for transport infrastructures

Farzan A. Ghavanini and Helena Theander

Chalmers Industriteknik

Last update

Monday, January 26, 2015

CHALMERS INDUSTRITEKNIK

Contents

1 Background

Graphene has been subject to a scientific explosion since the ground breaking experiments less than fifteen years ago, recognized by the Nobel Prize in Physics in 2010 to professors Andre Geim and Konstantin Novoselov at the University of Manchester. Graphene's unique combination of superior properties makes it a credible starting point for new and potentially disruptive technologies in a wide range of fields. Consisting of a single layer of carbon atoms, it is stronger than steel, but still light and flexible. Electrons move up to 100 times faster in graphene than in silicon. Graphene is also transparent and combines electrical and optical features in an exceptional way. These unique properties can be exploited in several industrial areas, to the point where graphene can ignite a technological revolution. The material has the potential to impact several current challenges within, for example, the areas of sensors, ICT, energy, multifunctional materials and life science.

Three significant properties on the atomic/molecular level form the basis for the exceptional physical, mechanical, and chemical properties of graphene on the macro level:

- ***The carbon-carbon bond*** is very strong (*cf*. hardness of diamond) which gives rise to excellent strength, as well as chemical and structural stability.
- ***sp^2 hybridization*** leaves one electron in a π-orbital that does not contribute much to the strength but is free to move around. The three σ-bonds per carbon atom result in the planar two-dimensional structure, while the π-electron allows graphene to conduct heat and electricity extremely well.
- The ***symmetry*** of the hexagonal lattice results in an electronic structure half way between metals and insulators (*semimetal*). The linear energy spectrum near the Dirac point gives rise to a constant optical absorption ($A = e^2/(4\pi\varepsilon_0\hbar c) \approx 2.3\%$) independent of wavelength. This unusual energy spectrum also causes electrons to behave as if they had no mass, resulting in novel and counterintuitive phenomena which can be exploited in optoelectronic devices.

Graphene is the material that holds the most amount of superlatives:

- Thinnest imaginable material
- Largest surface area (~2,700 m2 per gram)
- Strongest material 'ever measured' (theoretical limit)
- Stiffest known material (stiffer than diamond)
- Most stretchable crystal (up to 20% elastically)
- Record thermal conductivity (outperforming diamond)
- Highest current density at room temperature (106 times of copper)
- Completely impermeable (even He atoms cannot squeeze through)
- Highest intrinsic mobility (100 times more than in Si)
- Conducts electricity in the limit of no electrons
- Lightest charge carriers (zero rest mass)
- Longest mean free path at room temperature (micron range)

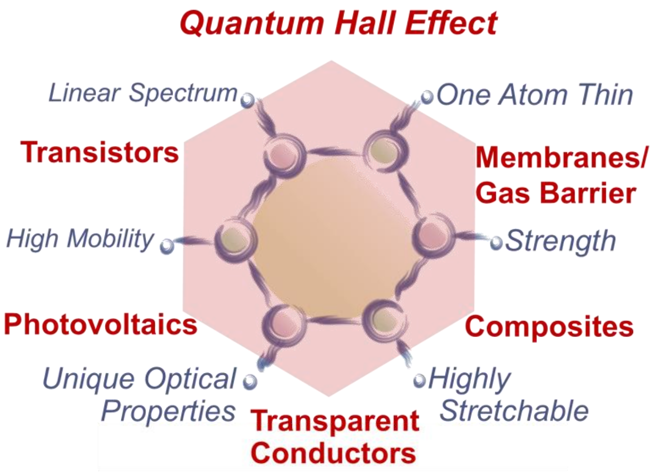


Figure 1. *Graphene properties*

These exceptional properties enable graphene to meet challenges within diverse areas, like the suggested:

- Flexible electronics: pressure sensors for pressure sensitive displays, electronic paper, flexible mobile phones, printed antennas.
- Composites: lighter structures enabling more energy efficient transportation, electrically and thermally conducting composites.
- Energy applications: supercapacitors, batteries, electrodes and active materials for solar cells.
- High frequency electronics and optoelectronics: ultrafast communication systems, terahertz imaging.
- Life science: artificial retina, real time DNA sequencing, real time MR scan.
- Biochemical and chemical gas sensors with high sensitivity and selectivity.
- Nano- and micro-fluidic applications: water purification and desalination of sea water, biomedical applications.
- Barriers and membrane technologies: gas separation and filtration, food packaging or medical applications, multifunctional coatings.

Examples of new products that are enabled by graphene technologies include fast, flexible and strong consumer electronics, such as electronic paper and conforming personal communication devices, and lighter and more energy efficient airplanes or cars. In the longer term, graphene is expected to give rise to new computational paradigms and revolutionary medical applications such as artificial retinas. Such applications are expected to contribute to solving several of the grand challenges in healthcare, clean and efficient energy, security, and green transport. Moreover, graphene based technologies are expected contribute to solving several sustainability challenges through;

- Replacement of scarce or toxic materials in existing products e.g. indium tin oxide (ITO) in displays, noble metals in catalysts or as electrodes in solar cells.
- Lower weight in vehicles to reduce fuel consumption.
- New products for challenges including: desalination, water purification, waste clean-up, antibacterial solutions (implying less need for antibiotics), identification and removal of toxic substances inside the body.

- More efficient energy conversion (solar cells), storage (hydrogen storage, Li-ion batteries, supercapacitors), and transport (power cables with lower losses) to reduce the carbon footprint and enable new energy-efficient solutions.

The industrial exploitation of graphene based materials will require large scale and cost-effective production methods, while providing a balance between ease of fabrication and final material quality with on-demand tailoring properties. One advantage of graphene is that, unlike other nanomaterials, it can be made on large and cost-effective scale by bottom up (atom by atom growth) or top-down (exfoliation from bulk) techniques. Figure 2 summarizes the main techniques that are used today to produce graphene. Detailed information of some of these fabrication techniques is given in Table 1.

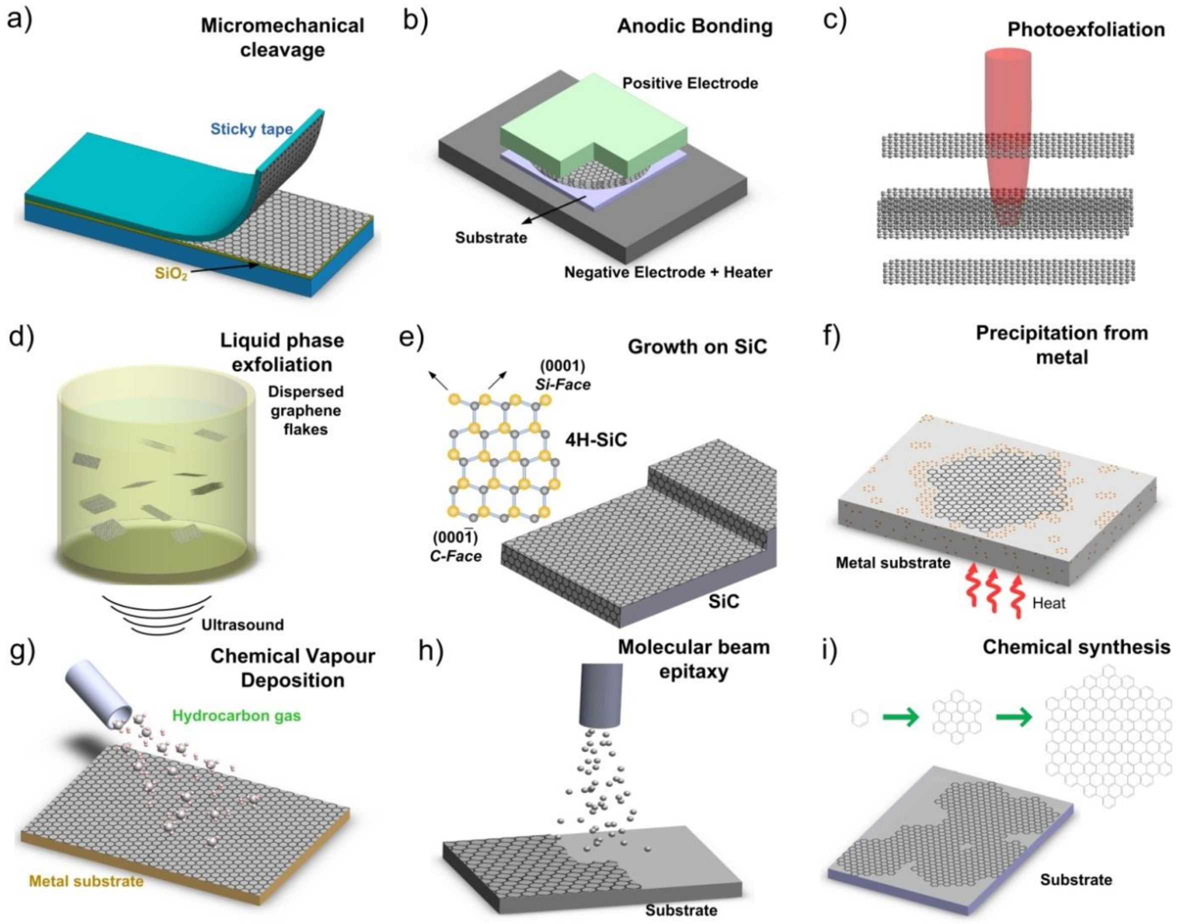


Figure 2. *Schematic illustration of the main experimental setups for graphene production.(a) Micromechanical cleavage (b) Anodic bonding (c) Photoexfoliation. (d) Liquid phase exfoliation. (e) Growth from SiC. At elevated temperatures, Si atoms evaporate (arrows), leaving a C-rich surface that forms graphene. (f) Precipitation from carbon containing metal substrate. (g) CVD process. (h) Molecular beam epitaxy. Different carbon sources and substrates (i.e. SiC, Si, etc.) can be exploited. (i) Chemical synthesis using benzene as building blocks.(ref. Graphene Flagship road map).*

It should be noted that there is a correlation between the quality of the graphene and the scalability of technique used for its fabrication. This correlation represents itself clearly in the final cost of fabrication with that specific technique as shown in Figure 3.

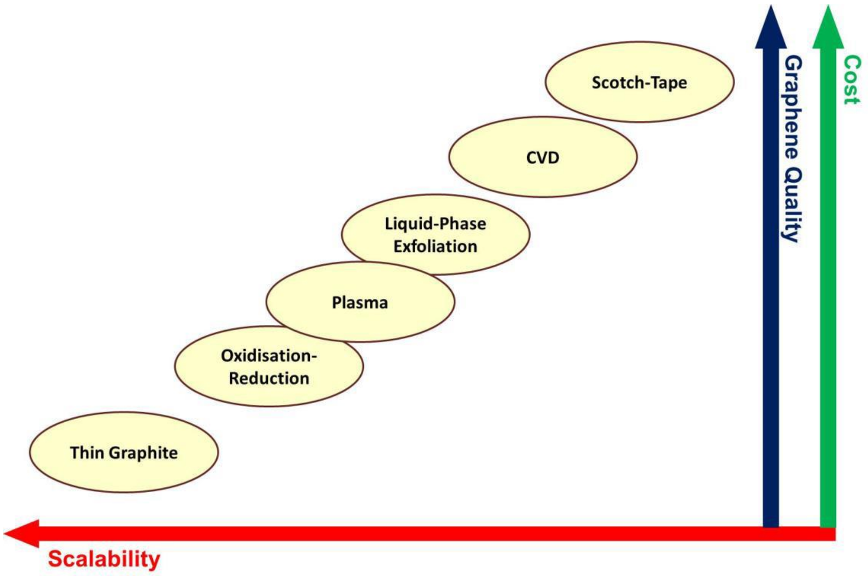


Figure 3. *Scalability versus quality and cost for different production methods.*

Table 1. *State of the art of the main production methods and foreseen applications*

Method	Crystallites Size, μm	Sample Size, mm	Charge Carrier Mobility (@R*T*)	Applications
Micromechanical Cleavage	1,000	1	2×10^{5} cm^{2}/V·s 10^{6}cm^{2}/V·s (@low *T*)	Research and proof of principle devices
LPE of graphite	0.1-1	0.1-1 (∞ as overlapping flakes)	100 cm^{2}/V·s (for a layer of overlapping flakes)	Inks, coatings, paints, batteries, supercaps, solar cells, composites, sensors, TCs, photonics, flexible electronics and optoelectronics,bio-applications
LPE of GO	>1	>1 (∞ as overlapping flakes)	1 cm^{2}/V·s (for a layer of overlapping flakes)	Inks, coatings, paints, batteries, supercap, solar cells, composites sensors, TCs, photonics, flexible electronics and optoelectronics, bio-applications
Growth on SiC	100	100 (6’’)	10^{4} cm^{2}/V·s	RF transistors, other electronic devices
CVD	1,000	1,000	10^{4} cm^{2}/V·s	Photonics, nanoelectronics, TCs, sensors, bio-applications

The potential for graphene has been recognized worldwide, with substantial investments that have already been made and are being planned. Globally, the most aggressive implementation programme is under way in South Korea, led by Samsung and supported by a series of actions by the public sector. The emphasis of the Korean investment is in display and electronics technologies, but the programme also includes a substantial component in life sciences. China is also investing a great deal of effort into graphene technology in, for example, display technology and is expected to grow strongly.

While the scientific production is currently evenly divided between Europe, Asia and North America, the data on patent applications in several key areas shows that Europe is clearly lagging behind in technological exploitation of the scientific results – the *European paradox*. For instance, China has 2200 graphene related patents, US 1750, South Korea 1160, and UK 54 [1].

In Europe, national graphene centres and programmes are emerging in several countries. The most prominent is the UK where GBP 60 million has been invested in the National Graphene Institute at the University of Manchester. There is a comparable level of investment in an industrial graphene centre in Manchester and in an academic research centre at the University of Cambridge. The UK centres are particularly strong in printable electronics, optoelectronics, nanocomposites, and membrane technologies. They are also among the world leaders in several other fields.

In terms of financial investment, the Italian Institute of Technology in Genova is probably in the third position, although in terms of their research output they are not comparable with the UK sites. Their main research focus is presently on energy applications. Other national centres are being planned in, e.g. Aachen, Germany.

In terms of national research investment in graphene technology, some of the main players are Poland (14 MEUR), Germany (10 MEUR through a number of programmes) and Denmark (7 MEUR to fundamental graphene science). In the corporate sector, the main competition comes from Germany where BASF and the Max Planck Institute have established collaboration under the framework of a carbon research centre, and the Nokia Research Centre in Cambridge that collaborates closely with the local academic teams. A growing competitor is the ICFO research centre in Barcelona that focuses on optical applications but covers also graphene-based sensors.

The patent landscape including graphene so far can be categorised in the major groups:

- Manufacturing techniques
- Formulation and master batch formation
- Applications of logics and memory

There is however still room in patenting novel transfer processes in CVD set up or solvent chemistry for liquid phase exfoliation. In the end-use patent landscape there is still white space, but this is anticipated to change rapidly.

In Figure 4, the top ten assignees are presented, with Samsung far ahead.

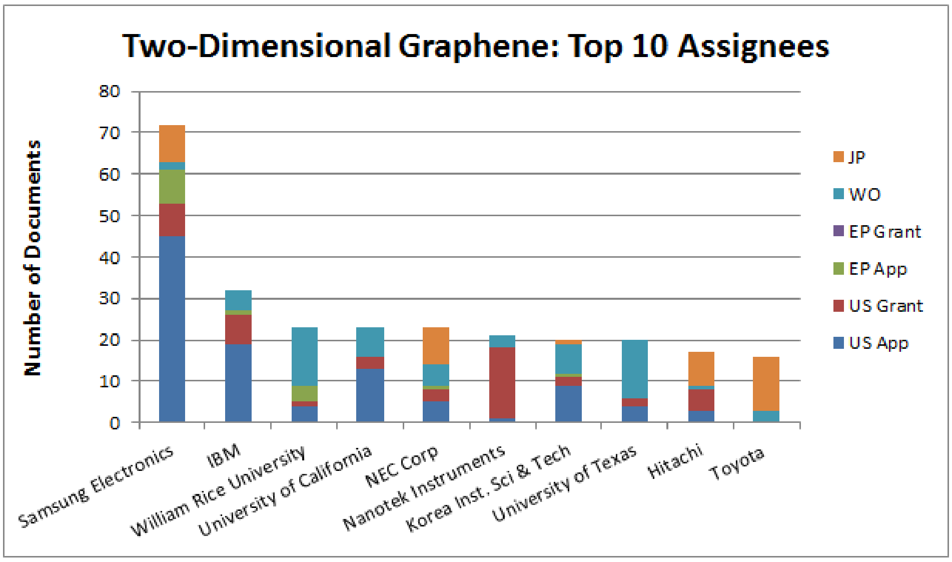


Figure 4. *The ten top assignees of graphene related patent applications.*

Environmental impact

Nanosafety, defined as all the safety issues associated with nanotechnology, is crucially required to translate any future development of new nanotechnologies into action, from industrial applications to health care approaches. Graphene is not devoid of possible risks on human health or on the environment and cannot be excluded from these two domains of investigation. It is of fundamental importance to explore the level of toxicity and to establish, if required, constraints for safety of use.

Several on-going projects are evaluating graphene's potential impact on health and the environment within the Graphene Flagship, as well as other on-going or finalized research projects. To date, results indicate that any potential safety issues can be handled using existing techniques. Health and environmental risks are most likely associated with the production phase of graphene nanoplatelets and not with the final products where graphene is integrated with other materials (e.g., a polymer matrix).

As graphene is a material class with a large diversity in both size, production method, as for incapsulation during life time, it is not possible to give general statements. There will be different safety precautions needed for different graphene materials and applications. No alarming reports have been published so far, but it is of course important to follow the research in this area and keep risk management in mind when developing new areas using new materials.

1.1 Chalmers Graphene Centre

In Sweden, academic research on graphene is carried out by a number of actors. The largest university in terms of research volume is Chalmers, with its graphene research education and innovation related to graphene gathered under the umbrella of the Chalmers Graphene Centre [2]. The centre is the obvious entry point to the Swedish network of graphene research and development, as well as to the EU's research initiative on graphene – the Graphene Flagship. The different areas included in the centre are:

1. Education
2. Research supported by Swedish research funding organisation
3. Research supported by the Graphene Flagship
4. Management and dissemination of the Graphene Flagship
5. Innovation management in the Graphene Flagship (by CIT)
6. Swedish strategic innovation program together with Industry (managed by CIT)
7. Graphene innovation Lab (GIL)

At Chalmers, the Graphene Centre currently has over ten research groups, encompasses about 20 senior researchers that are concentrated on graphene and related two-dimensional materials. A large amount is basic research, both theoretical and experimental. The research areas include computational modelling of graphene and other van der Waals materials, modelling of mechanical properties of graphene structures, thermoelectric properties, plasmonics, fabrication of graphene on a variety of substrates using chemical vapour deposition, metrological applications of graphene, graphene-based high frequency electronics and optoelectronics, to usage of graphene in lithium ion batteries and graphene-based composite structures.

Researchers at Chalmers are also developing production methods for graphene, primarily by chemical vapour deposition (CVD) in which gaseous substances reacts chemically to form a thin layer of graphene on a metallic surface. Other areas are graphene-based standard for resistance measurements, graphene composites as material for high-voltage cables, for instance, and graphene-based high-frequency electronics, primarily within the terahertz range. Examples of research topics are:

- CVD graphene
- Blue micro cavity lasers
- Graphene as heat dissipation material
- Electrical properties in nano-composites
- Datacom lasers and optical interconnects
- Imaging graphene membrane and components in high resolution microscopy Graphene-based THz Electronics – (space and life science)
- Non-linearity, dissipation and noise in graphene resonators
- Modelling graphene membrane under dynamic load in atomic models
- Nanoelectronics and spintronics with 2D materials - beyond Graphene
- NanoSphere: Interactions and risk analysis in Nano-Bio-Geo interfaces
- New Electronics Concept: Wafer-Scale Epitaxial Graphene
- Suspended graphene nanostructures

In addition to the Graphene Centre, the Graphene Innovation Lab (GIL) is a Chalmers initiative to strengthen the interaction between Chalmers' researchers and industrial partners. GIL is funded jointly by the regional government of Western Götaland (VGR), Chalmers and the GIL member companies. GIL arranges professional education activities in collaboration with Chalmers Professional Education, staffs a help desk on graphene-specific issues, organizes networking meetings between companies and Chalmers' staff and students, arranges research seminars/workshops at the partners' locations, provides technology intelligence reports, and offers tailor-made pilot scale graphene fabrication and characterization services. GIL targets urgent demands of companies, small scale fabrication, and specialized measurement and testing services.

1.2 Graphene Flagship

The Graphene Flagship and its sister vessel, the Human Brain Project, are the EU's largest research initiatives ever. With a budget of one billion euros, the Graphene Flagship is committed to moving graphene technology from academic laboratories into European society in ten years – thus generating economic growth, new jobs, and new opportunities for many Europeans as investors and employees. With these flagships Europe has launched a new form of joint, coordinated research initiative of unprecedented scale. The Graphene Flagship brings together an academic-industrial consortium aiming at a breakthrough for technological innovation. The effort will cover the entire value chain from materials production to components and system integration, and targets a number of specific goals that exploit the unique properties of graphene.

Initially, no Swedish companies were partners in the Flagship, but in the summer of 2014 Ericsson AB were approved to enter. From Swedish academia, Chalmers, Linköping University, Umeå University, Karolinska Institutet, and CIT are partners, with Chalmers as the coordinating partner.

The Graphene Flagship includes 11 technology areas as follows:

1. Materials
2. Fundamental science
3. Environmental & Health perspectives
4. Spintronics
5. High frequency electronics
6. Optoelectronics
7. Sensors
8. Flexible Electronics
9. Energy Applications
10. Nanocomposites
11. Production

Chalmers is managing the Graphene Flagship, with Jari Kinaret as the director. In addition, the dissemination work package is also managed by Chalmers, as well as Innovation (through CIT). Figure 5 shows the ten year vision of the Graphene Flagship, with the goals of going from academic workload to industry workload, from research to innovation, from components to system.

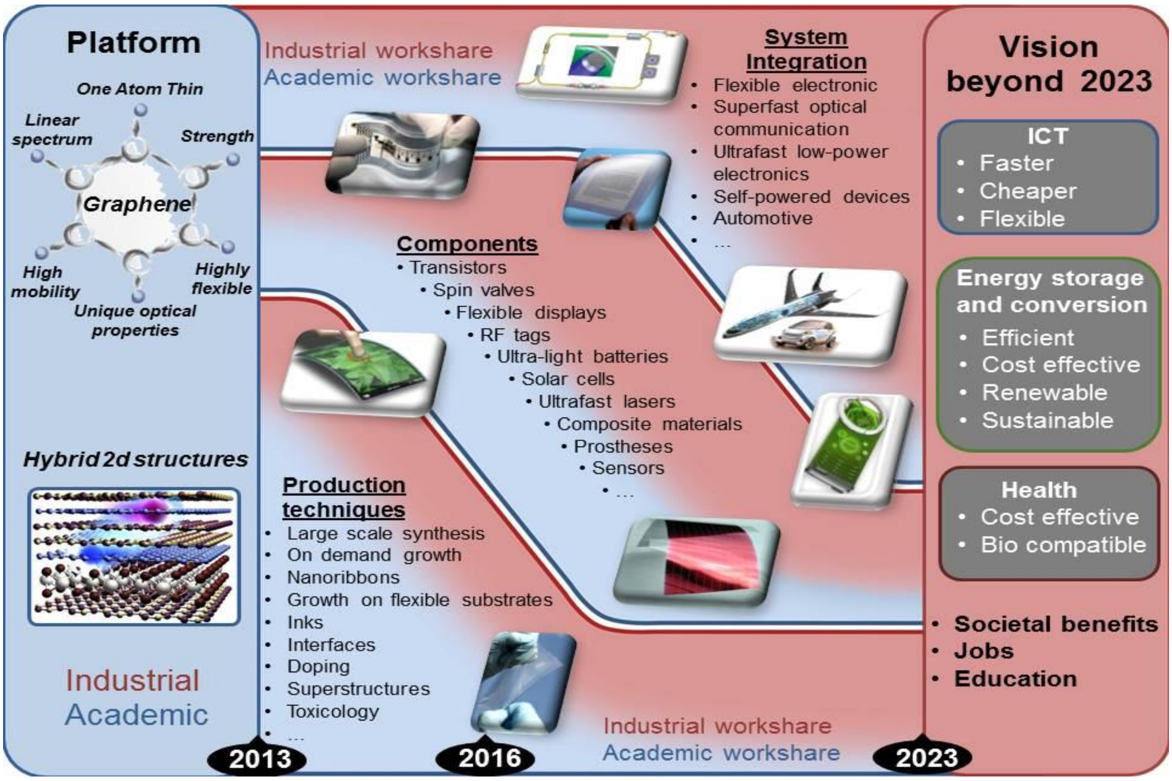


Figure 5. *The Graphene Flagship 10-years vision.*

1.3 SIO Grafen

In June 2014, the Swedish funding organisations VINNOVA, Energimyndigheten, and Formas, granted SIO Grafen as one of 5 new strategic innovation areas. During 2014, the programme office will be started up.

The goals of SIO Grafen are to establish graphene as a new material, strengthen knowledge transfer between industries and between companies and researchers, establish Sweden as one of the leading countries in Europe in graphene-based innovation, as well as develop and establish new value chains. In addition, long term goals of graphene-based products and processes will become a significant business advantage for Swedish companies. Together they want to begin to transform this immature and fragmented industry to a well-established industry where Sweden is one of the world leaders.

During 2015-2017 the activities will include open calls for demonstrator projects and for materials manufacturing, annual workshops, newsletters including intelligence reports on research, IP and business, as well as support to SMEs and entrepreneurship skills. Strategic planning and updates of the agenda is also included.

The programme is managed by Chalmers Industrial Technology, with Helena Theander as the programme director.

To be able to be a partner within the Swedish program SIO Grafen, it is necessary to have a Swedish registered organisation with R&D department in Sweden. The yearly cost to be a partner is 50 kSEK. More information can be found on: https://siografen.se

1.4 The scope of this study

In 2013, Statens Vegvesen and Chalmers University of Technology started a close collaboration concerning research and development in support of the new E39 as well as existing Norwegian roads; an agreement signed at the highest level. The aim of the collaboration is to:

- Bring together Chalmers research/researchers and Statens Vegvesen project researchers into collaborative projects
- Identify Phd/postdoc needs and opportunities
- Identify Masters projects
- Integration into Chalmers education programmes for 200 examined students having relevant knowledge for Norway and Sweden

The aim of this foresight study is to map Statens Vegvesen's future challenges with solutions which could be offered or improved by graphene. The results from a workshop with participants from Chalmers and Statens Vegvesen were used to identify the challenges. These challenges were later prioritized through mutual discussions and interviews. Chapter 2 gives a brief summary of these challenges.

Chapters 3 to 6 provide reviews of the state of graphene research in each of the prioritised areas. In Chapter 7, a roadmap for each of the areas is given, based on published market forecasts, literature reviews and discussions with European graphene expertise. Chapter 8 summarizes our analysis and conclusions in the form of suggested future work.

2 Workshop results

On February 18, 2014, a workshop was held at Statens Vegvesen headquarter office in Oslo. Introductory presentations on fundamental properties and fabrication methods of graphene, as well as its relevant applications in transport infrastructures were given by Prof Mikael Fogelström (Chalmers University) and Farzan Ghavanini (CIT). Moreover, an overview of the national and European research and innovation programs was presented by Helena Theander (CIT). The presentations were followed by round table discussion. The discussion aimed at identifying areas of interest for Statens Vegvesen where graphene could offer an attractive solution.

The discussion resulted in the following prioritised areas:

1. Construction material (concrete, steel, polymers).
2. Sensors for measuring surrounding environment.
3. Energy harvesting.
4. Heat transfer in roads.
5. Coating and barrier materials.
6. Communication – vehicle to vehicle, vehicle to road..

For construction materials the following properties are of interest:

- Possibility to avoid thermal cracking of concrete during the drying phase.
- Increase durability of construction materials (for example by suppressing corrosion).
- Control of water content in concrete.
- Water tight materials for pontoons, for protection of electronics inside.

This area is covered in Chapter 5.

For sensors, described in Chapter 4 the following properties are of interest:

- Information on road status.
- Hazard detection (smoke, gases, accidents, car stops)
- Salt detection for corrosion monitoring.
- Early warning systems for avalanche.

Energy harvesting and storage (Chapter 3):

- Using sound barriers for harvesting solar energy.
- Advertising on sound barriers by printed electronics.

Heat conductivity

- Heat transfer from asphalt to increase durability.

Coatings (Chapter 6):

- Corrosion protection from UV, salt water, sulphur, etc…
- Coating/sensor – warning if the coating properties changes
- Diminish electricity running wild in the armament.

For communication, the 5G network is of interest. The possibility of using the graphene in this area lies so far in the future that we decided on excluding it in this study. There will be high frequency communication devices developed in the next decade, but this is not the core business of Statens Vegvesen and has too low technology readiness, to be a focus area in this study. Four main areas were prioritised in the following study:

A) **Energy**
This area includes topics such as energy harvesting from transport infrastructures, car batteries improvement, advanced energy storage systems, and heat transport in road surfaces. Chapter 3 in this report discusses these topics.

B) **Sensors and electronics**
This area focuses on the application of graphene in developing electronics that can be used to build smarter roads. Topics such as road to vehicle communications, vehicle to vehicle communications are included in this area. Sensors for sensing the road environment are also covered. A good example of this type of sensors is graphene based gas sensors. This area is discussed in chapter 4.

C) **Materials for construction**
Materials play an important role in road construction and their enhancement was identified as a vital issue for Statens Vegvesen. Graphene-enhanced polymer matrices, metal composites, cement composites, and glass matrix composite are all covered in this area. Chapter 5 gives the respective summary.

D) **Coatings and barriers**
A graphene layer can prevent gases and liquids to penetrate the material, making possible to use for corrosion prevention. Graphene is super hydrophobic, while graphene oxide is hydrophilic. Graphene coatings are covered in Chapter 6.

3 Energy applications

Graphene based materials are suggested to bring disruptive solutions to the current industrial challenges related to energy generation and storage applications, first in nano-enhanced products, then in radically new nano-enabled products. Graphene-based systems for energy production (photovoltaics -PV-, fuel cells), energy storage (supercapacitors, batteries) and hydrogen storage will be developed for instance within the Graphene Flagship and of course also other actors.

Furthermore, graphene technology will provide new power management solutions, key to allow efficient and safe use of energy. To date in Europe nearly the 60% of the total energy consumption is electrical (lighting, electronics, telecommunications, motor control, etc.). Of the remaining 40%, nearly all is used for transportation. In the coming years it is predicted that the transport of peoples and goods will change from wheel to rail in a large extent (high speed railways, subways, and trams). On the wheel, transportation will exploit hybrid or totally electric vehicles, it is envisaged that around 80% of the used energy will be electrical.

In the Graphene Flagship, Etienne Quesnel at CNRS, France, leads the energy work package. Partnering companies are Thales, Nokia and Repsol. One Swedish actor, Umeå University is also partner in this work package. Another company with interest in energy applications, Varta MicroInnovation is partner in the flexible electronic work package. By focusing on specific functions involved in applications including photovoltaics, energy storage, fuel cells and hydrogen storage, they intends to “connect” the fundamental and technological graphene expertise to the designers and developers of energy conversion and storage devices. This investigation into energy applications will enable to:

- Define the applicative graphene specifications on the basis of experimental/modelling approaches.

- Achieve proofs of concept of graphene-related materials in different energy conversion and storage devices.

Several of these concepts will be possible to include in future road applications, even though it is not on the agenda for the Graphene Flagship, at least not today. In the following sections we will discuss how graphene can be used to possibly increase the efficiency of harvesting energy from transport infrastructures. Moreover we will look into how the storage of the harvested energy can be assisted by using graphene.

3.1 Graphene assisted energy harvesting

Asphalt pavements are excellent materials when it comes to utilizing the solar energy. They are bare surfaces that are faced directly to sun and because of their low thermal conductivity and large heat capacity experience considerable temperature increase. A very simple and straightforward method to harvest this free energy is to embed pipes beneath the road surface. If a fluid such as water is pumped through the pipes it will absorb the heat stored in the pavement and transport it to a point where the thermal energy can be converted into electricity or used to heat a secondary source. This method of harvesting energy from paved roads is not new and many aspects of it have been well studied (see Figure 6).

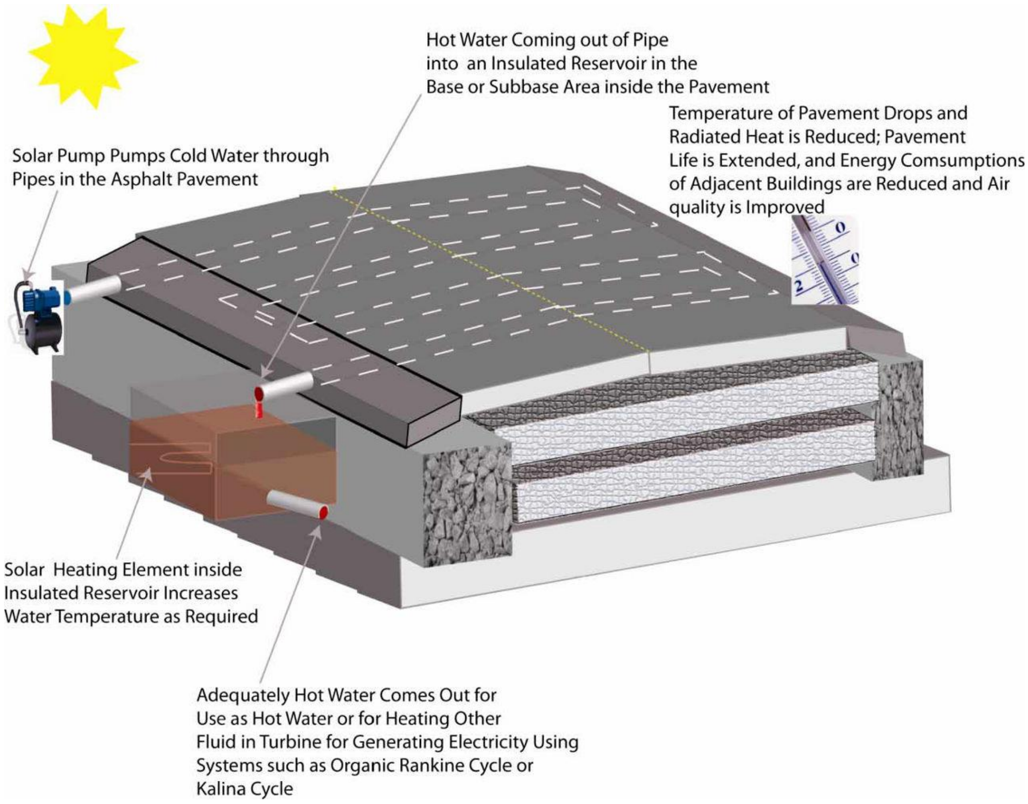


Figure 6. *Harvesting solar energy from paved roads by using an embedded network of pipes. Source: http://users.wpi.edu/~rajib/*

There are many different parameters to take into account for improving the efficiency of the solar collectors. These include, for example, the density and the number of pipes, their distance from the surface of the road, the flow rate at which water is pumped into the pipes, exposure to wind, the effect of ambient temperature, and many others. However, there is one parameter that plays a pivotal role in the overall efficiency of the system: How well the thermal energy can be transferred from the pavement material to the pipes. This, indeed, translates to the thermal properties of pavements. Dehdezi et al. [4] and Dawson et al. [5] have studied how asphalt and concrete pavements that incorporate aggregates and additives such as limestone, quartzite, lightweight aggregate and copper fibre can be designed to be more conductive.

This is exactly the point where the superior thermal properties of graphene can be nicely exploited. The thermal conductivity of graphene is in the order of 4000 to 5000 $W/m \cdot k$ which is more than an order of magnitude larger than that of copper (~ 400 $W/m \cdot k$). This suggests that adding only small quantities of graphene can possibly enhance the conductivity of the pavement a great deal. This has greater consequences than one may think. As it was mentioned earlier an important characteristic of pavement materials that makes them suitable for collecting solar energy is their great heat capacity. Adding a small amount of graphene would have a negligibly impact on the heat capacity, increasing the conductive making an effective and efficient transfer of the stored heat to the piping system.

The challenge is to incorporate graphene in a material matrix and keeping the superior properties of graphene inside the matrix. The quality of graphene as well as the other material in the composite matrix is of utter importance, as well of the distribution of graphene within.

3.1.a Photovoltaic cells embedded in roads

The developments in silicon technology have offered economic fabrication of photovoltaic (PV) cells that convert the solar energy directly to electricity. During the last 20 years photovoltaic solar cells have started to appear in many different places. One may not immediately think of placing a layer of PV cells right beneath the surface (see Figure 7) of the roads because of the tremendous amount of stress and wear that such a surface is subject to.

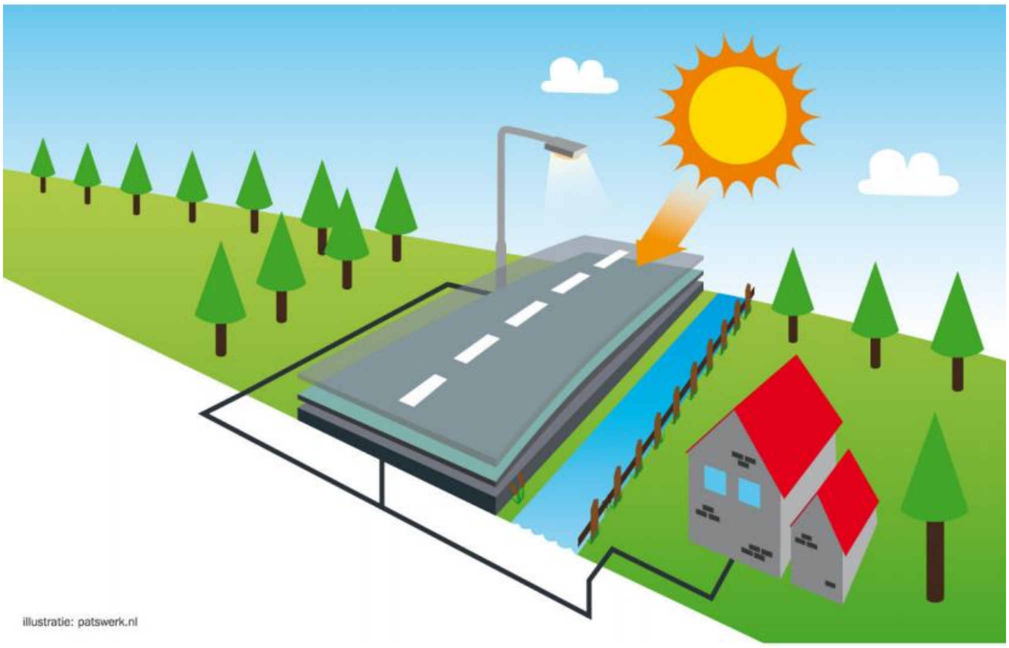


Figure 7. *A road with embedded solar cells. Source: http://www.tno.nl/*

However, the technological advancement in fabricating thick harnessed glass layers has made this feasible. In the Netherlands the TNO SolaRoad projects has aimed at embedding solar cells beneath a bicycle road. Bicycle roads have been targeted for this pilot project because of their lower traffic load and their fewer safety requirements. Such integration between the road and the solar cells would not introduce any landscape pollution and does not need extra space for installation which could be a major bottleneck in many situations.

The TNO SolaRoad cycle path as shown in Figure 8 is constructed of concrete elements with segments of 1.5 by 2.5 meters. Each segment is sealed with a 1-cm thick harnessed glass. Under the glass cap lays the silicon photovoltaic cell. The main challenge in projects which aim at embedding the solar cells beneath the surface of the road is their huge implantation cost. In other words, the electricity that would be produced by such a construction should be large enough to return the investment in an acceptable period of time. This is the problem today and this is exactly the point that graphene can come to rescue.

Research in photovoltaic application of graphene is still in its infancy. Nevertheless, promising results have already been shown. Silicon generates only one current-driving electron for each photon it absorbs, while graphene can produce multiple electrons. This means that graphene can potentially lead to the fabrication of solar cells with considerably higher efficiency. In 2013, Wang and his co-workers demonstrated graphene based solar cells with remarkable performance of up to 15.6 % conversion efficiency [6]. Larger conversion efficiency translated to larger electricity produced per square meter of solar roads which itself translates to a shorter return time on the original investment. Therefore, future development in graphene based solar cell technology can make the construction of roads with embedded solar cells economically viable.

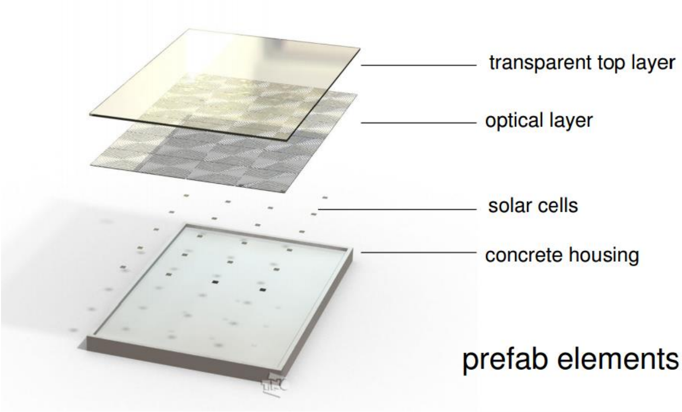


Figure 8. *Technical specification of the road building block for the TNO SolaRoad project which embeds solar cells beneath the surface of the roads. Source:* *https://www.tno.nl/*

3.1.b Photovoltaic cells as highway sound barriers

An alternative way of harvesting solar energy by transport infrastructure is the use of photovoltaic cells in highway sound barriers. Transport infrastructure has been using PV noise barrier since the 90s. In addition to highways the PV nose barriers have been used along railways in Europe. An example is shown in Figure 9.

Figure 9. *Solar cells installed as highway sound barriers.*

The advantage of using graphene based solar cells instead of the ones made of silicon as sound barriers in highways is their transparency. The unique combination of electrical properties and optical transparency of graphene renders it a superior material. Transparent noise barriers would create a much nicer atmosphere for the residential areas adjacent to the highways while tapping the valuable solar energy and converting it to electricity.

Needless to say that the aesthetic impact of any installation is a major factor in its success and eventual acceptance. Such transparent and highly beneficial sound barriers could motivate larger fraction of people to invest on it and adopt it as an acceptable solution.

3.1.c Piezoelectric energy harvesting from roads

Piezoelectricity is a property which enables certain material to convert mechanical energy into electrical energy. When mechanical stress is applied to certain crystals their atomic structure is slightly modified resulting in redistribution of electric charges within their crystalline structure. This charge redistribution is represented by a net electrical potential difference along the crystal which can force electrons to move in an electrical circuit. In some materials this effect is very small and cannot be effectively exploited. However, some crystals such as quartz and zinc oxide produce large enough voltages. These materials have been used for many different sensing and actuating applications. Energy harvesting using piezoelectric materials has been mainly researched for military applications where motions and movements of soldiers are harvested and converted to electrical energy and is later used to charge up the equipment carried out by the soldier.

Roads are constantly subject to stress and vibrations which usually result in surface deformation that can be easily spotted. These mechanical vibrations can be tapped and converted to electricity by taking advantage of the piezoelectric effect (see Figure 10).

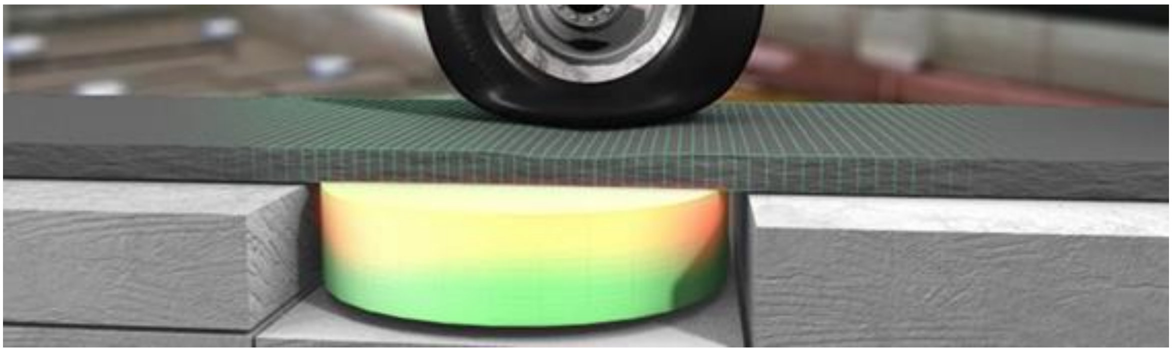


Figure 10. *Harvesting the energy from traffic induced vibrations using piezoelectric materials. Source: http://www.innowattech.co.il/*

Piezoelectric energy harvesting from traffic induced vibrations has been studied in length [7-10] and is being developed for commercial application. Innowattech Ltd., for example, is deploying and testing a network of piezoelectric generators (IPEG) embedded under the surface of a 100 meter long road. IPEGs are mounted with electronic cards supplying the storage system and can be implemented either in a concrete road or an asphalt road. They can be installed during the construction or during the course of the maintenance work providing a considerable flexibility. According to the company the system is expected to produce up to 400 kW form a 1-kilometer of a dual carriageway [11]. Such energy harvesting systems can be applied to other transportation infrastructures such as railways, pedestrian pavements, and on the walls of tunnels.

Graphene is in its general state non-piezoelectric. However in a paper published in 2012, researchers from Stanford University discover that piezoelectric effects can be engineered into non-piezoelectric graphene through the selective surface adsorption of atoms.

They showed that doping a single sheet of graphene with atoms on one side results in the generation of piezoelectricity by breaking inversion symmetry. Despite their 2D nature, piezoelectric magnitudes are found to be comparable to those in ordinary piezoelectric materials.

The realm of engineered 2D piezoelectric materials such as graphene is very young and is still in its fancy. More research still needs to be carried out and it is not far from reality that in near future specially engineered nanomaterials can be designed to show large piezoelectricity that can render the energy harvesting from roads using this method more economically friendly.

3.1.d Thermoelectric energy harvesting from roads

Thermoelectric effect refers to the conversion of thermal energy directly to electrical energy and vice versa. In particular, the conversion of temperature difference between two points directly into an electrical potential difference is referred to as the Seebeck effect named after the German scientist, Thomas Seebeck. The principal concept behind thermoelectric energy harvesting from roads is based on exploiting the temperature difference at the road surface and the layers beneath it. The roads surface is exposed to the ambient and receives considerable thermal energy by radiation from sunshine or by convection from the air. This creates a vertical temperature gradient from the road surface and downward that can be exploited by a thermoelectrical energy generator (TEGs). Such thermoelectrical energy harvesters have already been implemented at roads at a laboratory scale [12, 13]. Although TEGs are environmentally benign with no moving component which probably will translate to long life time and low maintenance, their conversion efficiency is very low. In order to improve their efficiency, new materials with larger thermoelectric figure of merit ZT has to be developed (the thermoelectric figure of merit indicates the conversion efficiency of a material).

Studies on the thermoelectric properties of graphene are promising and they show a giant Seebeck coefficient [14, 15]. This could dramatically improve the efficiency of thermoelectric energy generators in future and make their commercial use for extracting stray thermal energy from roads feasible.

3.2 Graphene assisted energy storage

As the use of electrical cars increase, and as more and more electrical energy is produced from renewable sources, the capacity to store and distribute this energy need to improve. Previous section provided a list of different approaches where stray thermal and mechanical energies at roads can be converted to electricity. In order to implement these approaches successfully, efficient, compact, and cheap solutions for storing the harvested electrical energy is needed.

3.2.a Graphene assisted Li-Ion batteries

Increasing energy storing capacity in smaller volumes is the key driving factor in the battery research. In technical terms, this is translated to specific capacity stated in Watt-hour per kilogram or analogously in milliamp-hour per gram.

The anode material plays an important role in determining the final specific capacity and much attention has been paid to find better and more efficient materials. The standard commercialized anode material for Li-ion batteries is graphite which has a theoretical specific capacity of 372 mAh/g. New materials with high specific capacity such as silicon (4200 mAh/g), tin (994 mAh/g), and tin oxide (782 mAh/g) have been intensively investigated. However, these materials suffer from other complications such as large volume expansion and structural degradations.

Two approaches are being investigated by researchers to increase the energy capacity of the anode. One tactic focuses on the development of electrode materials based on nanostructures that minimize the strain during the volume expansion. The second approach is based on integrating the electrode material with a carbonaceous matrix such as graphene. Graphene may be the ideal conductive additive for hybrid nanostructured electrodes because of its extraordinary surface area (3630 m^2/g) which maximizes Li-ion absorption. In a recent work, a composite anode made from graphene nanoribbons and tin oxide nanoparticles (see Figure 11) was synthesized which showed a specific capacity of over 1130 mAh/g [16].

Graphene could also be used as the cathode to fabricate flexible, thin film Li-ion rechargeable batteries. In this case, graphene can act as a flexible current collector replacing traditionally used Al, offering additional volumetric capacity, electrochemical stability and mechanical flexibility.

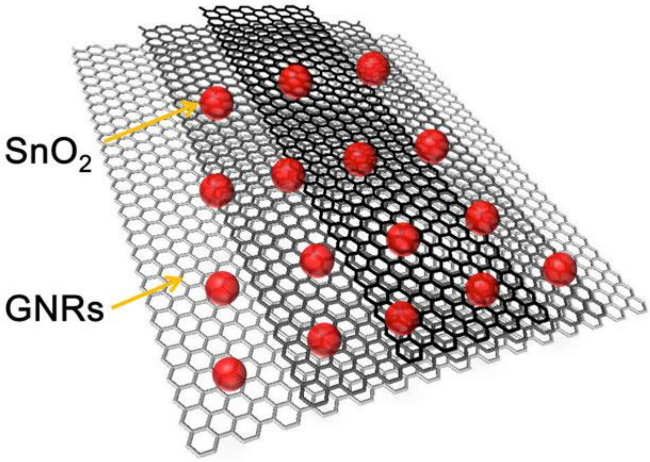


Figure 11. *A new anode material for Li-Ion batteries made of graphene nanoribbons and tin oxide nanoparticles [14].*

3.2.b Graphene based supercapacitor

A supercapacitor combines the high energy storage capacity of batteries and the high power possibilities of capacitors.

Electrical capacitance is measured in units of Farad and is an indication of the ability of a device to store electrical charge. One Farad is the capacitance of a two-terminal device with one coulomb (C) of stored electrical charge when an electrical potential difference of one volt (V) is applied to its terminals. In an ordinary electronic circuit board one can find capacitors in the range of pF to µF. The electrical charge in such capacitors is so small that it cannot be used as an energy source. In order to be of practical significance as an energy source a capacitor must have an electrical capacitance in the range of a few thousand Farads; hence a supercapacitor.

Supercapacitors store electrical energy directly in form of electronic charge, compared to batteries storing electrical energy in form of chemical bonds. The conversion of chemical energy to electrical energy is a time consuming process and therefore by circumventing this conversion, a supercapacitor can charge up as well as deliver electricity at a very high rate. The figure of merit to describe the ability of a battery to deliver energy at a high rate is called power density and is expressed usually in kW/kg.

Another important figure of merit for a battery is its energy density which is usually expressed in W·h/kg (Watt-hour per kilogram). This parameter tells us how much electrical energy is stored in a battery per unit of kilogram. Although supercapacitors deliver energy very fast (high power density), they offer low energy densities. This is due to the fact that storing energy in chemical bonds requires much smaller space compared to storing electrons in a conducting medium. Figure 12 compares supercapacitors with chemical batteries according to their power and energy densities.

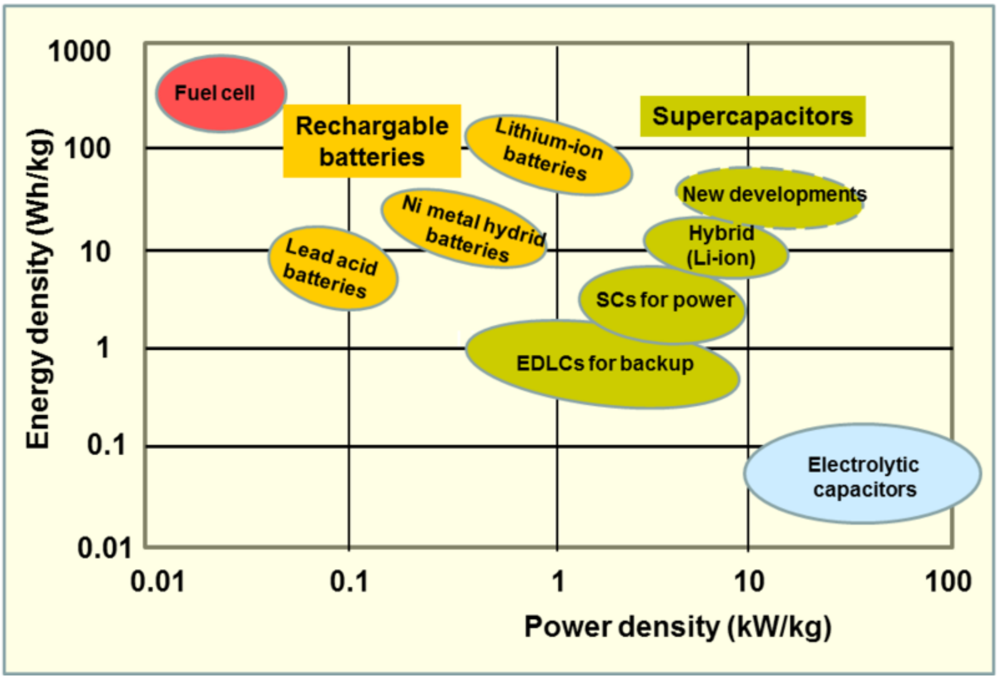


Figure 12. *Ragone chart comparison between various energy storage technologies (Batteries and Supercapacitors) in terms of power density versus energy density.*

An *electric dual layer* (EDL) is the heart of a supercapacitor. An EDL is an electronic structure that appears when a charged solid conductor is immersed in a conductive liquid or an electrolyte. The double layer is formed by two parallel layers of charge around the conductor. The surface charged (the first layer) composed of ions with opposite charge adsorbed on the surface of the electrode. The second layer is manifested by the adherence of the ions attracted to the first layer through the Coulomb force. Since the separation of the opposite charges is within sub-nanometer distance, the resulting capacitance is very high (see Figure 13).

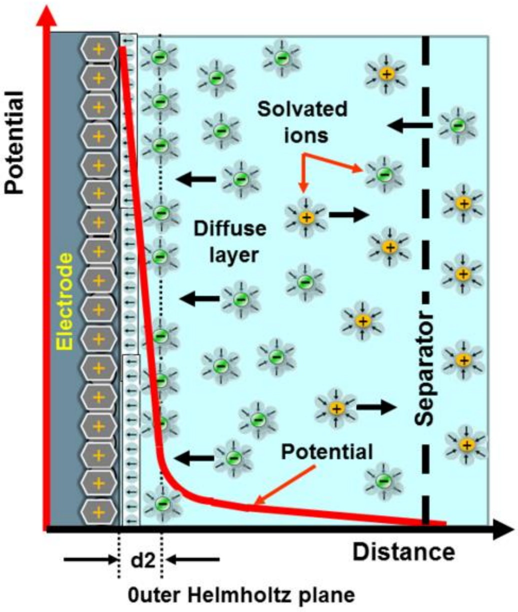
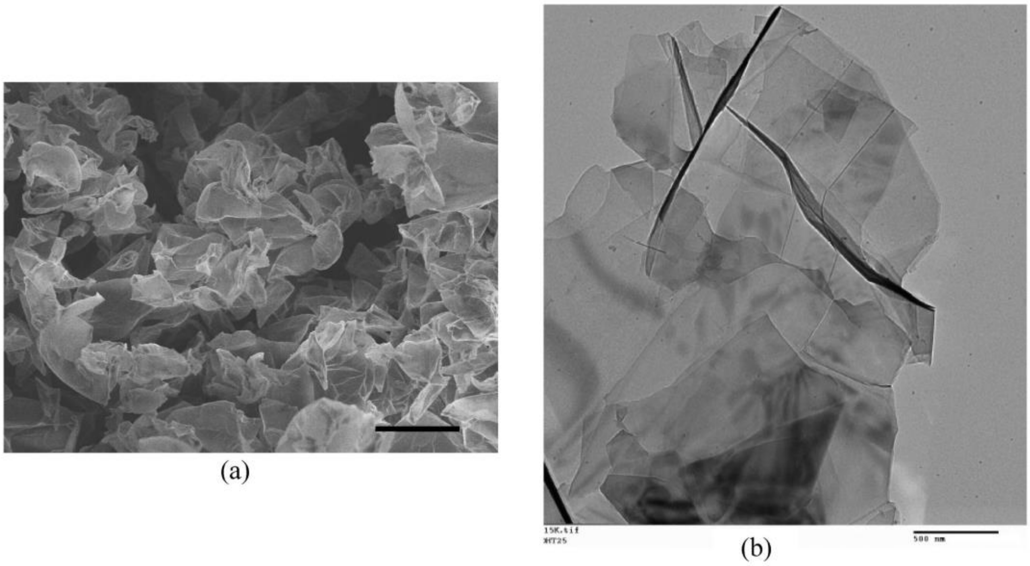


Figure 13. *An illustration of the electrical double layer formed when a charged electrode is immersed in an electrolyte.*

The performance of a supercapacitor in terms of its energy density greatly depends on the surface area of the EDL layer. In addition, the material should have high conductivity, good corrosion resistance, controlled structure, high temperature stability and must be easily processed an incorporated in a composite structure. The extreme surface to volume ratio of graphene together with its excellent properties offers a very attractive option. This has been proven by recent fabrication of graphene based supercapacitors. A team of scientists at Nanotek Instruments in USA have made a graphene-based supercapacitor that can store as much energy per unit mass as nickel metal hydride batteries [17]. They showed an energy density of 85.6 Wh/kg at room temperature and 136 Wh/kg at 80 °C. The supercapacitor has electrodes made of graphene mixed with 5wt% *Super P* (an acetylene black that acts as a conductive additive) and 10wt% PTFE binder. A representative scanning electron microscope image of the curved graphene sheets acting as the electrodes in the supercapacitor are shown in Figure 14.



(a) (b)

Figure 14. *Scanning electron microscopy image (a) and transmission electron microscopy image (b) of graphene sheets prepared for supercapacitor applications.*

Recent works have shown the possibility to develop graphene based supercapacitors with even higher performance [18-23], outperforming existing supercapacitors. A major challenge is to bridge the performance gap between Li-ion batteries and supercapacitors by developing technologies that can take advantage of both devices.

Hybrid supercapacitors offer a solution to this problem by combining a capacitive electrode for delivering high power densities with a Li-ion like electrode for delivering high energy densities. Graphene based metal oxide-shell nanostructured materials have already been proposed as a possible solution. Developing graphene based hybrid supercapacitors with superior power and energy capability is underway.

3.2.c Graphene based fuel cells and hydrogen storage

In the previous sections a few methods were discussed to harness the renewable energy sources available at or around the transport infrastructure. A radically different approach to cut the dependency on petroleum is to search for alternative fuels. One of the most promising alternatives is a fuel cell in which the chemical energy from a fuel is converted into electricity through a reaction with oxygen. Hydrogen is currently considered one of the most promising “green” fuels for cells [24], since its specific energy exceeds that of petroleum by a factor of three and most importantly the product of its combustion is water vapour.

One of the major hurdles for commercialization of the fuel cell technology is the oxygen reduction reaction (ORR) at cathode [25-27]. So far, high cost and scarce precious platinum (Pt) and its alloys have been considered to be the most reliable option [28-30]. In addition to the high cost, however, Pt and its alloys are also suffered from methanol crossover poisoning effects and poor operation stability. Therefore, it is essential to search for non-precious metal or metal-free electrocatalysts with a high catalytic activity and long-term operation stability.

The application of graphene based for fuel cell cathodes has been recently published. A group of researchers have reported that a cathode coated with iodine-edged graphene catalyst generated 33% more current compared to commercial cathodes coated with platinum [31]. In terms of durability, electrodes coated with the iodine-edged graphene nanoplatelets maintained 85.6–87.4% of their initial current after 10,000 cycles compared to 62.5% for the platinum-coated electrode; a clear demonstration of stability.

An important consideration for the application of fuel cells in cars is the development of suitable tanks for storing hydrogen. During the past decades several means for hydrogen storage were considered. Compared to existing solutions, graphene offers several potential advantages when considered as a medium for hydrogen storage. Graphene is stable and robust and the same time mechanically flexible, which allows for charging and discharging strategies at room temperature.

3.2.d Thermal energy storage

Asphalt pavements are excellent surfaces for absorbing solar energy. Anyone who has walked on an asphalt pavement in a warm day has experienced that the asphalt surface is considerably warmer than the surrounding environment. This is a valuable source of energy that can be harvested, for example, by placing a network of pipes underneath the surface. Such a solution not only yields energy that can be used for other purposes but also reduces the pavement's surface temperature which increases its lifetime.

As shown in Figure 15 once the thermal energy is harvested it has to be stored for future use. The problem arises here is the storage of thermal energy in high density. In the simplest way the thermal energy can be stored by raising the temperature of a solid or liquid with a high specific heat coefficient. This is referred to as *sensible heat storage* (SHS).

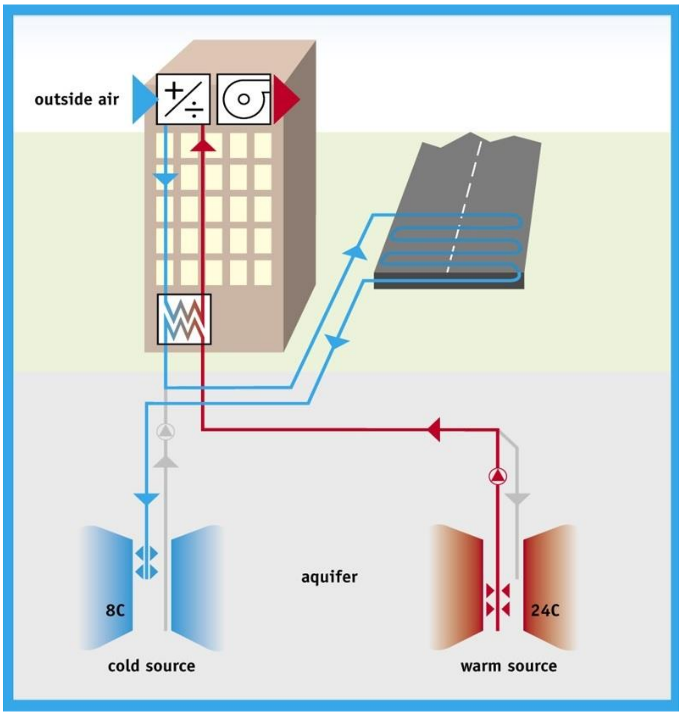


Figure 15. *Absorbing heat from the road surface and storing it for later use*

To put things in perspective, the specific heat of water is roughly 4.18 kJ/kg·K and that of concrete is 0.88 kJ/kg·K. A much more efficient method of storing energy is referred to *as latent heat storage* (LHS). This method is based on the fact that when a material changes its phase from solid to liquid or from liquid to gas it absorbs considerable amount of energy. Latent heat storage materials are referred to as *phase change materials* (PCMs). Unlike the sensible heat storage materials, PCMs absorb and release heat at a nearly constant temperature. Most importantly, they are able to store more than 10 times thermal energy per unit of volume compared to SHS materials. Fatty acids and salt hydrates are among the most commonly used PCMs today with an energy storage density of 100 kJ/kg·K to 250 kJ/kg·K. PCM materials are usually stored in cylindrical containers and placed inside large tanks as shown in Figure 16.

It is important to note that common PCMs are characterized by very low thermal conductivity with typical values in the range of 0.17 – 0.35 W/mK at room temperature [32]. For comparison, the room temperature thermal conductivity of silicon and copper are about 145 W/mK and 381 W/mK, respectively. This translates to a very slow heat exchange process which for some applications becomes a problem.

It has been shown that the use of graphene and few-layer graphene as fillers in PCM materials allows one to increase its thermal conductivity by more than two orders of magnitude while preserving its latent heat storage ability [33]. The strong enhancement is achieved via easy binding of graphene flakes to paraffinic hydrocarbons resulting in good thermal coupling. The exceptionally large thermal conductivity of graphene improves the heat conduction ability of the phase change material.

Figure 16. *PCM rods placed inside a water tank.*

4 Graphene for sensors and electronics

4.1 Sensors

The rapidly increasing use of sensors throughout society, and the demand for cheaper and better devices with less power consumption, depends critically on the emergence of new sensor materials and concepts. Graphene has potential for sensor development within a very wide range of applications, including industrial monitoring, surveillance, security, interactive electronics, communication, lab-on-chip, point-of-care, environmental monitoring, transportation and automation. Graphene technology could result in a wave of cheap and compact sensor devices, with functionalities not seen in existing sensor technology.

Supported graphene layers and various forms of graphene films offer the ultimate sensitivity to detect tiny stimuli (from low concentrations) due to their large surface-to-volume ratio, while graphene membrane sensors can also benefit from their excellent mechanical properties i.e. high rigidity, flexibility and strength. Another important parameter of sensors is specificity which refers to the detection of just one specific substance and no other. To do so, the graphene surface needs to be functionalized.

The sensors work package is one of the eleven technology areas in the Graphene Flagship. It comprises modelling of mechanical properties, opto-mechanics, gas sensors, resonators for pressure sensing, DNA sequencing, and mass and force sensing using graphene membranes. It is however, so far, a small work package in terms of budget and only includes academic partners. This work package is led by Prof. van der Zant in TU Delft, but Chalmers is also a partner (Prof. Jari Kinaret and Prof. Andreas Isacsson).

From mechanical perspective, a suspended graphene sheet is the ultimate membrane. Such a membrane can be configured differently in order to be sensitive to different mechanical inputs such as stress, strain, mass load, and others. Literature already contains numerous reports on emerging mechanical sensors based on graphene. From transport infrastructure perspective, mechanical sensors can be used for example to monitor the stress level on bridges and critical road points. New reports have shown that optimized graphene based sensors can maintain their high sensitivity in harsh unfavourable environments (extremely high humidity, strong acidic or basic) which is usually a requirement for road applications [34].

In graphene each atom is in direct contact with the surrounding environment. This is an important advantage from chemical sensing perspective which means that even small amounts of a target substance (down to an individual molecule) can induce a detectable effect. Therefore graphene sensors can be made to be extremely sensitive. Apart from this, a graphene based sensor can be accurately tuned or optimized to discriminate a specific molecule or groups of molecules from others. This is achieved by chemical functionalization or deliberate introduction of defects. Gas sensing would be one area in which such a sensor can deliver exceptional results. Exceptional results for a wide range of graphene based gas sensors have been recently published. The list includes sensors for carbon dioxide (CO_2) [35], Nitrogen dioxide (NO_2) [36, 37, 38], Nitrogen oxide (NO) [39], ammonia (NH_3) [40], Carbon monoxide (CO) [41]. Detection and measuring the level of many of these gasses are important from transport infrastructure perspective. For example monitoring the level of nitrogen oxide and carbon monoxide inside tunnels is very important and currently being done using other technologies. Graphene based sensors can in future perform the same task more accurately at a lower price.

Humidity sensors are another important type of sensors with great importance from transport infrastructure perspective. Researchers at Nokia centre have developed an ultrafast and transparent graphene oxide humidity sensor with extremely high accuracy. The sensor is so fast that it resolves the minute fluctuations in the humidity level caused by whistling different tunes in front of it [42]. They showed that the sensor could be fabricated using highly scalable processes suggesting a low cost final product.

4.2 Electronics

Experimental measurements, in agreement with theoretical predications, have shown that graphene has remarkably high electron mobility at room temperature. Electron mobility is a measure that characterizes how easily electrons can move within a conductive or semi-conductive material when subject to an electrical field. For comparison, electron mobility in silicon from which most of electronics are made today is about 1400 $cm^2 \cdot V^{-1} \cdot s^{-1}$ while the same value for graphene is in excess of 15000 $cm^2 \cdot V^{-1} \cdot s^{-1}$. This is one of the main reasons why graphene has attracted so much attention from the microelectronics industry. The great promise of graphene is testified by the increasing number of chip-makers now active in the research.

However, there is one major obstacle. A transistor which is the basic building block of electronics is in principle an electrical switch which can be set to either “on” mode or “off” mode. This means that the material based on which the transistor is made must possess both electrical conducting and electrical isolating properties. This is why the electronics are made of semiconductors and not metals. The technical term for such a property is “band-gap”. Unfortunately, graphene has a zero band-gap which makes building electronic switches based on it extremely difficult. Currently, there are many techniques that can be used to introduce a band-gap to graphene. All these techniques come at a cost which is the reduced electron mobility. However, one should remember that, it is not the extremely high electron mobility of graphene, but rather the possibility of making devices with extremely small size that is the most forceful feature of graphene based transistors. This can translate to faster, smaller, and more power efficient electronics in future. In the following a few anticipated applications of graphene based electronics which are relevant from transport infrastructure perspective are presented.

4.2.a Automotive electronics

Active safety systems have started to play a major role in reducing traffic fatalities. Tradition passive safety systems such as airbags and safety belts are designed to reduce the risk of death or major injuries in the event of an accident. In contrast, active safety systems are designed to prevent such accidents. This includes collision warning systems with automatic steering and braking intervention as well as pedestrian detection systems. In both cases, a signal is transmitted by the vehicle and its echo from the nearby objects is analysed by a receiver. Modern cars are usually equipped with a number of radar systems to cover different viewing angels as shown in Figure 17. Front car radar electronics must operate at frequencies as high as 77 GHz and therefore are fabricated using expensive materials such as silicon germanium. Graphene as material platform is an attractive choice for high frequency electronics because of its enormous electron mobility and its ultimately thin character. Graphene based transistors with operating frequencies of up to 100 GHz have already been demonstrated [43] and research results for even higher frequencies are being published. Once the growth and fabrication technology of graphene has matured, one can expect that it can offer operations at higher frequencies at a lower price compared to alternative technologies.

Another emerging technology in the car industry is the vehicular communication systems which would eventually render cars and roadside units as communication nodes within a large network. Such communications can be employed to optimize traffic flows while reducing the risk of accidents. Vehicle to vehicle (V2V) communication is one specific type of vehicular communication which is already in active developments by automobile manufacturers such as General motors. Similar to car radars, the communication system between the vehicles is also based on sending and receiving radio-frequency signals. Although the frequency range in which a vehicular network would operate is not as high as the case for radar systems, the fabrication cost of such systems may be greatly influenced by the adoption of graphene based high frequency electronics, foreseen in the late 2020.

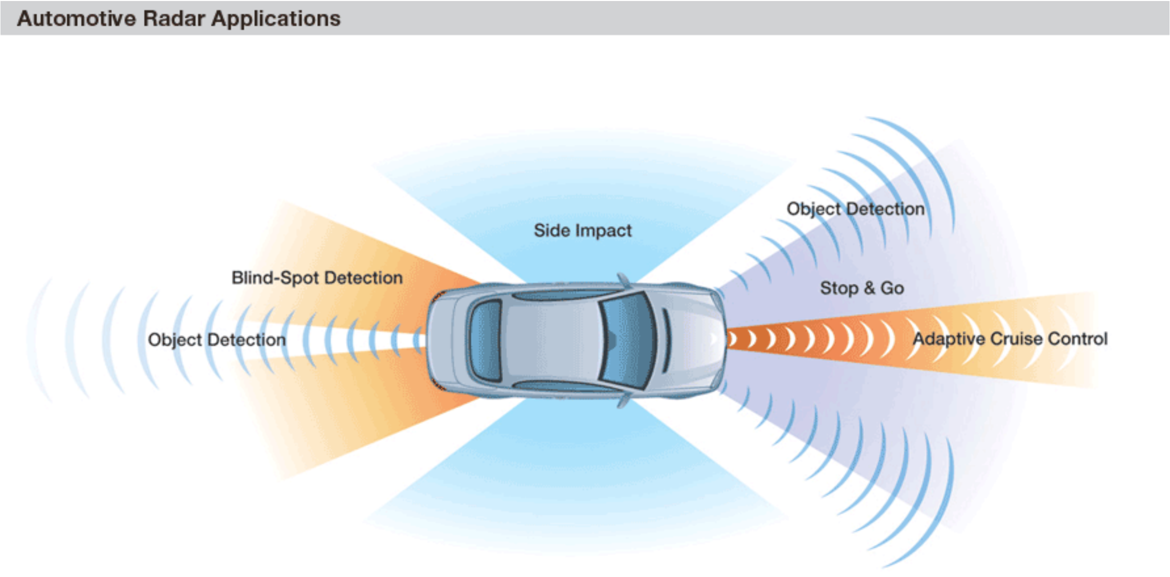


Figure 17. *A car equipped with multiple radar transceivers*

4.2.b Smart roads

For a long time, roads have been considered as static infrastructures to facilitate transportation. The technological advancements have now made it possible to construct "dynamic" roads that interact with the environment and with the vehicles passing over them in a smart way. In the previous sections we talked about different ways of harvesting stray energies the roads are exposed to; a good example of interaction between the road and its surrounding environment. The interaction can be taken one level further by building roads that also interact with the cars as well as the drivers. New concepts have already emerged in a number of research programs which manifest these interactions. In the following we mention a few of these concepts and discuss possible contribution from graphene for future realizations and implementation.

Figure 18 shows road markings using paints that glow in the dark. Such paints absorb energy from sunshine during the day and emit the absorbed energy in the form of visible glow at night. This type of road marking can be used as a complementary solution for conventional road illumination at nights resulting in considerable cost reduction in terms of energy consumption and maintenance. Glow-in-the-dark paints contain phosphorescence pigments which are "charged" by exposure to light and re-emit the absorbed energy in a long time interval. This process is referred to as photoluminescence. Research has shown that the finite

Figure 18. *Glowing road markings for smart roads. (Image from www.smarthighway.net)*

band-gap in graphene oxide generated due to the oxygen bonds exhibit highly efficient photoluminescence [44]. However, the emission event in graphene oxide is extremely fast and it is in the order of nanoseconds (similar to many photo luminescent materials). Therefore material engineering must be done in order to tune the luminescent properties of graphene oxides or other graphene related materials before they can be used for applications such as road markings.

Another feature of smart roads of future would be the electric priority lane. The number of hybrid cars and plug-in electric vehicles on the roads is constantly increasing. For instance, the number of plug-in cars sold in 2014 shows more than 50% increase compared to the sales in 2013. The increase in the number of electric cars will set new demands on innovative methods for charging them. One such method takes advantage of the area already available on highways and roads to charge the cars while on the move. This concept is based on inductive charging, which transfers the electrical power from one point to another without the need of any cable. Inductive power transfer has been in use for a long time and goes back to the works of Tesla almost a hundred years ago. However, efficient wireless transfer of large electrical powers has only very recently started to be possible. Electric priority lanes, as shown in Figure 19, would be built by installing wireless power transmitter under long stretches of dedicated lanes. When an electric car approaches such sections in a road it will move over the dedicated lane and slows down. Combining the electric lanes with previously discussed graphene based energy harvesting systems and in-road energy storage can create a powerful solution for future roads.

Dynamic road marking is another technology that we would witness in future roads. This technology would enable road markings to be flexible and adjusted depending on traffic load and other critical parameters. For example, a continuous line can be converted to a dotted line for increasing the flow or changing the number of lanes available on each side based on the traffic. Configurable traffic signs can also be shown on the road surface directly in front of the driver to inform her about road condition or other important information (see Figure 20).

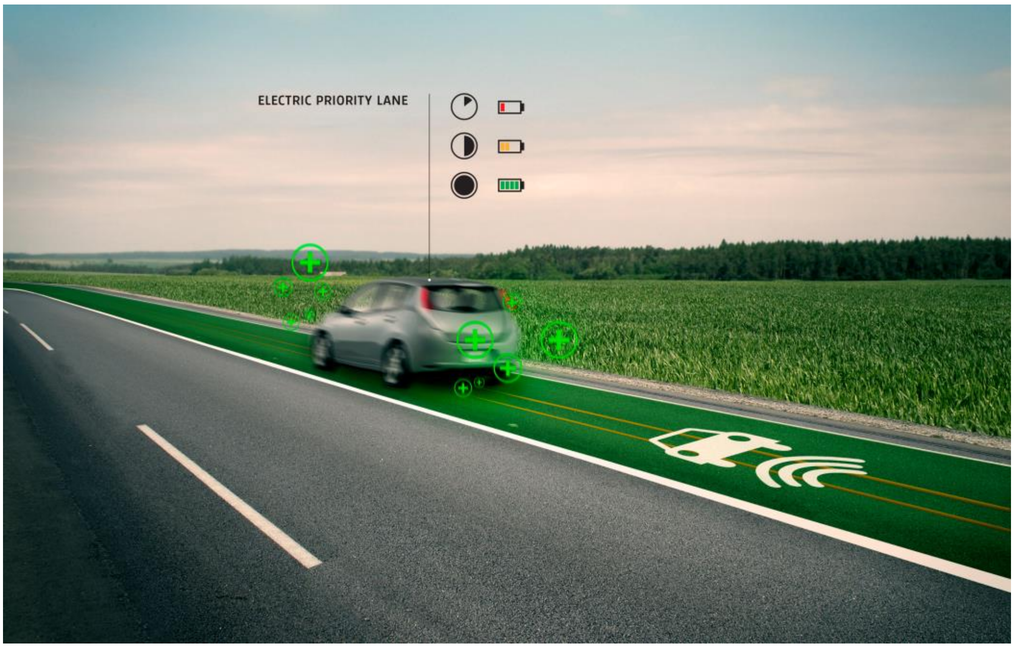


Figure 19. *Electric priority lanes for charging electrical vehicles while on the move. (Image from www.smarthighway.net)*

Dynamic marking can be achieved by embedding arrays of light sources under a transparent road surface. We have already discussed graphene-glass matrices that can be used as a transparent protective surface but graphene can also be used to deliver power efficient and strong light sources. In a recent work, it was shown that efficient and bright light emitting diodes (LED) can be fabricated using single layer graphene electrodes [45]. An important advantage of this LED is its flexibility and bendability, which comes from using graphene. This is especially important if the final product has to be used under large mechanical stress. Although promising, it must be noted that the light emitting application of graphene is fairly new and time is needed before one can judge its relevance and superiority.

Figure 20. *Dynamic road marking on smart roads.*

5 Materials

Graphene has outstanding properties as a single layer, but could also be included in heterostructures (sandwich materials) or in composites. Single layer graphene has been produced by a roll-to-roll production by Sony at the impressive length of 100m (width 27 mm). Samsung has also produced a 30 inch graphene sheet in a roll-to-roll production (see Figure 21). Although very attractive as an electronic substrate, a single layer of graphene would be irrelevant as a construction material.

To be used as construction material, a composite or a heterostructure needs to be used, rather than a self-standing one atom thick layer. A number of studies where graphene flakes or graphene oxide nanoparticles have been mixed with other materials into composites with unique properties have been reviewed. Several studies on different polymers have been successful, showing large increasing tensile strength with just a few % added graphene flakes or powder. However, in order to receive other properties like electric and thermal conductivity, processes development is needed. Although the preliminary results are very exciting, this area is relatively young and still requires more research and development.

The scientific and technological challenge addressed in the Nanocomposites group of the Graphene Flagship originates from a simple but fundamental concept: the impressive properties quoted for graphene refer to individual, defect-free sheets, usually obtained by mechanical exfoliation, and suspended to avoid interaction with any perturbing substrate. In many applications, however, graphene layers with properties inferior to the ideal ones will need to be used. In order to have an impact upon society, the ideal properties of graphene sheets will have to be transferred from the atomic scale to the macroscopic level (continuous layers or bulk materials). The objectives for the first years are to transfer the ideal properties of single graphene sheets from the atomic scale to the meso-macroscopic level (continuous layers or bulk materials) and to understand the failure mechanisms of graphene composites by studying their behaviour at the macro/micro/nanoscale, while the material undergoes electrical and/or mechanical stress.

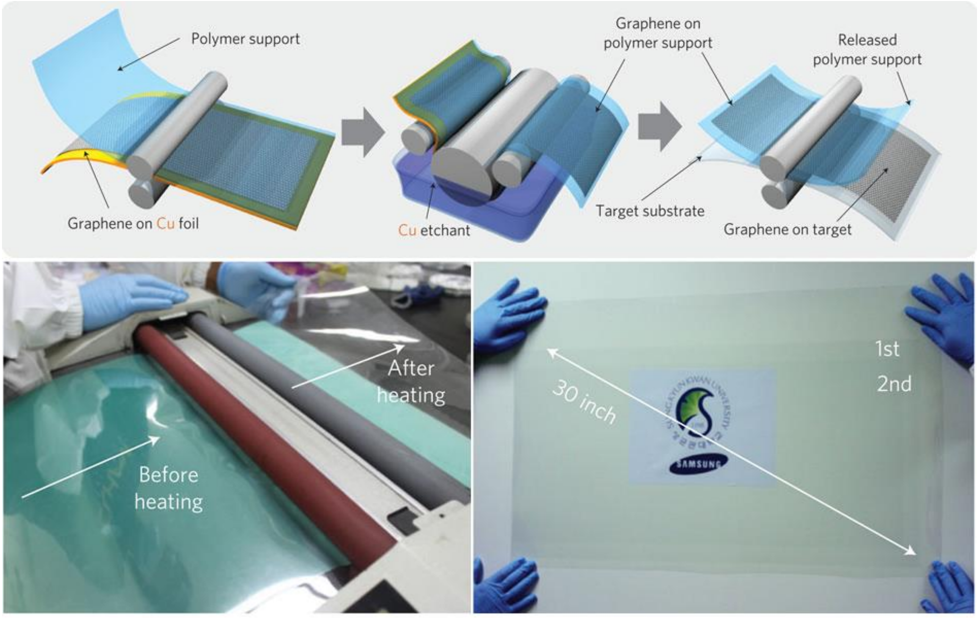


Figure 21. *Description of Roll-to-roll production of 30 inch graphene by Samsung, Source: BAE, S. et al.; Nature Nanotech. 5, 574-578 (2010)*

5.1 Polymer composites

Polymer composites have become an important part of many different industries. Transport infrastructure has also benefited from incorporating polymers. For example, fibre reinforced polymers (FRPs) have been used in the fabrication of steel-free concrete decks. Recently, bridge decks made entirely out of FRP composites have been demonstrated. The main advantages of fibre reinforced composites are their high young's modulus compared to their weight, high strength-to-weight ratio, and high resistance to corrosion.

Graphene is a new promising candidate that can be used to reinforce polymers. There has been considerable effort in incorporating graphene as nanofiller into polymer matrices. So far, the research results have shown large increases in Young's modulus [46], tensile stress [47], Electrical conductivity [48], and thermal conductivity [49]. The advantage of graphene over traditional fillers and other materials stems from its combination of mechanical and electronic transport properties, as well as chemical and thermal properties, high surface area, and low thermal expansion coefficient. The large surface area of graphene implies that, in a composite, the graphene-matrix interface is also very large, thus becoming a powerful engineering parameter to tailor composite properties.

The novel graphene based polymers can be used in a number of road applications to bring new functionalities or improve the performance of current solutions. A clear example, as mentioned above, is bridge decks, but could also be of interest in tunnels PCMs are another group of materials that would benefit by incorporating graphene.

Phase change materials have also great potential to be used directly underneath the surface of the roads for controlling the temperature fluctuations. As mentioned above, at the phase transition temperature, PCMs absorb or release considerable amount of energy with negligible change in their temperature. This quality can be used to keep the roads surface free of ice during winter and relatively cool during the summer time. However, in order to make their function effective, they have to be placed close to the surface. This is due to the fact that asphalt pavements are not good thermal conductors. Consequently, the PCM placed closed to the surface will be subjected to substantial stress and wear imposed by the passing by vehicles. A plausible solution would be to increase the thermal conductivity of the asphalt pavement by adding thermally conducting materials into it. Such a solution would allow placing the PCMs at a deeper level and thus protecting them better. Industrial grade graphene and graphite can be mixed with asphalt to considerably increase its thermal conductivity without an impact on other important properties.

Airbus, Saab, and Thales Alenia Space are interested in graphene based nanocomposites for lightweight materials with added functionalities like electric and thermal conductivity, mechanical strength and radiation resistance. They will put an effort in developing this area, which will be useful also for other application areas. It is however important to remember that airplane development cycles are fairly long.

5.2 Metal-graphene composites

The elastic modulus (Young's modulus) of graphene is one of the highest amongst materials. In one of the most reliable experiments the Young's modulus of graphene was estimated by measuring the strain applied by a pressure difference across a graphene membrane using Raman spectroscopy. By comparing the measurement data with numerical simulation the Young's modulus of single- and bilayer graphene was obtained to be 2.4 ± 0.4

and 2.0 ± 0.5 TPa, respectively [50]. These values exceed any previously reported elastic moduli.

Despite the very promising values of graphene's Young's modulus, efforts in using graphene to make metal composites had not resulted in increased strength in the doped material. However, this was changed in a breakthrough research published in Nature by a group of scientists from Korean Advanced Institute of Science and Technology (KAIST) in 2013 [51]. They used Chemical Vapour Deposition (CVD) method to grow a single layer of graphene on copper films. Next, they transferred the monolayer to a metal-deposited substrate by a special technique. By repeating the same step, they managed to produce nanolayered graphene-metal composite both on copper and nickel. This process is shown in details in Figure 22. Through especially devised testing method which is also shown in Figure 22 the yield strength of the composite material was measured to be as high as 4000 MPa - the highest ever reported.

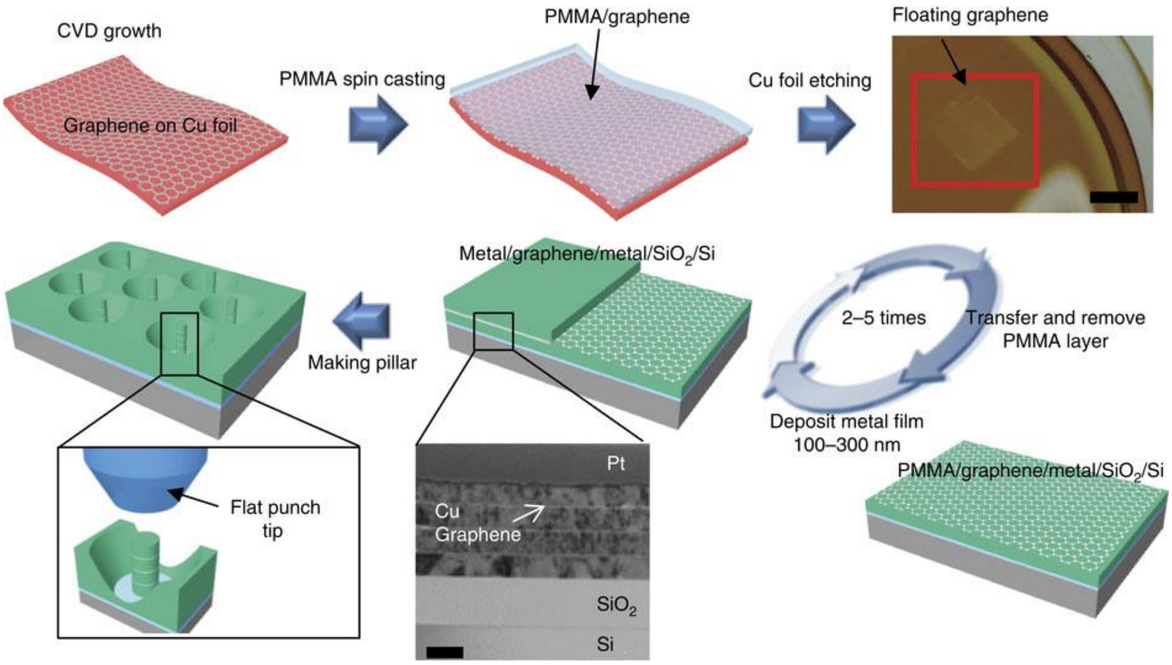


Figure 22. *Schematic of metal–graphene multilayer system synthesis as reported by the researchers from KAIST University.*

This result is astonishing as adding only 0.00004% graphene (total weight percentage) increased the strength of the metal by two orders of magnitude. This is a promising result for the future of material engineering; once, the roll-to-roll fabrication of graphene is achieved, large scale processes can be developed to sinter graphene into metallic sheets for mass production. Such composites will pave the road for the fabrication of super materials with extreme mechanical strength at a very low weight.

5.3 Cement-graphene composite

The most important and the most common modern building material is cement composite. Despite the tremendous efforts in developing stronger and higher performance cement composites, their inherent brittleness has remained an important issue. Cement composites can endure very high compressive stress, but they are comparatively weak when it comes to tensile and flexural stress which is an indication of their brittleness. In fact, developing methods to improve the strength of the cement composites has been one of the primary research areas of building technology. So far, materials such as steel bars, carbon fibres, polymer fibres, and mineral fibres have been used as reinforcing components. Although these materials have greatly improved the overall strength of concrete, the brittleness problem which is the prime cause of the cracks has persisted. It has been speculated that the main reason is the overdependence of the toughening methods on reinforcing materials and neglecting the regulation of the microstructure. Graphene as a nanomaterial with extreme surface to volume ratio and ultrahigh mechanical strength can provide the possibility to improve the toughness of hardened cement through manipulation of the microstructure.

It has already been reported that graphene oxide easily forms composite with polymer and ceramic materials and enhance their toughness properties [52, 53]. In a recent work, researchers have mixed graphene oxide nanosheets with cement [54] and showed that the nanosheets can regulate the cement microstructure to form flower-like crystals (see Figure 23). The cement composite created in this way exhibits 78 % increase in tensile strength, 60 % increase in flexural strength, and 39 % increase in compressive strength.

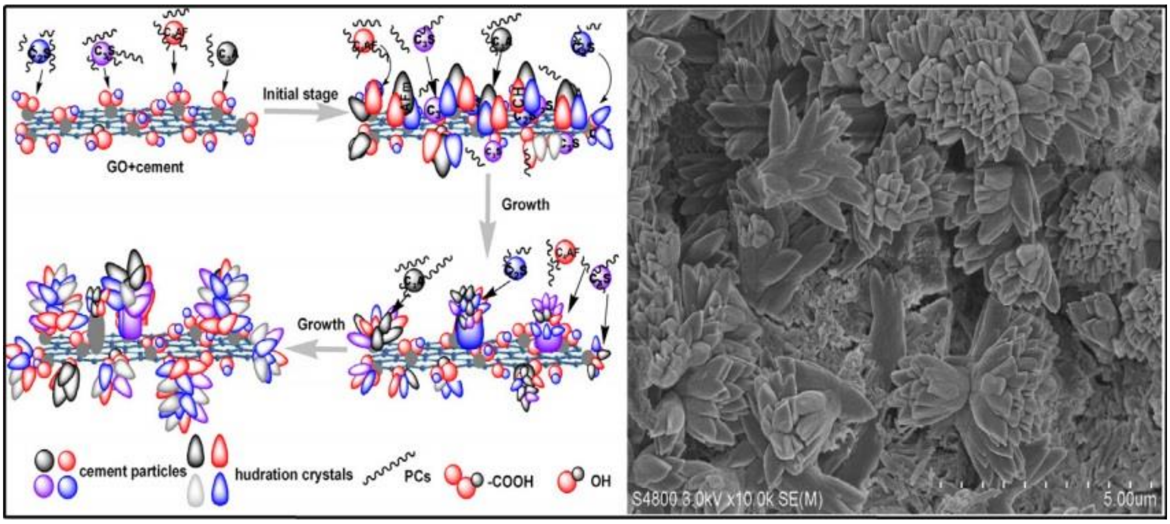


Figure 23. *Flower-like crystals of cement- graphene oxide composite.*

In another work conducted by researchers at Monash University, graphene oxide was mixed with ordinary Portland cement and significantly improved mechanical and physical properties were reported [55]. They showed that only 0.05% of graphene oxide is needed to improve flexural strength of the composite by 41% to 59% and compressive strength by 15% to 33%. At the same time, the total porosity was decreased by 32.6% to 28.2%, providing higher compressive strength and a more durable product.

In another research project, it was shown that thermal diffusivity and electrical conductivity of cement composite increased with increasing the graphene content [56]. The increase in thermal diffusivity of the hydrated graphene cement composite was attributed to the heat sink capacity of graphene. This effect is of significant importance especially during the exothermic reactions taking place during the initial stages of hydration of Portland cement. Such enhancement in the thermal properties would potentially reduce the early age thermal cracking and lead to improved durability of the concrete structures. The enhanced electrical conductivity of the composite indicates the potential of using graphene in applications where electrostatic dissipation (ESD) of charge is desirable.

Research is currently carried out by Prof. Luping Tang at Chalmers University of Technology on cement-graphene composites. However, at the time of compiling this report no published data was available for comparison.

5.4 Glass matrix composite reinforced with graphene

Despite considerable amount of work reported on polymer-graphene composites in the literature, the use of graphene for reinforcing ceramics and glass matrices is relatively limited. The majority of work on ceramic and glass composites has been focused on another carbon nanomaterial; carbon nanotubes. Recently, additional advantages of graphene over carbon nanotubes such as higher surface area and lower tendency to agglomerate have attracted new research work. The fact that graphene flakes are less prone to tangle makes them better candidates for dispersing in a matrix and thus leads to easier processing and better results. Graphene is also relatively inexpensive to produce compared to nanotubes and it is potentially less toxic.

In a recent study graphene nanoplatelets (GNP) and graphene oxide nanoplatelets (GONP) were used to reinforce silica [57]. This was done by dispersing GNP and GONP in the silica matrix and then consolidating the resulting composites using spark plasma sintering. Mechanical tests showed that the fracture toughness of the silica composite with the addition of 2.5 vol % GONP improved for about 35%. It was also reported that the new composite has a better machinability compared to pure silica. Compared to silica-nanotube composites the graphene oxide nanoplatelet enhanced matrix showed improved mechanical properties and better processability. These improvements are mainly attributed to the extraordinary large surface area of the graphene flakes and the fact that they are more evenly dispersed within the matrix compared to nanotubes which tend to agglomerate.

The new research suggests that graphene flakes can act as an effective reinforcing agent to produce tougher glass matrix composites. Such a material can be very attractive for applications where mechanical strength and clarity are both equally important. For example, in case of road related application, PV solar cells can be installed underneath a layer of durable, see-through, and mechanically strong graphene reinforced glass on roads surfaces.

It is important to remember that one layer of graphene is transparent (absorption of 2 % over whole visible spectrum). However, for each layer graphene, 2 % of the incoming light is absorbed, diminishing the transparency with each layer. Graphene reinforced materials will thus not be transparent on a macro-level.

6 Coatings/Barrier material

No gas or liquid can penetrate a perfect graphene layer. This ability serves as a good ground to develop coatings and barrier materials for corrosion barrier, barrier for gases and liquids, as well as chemical resistance and super hydrophobicity.

Several ongoing research projects evaluate the possibility to produce graphene on different kind of substrates. This area will grow in the coming years, and as knowledge increases, the potential will be better understood.

Even though no gas or liquid penetrate graphene, it is possible to use graphene in filter applications by introducing small holes in the membrane. Simulations with desalination of salt water through a porous graphene membrane have been made and subsequent patent has been applied by Lockheed Martin.

6.1 Graphene as a corrosion barrier

The ability to protect refined metals from reactive environments is vital. Many transport infrastructures employ large quantities of metals. These metals are exposed to harsh environmental conditions which is an important factor in accelerating corrosion process. At the same time there is a significant pressure on the safety, reliability, and life time of such structures. Moreover, many current coating solutions contain hexavalent chromium, a probable carcinogen. During the last few years, research has been conducted to evaluate the potential of graphene as an efficient coating material. The lightweight, extreme hydrophobicity and excellent electrical conductivity are the main reasons for nominating graphene as a corrosion barrier. For example, the high electrical conductivity of graphene would effectively shift the electron exchange process which is the underlying mechanism for corrosion to the protective graphene layer instead of the metal.

Oxidation resistance of graphene coated copper and copper/nickel alloy was demonstrated by Chen and his co-workers [58]. They directly grew graphene on top of Cu and Cu/Ni alloy using well-established processes. Their results confirmed that graphene films could efficiently protect the surface of the metals from oxidation in air even after heating at 200 ºC for a prolonged time period. Successful protection against oxidation was even shown in a harsh condition of hydrogen peroxide. This is a remarkable result taking into account the fact the protective graphene layer is only one atomic layer thin and nevertheless offers an excellent protection.

Figure 24 is a demonstration of successful oxidation protection of copper by graphene. In this image two penny halves are displayed, both of which were exposed to hydrogen peroxide solution for 2 minutes. The upper coin is coated with graphene before exposure while the lower half is uncoated. The stark darkening of the lower coin is the consequence of oxidation while the upper coin has maintained its original appearance.

In another study the efficiency of multi-layer graphene coating on metals against corrosion was quantified [59]. It was shown that copper films coated with a single layer graphene grown via chemical vapour deposition are corroded 7 times slower in an aerated Na2SO4 solution as compared to the corrosion rate of bare copper. Their analysis also revealed that nickel with a multilayer graphene film grown on it corrodes 20 times slower while nickel surfaces coated with four layers of mechanically transferred graphene corroded 4 times slower than bare nickel. At the same time it was found that preventing cracks in the protective graphene layer is a major challenge and must be completely eliminated if graphene to be adopted as a protective barrier in future.

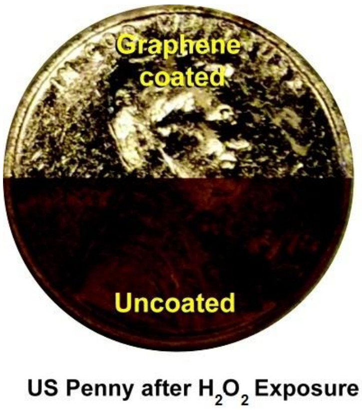


Figure 24. *Photograph showing graphene coated (upper) and uncoated (lower) penny after* H_2O_2 *treatment (30%, 2 min).*

Successful protection of iron by graphene against oxidation has also been demonstrated. In a study, iron foils were coated by graphene oxide sheets and then were heated up to 200 ºC [60]. After 2 hours, foils with graphene oxide protection were intact while unprotected foils were severely corroded.

6.2 Fire resistant Polyurethane grouting

Grouting is an engineering tool that has been used worldwide in tunnel construction. Grouting is used commonly to seal cracks in the rocks where the water can enter into the tunnels. Tunnels have been built under a broad range of geological, hydrogeological, and structural conditions. This inevitably has translated to the use of different grouting technologies and materials. One of the most accessible and most common grouting materials has been cement which usually results in acceptable results under a wide spectrum of conditions. However, there are conditions where cement would not work and alternative materials must be used.

Polyurethane grouting has been used successfully instead of cement under specific conditions. This grouting technique involves the injection of expanding polyurethane to cut off water flow through concrete joints or rock cracks or to fill the voids. The grout is injected under low pressure through a predrilled hole. The grout then expands to fill the crack or void. One should bear in mind that polyurethane is a thermosetting polymer resin which has numerous advantages over cement but it burns easily which is an important issue. Considerable research has been carried out to obtain fire retardant resins. One of the most efficient ways to reduce the heat release rate of resin is to use carbon materials. Graphene sheets hold potential as new nano-filler and may be preferred over other conventional carbon based nano-fillers such as CNT and carbon nano fibres owing to their higher surface area, aspect ratio, tensile strength, and thermal conductivity [61]. For example, graphene oxide has been blended with epoxy resin to produce an epoxy nanocomposite with excellent thermal conductivity [62, 63].

The results are promising but a technological challenge is to develop light-weight graphene based epoxy composites at a large scale and a competitive price.

7 Roadmap for graphene applications

As shown in the previous chapters, a plethora of outstanding properties arise from this remarkable material. Many are unique and far superior to those of any other material. Such combination of properties cannot be found in any other material. So, it is not a question of if, but a question of when and how many applications it will be used for, and how pervasive will it become.

The advancing R&D activity has already shown a phenomenal development aimed at making graphene suitable for industrial applications. The production of graphene is one striking example of rapid development towards commercialisation, with progress from random generation of micro scale flakes in the laboratory to large-scale, roll-to-roll processing of graphene sheets of sizes approaching the metre-scale. It is reasonable to expect a rapid clearing of further technological hurdles towards the development of a graphene-based industry in the coming years.

The killer application for graphene is still lacking. So far, there are only discussions concerning applications where graphene replaces other materials in existing product types. It is anticipated that totally new concepts will arise – which will alter this forecast completely.

For the next 5 years, the suggested markets with the largest potential for graphene are [64]:

- Graphene based **Super capacitors**, anticipated to start off in 2018 and quickly accelerate to 10% market share in 2024 [64] . The initial use will be within handheld devices, mobile phones – where size restriction places a higher premium on performance.
- Graphene can be used in **sensors** as (functionalised) sensor element or as transparent electrodes. New sensor concept will be introduced on the market 2015/16, with an anticipated 12 million US dollar sale.
- **RFID** is an increasing market, where graphene ink can be used for printed antennas. The limitation with graphene is the high sheet resistance, which will limit the reading distance. IDTech Ex anticipate the RFID graphene market to 1,5 billion tags (4% of the market), worth 6 million US dollars.
- **Smart packaging,** including printing interconnects and functional inks, is another market opportunity for graphene inks. However, the business opportunity for the next five years will be limited.
- **Replacements of ITO** (Indium Tin Oxide), used as transparent electrodes in solar cells and similar applications has been suggested as a strong market candidate for graphene. However, graphene is a late entrant to this market and does not offer a strong performance benefit. The market share seems limited during the coming years.
- High strength **composite materials** will be a promising application on the long term. Graphene based composites will find use in applications demanding high performance and added value of electric or thermal transport, protection of radiation, integrated sensors, tailored surface properties, multi functionality, and so on. The market share for graphene based composites is anticipated to 0.4 % in 2024, which translates into over 50 tonnes of graphene. However, many applications, for instance in aerospace sector have long and vast development cycles, implying a long time to market. Thus, there is a huge possibility, but it will take at least ten years until the market really hit off in terms of large production volumes.
- Other applications might be lubricants (replacing carbon black).

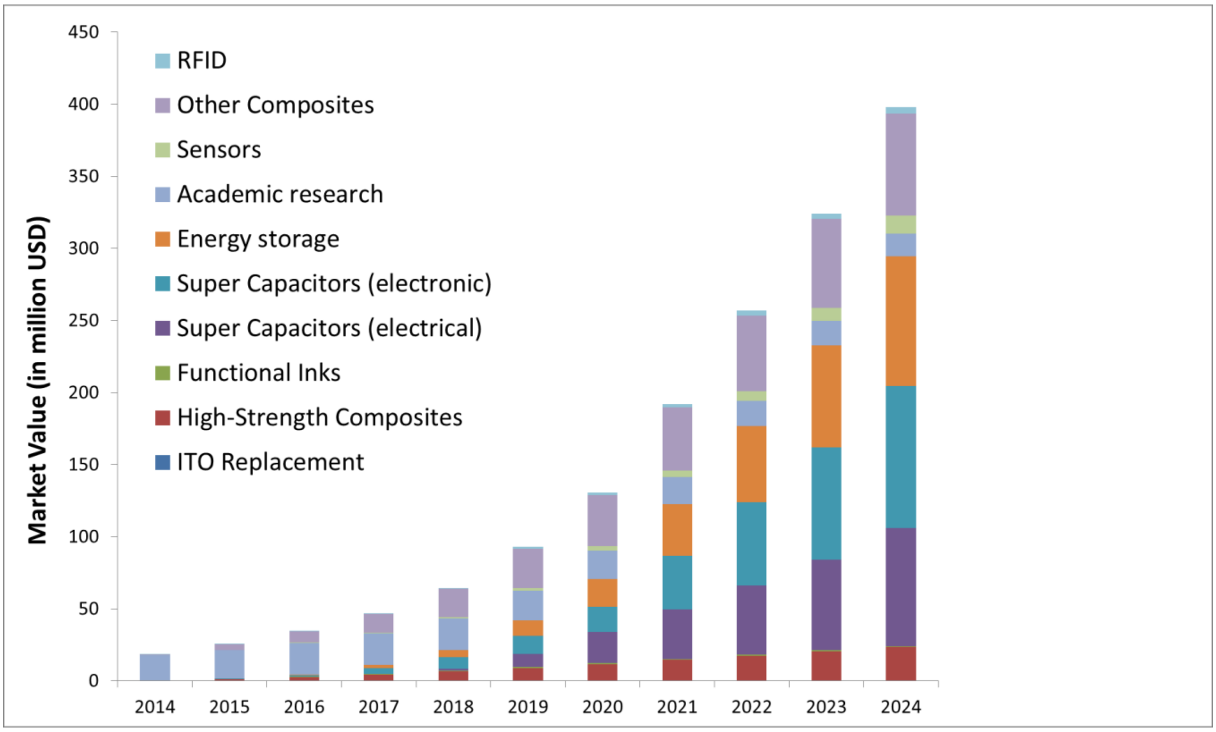


Figure 25. *Market forecast for graphene in different applications between 2012-2018(Source [64] .*

7.1 Road map for the prioritised areas

7.1.a Materials

So far, composites of graphene in polymers are the only material combination mentioned in market analysis and dominating the published academic literature. The low cost and scalable manufacturing techniques that are sufficient for graphene reinforced composites, makes an interesting business opportunity.

The tuneable properties including electrical conductivity, mechanical and tensile strength, flexibility, heat resistance, impermeability to moisture and other gases, etc. are the major driving forces today. However, production process development is still needed to produce composites with multiple sought properties. Today, increased tensile strength has been shown, but increasing the heat and electrical transport properties has only been shown in small scale.

Graphene is likely to deliver the most value on applications requiring high performance such as aerospace, wind turbines, sport cars, etc., at least in the coming years.

The main targets in the Graphene Flagship, within the nanocomposite area are:

- **3 years**: Functional composites for packaging; Hybrid composites.
- **3-7 years**: Large scale production of nanoplatelets
- **7-10 years**: Fully-graphene based functional composites for mechanical, photonic and energy applications.

It is believed that in 2018 there will be graphene composite available for mechanical engineering, flexible electronics, and energy applications.

Due to production costs, it will never be suitable for bulk construction materials, but could find ways of solving challenges in environments where the combination of the listed properties above are sought. For Statens Vegvesen, this could imply new materials to be used in off shore applications, in tunnels or in other applications with specific demands.

7.1.b Sensors for measuring surrounding environment

It is foreseen that several different sensor components will be available on market within five years. Gas sensors, microphones, amplifiers and mass sensors being the first, followed by chemical, pressure, and magnetic field sensors.

Nokia have developed an ultrafast humidity sensor. The prototype shows several outstanding properties, but still lacks long term stability. If this problem can be mastered, commercialisation will start. The main targets for Graphene Flagship, within the sensor area are:

- **3 years:** Single layer membranes. Gas sensors.
- **3-7 years:** Mass, chemical and pressure sensors.
- **7-10 years:** Magnetic field sensors. On-chip scalable GRM sensors.

On-chip sensor systems and selective mass sensors are foreseen to be ready for commercialisation in 2020.

For Statens Vegvesen, this could imply new sensors to be used in tunnels to monitor the environmental conditions or in other applications with specific demands.

7.1.c Energy – harvesting, batteries/charging electronic vehicles.

Supercapacitors combine the high capacitance possibility from capacitors and the high energy density of batteries (with maximum charge and discharge possibilities). Graphene enhances the performance of supercapacitors. It will increase the cost per cell, but will eventually drive down the total cost in euro/kWh.

Supercapacitors could be used both in small electronic devices, but also for electrical vehicles and buffering wind turbines or solar or other harvested power.

Components might be available in a few years, and systems of photovoltaic cells (PV) are believed to be available within 5 years.

Within five years it is predicted that photovoltaic cells using graphene and hybrid components, fuel cells with low Pt graphene-based electrodes, high power and cyclable batteries and supercapacitors, as well as energy saving hydrogen uptake/release have been demonstrated (ref Graphene Flagship road map).

Within ten years light and flexible PV cells, highly sustainable biomimic PV cells, light electrical storage systems (batteries with 250Wh/kg, supercaps with 200 kW/kg), as well as light hydrogen storage systems are produced (ref Graphene Flagship road map).

The area of supercapacitors is not the core business for Statens Vegvesen, but should be interesting for charging of vehicles, and for power supplies in relation to wind and solar power. This area is also one of the most promising early markets for graphene. It could be one interesting area to cover together with other partners in a group, where Statens Vegvesen could act as end user, providing demands and user specifications.

7.1.d Heat transfer in roads

This area is not coupled to any suggested promising area in graphene market studies so far. It is however likely that graphene can make a difference.

There is a need to define functionality specifications (for transport infrastructure) and develop processes for mixing graphene flakes with bitumen/asphalt in a way that the flakes are in contact with each other to provide a circuit for the heat transfer.

For instance Prof Johan Liu at Chalmers is studying heat transfer of graphene and other carbon based materials.

No activity reported so far

7.1.e Coating/Barrier material to protect other materials

There is a lot of ongoing research trying to produce graphene on different substrates. This knowledge can be used for designing coatings and barriers on different materials. As graphene is impermeable to gases and vapours, it can effectively work as barrier for oxygen, water vapour and so on.

This is an area where it will be easy to start R&D projects together with Chalmers, as there are many groups working with Chemical Vapour Deposition of graphene on different substrates, as well as developing transfer processes between different carrier/substrate materials. These groups are generally very interested in participating in projects were specific materials of choice from Statens Vegvesen could be investigated.

No coherent market. Coatings can be purchased from spin-off companies coupled to UK universities for certain substrates. Standardisation and up-scaling are needed.

7.1.f Communication – vehicle/vehicle, vehicle/road, Smart communication

Communication is not the core business of Statens Vegvesen, but an interesting future area where collaboration between Statens Vegvesen and others will be necessary.

As mentioned before, it will take at least 10 years until graphene based high frequency communication systems will be available on the market. We would therefore not recommend this area to be the first graphene area for Statens Vegvesen.

However, The Swedish Company Ericsson is joining the Graphene Flagship during summer 2014, and if Statens Vegvesen still would like to pursue this market, collaboration with Ericsson could be a way forward (together with the Chalmers group of Prof. Herbert Zirath).

Low TRL and uncertain market forecasts

8 Foresight for Statens Vegvesen

Graphene certainly has many astonishing advantages. At the same time, it is important to remember that the technology readiness level (TRL; see Appendix A for the definition) is fairly low for most applications areas. As a lot of effort is put into developing graphene based electronics and composites, the TRLs are believed to increase rapidly over the coming years. However, as described in the earlier chapters, so far, the efforts within the transport infrastructures are very limited.

Several companies are trying to take their share of the coming market opportunities coupled to graphene inventions, but no solid supply chain or business structure is in place. Statens Vegvesen can use this uncertainty to steer certain companies and researchers towards transport applications through collaborative research and innovation projects, bilateral agreements, and taking part in important clusters and organisations such as the Graphene Flagship or similar national programs.

We suggest five different areas where Statens Vegvesen could consider working with graphene R&D. These suggestions are within the prioritised areas and are also based on the readiness level of the graphene technology for that application area, overall market interest, the intensity of the research activities as well as the competence level within Chalmers or our partners.

Before decisions are made, we of course suggest that a thorough evaluation of each specified area is made to ensure that graphene really has the possibility to make an impact on the functionality, is capable of meeting the needs and requirements, and is economically viable.

For every suggested area, we suggest a continuous evaluation of business relevance and to monitor technology and business status in the world, in parallel with research and development activities:

1. **Graphene coating** f**or oxidation barrier and/or corrosion protection**.

   As described earlier no gas or liquid penetrates a perfect graphene membrane, making graphene an excellent choice for protecting surfaces.

   We recommend that Staten Vegvesen chooses a few primary substrate materials on which Chalmers together with CIT would conduct research and development. The R&D work may include process development for new coating techniques, upscaling studies for available processes, and studies on the influence of grain boundaries on the protection performance. CIT/Chalmers can also be involved in technology and intelligence scouting as well as performing more targeted feasibility studies.

2. **Graphene reinforced composites as construction material**.

   Graphene can be used to strengthen polymer composites and to add new properties such as electrical and thermal conductivities.

   We suggest that a clear specification for such composites is developed first based on which R&D projects can be formulated.

   This area is strong within the Graphene Flagship with several strong commercial actors such as Airbus and BASF putting R&D efforts.

At Chalmers, Prof Mikael Rigdahl and his group could be involved in future research projects. Research and process development are needed to obtain acceptable mixing of the graphene flakes in the polymer matrix.

3. Graphene reinforced asphalt and concrete with emphasis on enhanced heat transport capability.

Statens Vegvesen has already initiated a research project at Chalmers with the aim of studying graphene enhanced cementitious materials together with Prof. Luping Tang. This study could be complemented with business evaluation and market analysis. Moreover, the use of graphene must be motivated more clearly in terms of exact targets and enhancements it is aiming at.

The area, in general, needs process development for mixing graphene and the target material. The R&D work should be designed accordingly to reflect this. At Chalmers, the group of Prof. Johan Liu is studying heat transport properties in graphene and other carbon nanomaterials, so there are available resources to couple to, for future projects if needed.

4. Graphene enhanced phase change materials (PCMs)

Phase change materials play an important role in storing the harvested thermal energy from road surfaces. The stored energy can be used to heat up the roads during cold episodes resulting in ice-free surfaces. The success of such implementation, to a large extent, depends on the efficiency of thermal storage. Research data shows that graphene can be used to enhance the thermal performance of phase change materials.

Statens Vegvesen has funded two doctoral projects at Chalmers under the supervision of Dr. Bijan Adl-Zarrabi to develop the next generation of ice-free roads.

We recommend starting with a feasibility study to determine the business relevance of graphene based PCMs, together with theoretical and experimental evaluations of suitable materials (graphene type and PCM type) and the process of mixing them.

5. Gas sensors for O_2, CO, NOx, and other gasses

Gas sensing is among the active areas in graphene research. Even though the corresponding technology readiness level (TRL) is fairly low, the area has received considerable attention from many commercial actors and companies. Therefore, we expect that more investments will be directed toward this area in near future. This creates an opportunity for Statens Vegvesen to steer the future developments according to its interest by acting as the provider of specifications and by setting the commercial needs.

We recommend that a detailed feasibility study is performed to identify Statens Vegvesen’s specific needs for gas sensing. Then, R&D projects can be defined not only together with CIT and Chalmers but also with Uppsala University, Linköping University, as well as partners from industry.

Research in functionalization and development of prototypes would be needed. It will probably be possible to use calls in Flag-ERA or national calls to co-finance such studies.

9 Appendix A: Technology Readiness Levels definition

Technology readiness levels (TRLs) are a systematic metric system that supports assessments of the maturity of a particular technology and helps to consistently compare the readiness of different technologies. TRL metric was originally developed at NASA to support space technology planning during the 60s, but since then, it has been gradually adopted by other institutions and large companies in many different sectors.

The TRL metric system defines 9 levels. The level 1 refers to a technology with the lowest maturity and implies that it is just invented. Eventually, when a technology is completely mature and its application is demonstrated through successful operation in the desired environment, it is assigned a level 9 of readiness. It should be noted that the number of levels and their respective definitions vary slightly depending on the sector. In this report, we use the standard 9-level metric system where the levels are defined as the following:

Technology Readiness Level	Description
TRL 1.	Basic principles observed and reported.
TRL 2.	Technology concept and/or application formulated.
TRL 3.	Analytical & experimental critical function and/or characteristic proof-of-concept.
TRL 4.	Component and/or breadboard validation in laboratory environment.
TRL 5.	Component and/or breadboard validation in relevant environment.
TRL 6.	System/subsystem model or prototype demonstration in a relevant environment.
TRL 7.	System prototype demonstration in the relevant environment
TRL 8.	Actual system completed and qualified.
TRL 9.	Actual system proven in operational environment which translates to competitive manufacturing in the case of key enabling technologies.

10 References

[1] Sources; Patent data: Graphene Patent Landscape dataset CambridgeIP (January 2013); Journal article data, Global Research Report, Material Science and Technology, Thompson Reuters (2011).

[2] www.Chalmers.se/Graphene

[3] U.S. Environmental Protection Agency. Available: http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

[4] P. K. Dehdezi, M. R. Hall, and A. Dawson, "Thermophysical Optimization of Specialized Concrete Pavement Materials for Collection of Surface Heat Energy and Applications for Shallow Heat Storage," Transportation Research Record, pp. 96-106, 2011.

[5] A. R. Dawson, P. K. Dehdezi, M. R. Hall, J. Z. Wang, and R. Isola, "Enhancing thermal properties of asphalt materials for heat storage and transfer applications," Road Materials and Pavement Design, vol. 13, pp. 784-803, 2012.

[6] J. T.-W. Wang, J. M. Ball, E. M. Barea, A. Abate, J. A. Alexander-Webber, J. Huang, et al., "Low-Temperature Processed Electron Collection Layers of Graphene/TiO2 Nanocomposites in Thin Film Perovskite Solar Cells," Nano Letters, 2013.

[7] M. Peigney and D. Siegert, "Piezoelectric energy harvesting from traffic-induced bridge vibrations," Smart Materials and Structures, vol. 22, Sep 2013.

[8] M. Vazquez-Rodriguez, F. J. Jimenez, and J. de Frutos, "Optimal Linear Model for Piezoelectric Materials Involved in Road Traffic Energy Harvesting Applications," 38th Annual Conference on Ieee Industrial Electronics Society (Iecon 2012), pp. 1110-1115, 2012.

[9] M. Vazquez-Rodriguez, F. J. Jimenez, and J. de Frutos, "Energy Harvesting Input Stage Model for Piezoelectric Materials Involved in Road Traffic Applications," 2012 Ieee International Conference on Industrial Technology (Icit), pp. 7-12, 2012.

[10] H. J. Xiang, J. J. Wang, Z. F. Shi, and Z. W. Zhang, "Theoretical analysis of piezoelectric energy harvesting from traffic induced deformation of pavements," Smart Materials and Structures, vol. 22, Sep 2013.

[11] Available: http://www.gizmag.com/piezoelectric-road-harvests-traffic-energy-to-generate-electricity/10568/

[12] M. Hasebe, Y. Kamikawa, and S. Meiarashi, "Thermoelectric Generators using Solar Thermal Energy in Heated Road Pavement," in Thermoelectrics, 2006. ICT '06. 25th International Conference on, 2006, pp. 697-700.

[13] G. Y. Wu, Xiong, "Thermal Energy Harvesting Across Pavement Structure," in Transportation Research Board 91st Annual Meeting, Washington, DC , USA, 2012.

[14] D. Dragoman and M. Dragoman, "Giant thermoelectric effect in graphene," Applied Physics Letters, vol. 91, pp. -, 2007.

[15] R. Verma, S. Bhattacharya, and S. Mahapatra, "Thermoelectric Performance of a Single-Layer Graphene Sheet for Energy Harvesting," Electron Devices, IEEE Transactions on, vol. 60, pp. 2064-2070, 2013.

[16] Jian Lin, Zhiwei Peng, Changsheng Xiang, Gedeng Ruan, Zheng Yan, Douglas Natelson, and James M. Tour, “Graphene Nanoribbon and Nanostructured SnO2Composite Anodes for Lithium Ion Batteries”, ACS Nano (2013), Vol- 7, No.7

[17] Chenguang Liu, Zhenning Yu, David Neff, Aruna Zhamu, and Bor Z. Jang, “Graphene-Based Supercapacitor with an Ultrahigh Energy Density”, NANO Letters 2010, 10, 4863-4848.

[18] Meryl D. Stoller, Carl W. Magnuson, Yanwu Zhu, Shanthi Murali, Ji Won Suk, Richard Pinera and Rodney S. Ruoff, “Interfacial capacitance of single layer graphene”, Environmental science 2011, 4, 4685

[19] Yanwu Zhu, Shanthi Murali, Meryl D. Stoller, K. J. Ganesh, Weiwei Cai, Paulo J. Ferreira, Adam Pirkle, Robert M. Wallace, Katie A. Cychosz, Matthias Thommes, Dong Su, Eric A. Stach, Rodney S. Ruoff1, “Carbon-Based Supercapacitors Produced by Activation of Graphene”, Science 2011, 332, 1537-1541

[20] Tae Young Kim, Hyun Wook Lee, Meryl Stoller, Daniel R. Dreyer, Christopher W. Bielawski, Rodney S. Ruoff, and Kwang S. Suh, “High-Performance Supercapacitors Based on Poly(ionic liquid)-Modified Graphene Electrodes”, ACS Nano 2010, 5, 436-442

[21] Longyan Yuan, Xi-Hong Lu, Xu Xiao, Teng Zhai, Junjie Dai, Fengchao Zhang, Bin Hu, Xue Wang, Li Gong, Jian Chen, Chenguo Hu, Yexiang Tong, Jun Zhou, and Zhong Lin Wang, “Flexible Solid-State Supercapacitors Based on Carbon Nanoparticles/MnO2 Nanorods Hybrid Structure”, ACS Nano 2011, 6, 656-661

[22] Yan Wang, Zhiqiang Shi, Yi Huang, Yanfeng Ma, Chengyang Wang, Mingming Chen and Yongsheng Chen, “Supercapacitor Devices Based on Graphene Materials”, J. Phys. Chem. C, 2009, 113, 13103-13107

[23] B. E. Conway, “Transition from “Supercapacitor” to “Battery” Behavior in Electrochemical Energy Storage”, J. Electrochem. Soc., 2013, 160, A1-A6

[24] L. Schlapbach, “Hydrogen-fuelled vehicles” Nature, 2009, 460 ,809

[25] Stamenkovic, V. R. et al. “Improved oxygen reduction activity on Pt3Ni (111) via increased surface site availability” Science 2007, 315, 493–497

[26] Zhang, J. et al. “Mixed-metal Pt monolayer electrocatalysts for enhanced oxygen reduction kinetics” J. Am. Chem. Soc. 2005, 127, 12480–12481

[27] Xiao, L., Zhuang, L., Liu, Y. and Lu, J. “Activating Pd by morphology tailoring for oxygen reduction” J. Am. Chem. Soc. 2008, 131, 602–608

[28] Peng, Z. & Yang, H. “Synthesis and oxygen reduction electrocatalytic property of Pt-on-Pd bimetallic heteronanostructures”, J. Am. Chem. Soc. 2009, 131, 7542–7543

[29] Zhang, S., Shao, Y., Yin, G. , and Lin, Y. “Carbon nanotubes decorated with Pt nanoparticles via electrostatic self-assembly: a highly active oxygen reduction electrocatalyst” J. Mater. Chem. 2010, 20, 2826–2830

[30] Lim, B. et al. “Pd-Pt bimetallic nanodendrites with high activity for oxygen reduction”, Science 2009, 324, 1302–1305

[31] In-Yup Jeon, Hyun-Jung Choi, Min Choi, Jeong-Min Seo, Sun-Min Jung, Min-Jung Kim, Sheng Zhang, Lipeng Zhang, Zhenhai Xia, Liming Dai, Noejung Park, and Jong-Beom Baek, “Facile, scalable synthesis of edge-halogenated graphene nanoplatelets as

efficient metal-free eletrocatalysts for oxygen reduction reaction", Scientific Reports 2013, 3, 1810

[32] Sharma, S. D., Sagara, K. (2005) Latent heat storage materials and systems: A Reveiew. J. Green Energy, 2, 1

[33] Pradyumna Goli, Stanislav Legedza, Aditya Dhar, Ruben Salgado, Jacqueline Renteria, Alexander A. Balandin, "Graphene-Enhanced Hybrid Phase Change Materials for Thermal Management of Li-Ion Batteries", Journal of Power Sources, 248, 37 - 43 (2014)

[34] Surajit Some, Yang Xu, Youngmin Kim, Yeoheung Yoon, Hongyi Qin, Atul Kulkarni, Taesung Kim, Hyoyoung Lee, "Highly Sensitive and Selective Gas Sensor Using Hydrophilic and Hydrophobic Graphenes", Nature 2013, 3, 1868

[35] Hyeun Joong Yoona, Do Han Junb, Jin Ho Yanga, Zhixian Zhouc, Sang Sik Yangb, Mark Ming-Cheng Chenga "Carbon dioxide gas sensor using a graphene sheet", Sensors and Actuators B: Chemical 2011, 157, 310-313

[36] M.W.K. Nomani, R. Shishira, M. Qazia, D. Diwana, V.B. Shieldsb, M.G. Spencerb, G.S. Tompac, N.M. Sbrockeyc, G. Koley, "Highly sensitive and selective detection of NO2 using epitaxial graphene on 6H-SiC", Sensors and Actuators B, 150 (2010), pp. 301–307

[37] G. Lu, L.E. Ocola, J. Chen, "Reduced graphene oxide for room-temperature gas sensors Nanotechnology", 20 (2009), pp. 445502–4455011

[38] R. Pearce, T. Iakimov, M. Andersson, L. Hultman, A. Lloyd Spetz, R. Yakimova, "Epitaxially grown graphene based gas sensors for ultra sensitive NO2 detection", Sensors and Actuators B, 155 (2011), pp. 451–455

[39] O. Leenaerts, B. Partoens, F.M. Peeter, "Adsorption of H2O, NH3, CO, NO2, and NO on graphene: a first-principles study", Physics Review B, 77 (2008), pp. 125416–125422

[40] C.H. Kim, S.W. Yoo, D.W. Nam, S. Seo, J.H. Lee, "Effect of temperature and humidity on NO2 and NH3 gas sensitivity of bottom-gate graphene FETs prepared by ICP-CVD", IEEE Electron Device Letters, 99 (2012), pp. 1–3

[41] G. Singh, A. Choudhary, D. Haranath, A.G. Joshi, N. Singh, S. Singh, R. Pasricha, "ZnO decorated luminescent graphene as a potential gas sensor at room temperature", Carbon, 50 (2012), pp. 385–394

[42] Stefano Borini, Richard White, Di Wei, Michael Astley, Samiul Haque, Elisabetta Spigone, Nadine Harris, Jani Kivioja, and Tapani Ryhanen, "Ultrafast Graphene Oxide Humidity Sensors", ACS Nano 2013, 7, 11166

[43] Y.-M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris, "100-GHz Transistors from Wafer-Scale Epitaxial Graphene", Science, 2010, 327, 662

[44] Qingsong Mei, Kui Zhang, Guijian Guan, Bianhua Liu, Suhua Wang, and Zhongping Zhang, "Highly efficient photoluminescent graphene oxide with tunable surface properties", Chem. Commun., 2010, 46, 7319

[45] Ning Li, Satoshi Oida, George S. Tulevski, Shu-Jen Han, James B. Hannon, Devendra K. Sadana, Tze-Chiang Chen, "Efficient and bright organic light-emitting diodes on single-layer graphene electrodes", Nature, 2013, 4, 2294

[46] R.J. Young, I.A. Kinloch, L. Gong, K.S. Novoselov, “The mechanics of graphene nanocomposites: A review” COMPOSITES SCIENCE AND TECHNOLOGY, 2012, 72, 1459

[47] Vadukumpully, S.; Paul, J.; Mahanta, N.; Valiyaveettil, S., “Flexible conductive graphene/poly (vinyl chloride) composite thin films with high mechanical strength and thermal stability”, Carbon, 2011, 49, 198-205

[48] Fuan He, Sienting Lau, Helen Laiwa Chan, and Jintu Fan1, “High Dielectric Permittivity and Low Percolation Threshold in Nanocomposites Based on Poly(vinylidene fluoride) and Exfoliated Graphite Nanoplates”, Adv. Mater. 2009, 21, 710

[49] Chih-Chun Teng, Chen-Chi M. Ma, Chu-Hua Lu, Shin-Yi Yang, Shie-Heng Lee, Min-Chien Hsiao, Ming-Yu Yen, Kuo-Chan Chiou, Tzong-Ming Lee, “Thermal conductivity and structure of non-covalent functionalized graphene/epoxy composites”, Carbon, 2011, 49, 5107

[50] Jae-Ung Lee , Duhee Yoon , and Hyeonsik Cheong, “Estimation of Young’s Modulus of Graphene by Raman Spectroscopy”, Nano leters, 2012, 12 (9)

[51] Kim et. al, “Strengthening effect of single-atomic-layer graphene in metal–graphene nanolayered composites”, Nature Communications 2013, 4

[52] Hummers WS, Offeman RE, “Preparation of graphite oxide”, J Am Chem Soc 1958, v 80, Issue 6, pp. 1339–48.

[53] Fu Ling, Liu Hongbo “Technology research on oxidative degree of graphite oxide prepared by Hummers method” Carbon 2005, v 4

[54] Shenghua Lv, Yujuan Ma, Chaochao Qiu, Ting Sun, Jingjing Liu, Qingfang Zhou, “Effect of graphene oxide nanosheets of microstructure and mechanical properties of cement composites”, Construction and building materials, 49 (2013) 121–127

[55] http://www.monash.edu.au/assets/pdf/industry/graphene-oxide-reinforced-concrete.pdf

[56] Ahmadreza Sedaghat, Manoj K. Ram, A. Zayed, Rajeev Kamal, Natallia Shanahan, “Investigation of Physical Properties of Graphene-Cement Composite for Structural Applications”, Open Journal of Composite Materials, 2014, 4, 12-21

[57] Harshit Porwal, Peter Tatarko, Salvatore Grasso, Chunfeng Hu, Aldo R Boccaccini, Ivo Dlouhy, and Mike J Reece, “ Thoughened and machinable glass matrix composites reinforced with graphene and graphene-oxide nano platelets”, Technol. Adv. Mater. 2013, 14, 055007

[58] Shanshan Chen, Lola Brown, Mark Levendorf, Weiwei Cai, Sang-Yong Ju, Jonathan Edgeworth, Xuesong Li, Carl W. Magnuson, Aruna Velamakanni, Richard D. Piner, Junyong Kang, Jiwoong Park, and Rodney S. Ruoff, “Oxidation Resistance of Graphene-Coated Cu and Cu/Ni Alloy”, ACS Nano 2011, 5,1321

[59] Dhiraj Prasai, Juan Carlos Tuberquia, Robert R. Harl, G. Kane Jennings, and Kirill I. Bolotin, “Graphene: Corrosion-Inhibiting Coating”, ACS Nano 2012, 6, 1102

[60] Dongwoo Kang, Jee Youn Kwon, Hyun Cho, Jae-Hyoung Sim, Hyun Sick Hwang, Chul Su Kim, Yong Jung Kim, Rodney S. Ruoff, and Hyeon Suk Shin, “Oxidation Resistance of Iron and Copper Foils Coated with Reduced Graphene Oxide Multilayers”, ACS Nano 2012, 6, 7763

[61] Guoxiu Wang, Juan Yang, Jinsoo Park, Xinglong Gou, Bei Wang, Hao Liu, Jane Yao, “Facile Synthesis and Characterization of Graphene Nanosheets”, J. Phys. Chem. C, 2008, 112, 8192

[62] Chih-Chun Teng, Chen-Chi M. Ma, Chu-Hua Lu, Shin-Yi Yang, Shie-Heng Lee, Min-Chien Hsiao, Ming-Yu Yen, Kuo-Chan Chiou, Tzong-Ming Lee, “Thermal conductivity and structure of non-covalent functionalized graphene/epoxy composites”, Carbon, 2011, 49, 5107

[63] Shiren Wang, Madhava Tambraparni, Jingjing Qiu, John Tipton, Derrick Dean, “Thermal Expansion of Graphene Composites”, Macromolecules, 2009, 42, 5251–5255

[64] IDTechEx. Graphene Markets, Technologies and Opportunities 2014-2024

Statens vegvesen
Vegdirektoratet
Publikasjonsekspedisjonen
Postboks 8142 Dep 0033 OSLO
Tlf: (+47 915) 02030
publvd@vegvesen.no

ISSN: 1893-1162

vegvesen.no

Trygt fram sammen