GRAPHENE ROADMAP

Electronics

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List of acronyms

2D	Two-dimensional
A/W	Amperes per watt
Bn	Billion
CMOS	Complementary metal oxide semiconductor
CVD	Chemical vapour deposition
dB	Decibel
eV	Electron Volt
f_{MAX}	Maximum oscillation frequency
FET	Field effect transistor
FoM	Figure of Metric
Gbps	Gigabits per second
GHz	Gigahertz
GO	Graphene Oxide
H2020	Horizon 2020
Hz	Hertz
IP	Intellectual property
ITO	Indium tin oxide
KTH	The Royal Institute of Technology
LiU	Linköping University
LPE	liquid-phase exfoliated pristine graphene
meV	millielectronvolt
MSEK	Million Swedish Krona
PET	Polyethylene terephthalate
rGO	reduced Graphene Oxide
RISE	Research Institutes of Sweden
RnD	Research and Development
Si	Silicone
SiC	Silicon Carbide
SMEs	Small and medium-sized enterprises
THz	Terahertz
TIM	Thermal interface material
TRL	Technology Readiness Level
USD	United States Dollar
UU	Uppsala University
V/W	Volt per watt

Introduction

Graphene is a two-dimensional (2D) material where the atoms, in this case carbon, form a two-dimensional lattice with unique electronic properties. Characteristic features are high charge carrier mobility, high charge concentration, and high maximum hole and electron velocity. These properties make graphene particularly amenable to electronics research and devices.

Graphene has unique properties, including

- high electrical and thermal conductivity
- large specific surface area
- good chemical and electrochemical stability
- excellent mechanical strength and flexibility
- interesting optical and optoelectronic properties
- low surface friction
- special quantum Hall effect features

Many of these properties are of interest to electronics. Graphene's features give rise to new applications and are explored in various research projects and ventures in Sweden.

Application Domains & Societal Impact

The impact of graphene on domains such electronic system integration and performance, are in progress. There is no doubt that there will be applications in the future where you will find graphene as building blocks in new devices, such as wireless, system integration and sensors, that will have large societal impact. It usually takes several decades to establish new material systems on a commercially viable level in electronics, and graphene is in the beginning of this development. To be clear, graphene will not necessarily replace other material systems; instead it creates new possibilities to stretch performance of devices and applications further. For example, the conduction (electrical and heat), transparency, mechanical strength and flexibility et c. offers possibilities and new solution to problems that haven't been solved previously with other materials. Graphene will be a building block in combination with other technologies, and right now technologies and processes are under development.

For example, benefitting from its unique properties, graphene has promising application in a large variety of sensors, such as biological, electrochemical, electrical, magnetic, optical, temperature, mechanical, and gas sensors. Compared with conventional materials, the extremely large surface-to-volume ratio of graphene significantly increases the sensitivity of almost all kinds of sensors. Its high electrical conductivity, along with excellent chemical stability and biocompatibility, makes it possible for graphene to replace present metal electrodes and enable new sensing applications, such as those operating under harsh environment or when fully biocompatible devices are needed. These merits offer great opportunities to substantially advance the present sensor technologies and create market advantages. The extended applicability of graphene sensors will also greatly contribute to many strategically important fields, such as advanced medical monitoring, healthcare and diagnostics.

For printed graphene, an application of long reaching societal impact would be that of transparent conducting electrodes. That is what everyone looks through into display pixels of smartphone displays, laptops and TV sets for hours every day. Indium oxides are currently used for this purpose, but global supplies are scarce. Replacing it with graphene could have a large environmental as well as societal impact, by making display devices more sustainable.

In high frequency electronics, graphene has the potential to become a key technology in future systems for wireless communication, radar sensors and imaging sensors. These applications are of high interest for Swedish industries like telecom and automobile.

The capacity to produce graphene in high volume, to the right quality and right price, is of fundamental importance to graphene electronics. This capacity is increasing, but remains in early stages. From this perspective it is correct to say that the viability of graphene in electronics has not yet been tested. Several techniques and applications are promising, and they need support in order to become established technologies with impact on society.

Roadmapping process

Background

SIO Grafen is a strategic innovation program that supports industrial graphene development in Sweden. The program is supported by Swedish government agencies *Vinnova*, *Energimyndigheten* and *Formas*. To assist in achieving the goals of the program it is necessary to develop the Swedish roadmap for graphene. This is broken out into six identified areas of national strengths. During 2016 a roadmap was created for two of these areas, Surface Coatings and Composites [see ref. 1]. This report addresses a third area of Swedish excellence: Electronics. The area is subdivided into Printed Electronics, Sensors, High Frequency Electronics and Electronic Cooling. This first ever Swedish roadmap for graphene use in electronics was commissioned by the board of *SIO Grafen* as a part of its strategic work. It complements the roadmap developed by the *European Graphene Flagship* [see ref. 2], and features a chapter that summarises its activities in 23 countries, as a perspective to the technological developments of Sweden.

An Open Roadmapping Process

Coordinated by the Research Institutes of Sweden (RISE), five researchers with significant insight and network within their respective graphene electronics fields were onboarded on the Roadmap Project. Meetings were conducted in 2018, and contacts initiated with Swedish academia, SMEs and industry. Preliminary data suggested that an open survey would be a good mode of retrieving data and connecting further with the Swedish graphene electronics landscape.

A national survey was produced that allowed fully anonymous or credited feedback. It also served to facilitate follow-up contact. Survey questions tackled a wide scope, ranging from present-day applications, technology readiness, support needs, international collaboration to futuristic vision. Such general questions were accompanied by field-specific questions to retrieve quantitative as well as qualitative input, and comments.

The survey had over 30 respondents from across Sweden, and average time taken to respond was 35 minutes. This input was followed by conducted interviews and research. A presentation of preliminary data at the 2019 *Advanced Engineering* fair in Gothenburgh contributed further end-user needs and queries.

The result of the past year's efforts is this report. The report is divided into four thematic technology chapters, followed by a brief discussion on other relevant types of graphene electronics not touched upon in the technology chapters. Ongoing work in Sweden is then contrasted to efforts in the rest of Europe, with emphasis on the intellectual property landscape. The report concludes with a final chapter that outlines ongoing work, impact and needs, and proposes next steps.

The report will form the basis of a European funding call proposal with emphasis on Swedish research and development needs in order to take Swedish graphene electronics beyond the promising level that it is currently at.

This roadmap is the joint effort of Swedish industry, academia, startups and supporting government agencies, and of course the team of authors responsible for the chapters contained herein.

Technology Chapters

Sensors (Li)

Key Research and Applications

At least eight different types of sensors have been under development in Sweden with varying degree of technical maturity (as summarised in **Figure 2**). Out of these sensors, electrical sensors, temperature sensors and optical sensors are developed by the largest number of players. It is exciting to see almost all the types of sensors have reached an average technical maturity of about or above 5 (at the scale of 0-10 with 0 being the status of just ideas and 10 meaning shipped products). It is worth noting that many players are developing multiple types of graphene sensors (among 13 survey respondents, only one intends for a single product). In particular, *Chalmers* and *Linköping University* have reached technique maturity of 10 (shipped products) and both of them are developing 3-5 types of graphene sensors. Magnetic sensors are the common sensor type that the two universities are developing, and both report top technique maturity. Besides academia, the company *Graphmatech* is developing 3D printable solutions for graphene, which facilitates fabrication of all types of graphene sensors. They report a high technique maturity of 9 out of a maximum 10.

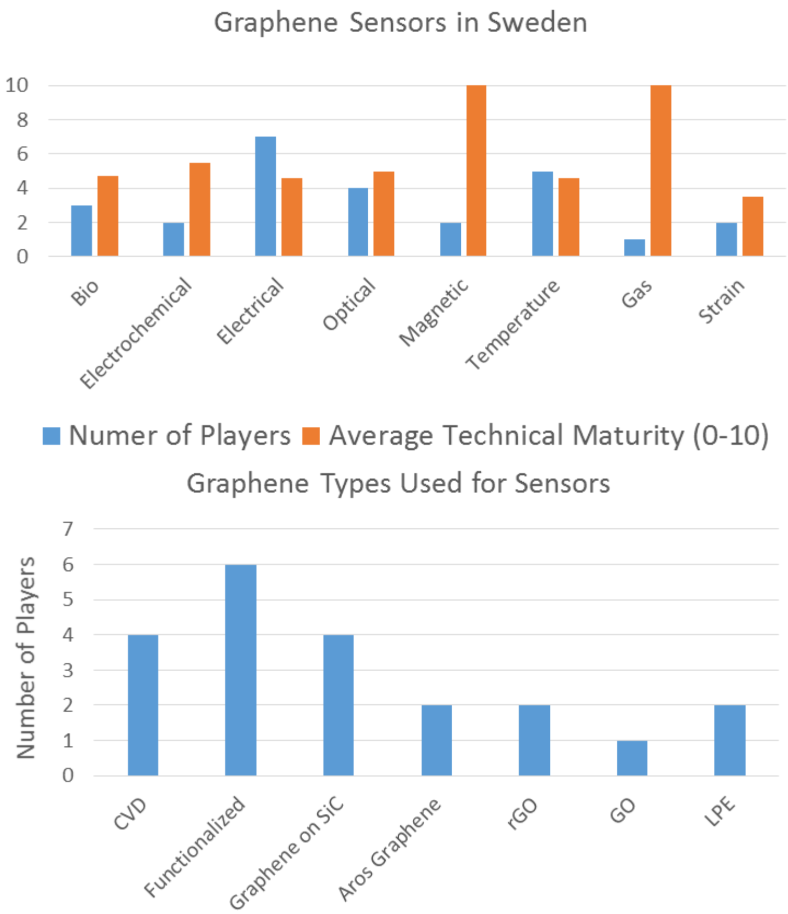


Figure 1. (Top) The development status of different types of graphene sensors in Sweden: the number of players and average technical maturity. Technical maturity ranges from 0 (idea stage) to 10 (shipped product). (Bottom) Types of graphene materials used for sensors. rGO, GO and LPE stand for reduced graphene oxide, graphene oxide and liquid-phase exfoliated pristine graphene, respectively. Aros Graphene is the product developed by the company *Grapmatech*.

Almost all types of graphene material have been used for sensor applications. The three most frequently used graphene types are functionalised graphene, mono- or few-layer graphene by chemical vapor deposition (CVD) and SiC-derived graphene. And all these three types of graphene have been used in development of almost all of the eight sensor types. For example, for biological applications, biosensors based on CVD graphene have proven effective for detecting infections and disease markers. Even without any functionalisation, the sensor can detect specific bacterial strains. Graphene-based electrical sensors have promising applications in power detectors. Graphene optical sensors are competitive with respect to high sensitivity and wavelength tunability and prospect for a standard micro-optic detector component to enhance the present System-on-Chip nondispersive infrared sensor techniques.

Potential Applications and Impact for Sweden

Given the technical maturity and market situation of the existing technologies, the graphene sensors are expected to create significant economic and societal benefits to Sweden in the immediate future (within 5 years) or longer term (within 10 years). For example, the temperature and electrical sensors under development at *MacDonald-Arnskov AB* may more precisely monitor the operation status of machinery (e.g., displacement between different components of a machine, local temperature of a component) especially under harsh working conditions [3]. Similar graphene sensors have potential to be introduced into the large market of machinery to strengthen the advantage of Swedish industry as a whole. In the long term, some biosensors are anticipated to fulfill advanced medical needs in Swedish hospitals such as *Sahlgrenska* and strengthen a cluster of companies covering production and commercialisation of sensor devices for different end users (patients, clinicians, diagnostic labs, etc.). Many players also predict that magnetic sensors and optical sensors may have a large global market.

Definition of FoMs

A set of FoMs is used for graphene sensors, including signal-to-noise ratio, response time, sensitivity and selectivity. According to a qualitative analysis (**Figure 2**), in general the graphene sensors excel in sensitivity and response time, while selectivity is mostly ranked as 'adequate'. Some players report commendable quantitative values and specific metrics for their sensors. For examples, the graphene electrical sensors developed by Andrei Vorobiev's group at Chalmers have attained responsivity up to 74 V/W at 400 GHz, which is the highest responsivity obtained for graphene FET THz detectors reported to date [3]. Another group reports graphene electrical sensors with linearity over 4 orders of magnitude. The group of Samuel Lara in Chalmers also reports Hall sensors with sensitivity of 300 mV/VT, quantum hall resistance standard with 0.08 part per billion accuracy operated at 4K and magnetic field $B < 5$ Tesla [in collaboration with Linköping University, see ref. 4], optical detectors with quantum-limited detection above 1 THz, and gas sensors that allow part-per-billion detection [3].

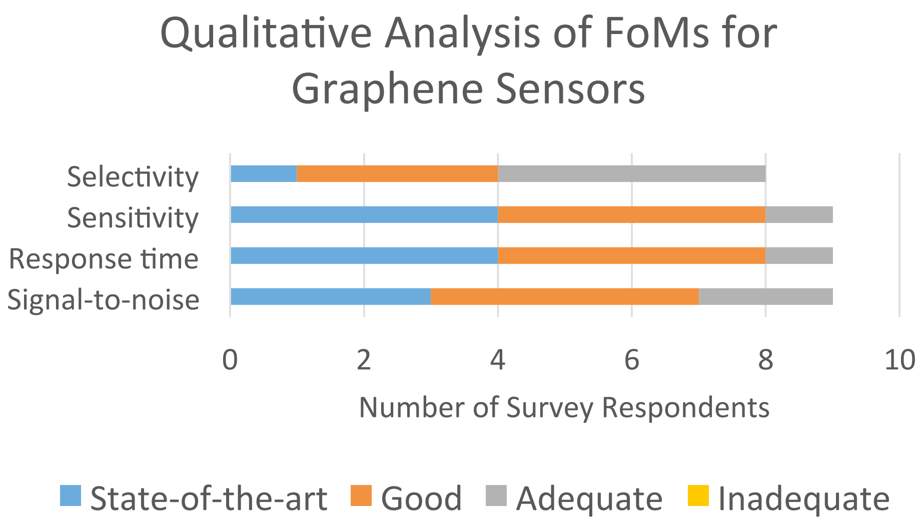


Figure 2. Qualitative analysis of FoMs of graphene sensors, based on the inputs of 9 survey respondents. No respondent assessed their technology as inadequate.

Technology and Design Challenges

The most common challenge in graphene sensor technologies appears to be the lack of scalable and high-yield production techniques for high-quality graphene with few defects. Some sensor technologies require better monolayer quality. Such raw material-related issues increase sample-to-sample variation and hence severely reduce sensor reliability and reproducibility. Other challenges include time-consuming processing, difficult manipulation of monolayer graphene, and performance reduction caused by non-uniform graphene starting material. Such processing-related issues hinder upscaling of the entire graphene sensor technology field.

Other Issues and Challenges

One critical non-technical challenge is the limited funding resources for comprehensive RnD of the new material-based processes and products. Almost all players need at least 2 million SEK before their technologies can reach TRL 6. In addition, the lack of reliable supply of high-quality graphene at low price is another difficult challenge, which severely hinders the development and commercialisation of graphene sensors. Most players have international collaborators in Europe and North America, and some academic players voice their concern about the lack of Swedish industry to partner up with, which they would prefer to collaborate cross-border.

General Recommendations

The availability of high-quality graphene materials has become a limiting factor for sensor development. It is strongly recommended that funding bodies strengthen the support of research on synthesis of high-quality graphene materials to improve the market situation and complete the value chain, and/or help Swedish researchers and manufacturers identify reliable international suppliers.

Many players need substantial financial support. Longer-period and larger-scale grants are preferred to short-term alternatives in order to systematically address critical challenges.

Therefore, it is recommended that long-term grants (e.g., > 3 years) are offered to complement the present grant types available from *Vinnova* (up to 18 months).

The state-of-the-art performance is mainly attained in academia. Some academic players lack Swedish industry partners, in spite of partnership with foreign industry. Further enhancement of academia-industry cooperation and support of spin-offs from academia are highly recommended.

Magnetic sensors have been developed independently by two academic players and both have attained high technical maturity (shipped products). It would be reasonable to support this field by offering help with market identification and financial support for further business development.

High Frequency Electronics (Zirath)

Key Research and Applications

The properties of graphene make it interesting in applications such as sensors for imaging and ranging (radar), and wireless high data rate communication using frequencies up to Terahertz (THz). Due to the excellent linearity of key components, circuits made by graphene can handle complex signals almost without distortion. Today, terahertz (0.1-10 THz) applications are found in areas such as biology, medicine, atmosphere science and security, as well as traditional space science. Besides THz applications, Sweden has for a long time maintained a very strong position in microwave and mm-wave electronics. In fact, a significant portion of the internationally competitive Swedish industry resides within this technology field. Surging demands for higher bandwidth, imaging resolution and functionality warrants an increase in operating frequency for many applications. The migration from microwaves towards THz is a natural next step to ensure continued Swedish competitiveness in this industry sector, and is thus of strong strategic importance. Swedish academic groups at *Chalmers* have so far (within the *H2020 Graphene Flagship* program) reached a TRL-level of 5-6, i.e. demonstrated graphene-based circuits suitable for sensor and communication systems. Ongoing work within the newly started H2020 project, *Car2tera*, is aiming at system/subsystem development for new car-radar safety system at 238-248 GHz (by *Veoneer, Infineon* and *Chalmers*), as well as sub-systems for millimetre wave polymer plastic fibre communication (by *Ericsson, Infineon* and *Chalmers*) at TRL>7, with high datarate (100 Gbps). Several different Swedish groups manufacture graphene material for high-frequency electronics; *Graphensic* and *Linköping University* (*LiU)* can grow graphene on silicon carbide, graphene on copper for transfer to any material is developed at *MC2* of *Chalmers University*. High frequency components and circuits are manufactured and characterised at *MC2*, *Chalmers*, in two laboratories, *MEL* and *TML*. *MEL* focuses on linear circuits for communication and sensors for frequencies from 60 GHz up to 250 GHz, based on graphene transistors with silicon carbide as substrate. TML focuses on the graphene transferred to silicon substrate or plastic film for frequencies up to and above 1 THz. Both groups generate world-class results in the high-frequency graphene area [3].

Potential Applications and Impact for Sweden

High frequency applications can be found in many fields for components operating in the GHz up to several THz frequencies, including astrophysics, atmospheric studies, gas-detection, security, drug and explosion detection, material inspection, biological, satellite communication and other airborne activities, phased-array radar, electronic warfare, consumer electronics related to high speed communication, data-centre communication, and radar for autonomous vehicles.

The band gap of graphene is low; it can vary between 0 eV and a few tens of meV. This makes graphene most interesting for low power applications related to signal processing. Whether or not graphene can play a role for the future of electronics depends on whether the material's unique properties can be exploited, and whether specific areas of use for these unique properties can be found. The most important features, and the possibilities that they open up for, are listed here:

1. Graphene can be grown on certain materials such as copper and then transferred to any substrate that enables integration with other semiconductor components such as silicon. Other possibilities are transfer on flexible substrates, e g different plastic materials. This provides the possibility of manufacturing flexible, conformable high-frequency circuits. The graphene can also be grown on silicon carbide, which is an excellent substrate for higher frequency components and which can be combined with AlN-InN-GaN based materials also known as III-N materials. The III-N materials are characterised by its high breakthrough field and is thus complementary to the graphene.
2. Graphene channel field effect transistors have symmetry in the voltage-current characteristic that provides unique and attractive circuit characteristics for frequency mixers and power detectors. These components are key components of wireless communication and sensors. The linearity of these components is significantly better than other technologies [see ref. 5]. By using graphene-based components, one can thus improve, or simplify, the design of communication systems and sensors.
3. Because of the low band gap, graphene-based electronics of today generally have difficulties competing with conventional electronics because the power amplification is relatively low (a measure of the power gain is f_{MAX}, the maximum oscillation frequency; the frequency where the power amplification is equal to one). f_{MAX} is somewhere between 30-50 GHz today, which means that graphene-based electronics with amplifying circuits can be designed for frequencies up to 10-20 GHz with a decent gain. Thus, electronics on flexible substrates can find future applications up to these frequencies. Frequency mixers and power detectors could advantageously already be used up to several 100 GHz, perhaps above 1 THz, in applications where linearity is an important parameter.

Sweden has a wide range of companies, from SMEs to large multinational companies, related to microwave electronics. Depending on the ongoing work related to system demonstrators, graphene might find its way to commercial systems within 5-10 years. Interestingly, the complete value chain exists in Sweden, but RnD and manufacturing faces many challenges on the way, including wafer production, uniformity of the material, yield and reliability engineering, fab-production et. c.

Graphene-based circuits have, due to its high linearity, a potential to significantly improve the performance in systems for high data rate communication at frequencies above 100 GHz. New frequencies for 5G, and upcoming mobile communication systems, will be deployed within 5-10 years from now due to the signal crowding at lower frequencies. In addition, new frequency bands above 100GHz are now available for sensing such as radar, with wider bandwidth compared to lower frequencies, below 100 GHz. Such radar systems will be frequently used, for instance, in the car-industry in a near future. With wider bandwidth, higher resolution can be obtained for radar, and the antenna size will be smaller due to the higher frequency.

Definition of FoMs

Figures of Merits (FoMs) for graphene based high frequency components are summarised in **Table 1** and include frequency range, conversion loss, linearity, and LO power for frequency mixers. For detectors, frequency range and responsivity are listed. NB the meaning of key FoMs are explained in Appendix I.

Component	Frequency (GHz)	Conversion-loss (dB)	Linearity IIP3 (dBm)	Responsivity (V/W)	Substrate	LOpower (dBm)	Ref
Mixer	88-100	18	33 (sim)	-	SiC	8	6
Mixer	185-215	29+/-2	-	-	Si	11.5-12.5	7
Mixer + IFamp	185-205	25	-	-	Si	16	8
Detector	400	-	-	74 open circuit	Si	-	9
Detector	487	-	-	2 open circuit	PET Flexible	-	10
Detector	96	-	-	2 in 50 ohm, 6 open circuit	SiC	-	11

Table 1. Achieved FoM results in Sweden

Technology and Design Challenges

The material quality like charge density, carrier mobility, varies over the wafer area, which limits the yield of the fabricated circuits. The uniformity of the graphene is therefore a challenge that should be addressed. There are competence to improve the quality of graphene films at MC2 and LiU, but the intensity of the work should be increased with more resources with focus on Graphene material for high frequency components and circuits. The best high frequency material on Silicon Carbide is grown in China today. For optimum circuit results, the graphene should be of bi-layer type due to the superior ohmic contact resistance. The dielectric between the gate-electrode and the graphene, usually Aluminium oxide or Hafnium oxide, is another challenge, it has been shown that traps in this layer might give hysteresis in the transfer characteristics of a FET, which will deteriorate the overall performance. Due to the mentioned challenges, circuits are today limited to a few transistors, which is a severe limitation from system point of view. Due to the low bandgap, a graphene-based switch cannot be completely switched off which is another severe limitation in digital circuits. In analogue circuits this is not necessarily a problem, however the output conductance is typically higher compared to other technologies and transistors typically will not enter current saturation. This is the main reason that f_{MAX} is lower than other semiconductor technologies. In components such as frequency mixers and power detectors, this behaviour is used as an advantage instead.

Other issues and challenges

Swedish academia together with industry has very good opportunity to develop graphene and other 2D-materials to industrialisation thanks to the *H2020 Graphene Flagship* project, which continues for another four years. However, due to the broad scope of this program, the funding for high frequency electronics is under-critical to develop system demonstrators so that they reach TRL>5. Funding for such projects would be necessary in order to commercialise the technology.

General recommendations

Graphene material quality in terms of uniformity need to be improved for graphene-based high frequency integrated circuits, and the wafer size should be increased. Sweden has competence in growing graphene, but so far there is no high quality Swedish material for high frequency electronics at fairly large wafer size, i.e. >10 cm diameter.

Both radar and communication systems should be tested in real operating systems in order to assess their final performance. More intense research and development or projects at TRL5 and higher would then be necessary.

Printed Electronics (Sandberg)

Key Research and Applications

From a global perspective, one can observe that the field of graphene compositions for printed electronics is thriving with numerous reports on the progress of research, as well as commercial products in the form of inks for various printing and coating techniques.
The Swedish landscape for graphene in printed electronics consists of academic efforts into inkjet formulations, compositions based on liquid exfoliated graphene and application work where graphene inks are to replace other conducting materials. A short overview is provided by recent publications form academia in Sweden. Industrial activities in the field are difficult to measure but may be glanced by their participation in funded *SIO Grafen* projects having a bearing on printable and coatable graphene compositions. Both academic and industrial efforts, as well as relevant spinoffs, are described below.

Overview of research activities at Swedish universities
At *Uppsala University* (UU), methods to disperse graphene nanoplatelets, inkjet ink formulations and post-deposition treatments to increase conductivity have been developed. Further, methods to disperse graphene to accomplish coatings on particles have been developed and spun off into *Graphmatech AB*.
At *The Royal Institute of Technology* (KTH), research has resulted in several publications of inkjet printable graphene dispersions including methods to disperse graphene into highly concentrated compositions forming transparent conducting electrodes. A spin-off company, *Anincko*, has been launched.
At *Mid Sweden University* (Mittuniversitetet), technologies for scalable liquid exfoliation and graphene have been developed, a work from which *2DFab* has been spun off. Coatings based on the liquid exfoliated graphene have been explored as electrode material in supercapacitors. *2DFab AB* lists printable compositions among its products.

Current or completed SIO-graphene projects involving graphene for printed electronics, or coatings or paints based on wet deposition of graphene
"Graphene composite as electrode in a super capacitor" by *Bright Day Prototypes* and *RISE Acreo*
"GNOME 2.0 ACA" by *ScandiDos, Akzo Nobel, Mycronic, 2D fab* and *RISE Acreo*
"Graphene Coatings for High-End textiles" by *FOV Fabrics, Chalmers* and *Chalmers Industriteknik*
"Multifunctional paint through the addition of oriented graphene flakes" by *Saab Aeronautics, Linköping University* and *Danubia NanoTech*
"Graphene Coated Optical Fiber" by *Bitelecom, Chalmers (Industrial and materials science), KTH Optical Network Lab* and *RISE/Acreo Optical Lab*
"Stable dispersions of graphene and nanocellulose for future composite materials" by *RISE Innventia, RISE* and *Billerud-Korsnäs*
"Graphene in textiles" by *Inuheat Group, Smart Textiles at University of Borås* and *Swerea IVF*
"Graphene-based flexible and recyclable light sources for life science applications" by *LunaLEC* and *Umeå Univresity (Thomas Wågberg, Nano for Energy)*
"Graphene Enhanced Heat Spreaders for Electronics" by *KTH, Huawei Technol. Sweden* and *Aninkco AB*
"Nano coal coating" by *Applied Nano Surfaces Sweden, Epiroc, Trelleborg* and *Dalarna University*
"Graphene Barrier Coating for Paper Packaging" by *BillerudKorsnäs* and *SP (now RISE)*

"Graphene in radiation measurement" by *ScandiDos* and *Acreo Swedish ICT*
"iEnergy - Industrialization of inkjet printing technology with graphene for energy storage applications" by *KTH* and *XaarJet AB*
"Solution-based cathode for printable light" by *LunaLEC* and *Umeå University (Thomas Wågberg)*
"Printed graphene electrodes in high voltage products" by *ABB AB* and *RISE Acreo*
"Graphene-based coatings for heat exchangers" by *SP (now RISE), AlfaLaval Lund AB* and *KTH*
"Infrared-Chameleon" by *RISE Acreo, Linköping University* and *Saab Group*

Potential Applications and Impact for Sweden

Survey results suggest that graphene may find early uses as electrochemical energy storage electrodes and also as material for electric contacts. Transparency is mentioned as a desired property of printed graphene compositions.

Likely development of Swedish printed electronics in 2024

- Graphene characterised by high batch reproducibility is produced at an industrial scale in Sweden from raw materials indigenous to Sweden, or raw materials developed in Sweden. This development is likely to be based in liquid exfoliated graphene.
- Dispersions of single layer graphene is produced and used at an industrial scale in Sweden due to efforts at academic spin-offs.
- Printable graphene-based adhesives are key materials for assembly of printed electronic circuits and a range of other applications where conducting and corrosion stable adhesives are needed. This is the explicit goal of the ongoing *GNOME 2* project.
- Printed graphene is used for thermal management in electronics and energy storage. This is a result from an academic spin-off, driven by industrial need for thermal management.
- Graphene compositions has taken additive manufacturing far. Additively manufactured graphene materials forms parts and products that are found in telecommunication equipment and household electronics. Additive manufacturing of graphene is a field where Sweden has taken a leading position and can provide materials, products and know-how along the whole supply chain. Current start-ups like *Graphmatech* enable this development.

Likely development of Swedish printed electronics in 2029

Starting from production of raw materials, and stable and reproducible graphene compositions, and ending at finished products, graphene for printed electronics will represent a field where suppliers and makers in Sweden have leading positions all the way form the raw materials side to finished products in optoelectronics, energy storage, power electronics, additive manufacture, consumer products, and aerospace. Specifically:

- Given the current development in industry and institutes, printable graphene-based compositions are widely used for printing electrically conducting leads and electrodes and have replaced inks based on carbon black and provide the main material feed into the growing field of printed electronics.
- Swedish university spin-offs will create printable compositions forming transparent conducting electrodes. These compositions are based on single-layer graphene, are exported to makers of display screens and other electro-optical devices all over the world. Printed

and coated transparent conducting graphene electrodes are used domestically and forms the base for a Swedish optoelectronic industry sector producing smart windows, protective glasses, printed displays, and optic sensors.
- Battery manufacturers enable large volume industry of printable graphene compositions forming electrodes for electrochemical energy storage. Printing of electrodes instead of coating has enabled new designs and production methods for batteries and supercapacitors. These compositions are used in the industrial production of conventional batteries and form the base for a new niche of printegrated energy storage systems in Sweden.
- Driven by the needs of power grid components, mechanically, thermally and chemically robust prints and coatings of graphene is a speciality developed in Sweden. These coatings are used in the electro technical fields of power electronics and high voltage electronics, field where stability to high temperature is needed.
- Graphene-based materials forming flexible and elastic leads and interconnects are key materials for wearable sensors and other devices. This is driven by the development in printed and wearable electronics.
- Graphene is printegrated into airplane parts, to form parts of sensors and leads networks in wings and fuselages of aircrafts, for electromagnetic shielding and de-icing. This development is driven by the needs of the aerospace industry.

Printed carbon compositions are currently used to print heating elements and traces for capacitive contacts. Printed and coated graphene may replace other forms of printed and coated conducting materials, metal inks and inks based on carbon black. Already today, printable graphene compositions could replace several inks based on other carbon inks, carbon black inks. Most varieties of carbon black used in conducting inks are toxic and replacing them with less toxic graphene-based inks would open an already existing market for graphene inks.
The largest market for conducting inks today is the market for printed leads in photovoltaic cells. This market segment is mainly filled with silver inks. To replace those, it is necessary to significantly improve the conductivity of cured graphene inks from state-of-art conductivity levels.
The prospect of printing or coating transparent electrodes from single-layer graphene composition is highly attractive. Transparent conducting electrodes are key elements in optoelectronic devices, display screens for example, which are ubiquitous in modern society. The market is dominated by indium tin oxide (ITO) and the scarcity and cost of indium is of a great industrial concern, and the search for alternatives, including graphene coatings, is intense. The market for transparent conducting electrodes is expected to reach over eight Bn USD by 2026.

Another market of interest for printed graphene is as electrodes in electrochemical energy storage. Energy storage electrodes are typically applied by coating onto metal collector substrates. The prospect of printing instead of coating could open new possibilities of custom battery cells, and new schemes for integrating electrochemical cells into modules and systems.

Definition of FoMs

Quality of material compositions used for printed graphene should be evaluated according to ISO/TS 80004-13:2017. Evaluation should follow established standards for geometric characterisation of printed matter, such as edge and line definitions, surface roughness and thickness. For electronic properties, such as resistance, standards such as IEC 62899-202:2016 are recommended.

Technology and Design Challenges

Judging by the conducted national survey, the following properties are considered challenging for implementation of graphene in printed electronics: electrical conductivity, thermal conductivity, and flexibility. Other concerns are stability of graphene inks against aggregation and sedimentation, and that harmful solvents are frequently used in graphene inks. The poor electrical conductivity compared with silver particle inks is also pointed out.

Certain research issues concerning graphene for printed electronics are identical to general research issues for graphene, while others are more specific for printed devices and printable graphene compositions.

Quality and reproducibility are issues that printed electronics have in common with other graphene application areas. The low concentration of graphene suspensions and dispersions and the stability of these compositions pose problems for printable compositions. For printed electronics, high electrical as well as thermal conductivities are desired properties.

Such quality and reproducibility issues stem from differences in structure and properties of the starting material, typically graphite. These differences, in turn, originate from differential sources for naturally occurring graphite, or differences in process conditions in synthetic graphite sources. Another important quality issue concerns the availability and cost of dispersed compositions based on single layer graphene.

Graphene and graphene oxide dispersions and suspensions are of low concentration, typically parts of a percent or lower. Printing processes are generally not amenable to very low concentrated solutions, and addition of viscosity controlling compounds, dispersion agents and binders will dilute the solid content of graphene and may make it a minority component in the composition which result in low electrical and thermal conductivity. The origin of this problem is that the concentration and solid content of graphene in graphene oxide solutions and compositions is typically limited by the propensity of graphene to aggregate and laminate back to graphene, even in the presence of dispersing agents. Solving stable dispersions of graphene at high concentrations, while minimising the effect of the dispersing agent on the graphene properties in a printed device, is thus one of the key research issues for graphene in printed electronics.

Other issues and challenges

The most pressing non-technical issue is the absence of commercially offered products based on printed graphene compositions. Another issue is the observation that efforts in academia, institutes and industry are not well connected to one another, or experience a disconnect in the value chains of the sector. The efforts from the academic side, while highly relevant and promising –

in particular transparent conducting coatings and stable inkjet composition – have not translated into commercial offers or products. Commercial products from a startup based on liquid exfoliation are apparently not used for production. Moreover, printed graphene, evaluated at research institutes, does not move on to higher technology readiness level. The reason for this remains unclear.

General recommendations

A number of measures are recommended to bring this field forward, with the aim of placing printed graphene into value chains. There is a need to support

- commercialisation with qualifications and testing
- scaling efforts
- IP-work
- marketing efforts and network building

Construction of business cases based on research in academia and at institutes would be facilitated by financial support for time consuming activities such as IP-surveys to map patenting opportunities and freedom to operate. Moreover, testing and qualification of materials and devices can be time consuming and therefore costly. If access to facilities for testing and qualifications and financial support for these activities can be provided, the route to qualified and thereby marketable products would be better paved. Example of testing needs could include rheological tests of composition as well as function tests and accelerated ageing tests of devices. As printed electronic products are envisaged to be used widely in a range of products and reach the hands of consumers and eventually reach recycling and waste handling stages, implementation requires careful evaluation of life cycle aspects of the material, product and processes used in manufacturing. Full LCA-analyses are time consuming and costly, so support to this end with initial screening and possibly full LCA's would be worthwhile.

Commercialisation of printable compositions requires facilities for scaling while maintaining quality. Access to facilities and equipment for testing scalability of graphene compositions could therefore accelerate device commercialisation.

Finally, but not least, connecting and marketing the various research activities in the field towards potential customers, and an efficient use of facilities and know-how requires formation of efficient networks and marketing support activities.

Electronic Cooling (Nilsson)

Key Research and Applications

The field of electronics cooling faces several challenges now and in the future. Power demand in modern electronics tends to increase while volume shrinks, causing a trend towards severely high power density in consumer and e.g. aerospace industry.

The field of graphene as a material for thermal management is primarily at research and spin-off stage. Research and novel development activities are going on in areas depicted in **Figure 3**. In all fields but *Surface Properties*, one uses the superior thermal conductivity of graphene to cool electronics at different stages in the heat transport chain from the transistor cell (chip) to the ambient environment. They all use multi-layer graphene films with hundreds or thousands of layers. Single- and few-layer graphene is not useful for most of the cooling technologies shown. In several cases, graphene out-performs traditional cooling by aluminium and copper; only graphite is a fierce opponent and is already established on the market. The benefit of a graphene film is often a combination of favourable properties; thermal conductivity, superior flexibility (in contrast to graphite), ductility, low density, strength and potentially an extremely large surface area per kg. The drawbacks are poor cross-plane thermal conductivity and dispersion in e.g. adhesives (for a discussion on graphene dispersion issues, see the chapter on Printed electronics).

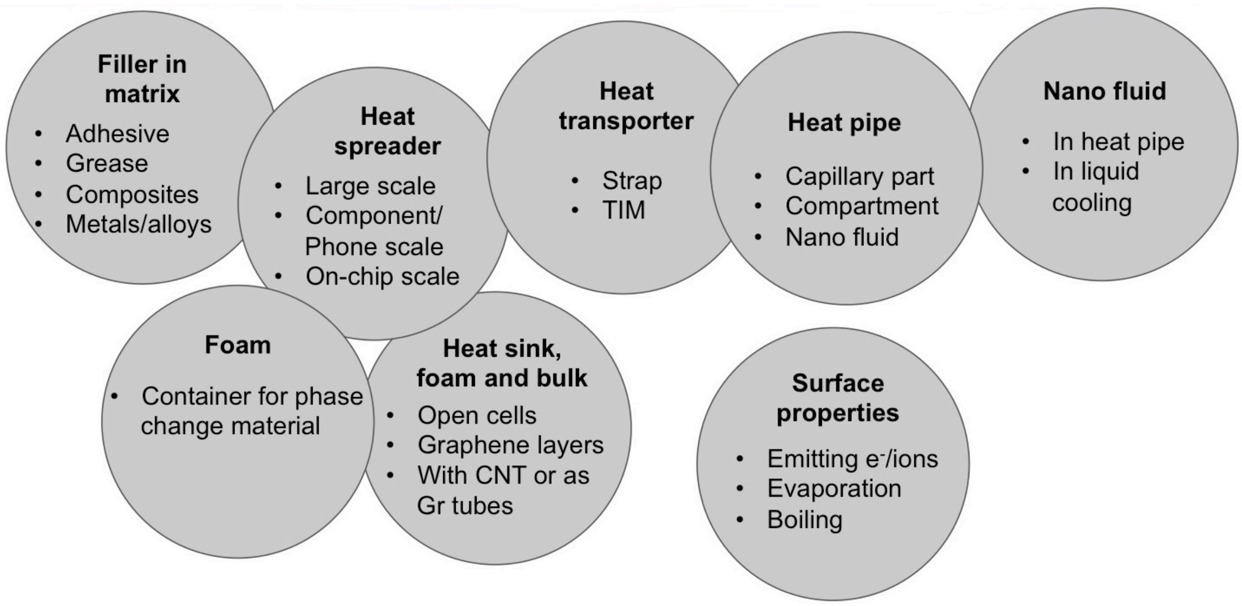


Figure 3. Research areas within thermal management

Internationally, there are few products that use graphene for thermal management. There are approximately two manufacturers of graphene in adhesives for component bonding, a handful of suppliers of phone-scale heat spreaders and thermal straps for heat transport, few starting venture tests with industry in component thermal interface materials (TIM), while graphene heat pipes for component cooling have not yet reached the market. Furthermore, the only graphene-based nanofluid for heat transport is for the oil industry and there is just one manufacturer of commercial graphene foam, but no application e.g. for thermal energy storage or as a heat sink on chip, component, printed circuit board or system level.

Looking specifically at Sweden, it is clear that there are activities in most of the areas shown in **Figure 3**, primarily using liquid exfoliated pristine graphene and functionalised graphene. TRLs range from 1-2 up to 7, and funding required to reach TRL 6 (demonstration in relevant environment) is mostly 2-5 MSEK. There are also some issues that funding alone cannot resolve, see the previous section on the graphene drawbacks.

Graphene as a filler material has proven to be much more difficult to achieve than anticipated a decade ago. Today the TRL is around or just above 2-3. There are two actors in Sweden in this field; *Nolato Silikonteknik* and to some extent *SHT*. *Graphmatech, Nolato* and *Ericsson* are partners in developing graphene filler in silicone based adhesives ("*Aros Graphene*-baserade termiska interfacematerial").

SHT works with heat spreaders and straps. A thermal conductivity of 3200 W/mK has been produced and measured for µm films, a number only achievable in graphene. The TRL is 3-5 with a plan to demonstrate a TRL 6 product in 2020. *SHT* works with *Chalmers* and *Saab* on a project on thermally conductive graphene film with radar and laser applications ("Värmeledande grafenfilm i termiska band och värmespridare för användning i radar och laser"). *Huawei, Aninkco* and *KTH* also work with graphene films as a heat spreader in a plate; "Graphene-enhanced heat spreaders for electronics", which is at TRL 3. This technology competes with the established k-Core™ graphite plate from *Aavid/Thermacore Ltd*.

Thermal interface materials have come farthest amongst graphene products. *SHT* and *CTH* have collaboratively reached TRL 7 with novel customer contracts. By contrast, graphene heat pipe research remains at low TRL both globally and in Sweden, where *Chalmers University of Technology* has reached TRL 2. Chalmers also studies graphene as a filler in liquids, where TRL 2 has been reached. Also, Australian-based *FlexeGraph* aims to establish itself in Europe and plans for technology development in Sweden (TRL unknown).

Foamed graphene has the prospect to solve one of the big challenges in electronics cooling; how to store heat at component level during power bursts. It has been prepared and displayed at *Chalmers* and the work continues (TRL 1-2).

Heat sinks with graphene can be made from foam or bulk. Chalmers has heat sinks on display and on-going research at TRL2.

Lastly, still in idea stage, *APR Technologies AB* is looking to use the surface properties of graphene to stimulate a flow in a medium, thus creating convective cooling in an enclosure.

Potential Applications and Impact for Sweden

Given a five-year perspective, the first product on the market will probably be graphene TIMs. In five years there could also be heat spreaders on component and phone scale level as well as thermal straps, provided that they show benefits compared to graphite. Heat spreaders encapsulated in metal are also likely to be available if there is a big enough market for this technology. Heat spreaders could open up novel electronics in 5G telecom, avionics, power electronics and space. There could be adhesives with graphene filler material, although a breakthrough would probably be necessary. Heat sinks from graphene are technically more likely to be developed, but the market is saturated in very cheap, good-enough product alternatives.

In ten years there could be breakthroughs in all above technologies. A crucial factor would be that the graphene products are cheap enough and can compete with alternative solutions that are developed simultaneously. In parallel, progress is made in the competing fields of diamond, SiC, ordinary heat pipes, vapour chambers, mini fans, 3D-printed structures, liquid cooling etc. It will be important to monitor competitor performance on the current and future market to judge whether to invest or decide that a particular graphene product will not be attractive to an end-user.

Future challenges that remain are the scaling up of production volume, and availability of well tested, high quality graphene raw material and graphene with few defects. People interviewed for this report prefer a Swedish supply chain of reliable players if possible. The use of graphene surface properties to create medium flow is interesting but the outcome is as yet unknown.

Technology and Design Challenges

Swedish graphene products face a number of issues until they reach the market. The most common opinion is that it hard is to get predicable quality of the material, ensuring that graphene-based TIMs, straps, adhesives, heat spreaders etc. fulfil normal 6σ requirements from industry. Reliable partners are a must, preferably a full Swedish supply chain. Currently purchased graphene is usually flawed or defective, with high contact resistance, and as a result does not perform well. A second concern is that scale-up methods must become robust and cost competitive. High volume production is always harder than production of laboratory samples.

Another issue is the poor dispersion properties. Graphene functionality excels in the material's stand-alone state, but as soon it has to interact with other materials or in multi-layer films, graphene's key properties decline.

Approximately 50% of survey answers claim that there are obstacles that cannot be overcome just by more funding. Fundamental graphene properties remain to be fully investigated, making it risky to invest in some projects.

Other Issues and Challenges

An observation is that material specialists and experts in electronics cooling are two separate populations whose competence rarely overlaps. Few Swedish people have both skills. Non-traditional networking between these two groups, across the community, could help matters.

A wish from the government-funded entities is to help the formation of a Swedish eco system in graphene and thermal management of electronics. Furthermore, they request a common arena for graphene demos that originate from academia, SMEs and larger companies.

An obstacle is financing the development work needed to reach e.g. TRL 6. Most responding entities of the survey need 2-5 MSEK to get there. Meanwhile, it is difficult for larger companies to put up internal funding and allocate key competence for low-TRL projects that require RnD.

Finally, pricing targets probably need to be fierce since competing technologies and materials are often cheap and are expected to remain so in the future.

General Recommendations

Many services that the partners ask for are already addressed by *SIO Grafen*. There is a newsletter, a community and regular workshop to find ideas and for networking.

In spite of the relatively small size of Sweden, some Swedish players view themselves as competitors. They apply for the same government money and company information that would aid Swedish progress is not shared in the community.

Academia and SMEs constantly ask for more involvement from large industry end-users in order to see their needs and problems that need to be solved. However, the internal industry budget for low TRL work is very small. As a consequence, few larger industrial companies are involved, which leads to much more technology push than market pull. This imbalance could be mitigated if the funding agency abandons the 50% in-kind financing rule.

Other Technology Areas

Graphene is a multi-faceted material, and besides the areas of printed electronics, cooling, high frequency and sensors, graphene is also of interest for the following electronics areas:

Because graphene is optically transparent and electrically conductive, it has been suggested as a good **transparent conductor** material that may replace ITO. So far large-area CVD graphene has been demonstrated as feasible for touch screen applications, while thin films of graphene flakes are good dissipative materials.

The large surface area, high electrical conductivity and excellent chemical stability also make graphene promising for energy storage. Relevant to electronics, miniaturised supercapacitors or **micro-supercapacitors** have great potential for the application of on-chip energy storage units in miniaturised self-powering systems.

Another application area where Sweden is present is within the field of **photonics**, where Ericsson in Italy is involved in creating graphene based optic modulators for data transfer. Work is performed within the *Graphene Flagship* project.

Graphene-polymer composites should also be good barrier materials for **packaging of electronics**. In fact, **graphene as a part of cellulose composite papers** is a field that is increasingly explored today. Considering the production capacity of paper making facilities, and the importance and strong positioning of the paper and pulp industries in Sweden, developments in this direction are expected to gain momentum and have an impact on both the materials supply side and on applications. Further, the field of cellulose-based graphene composites and paper and board comprising graphene can be related to and augmented by techniques to print graphene to form large-scale devices.

Graphene may also be used in **green tech research, for purification of water and air**. Water desalination and other purification processes using graphene as an active material have been demonstrated. Since large scale devices for abatement of water and air purification must be manufactured by low cost deposition processes, printing and coating processes are likely to be important in these emerging green-tech fields, so Swedish ventures could play a role.

Lastly, graphene may be used in **battery technology**, initiated by demands from the automotive industry and environmental requirements. Graphene can, due to its material properties, play a vital part in the battery technology as electrode material. It has been shown that graphene or graphene oxide can increase performance of batteries, and there is a large industrial interest for this field in Europe. This is also true for Sweden, due in part to mining and graphene production possibilities.

Mapping to the European Roadmap (Hammersberg)

Introduction

This is a summary of the ongoing work within the European *Graphene Flagship* and an outlook on the patent landscape for graphene electronics in Europe. It does not encompass all ongoing work within the area of electronics, graphene and Europe. However, the *Graphene Flagship* contains 150 partners in academia and industry, and 70 associated partners in 23 countries. The overview of the *Graphene Flagship* is therefore a good indication on the technology focus areas in Europe. However, there is industry, start-up companies and established companies outside the *Graphene Flagship*. The updated roadmap for the *Graphene Flagship*, ”Graphene and Other 2D materials Technology and Innovation Roadmap Version 3”, will shortly become publicly available.

Challenges in the fields of electronics, sensors, photonics, spintronics and waferscale technologies

Some questions always need to be addressed, regardless of the specific technology field:

- Added value to the application (market point of view):
    - New functionality vs. costs and risks
    - Better performance and system advantages vs. costs and risks
- Competition with existing mature semiconductor systems
- Compatibility with existing process and manufacturing techniques
- Production investment costs
- Producibility, repeatability and quality
- Scale ability and production cost
- Reliability
- The value chain (all links need to be willing to invest)

In most ventures, supply chain partners collaborate cross-borders. This implies that the above questions need to be answered not just for Sweden, but also on the European level in order to get a sustainable value chain for the implemented technologies.

A general aspect on material quality is also the work on material standardisation and classification. This topic is especially urgent for graphene flake products, in order to specify the material quality using a set of common rules and units. This work is ongoing in both Sweden and the rest of Europe. For wafer-based technologies, material homogeneity and other material properties and manufacturing processes are of major concern in the efforts to reach scalability. For example, the existing 2D material low temperature transfer techniques have solved integration issues with the rest of the semiconductor technology, incl. to CMOS, but the question is now if these techniques can be used on industrial scale considering the technical and quality requirements and economical aspects of running device production.

Research Areas

The research ambition concerning electronics and photonics in Europe covers a broad field. The majority of these can be considered fundamental technology research areas but there are also areas that are getting closer to commercialisation. Research areas in Europe are:

- Electronics: cross-cutting areas
  - Wafer scale integration
  - Interconnects
  - Thermal/heat dissipation material
  - Barrier material
  - Process and process equipment
  - New transistors beyond CMOS
- Telecommunication and photonics
  - Photonic networks
  - High frequency
  - Photonic devices
  - IR photodetectors
- Sensors
  - Pressure sensors
  - Magnetic sensors
  - Mechanical force/stress and strain sensors
  - Gas/chemical sensors
  - Biosensors
- Flexible and/or printed electronics
  - Flexible transistors
  - Flexible HF electronics
  - Flexible sensors and photonics
  - Printed electronics and conductive inks
  - Flexible conductors and smart textiles
  - Flexible conductive and transparent films
  - Flexible memory and batteries
  - Super capacitors

High potential focus areas

Several focus areas stand out as areas of high potential in Europe. Sweden, as part of Europe, contributes to several of these, both from academia and industry. The following focus areas/projects in Europe should be especially mentioned due to both scientific reports and technological maturity. The potential of the technologies in these areas/projects has been demonstrated but most technologies need further investments or partners to commercialise or scale up. From this perspective, most technologies are 3 to 9 years away from commercialisation. High potential areas/projects are:

- Photonics network devices, switches and modulators
- High frequency and wireless communication devices

- Biosensors
- Pressure sensors, on various substrates incl. flexible
- Flexible high frequency devices
- Gas and chemical sensors, electronic and photonic based
- Magnetic sensors, on various substrates incl. flexible
- Mechanical force/stress/strain/mass sensors on various substrates, incl. flexible
- Photonic SWIR detectors and cameras
- Printed electronics and conductive ink
- Thermal management
- Super capacitors
- Wafer scale technology
- Incipient foundry services for graphene electronic technologies

There are areas where Sweden has a strong position, for example some sensor applications, thermal management and high frequency electronics. Swedish ventures should pay more attention to photonic application areas, where both research and industry are strong in the rest of Europe. Super capacitor technology is also a strong field in Europe, with industrial applications close to commercialisation and with strong investments. The incipient foundry service in Europe also offers possibilities for Swedish initiatives and short circuits many steps in process development when new concepts for graphene-based devices are explored.

Industrial development

Mapping the industrial activities in new technologies is difficult, as the information related to the development in industry is often confidential. One way is to look into patent databases, but the difficulties to perform database analysis varies from field to field, depending on ability to patent and otherwise protect the ideas in the technology. For this reason, material processing or software implementations are often very difficult to find using patent database analysis. Hardware solutions on the other hand, such as electronic devices, are more often protected by patent applications.

Here we present patent application data for electronics, sensors, photonics and spintronics based on graphene, originating in Europe. The overall patent situation in April 2019 for applications with priority in Europe may be summarised as follows: [1]

- Electronics: 550 patent families (221 granted, 215 pending, 114 dead)
- Sensor: 490 patent families (189 granted, 199 pending, 102 dead)
- Photonics: 240 patent families (85 granted, 92 pending, 63 dead)
- Spintronics: 5 patent families (3 granted, 2 pending)

In all cases, with the exception of spintronics, which is a less active area, intellectual asset protection is of growing interest. Also noticeable is that well-known industrial companies own many

[1] Patent searches and graphs were made by Camilla Johansson at CIT using *Questel Orbit*.

of the patent families. Please note that some overlap exists among the grouped patent applications above due to overlap in words used in the claims in said applications.

European patent applications in the field of graphene electronics

NB See Appendix II for patent data on graphene use in the sub fields of sensors, photonics and spintronics.

Figures 4 and **5** show the present patent state, and historical patent data, respectively. Interestingly, both research institutes as well as number of well-known companies file patents within graphene electronics. Moreover, looking at the historical data, there is a growing interest concerning protection of technology developed.

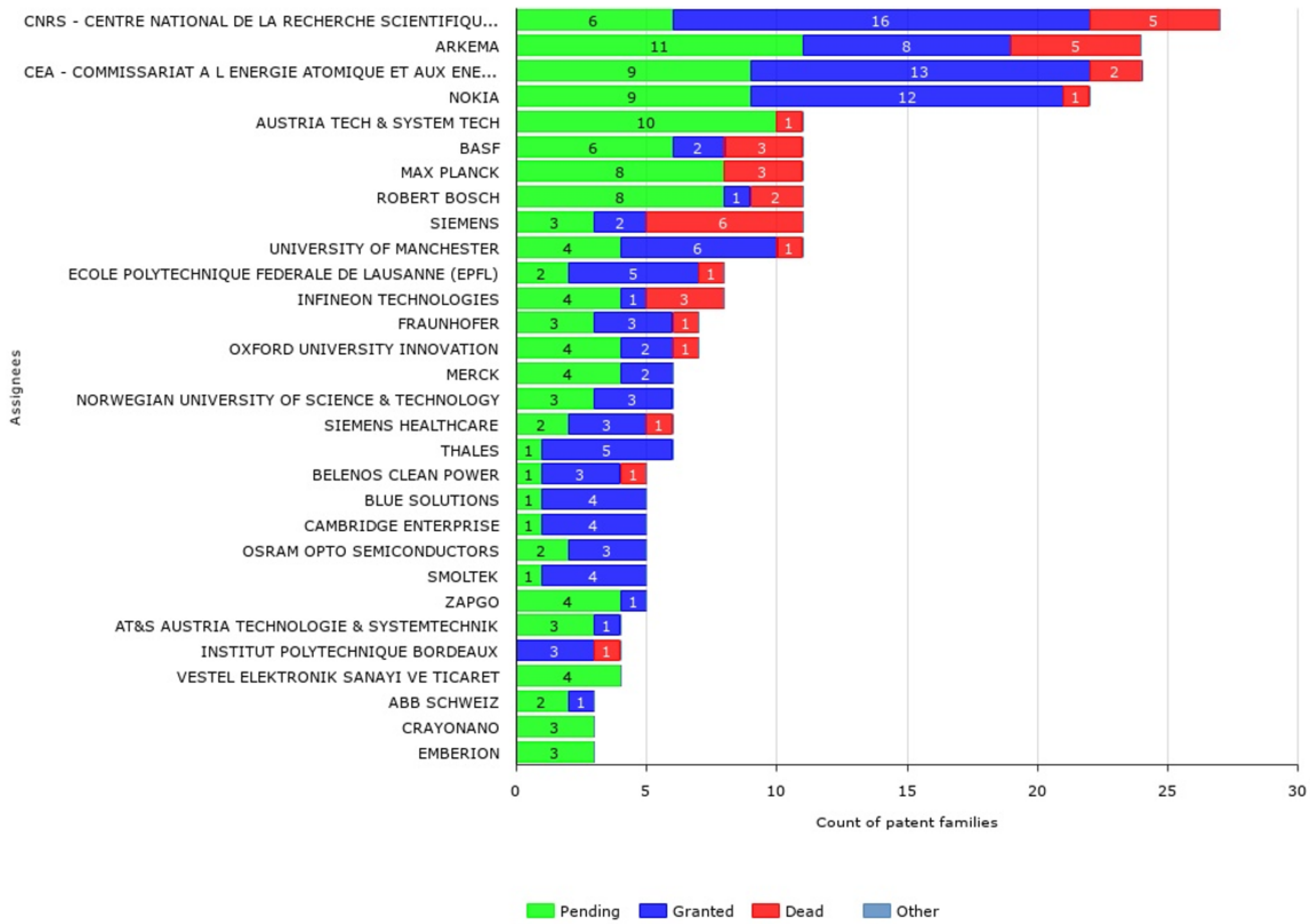


Figure 4: Top 30 European applicants filing applications in the area of graphene and electronics. Data generated in April 2019.

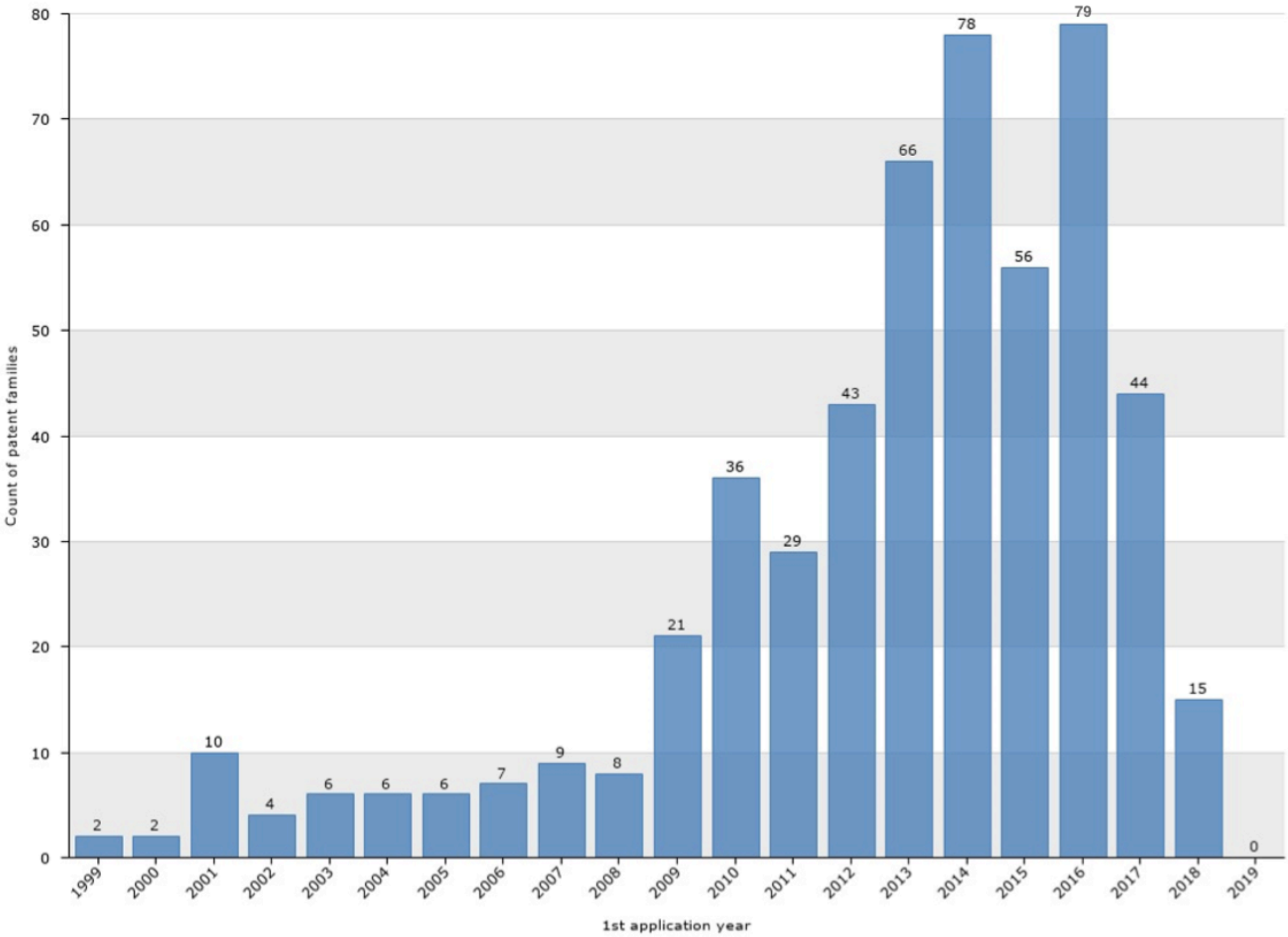


Figure 5: Number of patent applications filed per year in the area of graphene and electronics, with priority in Europe. Note that statistics for the last 18 months is affected by the optional delay in publishing post-filing.

Conclusions

It has been well demonstrated by both academia and industry that graphene is promising for a large variety of sensor applications to create significant economic value and societal benefits for Sweden. Graphene sensors' excellent sensitivity and response time have potential to generate market advantages, while the selectivity needs to be improved. The wide spread of graphene sensors awaits reliable supply of high-quality yet cheap graphene materials, and essential progress in the development of scalable processing techniques. State-of-the-art performance is mainly generated in academia. To expedite the commercialisation of graphene sensors and maximise the value for Sweden, the participation and substantial support of Swedish industry are of crucial importance.

On the printed electronics side, one can observe that printable compositions of graphene inkjet inks have been developed in Sweden, mainly at academia. Further, there is a source of liquid exfoliated graphene that can be formulated into coatings and printing inks. On the other hand, one can observe that there are still no products commercially available, neither as printing inks or printed products.

Within high frequency, due to the excellent linearity of graphene field effect transistors, there is ongoing academic research work to assess graphene technology for applications within wireless high datarate communication for future mobile systems with a leading Swedish telecom company. In addition, graphene is a promising technology for future flexible high frequency electronics such as imaging sensors, up to THz frequencies.

The outstanding thermal conductivity of graphene is attractive for used in thermal management. The material has possibility to find use in electronics, which face challenges of increasing density and higher total heat power. Therefore, industry is on the lookout for new materials and technologies that pave the way for more compact devices. However, a strong competitor to graphene is graphite, which has already present on the market.
The thermal sub categories of adhesives, heat spreaders, thermal interface materials, straps, heat pipes, nanofluids, foams for heat storage and heat sinks are promising fields at various stage of maturity. Swedish players work to some degree in most of these fields. Outside Sweden, first attempts to sell products on the market have been made for most of the sub categories. From Sweden the first marketable products are, or are expected to be, thermal interface materials and heat spreaders. There is active collaboration between academia, SMEs and end-users. Sweden is also involved in international collaboration at different levels.

General Recommendations and Next steps

In grant applications, we strongly recommend the **use of FoMs prior and post funding to evaluate graphene technology deliverables**. Not only does it provide a quantitative measure of the state of graphene electronics, but allows for easier evaluation by *SIO Grafen*.

Sweden has several ongoing graphene ventures that are cutting edge or state-of-the-art. However, we note that there is competition between Swedish players, which decrease progress. We hypothesise that **if collaboration between Swedish parties was an explicit requirement in funding applications**, progress might speed up.

For graphene in printed electronics, it is recommended that **financial support** for product and process qualifications as well as access to facilities for scaling production are provided. This is necessary in order to bring printable compositions to market from academia.

Financial support is also a limiting factor in sensor development. This limits availability of high-quality graphene materials. It is strongly recommended that funding bodies strengthen the support of research on scalable synthesis of high-quality graphene materials by offering long-term grants (over 3 years) to complement to present, shorter duration grant forms.

In thermal management there are almost a dozen technologies that could become state-of-the-art in cooling of compact devices in the future. Most research and development work towards that goal still remains to be done and requires governmental funding. Individual projects need funding (2-5 MSEK) in order to present demonstrators.

State-of-the-art sensors are mainly demonstrated in academia. Further **encouragement of academia-industry cooperation and support of spin-offs from academia** are highly recommended. Magnetic sensors have been developed independently by two academic players and both have attained high technical maturity (shipped products). It would be reasonable to support this field by offering **help with market identification and financial support for further business development**. High TRL and high potential fields need to be prioritised.

Interviewees have pointed out the importance of **a Swedish eco-system and full supply chain**, particularly with respect to electronics cooling with graphene. There are also requests for a **common arena for demos**. Such an area may preferably contain both prototypes and contact details to Swedish players. Concrete case displays may favourably be combined with educational resources and links to relevant academic papers and white papers published by Swedish universities, institutes and companies. A demo arena could be virtual, which would aid outreach and be cost effective. This would not only aid technology transfer and link parts of the Swedish eco-system both internally and to the world at large, but also establish Sweden firmly on the global map of graphene use in electronics.

We foresee that competition can be an obstacle to such an open demo arena, so the high rewards associated with participation and contribution need to be clear. Rewards may include large marketing opportunity, academic citation, help with IP strategy, physical demo touring opportunity and a highway to the *Graphene Flagship* eco-system. Success stories following arena launch, e.g. gained partnerships and international commercialisation, should be celebrated.

Academia and SMEs require **robust and reliable quality of purchased raw material** on the market. **Material standardisation and classification** is an urgent matter. We should strengthen research on graphene material synthesis and identify reliable material suppliers. Also, it is important to promote initiatives related to improving the yield and reliability of components. This could be a task for government or institutes. We welcome the new *ISO* standard for graphene properties and measurement techniques [see ref. 12] as well as the joint *SwedNanoTech*, *SIS*, *RISE* and *Chalmers Industriteknik* project on standardisation and best practice. Alternatively, or in addition to these efforts, supplier ranking, material characterisation and best practice could be identified through crowd sourcing, as part of the graphene electronics demo arena or a similar public platform. In the national survey performed as part of this report, participants willingly shared challenges related to achieved result with respect to promised quality.

The research on European level covers in many cases areas that are not covered by Sweden alone, such as; photonics, pressure sensors, some types of gas sensors, super capacitors, smart textiles et c. It is therefore **vital that Swedish industry take advantage of networks and opportunities in Europe** that is created through programs such as *the Graphene Flagship*. In many cases, research groups in Europe are looking for industrial partners with ambitions to explore their technology. Such industrial partners could be Swedish. Europe is also large enough to make it possible to find partners to build and invest in the whole value chain, starting at material suppliers, through device manufacturers to system users. In practice, this development could be encouraged by promoting initiatives where the complete value chain ‘material growth-components-systems-commercial applications’ is present. A prerequisite for this is continued and **strengthened information and communication channels regarding existing eco-systems and supply chains, both nationally and internationally.**

These recommendations as well as future prospects are illustrated overleaf.

Next steps

Quality

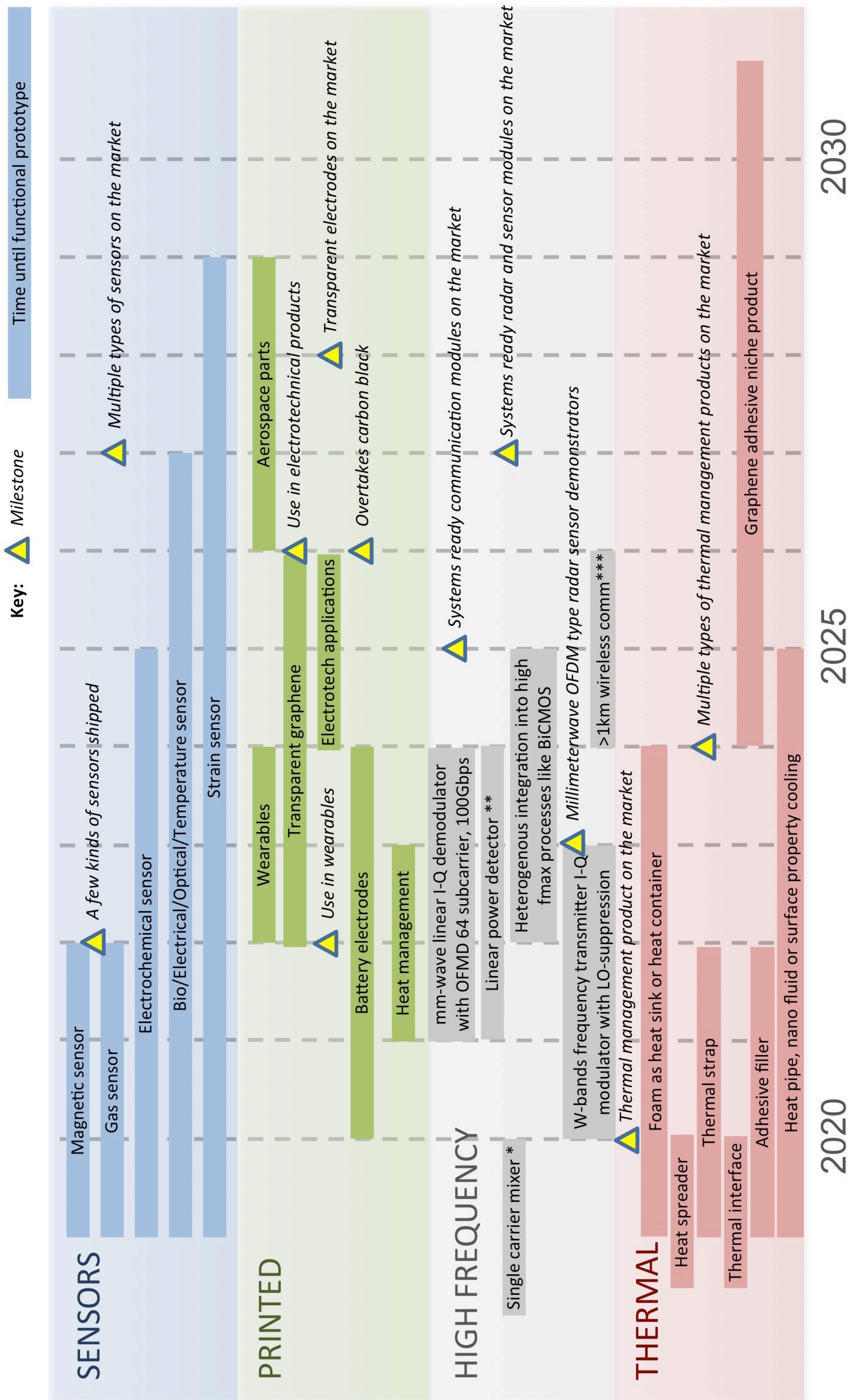
- Establish material standards
- Use FoMs before and after granted awards for evaluation purposes
- Investigate best practice (crowd-source)
- Identify reliable suppliers (crowd-source)

Funding

- Scale-up facilities
- Testing materials and processes
- Full supply chain
- Business development
- Majority requires 2-5 MSEK to reach TRL 6

Collaboration

- Establish a demo arena
- Collaboration as a requisite for funding
- Investigate and inform about the national and international eco-system and supply chain



* W-bands frequency (75-110GHz) single carrier mixer with conversion loss <15dB
** Millimeterwave (100-200GHz range) high speed linear power detector with >20 Gbps datarate in OOK/PAM4/PAM8
*** Long distance (>1km) wireless communication system demonstrators for W-band or higher frequencies

VISION 2030

SENSORS
- Multiple types of graphene sensors on the market
- State-of-the-art sensitivity and selectivity
- Operation in harsh environments
- Compatibility with emerging manufacturing techniques (e.g. 3D printing)

PRINTED
- Adhesives used in electronic microassebly
- Electrodes used in battery manufacturing
- Used as active material in aircraft parts

HIGH FREQUENCY
- Commercial products in the area of millimeterwave and THz such as radar sensors and high datarate communication are available on the market for demanding applications where linearity is important.

THERMAL
- Several Swedish or Swedish-based thermal management products integrated into electrical and mechanical systems
- New electrical products are made possible
- Cooling technologies have found their market niches

RECOMMENDATIONS

- Supported development of bilayer graphene on SiC and flexible substrates
- Business development
- Collaboration necessary for funding
- 2-5 MSEK external funding
- Information on eco-systems and supply chains
- Crowd-source good suppliers
- Facilities for scaling up
- Promoted Swedish supply chain and community
- Strengthened academia-industry collaboration
- Supported application-oriented R&D
- Open environment for printed graphene formulation and scaling
- Material standardisation and classification
- Use of standardised FoMs
- Network with European resorces
- Projects and efforts towards reproducibility
- Establish the Demo arena
- Encouraged national collaboration
- Establish full Swedish supply chains
- Stable supply of low-cost high-quality graphene raw material
- Open test environment for transparent conducting coatings
- Crowd-source best practice

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Credits

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Peter Nilsson, *APR Technologies AB*

Carina Zaring, *Aninkco AB*

Appendix I: Explanation of terms used in high frequency electronics and electronic cooling FoMs

Responsivity measures the input–output gain of a detector system. The responsivity of a photodetector is usually expressed in units either amperes, or volts per watt of incident power. For a system that responds linearly to its input, there is a unique responsivity. For nonlinear systems, the responsivity is the local slope. Responsivity is a function of the operating frequency; the units are volt per watt (V/W or amperes per watt (A/W). The most common way is to express the responsivity as V/W either as open circuit or at a specific resistive termination, often 50 ohm. If the detector is used as a demodulator for high data rate detection it is usually terminated in 50 in order to achieve high bandwidth. The responsivity is lower for such an operation case.

Conversion loss measures the input–output gain of a frequency converter (mixer). It is usually measured in dB. In a passive mixer, the output power is lower than the input power so the gain is always negative in dB. The conversion loss is the negative of the conversion gain (in dB) so it is always positive for a passive mixer. The conversion loss should be as low as possible in order to not deteriorate the signal to noise ratio of the system. A good mixer usually has a conversion loss between 5 to 10 dB. In the 'Core2' and 'Core3' of the *Graphene Flagship* project, *Chalmers* is working on decreasing the conversion loss to close to 10 dB.

Linearity: Linearity is an important figure of merit for circuits such as amplifiers, power detectors and frequency converters. Nonlinearities in components will distort the input signal and in addition create spurious signals at unwanted frequencies that will deteriorate the system performance. An often used *FoM* for linearity is the so called third order Intercept Point which is defined as the Input or Output power where the power of the wanted signal is equal to the power of a third order mixing product for an input signal consisting of two sinusoidal signals with equal power, close in frequency. This power can be referred to either the Input or the Output and is called IIP3 or OIP3 respectively. They are measured in power (dBm), and the number should be as high as possible.

Thermal conductivity: Measured in W/mK and is a property of a (solid) material of the ability to conduct power via phonon transport or by the electron gas. Thermal conductivity is always temperature dependent as well as hard to measure for highly conductive thin films, i.e. exactly the case with graphene. Ranges from 0 in vacuum, 0.026 for still air, 1 for plastics, 50-400 for metals, and up to 5300 for graphene.

Thermal resistance: A metric often used by mechanics and electrical engineers looking for useful data in catalogues. Measured in the unit K/W and can easily be compared between different candidate components, thermal interface materials, straps etc.

Appendix II. European Patent situation for the electronics fields sensors, photonics and spintronics

European Patent applications in the field of Graphene and Sensors

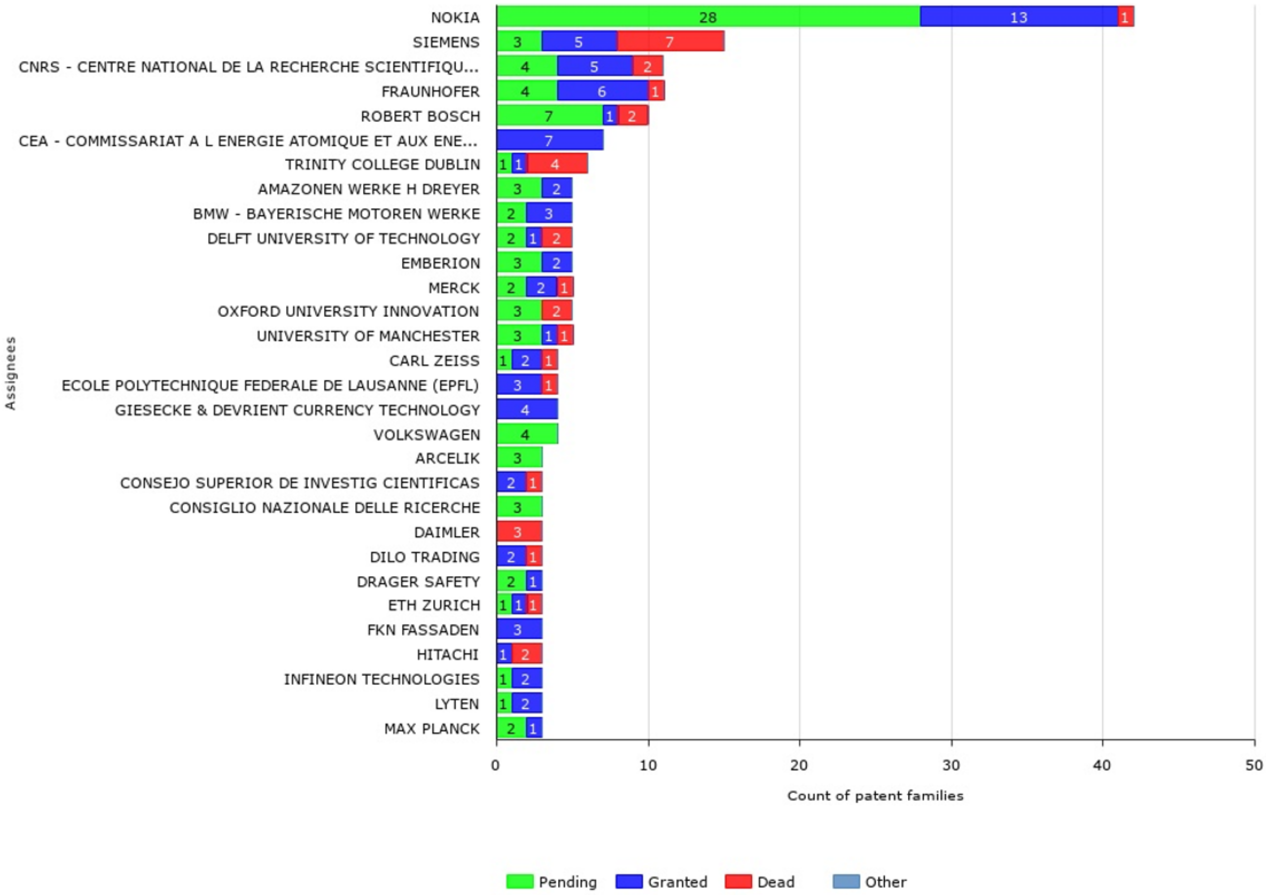

Figure 6: Top 30 Europe organisations/applicants filing patent applications in the area of graphene-based sensors. Both research institutes and well-known companies occupy the list. Data generated in April 2019.

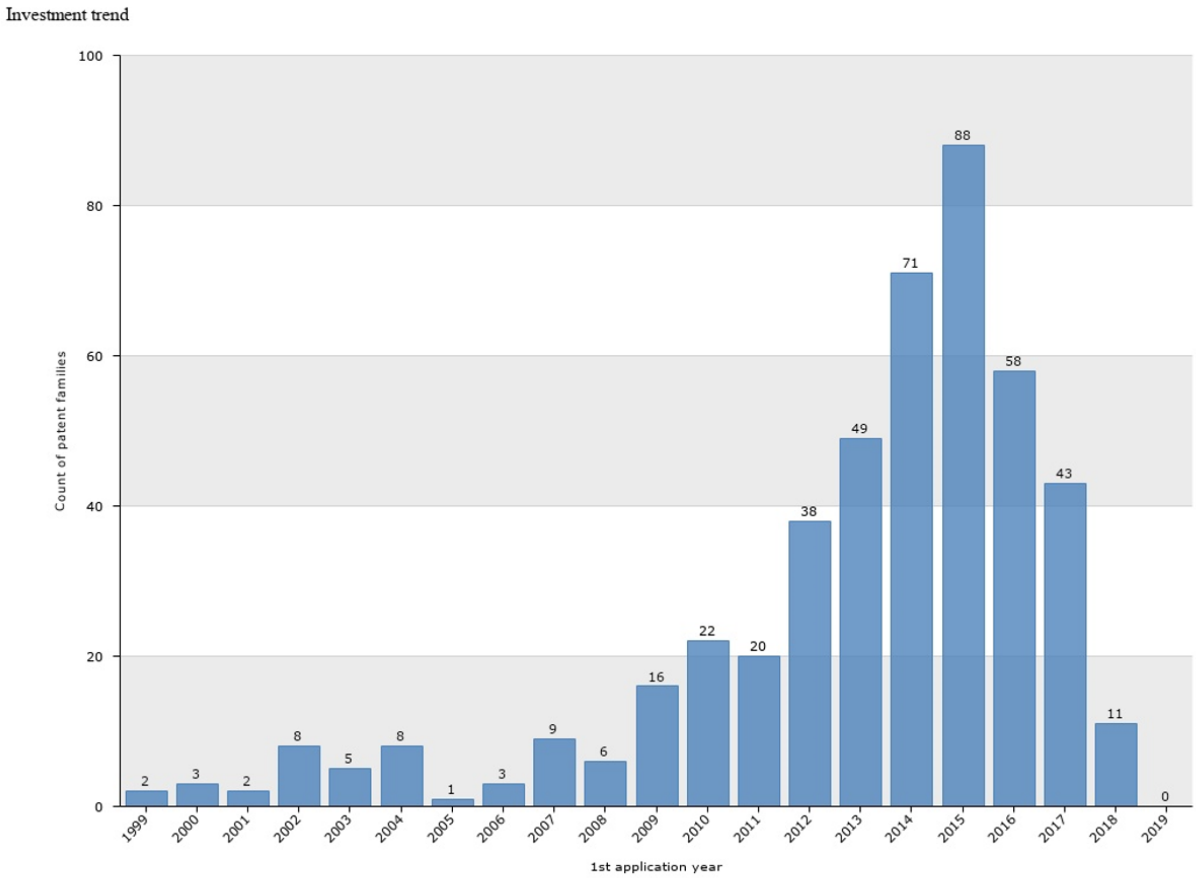

Figure 7: Number of patent applications filed per year in the area of graphene and sensors, with priority in Europe.

European Patent applications in the field of Graphene and Photonics

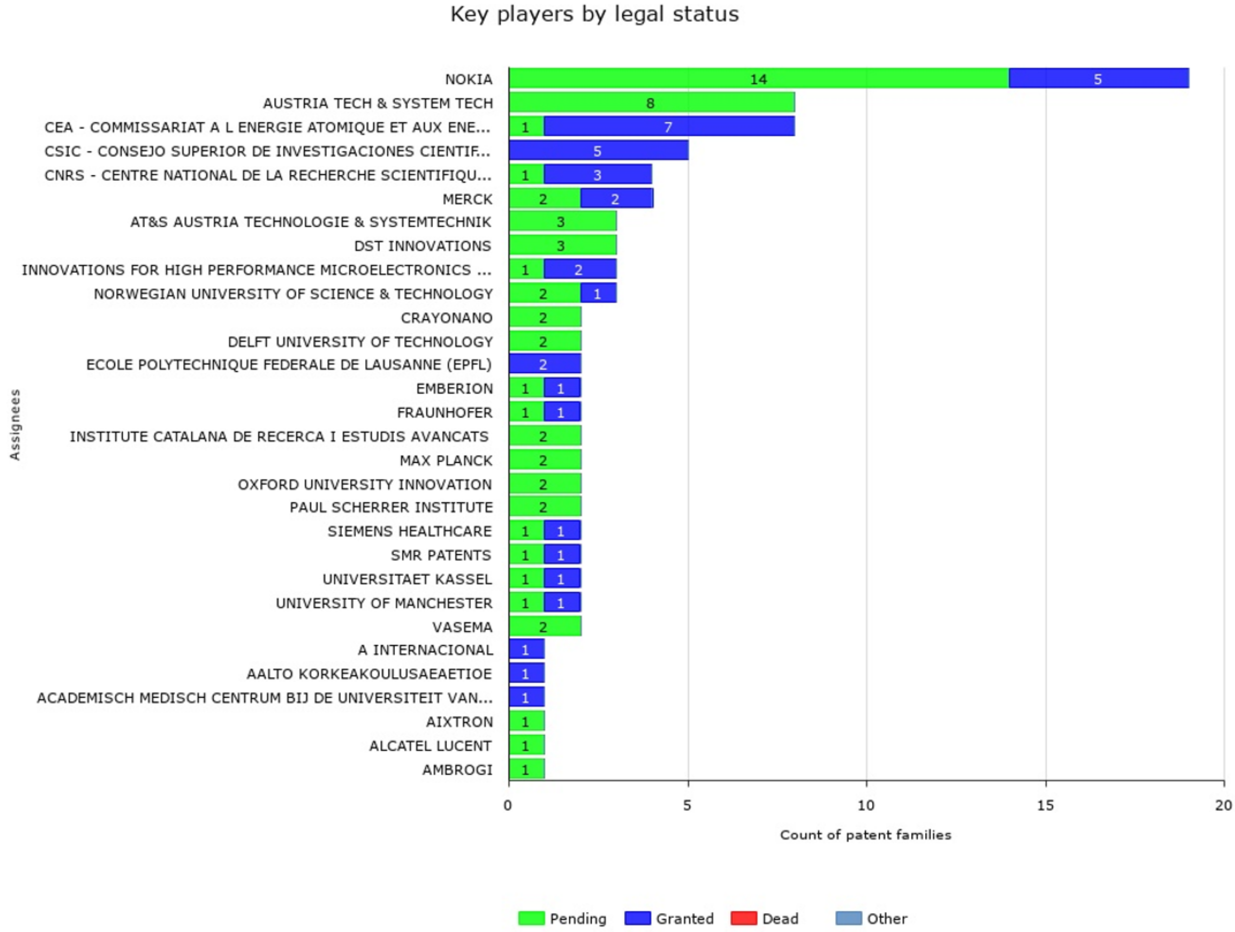

Figure 8: Top 30 European patent applicants in the area of graphene and photonics (including modulators, detectors, cameras and transparent contacts). Data generated in April 2019.

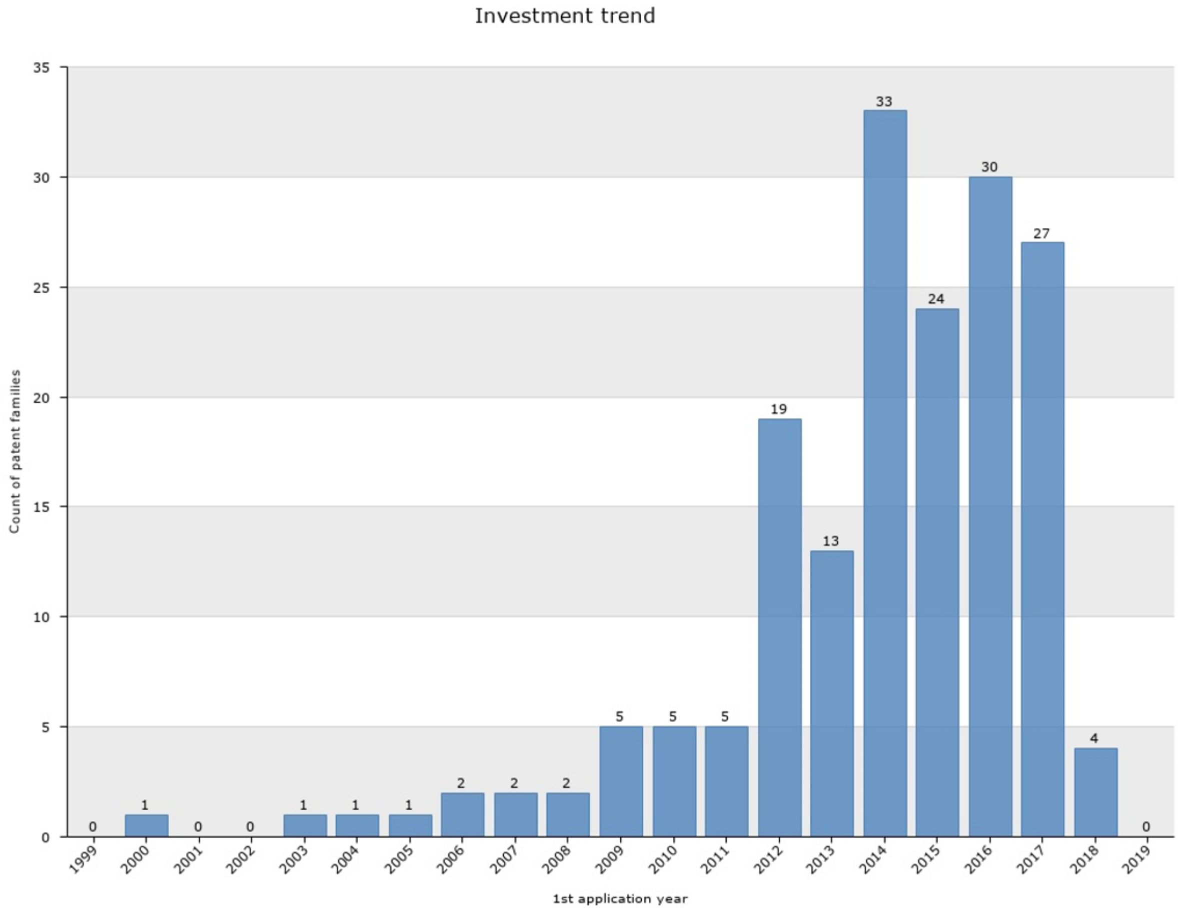

Figure 9: Number of patent applications filed per year in the area of graphene and photonics, with priority in Europe.

European Patent applications in the field of Graphene and Spintronics

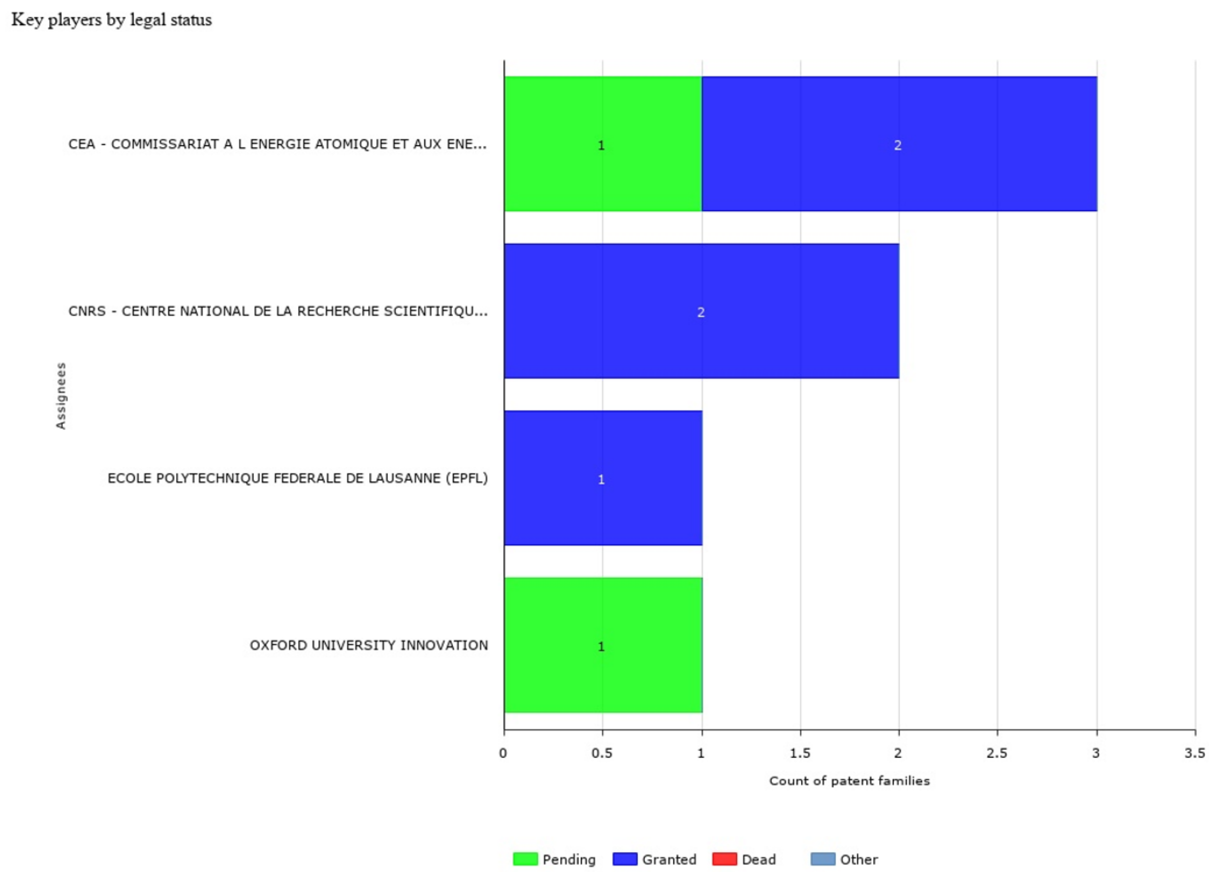

Figure 10: Top 4 European applicants filing patent applications in the area of graphene and spintronics. Only research institutes populate the list. Data generated in April 2019.

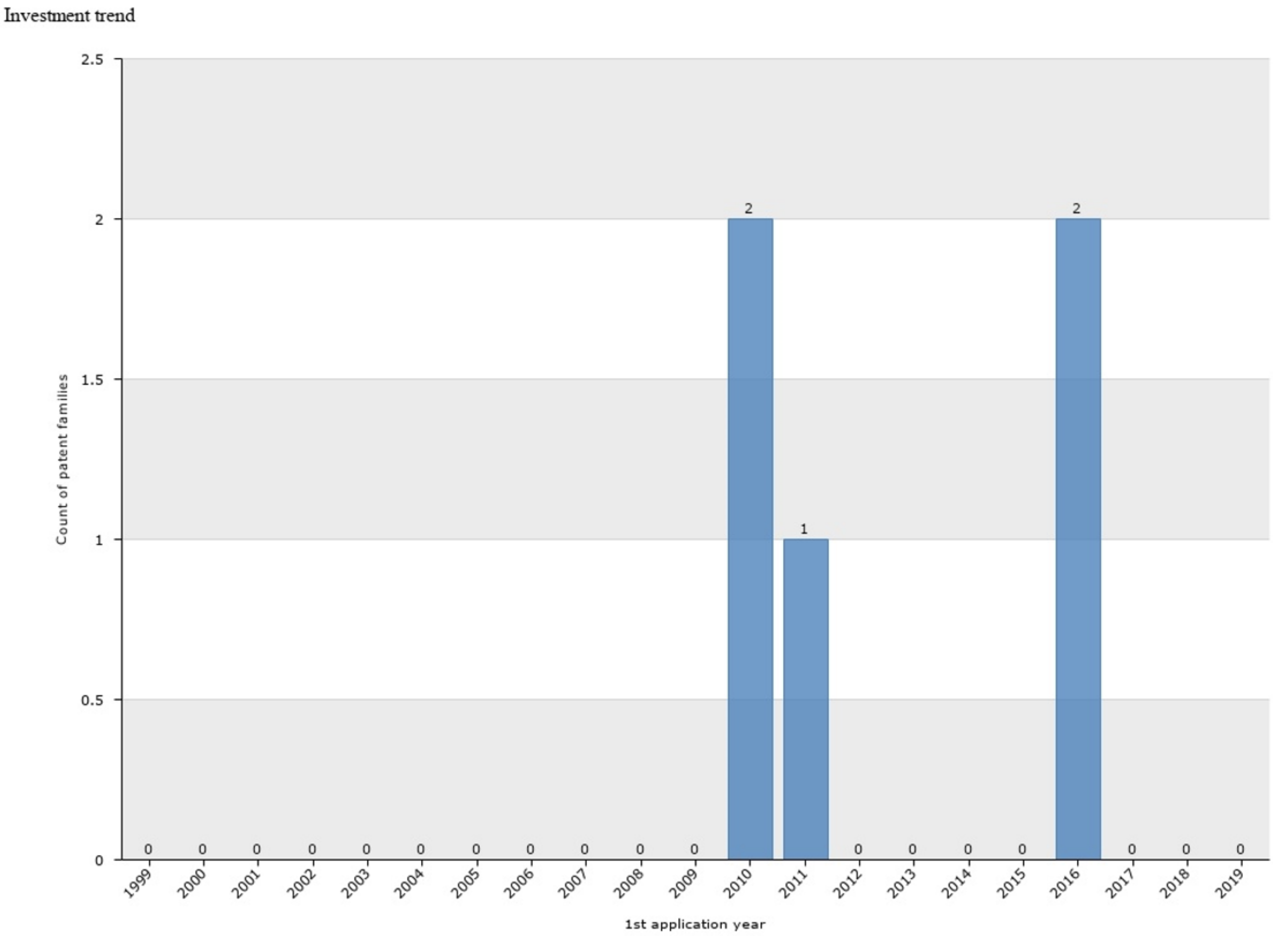

Figure 11: Number of patent applications filed per year in the area of graphene sensors, with priority in Europe.

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