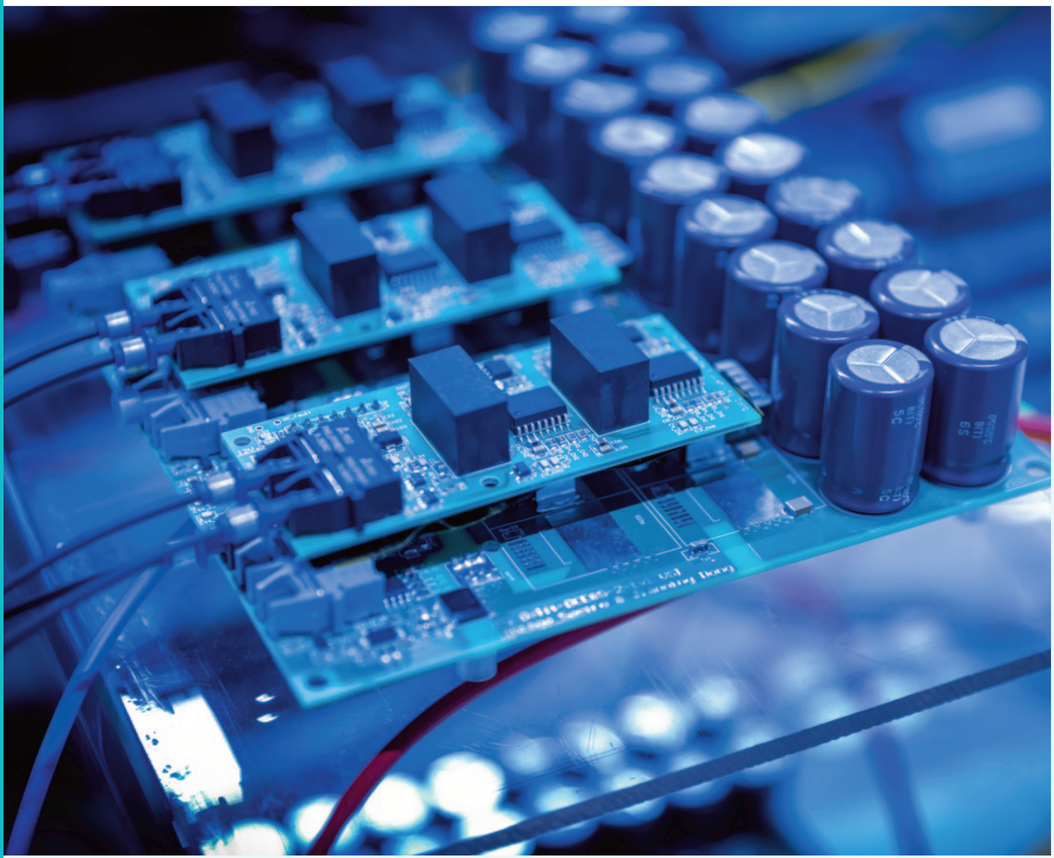
Research Assessment Electrical Engineering 2017-2022

Summaries and case studies of the Self-Assessment report

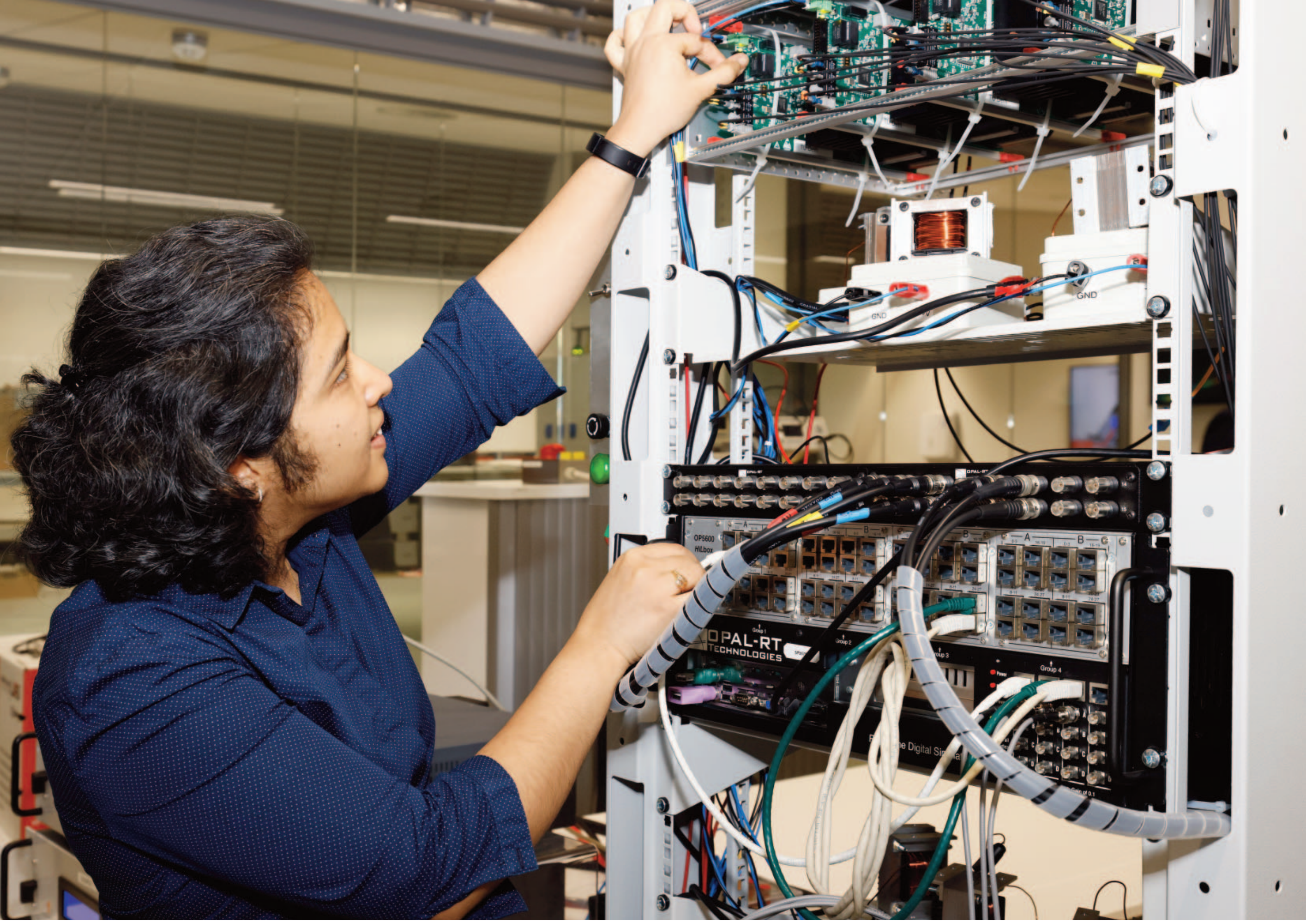
TU Delft

Contents



1

Microelectronics



1.1 Summary

The Department of Microelectronics (ME) aims to develop electronic technology that addresses societal and industrial needs. This involves creating value from knowledge by making it available for economic or societal use, and then, often together with industrial partners, translating it into products, services, processes, and entrepreneurial activity.

Research in the department is organised into three themes: Health and Well-Being, Next Generation Sensing and Communication, and Autonomous Sensor Systems. The research is mainly supported by external funding (about €10M annually) acquired from various national and European funding organizations and from industry. Members of staff have also been successful in attracting prestigious personal grants (3) from the NWO and the ERC.
These research themes have been strengthened by funding from the National Sectorplan, the 4TU and the Delft Technology Fellowship (for top female academics). This resulted in a significant influx of fresh staff (20), mainly at the assistant professor level. Gender diversity has also increased, to about 20%, bringing it in line with the composition of our student influx. To attract top candidates in a competitive job market, all fresh staff received start-up packages.

The department has a strong focus on disseminating knowledge to society. Research results are published in peer-reviewed journals and conferences, most of which are publicly accessible (via the TU Delft repository). In addition, ME staff regularly engage with society by giving interviews, public lectures, podcasts and contributing articles to newspapers.
The department also has a strong focus on transferring research results to industry. Much of the research is done with leading industrial partners, such as NXP, ASML and Infineon, and several part-time professors have been appointed from industry. In addition, three start-ups were launched and over 50 US patents were granted.

The department's research output is of consistently high quality. This has been recognized by several (20+ best paper) awards, editorships, and leadership roles in research-related organisations. There are currently 13 IEEE Fellows and two KNAW members in the department.

In the 2017-2022 period, over 600 MSc students graduated from the department, with 53% going to industry. In addition, over 100 PhD candidates graduated. It is worth noting that most of our graduates remain in Europe and the Netherlands, to pursue careers in academia and industry.

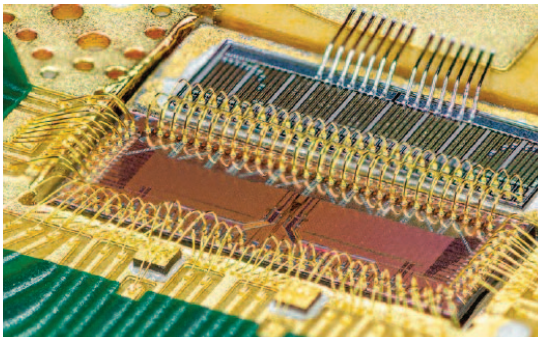
1.2 Case studies

In this Section, provide case studies to highlight parts of ME's research in more detail.

1.2.1 Next Generation Communication and Sensing

Digital RF transmitters

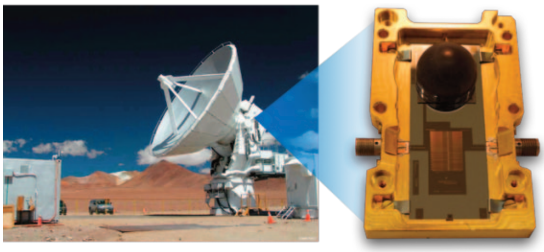
Although our modern world would be unthinkable without wireless communications, the proposed increase in the energy consumption of next-generation networks (5G/GG) is a major concern. In the DIPLOMAT and DRASTIC projects, revolutionary digital RF transmitters have been developed, which can efficiently deliver communications while consuming low static power. The transmit antennas are driven by thousands of switches on an RF power MMIC (monolithic microwave integrated circuit), which are controlled, via high-density interconnect, by a CMOS control chip. In this way, complex RF waveforms can be directly synthesized with superior amplitude and phase control, resulting in record performance in terms of system efficiency, bandwidth, and area. The photo above shows a power transmitter that delivers 10x more power than the state-of-the-art and achieves a record-breaking peak system efficiency of 72.9%.



Having successfully demonstrated this pioneering CMOS-on-MM technology, our next steps will be to include digital signal processing, clock generation, and (AI-based) error detection on the CMOS controller. The technology will then be transferred to our industrial partners, Nokia, Ampleon and Mediatek, who will incorporate it in the base stations of next-generation wireless networks, potentially halving their energy consumption.

On-chip spectrometers for submillimetre-wave astronomy

Studying the history of the early Universe is extremely challenging because much of it is hidden by cosmic dust, which absorbs visible light. DESHIMA, a groundbreaking far-infrared astronomical instrument, has been developed with SRON and funded by the EU (ERC Consolidator) and NWO (NWO-M, Veni/Vidi) to address this challenge. By detecting the bright emission line of carbon ions in galaxies, DESHIMA can measure the cosmological redshift of galaxies that existed 0.6 to 2.0 billion years after the Big Bang. The novel technology that enables this is a superconducting on-chip spectrometer coupled to a leaky-lens antenna. Both were pioneered by the TU Delft/SRON team and are combined on the chip shown in the photograph above.



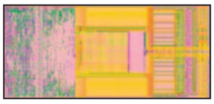
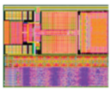
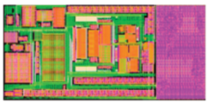
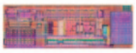
DESHIMA is operated by astronomers from the Netherlands and Japan at the Japanese ASTE telescope in the Atacama Desert of Chile (4,860 m above sea level). The photograph shows the DESHIMA team in 2017 after the successful installation of the DESHIMA cryostat in the cabin of the ASTE telescope. This led to a publication in Nature Astronomy. The next step will be to upscale DESHIMA by a factor of 100. This project (TIFUUN) has been running since 2022, supported by another ERC Consolidator Grant.

1.2.2 Autonomous Sensor Systems

High-Accuracy CMOS temperature sensors

CMOS temperature sensors are widely used in medical, industrial, and scientific applications due to their low cost, small size and digital output. However, to compensate for the manufacturing tolerances of CMOS processes, such sensors must be individually calibrated at a well-defined temperature, which is time-consuming and expensive in high-volume production.

A research collaboration with NXP Semiconductors, partly funded by NWO, resulted in the world's most accurate CMOS temperature sensor, with an inaccuracy of 0.1°C from -55°C to 125°C after a single calibration. A key breakthrough was the development of a low-cost calibration scheme that can be performed in a fraction of a second at any temperature, and which only requires the availability of a reference voltage. A further breakthrough was the development of a new analogue-to-digital converter (ADC) architecture, which achieves both low energy consumption and high resolution. The temperature sensor has been used by NXP in several commercial products, which, as shown in the photo, have been implemented in five generations of CMOS processes, ranging from 140nm (mature) to 5nm (highly advanced).

Technology	Layout (to scale)
140nm	
28nm HPC+	
28nm ESF3	
16nm	
5nm	

1.2.3 Health and Well-being

Low-Field Magnetic Resonance Imaging

Magnetic Resonance (MR) imaging is a medical diagnostic tool that is used worldwide. MR imagers typically employ large superconducting magnets with field strengths ranging from 1.5T to 7T. However, many developing countries do not have such machines simply because they are expensive, and their maintenance costs are high.

Low-field MR imagers address this problem. A collaboration with Leiden University Medical Center, partly funded by a TU Delft Global Initiative grant, resulted in an MR imager based on a 50mT array of permanent magnets. The imager's RF detection coils had to be redesigned to operate at such low field strengths. To do this, advanced electromagnetic field optimization techniques and design software were developed. Furthermore, dedicated compressed sensing and noise-suppressing imaging algorithms were developed to process the resulting signals, which are typically much noisier than those of high-field MRI. This resulted in 3-D images that are clear enough for clinical use.

In 2022, a prototype low-field MR imager was shipped to a partner hospital in Uganda, where it is being used to detect hydrocephalus in newborns. The pictures below show some prototype parts (left) and a brain scan made with the assembled instrument (middle and right).

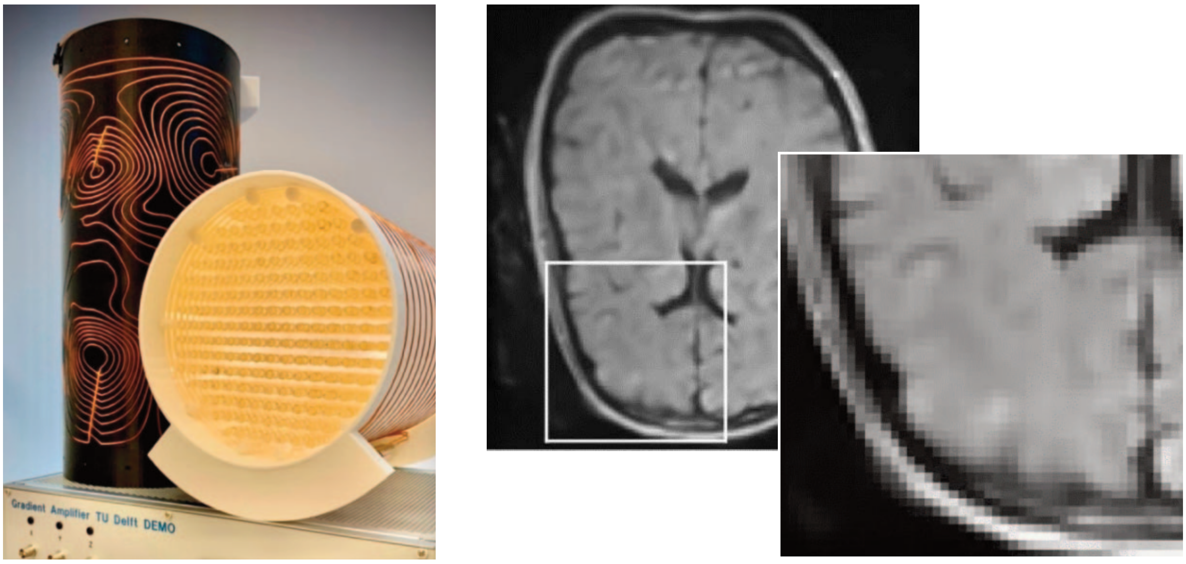
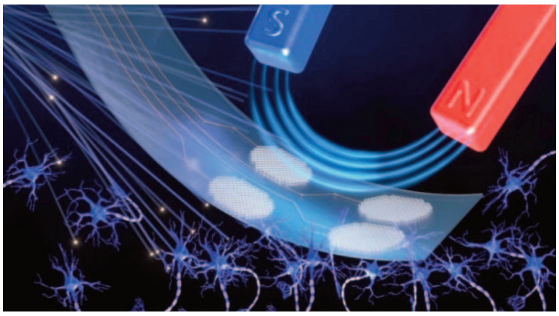
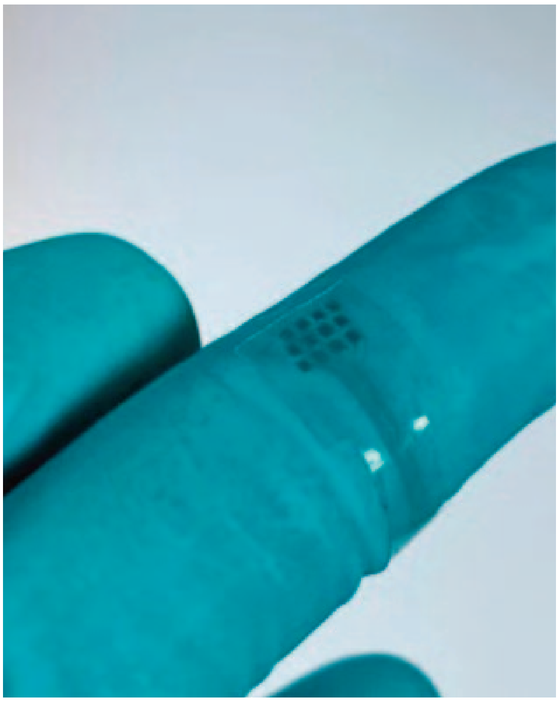


Figure 1 Prototype of the LFRMI scanner and a brain scan





Graphene electrodes for optically transparent MRI-compatible neural interfaces

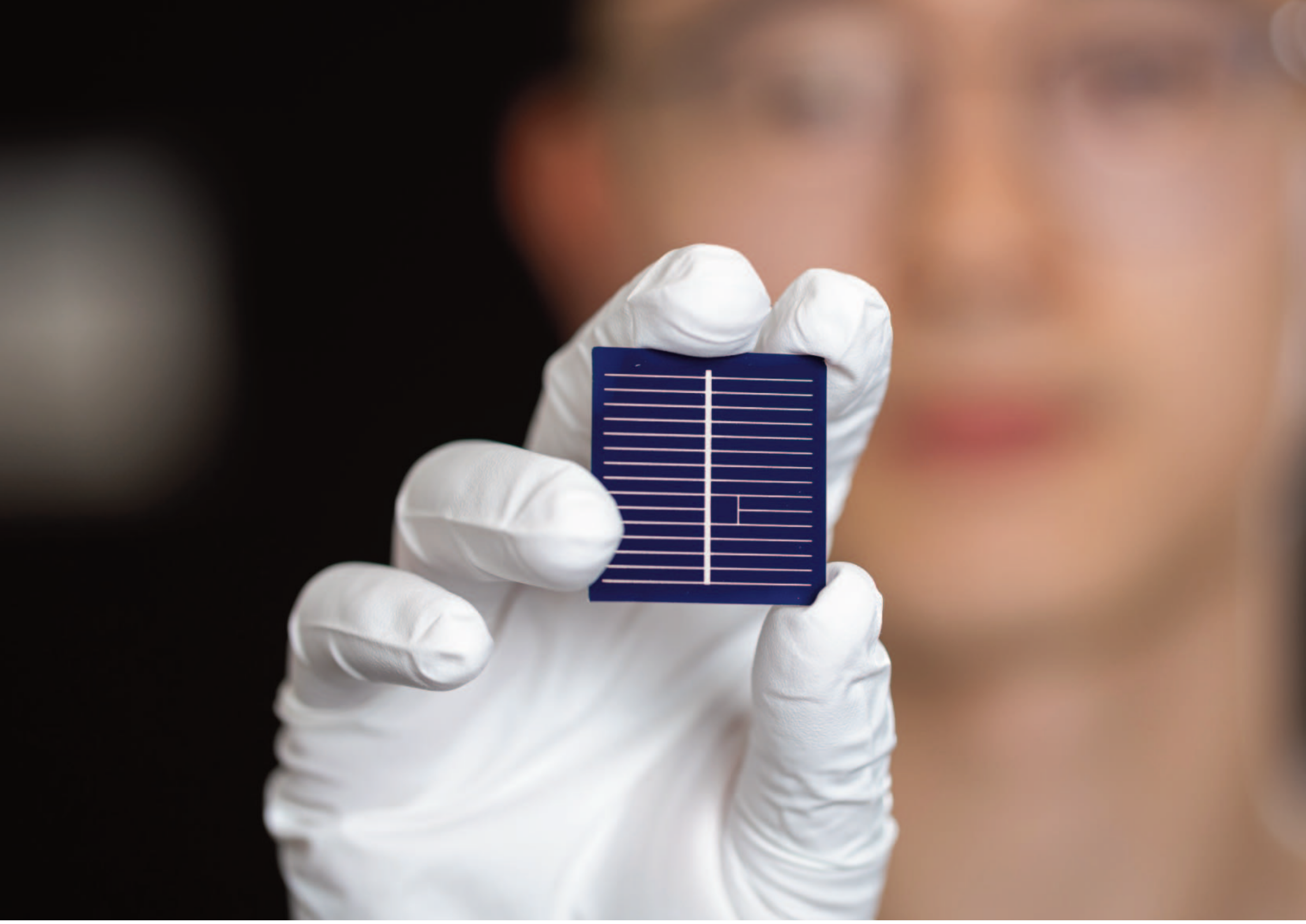
Future neural interfaces will require electrically conductive, optically transparent, and MRI-compatible electrodes. Graphene is a suitable material for such electrodes, as it is highly conductive and transparent, and so can be sandwiched between transparent biocompatible polymers. An artist's impression of an electrode array and a picture of the fabricated array are shown below.

In a collaboration with Fraunhofer IZM, funded by ECSEL JU, graphene electrodes were fabricated using chemical vapor deposition (CVD) in a wafer-scale transfer-free process. This work led to a publication in a top journal, see: https://www.nature.com/articles/s41378-022-00430-x

The impedance of the fabricated electrodes is comparable to that of conventional noble metal electrodes of similar size. Furthermore, they have the highest charge storage capacity (CSC) reported to date and do not cause optical or MRI image artefacts. The electrodes are being used by several of our neuroscience partners in the NeuroTech-NL consortium. They are currently being considered by one of them for use in a future product intended for clinical use.

2

Electrical Sustainable Energy



2.1 Summary

The research of the ESE department concerns the generation, processing, transport, and utilisation of green electricity for decarbonising the electrical power sector. We do this by carrying out innovative research in photovoltaics and wind energy, power electronics, distribution and transmission of electricity and digitalization and protection of the electrical power system. The shared vision underlying the department's research activities is to achieve a world of reliable, affordable and sustainable electricity for everyone. Across these different research areas, we routinely (i) demonstrate world record efficiencies, like the MoOx-based silicon heterojunction (23.83%) or the wireless power transfer (97% @ 20 kW), (ii) generate voltage discharges in DC up to 4 MV for testing electro duct cables, and (iii) perform hardware-in-the-loop tests for future power systems with real-time visualisation in the Control Room of the Future. The scientific standing and societal impact of our research is reflected in publications, awards, patents and spin-out companies.

During the period 2017-2022, the department has successfully executed a strategy that reflects the societal importance and urgency of the energy transition. One of the actions is the establishment of a dedicated High-Voltage Technology section. Together with the other three sections, it is well positioned to use the facilities offered by the Electrical Sustainable Power (ESP) lab, opened in 2021. The ESP lab is a unique facility that brings under one roof all the infrastructure needed for the development and testing of innovative technologies and components for future power systems.

In parallel, five Technology Centres are being established, for PV technology, Power Electronics, Power System Protection, High Voltage Technologies, and Control Room of the Future. These centres embody an open science approach, where researchers from the department collaborate with external partners (industry, knowledge institutions and academics) to develop and disseminate knowledge. This approach to research is further underpinned by the appointment of five ESE Fellows: research-oriented industry representatives who spend one day per week at the department to work with our scientists and students.

Strategic investments (e.g., sector plans, university funding) and successes in attracting project funding have led to rapid growth of the number of assistant professors and PhD students. This increases the research volume of the

department, but also necessitates paying attention to workload, onboarding and supervision, and support for career development of junior faculty. Cohesion within the department is achieved through a culture of reciprocal respect and various initiatives, such as meetings about let us meet new colleagues or introduction to the faculty, seasonal drinks, sports activities, and other social events.

The ESE department is a strong backer of FAIR data practices and open-source software, as evidenced by its founding membership of the CRESYM organisation for the development of open-source solutions for the energy sector. At the same time, working with sensitive data on energy infrastructure necessitates strong data security practices, and with geopolitical tension, knowledge security is increasingly important.

The energy transition is a tremendous societal challenge. We believe that a clean, affordable, and resilient energy system will stay in the spotlight in the years to come, and we are enthusiastic to work on it.

2.2 Case studies

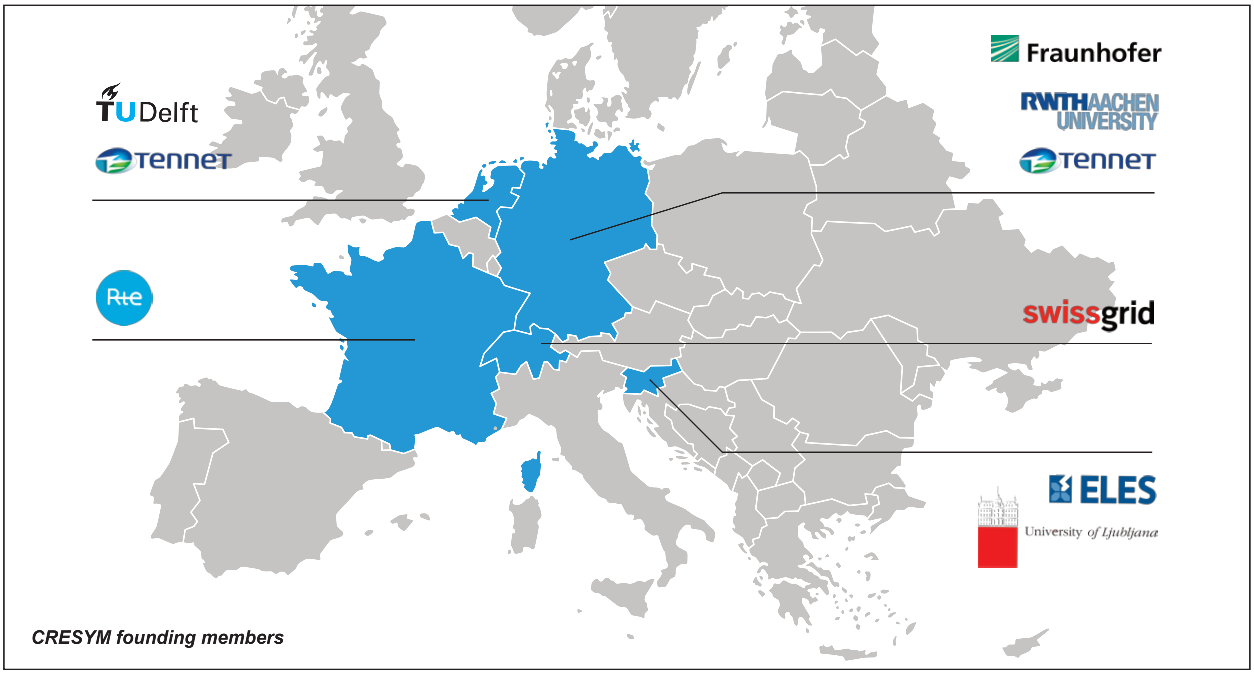
In this Section, we provide case studies to highlight parts of ESE's research in more detail.

2.2.1 ESP Lab

The energy transition towards sustainable energy is one of the greatest global challenges of our time. The core of the energy transition is a significant change in the mix of primary energy sources. Fossil fuels are replaced by variable renewable energy sources such as solar and wind energy. The result of this radical change is the renovation and development of a new electricity grid and an accelerated electrification of society. The ESE department facilitates the energy transition by generating knowledge and innovations for building a future intelligent energy system in which electricity is generated from local and large-scale renewable energy sources. To create conditions facilitating the energy transition through research and innovations, a new research infrastructure is required. The university decided in 2010 to support the emergence of a state-of-the-art laboratory, the ESP (Electrical Sustainable Power) Lab. Ministry of the Economic Affairs and Climate and TenneT supported the execution of the new laboratory. The ESP Lab was created by renovating the High-voltage laboratory and combining it with research facilities for PV, power electronics and digital technologies. Everything that has to do with electricity comes together in the ESP Lab: increasing use of electrical energy, sustainable and intelligent generation, transport, distribution, conversion, storage, and consumption. The laboratory has the unique ability to perform simulations and experiments with large-scale integrated systems. The ESP Lab is one of the few laboratories in the world where research into the **system integration** of new technologies and components in an energy system is done under one roof and on this scale.

2.2.2 CRESYM

CRESYM was founded in early 2023 after thorough preparation in 2022. It is a non-profit organisation with industrial and academic members association dedicated to facilitate research for open-source solutions in the energy sector. The core founding members were RTE, TenneT, RWTH Aachen, Fraunhofer IEE, and TU Delft. The association provides a platform for easy exchange and setup of projects. There is an internal budget from membership fees



CRESYM founding members

to maintain operations and perform general development and a - much larger - budget provided by the industry partners for specific developments and projects. The spirit is open: all results, tools, and algorithms will be shared in an open way. The governance is participatory and flat. The first projects were started even before the association was officially founded (under Belgian law). The scope of CRESYM is research and development of low-TRL software: once the code becomes economically viable it will be handed over to more commercial associations such as the Linux Foundation Energy to feed that code into products (in addition to its open-source variants). The membership of CRESYM currently consists of research institutions and electricity transmission system operators, but electricity distribution companies are already lined up to join. In the future, the entire energy system (including heat, gas, etc.) shall be covered.

2.2.3 ESE Department Apple Prize

The Apple Prize is awarded by the Electrical Sustainable Energy department for Pioneering and innovative work supported by excellent research and education results. Each year, during the department's annual Christmas get-together, the Apple Prize is awarded to a researcher selected by the ESE management team. The winner receives a glass art object designed by Miro Zeman, head of the ESE department. Winners in previous years and their pioneering and innovative contributions are listed below.

- Winner 2013: **Arno Smets**
  On-line education: First on-line MOOC course on Solar cells.
- Winner 2014: **Olindo Isabella**
  Light management in solar cells: fabrication of nanowire solar cells, demonstration of 4n2 absorption enhancement in thin c-Si slab
- Winner 2015: **Jose Rueda**
  Optimization algorithm: Development of Hybrid Mean-Variance Mapping Optimization Algorithm
- Winner 2016: **Gautham Ram Chandra Mouli**
  E-mobility: Charging e-vehicles from solar energy
- Winner 2017: **Guangtao Yang**
  c-Si PV technology: selective PECVD growth of p-type and n-type amorphous silicon on c-Si wafer
- Winner 2018: **Matija Naglič**
  Grid control: Control Room of The Future concept, new WAMPAC-ready simulation platform
- Winner 2019: **Andres Calcabrini**
  Performance of PV systems: quick approach for energy yield estimation of X-IPV systems
- Winner 2020: **Hesan Ziar**
  Photovoltatronics: establishing a new research area for intelligent PV components
- Winner 2021: **Wenli Shi**
  Contactless charging: world record power conversion efficiency (for car charging systems)
- Winner 2022: **Yifeng Zhao**
  c-Si PV technology: Best Dutch c-Si solar cell with 24% efficiency. For the first time, four-terminal perovskite/silicon tandem devices with certified top cell pass the barrier of 30%.

3

Quantum & Computer Engineering

3.1 Summary

The Quantum and Computer Engineering (QCE) department is among the European research leaders in Computer Engineering and Network Science and Architectures, with the ambition to become a recognised authority worldwide. The department's key strengths are in disruptive computing paradigms (both quantum and unconventional computing) and network science. Our shared mission is to enable the next generation of powerful, energy-efficient, hence affordable computer-based solutions for the grand challenges of society, science and engineering. The above is reflected in our high-impact publications, spin-off companies, awards and strategic collaborations with the leading industrial partners. It is worth noting that from 2017 to 2022, QCE's size in terms of (assistant/associate/full) professors increased from 10,2 FTE to 13,2 FTE, while it has reached 19,1 FTE by now.

In the period 2017-2022, the QCE department adjusted its strategic aims to various internal (e.g., recommendations, synergies) and external ones (e.g., technology roadmaps, societal challenges) circumstances in order to ensure high research quality, strong societal relevance and (short- or long-term) industrial impact. Therefore, the department has put five strategies in place to realise its targets. First of all, the department has adopted a holistic approach to the development and the design of computing chips; it addresses the entire design stack, with an emphasis on chip prototyping. This new approach has resulted in the identification of gaps in the available knowledge and skills. Second, key steps were taken to bridge these gaps; new people with well-defined profiles were hired, and new labs were defined and built from scratch. Third, to increase its productivity and efficacy, the department strengthened its synergy; three of the five QCE sections concerned with quantum computing were merged into a single research section, and the remaining activities were relocated to the appropriate departments. Fourth, QCE has reinforced a 5D strategic collaboration approach consisting of intra-department, inter-department, inter-faculty, national (e.g., EMC, TU/e, KPN, UVA, NXP), and international (e.g., Intel, IMEC, Fujitsu, IBM, Ericsson) dimensions. Fifth, the department has heavily invested in its positioning and outreach, not only by differentiating itself in the research topics and initiating strategic collaborations with worldwide key players, but also by investing in communication and visibility through a new website, a strong presence in national and international media, key contributions to national and international vision documents and roadmaps.

The above strategies have resulted in outstanding and recognised accomplishments, both related to research quality and relevance to society. Scientifically, many technical products were delivered (including software tools, IPs and designs); the number of top journal and conference publications (Tier A) has increased over the recent period; many top papers reporting chip prototypes (while addressing relevant topics or applications in collaboration with key stakeholders) were published; about 20 best paper awards and best paper nominations were received; over 100 keynotes and invited talks and over 13 tutorials were delivered at leading international conferences; about €17M total grants were received; and over ten prestigious appointments were assigned to QCE faculty. Regarding societal relevance, many products were delivered and used at large (e.g., Dutch Covid-19 Forecast Dashboard and the corresponding website); 11 patents were filed or granted; over 220 MSc and 63 PhD students graduated; three start-ups were created or operating in the department, from which a large American company acquired one; also over €6M of research funding from bilateral contracts with industrial partners was received. Moreover, QCE staff was awarded six pubic prizes and five memberships of civil-society organisations and appeared over 13 times in the media, including the Dutch national television.

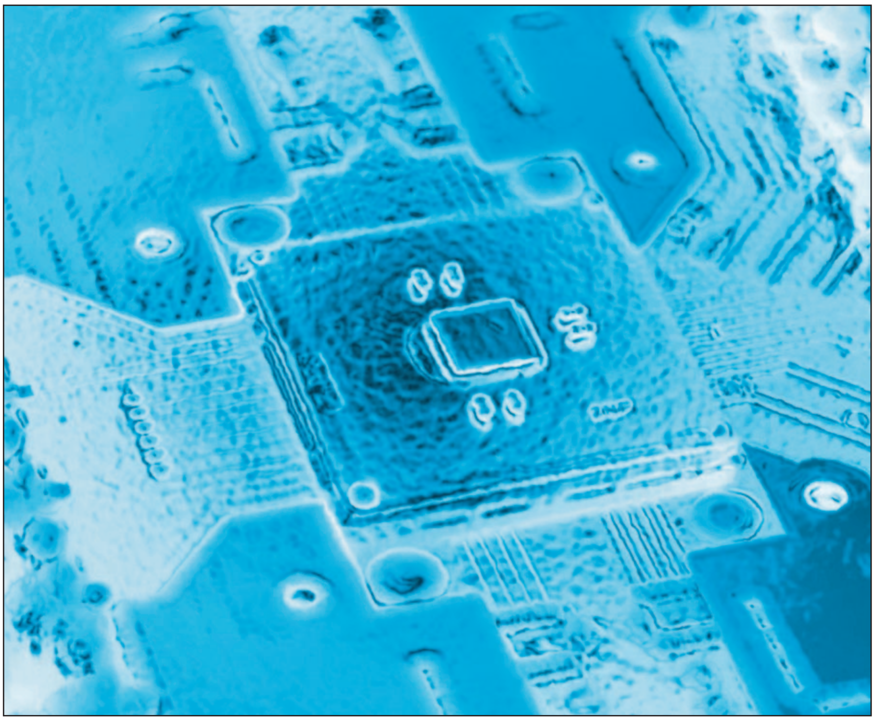


Figure 2 The Horse Ridge chip, co-developed by Intel and TU Delft, is the first cryo-CMOS microwave driver for spin qubits.

To achieve its ambitious goals ahead, QCE plans to strengthen its holistic, cross-layer approach focused on chip prototypes while addressing relevant societal challenges concentrating on *healthcare and wellbeing* and *safety and security*; additional investment in technical and non-technical support is required to sustain the department. To fulfil a very important role in the European Chips Act, the department is planning to further invest in topics related to chip design and manufacturing, specially design-for-test, design-for-reliability, and related topics. Reinforcement of the 5D collaborations to maintain the improvements in the research quality and societal relevance is needed. Moreover, additional effort in positioning the department, especially at the national level, and attracting top talents is necessary.

3.2 Case studies

In this Section, we provide case studies to highlight parts of QCE's research in more detail.

3.2.1 Intel

Intel has strongly collaborated with the key players on quantum technologies in Delft, i.e., the QuTech institute with their expertise on quantum devices and the Department of Quantum & Computing Engineering (QCE) bringing in know-how in nanodevices fabrication and integration, integrated circuit and computer engineering. Since quantum physicists working on quantum-computing hardware had a significant head start in such research fields, establishing long-running inter-faculty collaborations between QCE and QuTech was crucial. Strategically, several QCE staff members were seconded to QuTech with the spirit to engage in multi-disciplinary collaborations, which were supported by a culture of openness and mutual trust.

Throughout the years, this collaboration has resulted in outstanding results. Some activities were naturally downselected while others flourished, such as the research in quantum computing architectures and cryogenic electrical interfaces for large-scale quantum computers. The latter, in particular, led to the development of the Horse Ridge chip, first large-scale cryo-CMOS integrated circuit for the control of state-of-the-art spin qubits, a result of the joint endeavour of QCE, QuTech, and Intel, leading to top-notch publications (ISSCC, JSSC, Nature), awards (e.g., the Jan van Vessem award for Best European Paper at ISSCC 2020), and worldwide attention in the scientific and popular press.

Although some parts of the Intel collaboration dried up during the years, the link between Intel and QCE became stronger and stronger, resulting in TU Delft being the first university to access Intel's semiconductor processes, not to mention the extension of the collaboration beyond the originally planned 10 years.

3.2.2 Pandemics on Networks

Since 2008, NAS has studied the viral spread of items on networks, first motivated by computer viruses and malware diffusion on the Internet. The governing equations for epidemics on networks are mathematically the same for many different spreading instances, such as computer and biological viruses, the spread of social messages in online platforms like Facebook and Twitter, error and failure propagation, the spread of rumours and sentiments and epileptic seizures in the brain. NAS is perhaps the only group in the Netherlands that focuses on spreading in networks, while most other epidemiologists ignore the human contact network. We claim that epidemic waves can be explained by incorporating the human contacts that change over time. This topic of epidemic spread on temporal networks still stands on the NAS agenda for future research.

When the Coronavirus penetrated Europe from Wuhan in the Chinese province of Hubei around March 2020, the scientific experience of NAS resulted in an invitation from the RIVM (Rijksinstituut voor Volksgezondheid en Milieu or the Dutch Ministry of Health) to join a group of about 20 experts in the Netherlands from various disciplines (medical, biological, economic, engineering and social sciences) in order to support the Dutch government in addressing the COVID-pandemic. At first, NAS was active in working groups on exit strategies and the prediction of the number of infected persons in the Netherlands. Just before the COVID outbreak, NAS proposed the Network Inference-based Prediction Algorithm (NIPA), which was further developed into a web application to inform society about expected levels of COVID infection (Figure 3). Each day, reported data about infection cases from the RIVM are loaded into the NIPA web application. Based on the actual and historical data, the application presented predictions about the number of COVID-19 cases per province in the Netherlands, up to the time of writing (February 2023). NIPA has resulted in several papers.

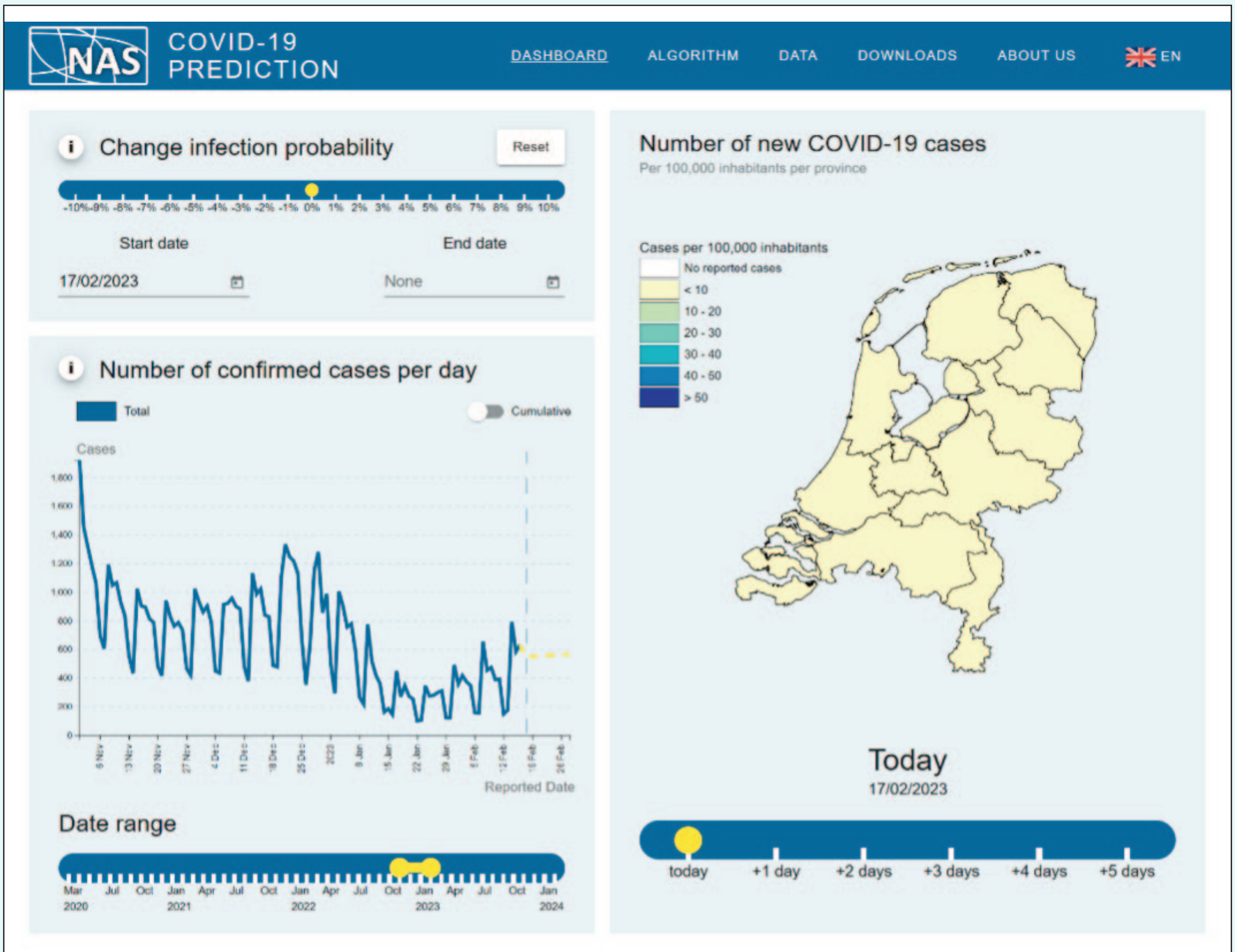


Figure 3 NAS web application - expected levels of COVID infection

Our decade-long expertise in viral spreading on networks has culminated with the COVID pandemic into increased research, an ERC advanced grant VISiON (VIral Spread On Networks), media interviews on radio and in newspapers and awards (IEEE Fellowship).

3.2.3 MNEMOSENE

QCE initiated the EU project MNEMOSENE with eight partners on ultra-low power computing based on emerging non-volatile devices. The project was granted 4 million Euros by the European Commission's Horizon 2020 Research and Innovation Programme in 2017. It was one of the first EU projects to address the new computing paradigm called "computation-in-memory", shown in Figure 4.

The project aimed at solving a major challenge related to bringing Artificial Intelligence to the edge; this will enable many applications such as personalised healthcare, smart agrifood, and smart homes. Such applications have stringent requirements regarding energy consumption, latency, real-time insights, exponentially increasing amounts of data, data privacy, etc. To cope with these requirements, MNEMOSENE explored new architectures that store and process data locally in the light of emerging device technologies such as RRAM and PCM. MNEMOSENE developed, designed and demonstrated a new class of energy-efficient accelerators based on computation-in-memory (CIM) architectures using different emerging devices, including RRAM, PCM, and STT-MRAMs. CIM tile microarchitectures were defined, designed, modelled, and validated by small-scale silicon measurements and large-scale SPICE and behaviour simulations. Such tiles were used to build a multi-tile accelerator with associated on-chip communication. The accelerator was validated based on simulation and integrated into a complete system afterwards. An end-to-end CIM Compiler was developed and deployed on the system that was created.

The project demonstrated the potential of CIM based on emerging non-volatile devices for six use cases from three application domains: data analytics, signal processing and machine learning. The results show that CIM can attain energy efficiencies of ~ 1fJ/operation, meaning up to 100X better than the state-of-the-art. Due to the project's outstanding results, it won the *European Commission Components and Systems Innovation Award for the most innovative H2020 project* at the European Forum for Electronic Components and Systems, 2020.

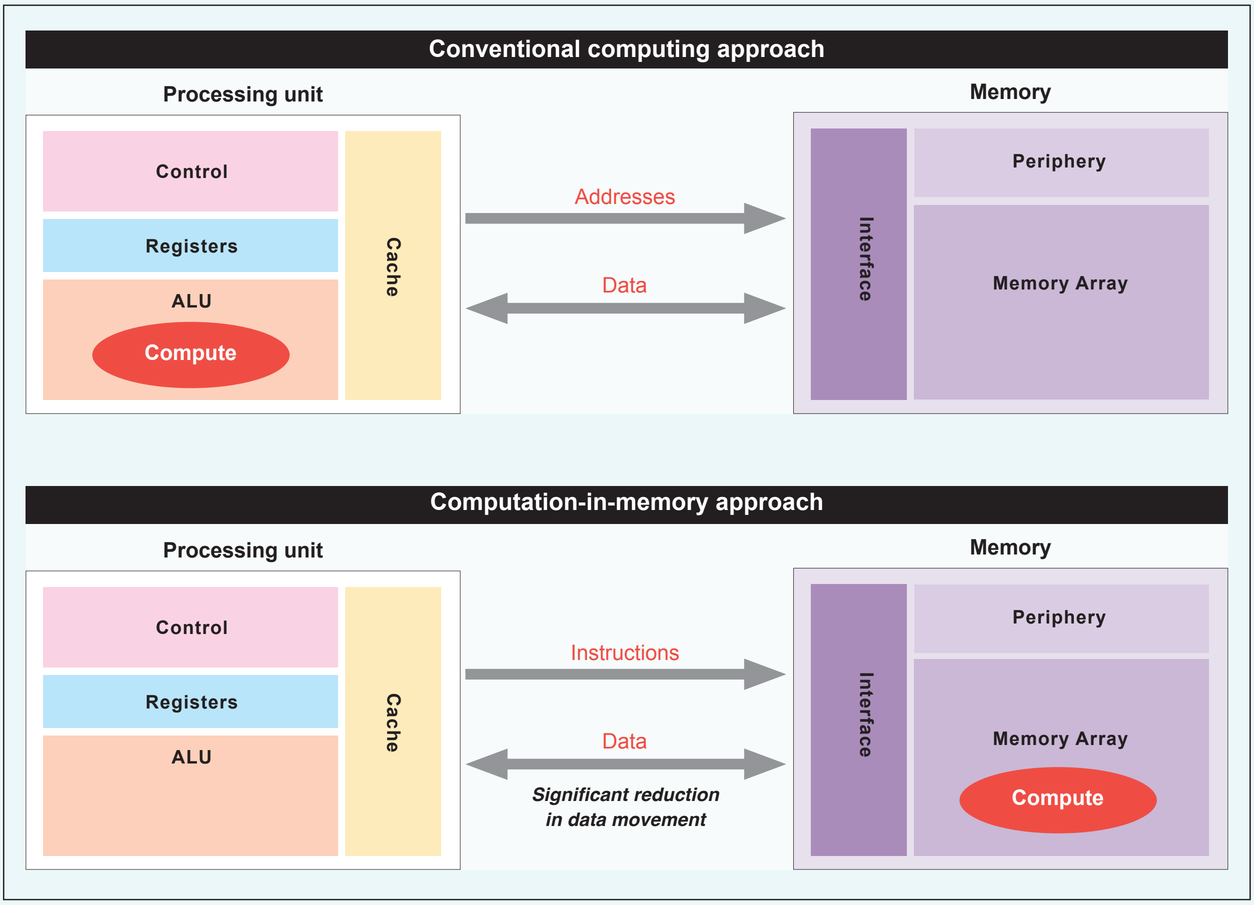


Figure 4 Conventional versus in-memory computation

Research Assessment Electrical Engineering 2017-2022

TU Delft

Faculty of Electrical Engineering, Mathematics and Computer Science
Mekelweg 4
2628 CD Delft
The Netherlands
https://www.tudelft.nl/en/eemcs