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The Twin Transition Century

The role of digital research for a successful green transition of society?

Morten Dæhlen

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Author: Morten Dæhlen, University of Oslo (Lead Author); with input from Julien Chicot and Jan Palmowski, The Guild of European Research-Intensive Universities

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About the author

Morten Dæhlen is Professor in Informatics and the leader of the Center for Computational and Data Science (dScience) at the University of Oslo (UiO). With a focus on artificial intelligence, machine learning, knowledge representation and digital twin technologies, Dæhlen is involved in a broad range of interdisciplinary research and education activities at UiO.

Through several leading positions, including eight years as Dean for the Faculty of Mathematics and Natural Sciences at the University of Oslo, Dæhlen has been engaged in research and education policymaking. In particular, he has been involved in questions and operations on how digitalisation changes and can be used to improve research and education, and how universities will be able to meet global challenges such as the climate and nature crises.

Another important element in Dæhlen´s work throughout his career has been to understand and develop academia's place and role in society. In particular, he has been engaged in finding expedient and effective mechanisms for collaboration between academia and industry, while at the same time strengthening basic long-term research.

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Throughout the paper we have included some examples from ongoing research projects around Europe that focus on topics requiring combined insight into both digital and green aspects of the development of society. The selected examples must be read as illustrations and they do not cover the breadth of the twin transition.

With the project name in parenthesis just after the names of the contributors, we thank Andrea Borghesi, Andrea Bartolini, Francesco Beneventi, Luca Benini, Michela Milano (**EXAMON**), Herbert Jaeger, Beatriz Noheda, Elisabetta Chicca, Giacomo Indiveri, Julie Grollier, Chris Eliasmith, Susan Stepney (**Neuromorphic computing**), Fred Espen Benth, Marianne Zeyringer, Christa Cuchiero, David Brayshaw (**Spatio-Temporal Uncertainty in Energy Systems**), Sabita Maharjan, Frank Eliassen, Yan Zhang, Olaf Owe, Roman Vitenberg, Geir Horn, Jofes Noll, Martin Bagherpour, Cato Bjørkli, Lee Andrew Bygrave, Cathrine Banet, Manunya Doroudi Moghadam (**Privacy-preserving Transactive Energy Management**), Allegra De Filippo, Michele Lombardi, Michela Milano, Mattia Silvestri, Federico Ruggeri (**Sustainable energy management**), Dorothea Sommer, Hauke Gronenberg, Ali Doosthosseini, Julian Kunkel, Sebastian Paczkowski, Melanie Brandmeier, Marta Paczkowska, Martin Stöcker, Irina Vortkamp, Henry Fock, Patrick Bieniek, Anja Kipfer, Achim Steudle, Pawan Datta (**ForestCare**), Anders Jonsson (**DELTA**), Marion Thain (**Attention Studies**), Florentin Wörgötter, Christian Tetzlaff, Ingo Fischer, Apostolos Agyris, Claudio Mirasso, Robert Legenstein, Lars Leiniger, Andreas Weinert (**Adaptive Optical Dendrites**), Aleš Ude, Florentin Wörgötter, Manuel

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Morten Dæhlen

List of abbreviations

AI	Artificial Intelligence
AU	African Union
EU	European Union
HaDEA	European Health and Digital Executive Agency
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IT	Information technologies
SSAH	Social sciences, arts and humanities
STEM	Science, technology, engineering and mathematics

Executive summary

What are the links between the digital and the green transitions, and what research is required to make the twin transition a success? The main reasons for asking these questions are the power of the digital transition of society, at a time when climate change, loss of biodiversity and environmental degradation are existential threats to the world. A global green transition of society can only be effective if it is underpinned by the digital transition currently underway. The ongoing and comprehensive digital transition of society can and must contribute towards the green transition, but the digital transition itself must also become greener. Based on our understanding of the dynamics and strength of digitalisation we discuss how the digital transition can contribute to the green transition, and how these two transitions can influence and reinforce each other.

These two transitions have been at the heart of EU policymaking, and they are critical challenges for every country in Europe and beyond. But what is lacking in wider policy discussions is a more careful articulation of how these challenges relate to each other. What changes are needed, when we think of the two transitions not simply as parallel processes, but as transformations that can and should affect each other deeply? And in these transitions as interrelated processes, what is it that we understand – and more importantly, what do we not yet know but need to understand?

This study asks what are the key questions for research that underpin the challenges of the digital and green transitions. It aims to inform policymakers, funders and decision-makers in universities what some of the frontiers are in digital research, and how these can (and must) be harnessed to ensure the green transition can succeed. This study shows how the two transitions cannot succeed without significant investment in research across disciplines. In turn, we seek to outline to policymakers how research can help their aspirations to make Europe a global powerhouse for the green transition, based on widespread public support and acceptance.

The green transition of society is about reducing greenhouse gas emissions, preserving and restoring nature, reversing environmental degradation and ensuring that the energy of the future comes from renewable sources. The digital transition of society consists of all processes at all levels in society involving infrastructure, services, applications and human behaviour that depend on a digital representation of knowledge and computer power. The combination of these two transitions, green and digital, is referred to as the twin transition.

Although this paper focuses on the importance of digital research and the need for new digital solutions, it is important to underline that a digital research agenda for a successful green transition of society also requires a broad range of competences across science, technology, engineering and mathematics (STEM) as well as the social sciences, arts and humanities (SSAH).

The following is a short summary of our main recommendations.

1. Recommendations for the higher education sector

1.1. Strengthen efforts to find digital solutions to enhance institutional sustainability – and enhance institutional capacities for the environmental sustainability of data handling and computing for research and education purposes.

1.2. Strengthen interdisciplinary collaboration within and across institutions, including career recognition for risk-taking and team-science approaches addressing major twin transition challenges.

1.3. Develop content in education programmes and foster innovative pedagogies to ensure students have opportunities – within and beyond the curriculum – to engage with challenges around the twin transition.

1.4. Engage with regional, national and international communities to ensure universities are integral to identifying problems and finding green solutions, based on cutting-edge, interdisciplinary research.

2. Recommendations for policymakers

2.1. Ensure that policies to foster the digital and green transitions are connected, so that both reinforce each other. This may imply a governance model with a single research strategy on the twin transition instead of merely coordinated distinct strategies dedicated each to the green and digital transitions.

2.2. Ensure that the twin transition, and the solutions needed to implement it, are driven by a focus on the public good – so that commercial interests serve the public good, not vice versa. This requires public actors, including universities, to have a key stake in co-creating the vision for – and driving the implementation of – the twin transition.

2.3. Recognise – through appropriate and ambitious levels of research funding – that the twin transition cannot succeed without research, and that ambitious goals for making Europe a global powerhouse for the digital and green transitions cannot succeed without world-leading investment in research and innovation.

2.4. Ensure that research funding is distinguished by an appropriate balance of third-party and long-term institutional core funding of university research, enabling researchers to more efficiently identify bottom-up, interdisciplinary solutions addressing long-term transitions in society.

2.5. Recognise that long-term fundamental research – both disciplinary within the digital domain and interdisciplinary where digital research plays an important role – is of crucial importance for a successful twin transition, including promoting actions for saving nature, achieving not only the necessary energy transitions but also that the twin transition of society becomes just.

2.6. EU and national policymakers must remove obstacles to data sharing and instead promote and facilitate data flows – in compliance with privacy protection rules and principles – to ensure that researchers can access and re-use existing data for research purposes. A single market for data – also to the benefit of researchers – will enable data-intensive research for the development of solutions for the green transition, while reducing the consumption of resources needed for the collection and storage of new data.

3. Recommendations for funders

3.1. Given the need for research to enable a climate-friendly, fair and digitised society, it is critical that funders recognise the value of subjects in the whole disciplinary spectrum as important for the twin transition. It is essential to recognise that we do not know what new problems will arise, what solutions we will need, and what knowledge we will need to develop towards the end of this century. Hence, funders must recognise the value of open research arenas inviting the entire disciplinary range of university research, and not just ideas which directly pertain to the green and digital transitions.

3.2. Funding programmes that currently focus on addressing environmental sustainability or digital research should additionally focus more on the linkages between the two, encouraging researchers to explore the dynamics and the strength of the digital transition to shape a sustainable future, and make sure that "the digital part of the world" becomes greener.

3.3. Ensure that the EU Missions under Horizon Europe go beyond public relations exercises fostering ambitious long-term research goals, to enable researchers to tackle complex societal challenges connected to the twin transition. Noting that the key purpose of a mission is to provide systemic transformation through research, we propose an EU Mission towards 2040, for the development of the future energy system. This mission would require significant investment in research, including fundamental research. Therefore, this recommendation will be relevant only if the EU Mission model proves to be effective in mobilising various sources of funding to allow for high-risk high-reward research.

1. Introduction

If the digital transition is to enable the green transformation of Europe's society, what is needed? And how can research address those needs? How should a digital research agenda underpin Europe's twin transition?

This paper contends that, regardless of how prominent the digital transition of society is as a political objective, it is happening in practice. The fundamental question therefore is not whether this should happen or not, but what kind of digital transition we need, and how it should come about.

Most recently, the Intergovernmental Panel on Climate Change (IPCC), and in particular the content and recommendations in the latest publications under the Sixth Assessment Report, have outlined the existential threats we face through climate change, and its consequences, e.g. on ecosystems, biodiversity and human communities at both global and regional levels.[1,2] There is no doubt that radical action is needed, as the IPCC[3] emphasises: to achieve the global climate targets in the Paris Agreement, "rapid and deep and in most cases immediate" global greenhouse emission reductions are necessary across all sectors.

In fact, the work by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reinforces the urgency of addressing the loss of biodiversity, but it raises an important question in relation to the digital transition. It highlights that communities are becoming more and more similar to each other in managed and unmanaged systems, within and across regions.[4] The decline of the local high street caused by global online retailers, or the massification of food production with a focus on high yields, do not just have cultural consequences; they have deep environmental costs. How can we avoid global digital solutions accelerating the growing assimilation of everyday life?

It is clear, then, that the ongoing and comprehensive digital transition of society must avoid any negative impact on the green transition. It must in turn reinforce the green transition. But in addition, the digital transition itself must become greener. Based on our understanding of the dynamics and strength of digitalisation we discuss how the digital transition can contribute to the green transition, and how these two transitions can influence and reinforce each other.

While the digital and green transitions are a key challenge for every country, the European Commission has articulated the European Green Deal as a cross-cutting objective, with the aim of transforming the European Union (EU) into a resource-efficient and competitive economy. The Green Deal's aims stipulate that there should be no net emissions of greenhouse gases by 2050, and that economic growth must be decoupled from resource use. Both green and digital transitions have been core priorities of the European Commission, particularly since 2019[5], but the connection between them has been much less apparent.

The European Green Deal clearly highlights the need to "leverage the potential of the digital transformation, which is a key enabler for reaching the Green Deal objective".[6] The European Commission's communications for a European Growth Model towards a Green, Digital and Resilient Economy[7] and for Shaping Europe's Digital Future[8] follow a similar approach. They all acknowledge the need to support the development of digital solutions and the greening of digital technologies and infrastructures in order to underpin and accelerate the green transition. The Council of the EU, in its 2020 conclusions on Digitalisation for the Benefit of the Environment[9], supported the ambition of the European Commission to address the twin challenges Europe faces. The relationship between the two transitions, however, is postulated rather than articulated.

It is essential, we argue, to articulate what kind of digital transition we need in order to achieve the European Green Deal objectives. Moreover, we need much more clarity on what we can already implement and achieve if the political will exists; and what objectives require new knowledge through research, knowledge that does not yet exist.

2. The twinning of the twins

The digital transition of society has been with us since the number system was invented many thousands of years ago, but it is also fair to say that digitalisation really started with the invention of the computer. The transition escalated sharply after the Internet became part of everyday life, accelerated further by the fact that all kinds of data-producing sensors became ubiquitous. An exponentially growing flow of data has been with us for a couple of decades and will continue in full force for the foreseeable future. The amount of data, and the complexity and the speed at which it is produced, are clearly important issues to handle. The flow of data transforms society from small incidents in our everyday life to how the international community addresses huge global challenges.

The digital transition of society consists of all processes at all levels in society involving infrastructure, services, applications and human behaviour that depend on the digital representation of knowledge and computer power.

The digital transition of society has created various types of convergences and coincidences between disciplines and sectors, which in turn have led to new challenges and the need for new digital solutions. A well-known example is the merging of telecommunication networks and the Internet. As more and more devices are connected, security issues have changed and become more severe. The need for new systems architectures has also become evident as digital systems have become more and more connected across the Internet.

Moreover, machine learning and systems supported by artificial intelligence (AI) appear almost everywhere, and this again has given rise to numerous interdisciplinary challenges over the past decades. In our everyday life, for example, we increasingly often talk to robots, and all new cars are equipped with some kind of driving assistance. AI systems have the potential to improve the accuracy of medical diagnostics (e.g. analysis of x-ray pictures) while digital health solutions present opportunities to increase accessibility to healthcare – even in remote areas (if people benefit from appropriate connectivity), bolstering personalised medicine, enabling preventive health, and ultimately improving both the effectiveness and efficiency of healthcare systems in Europe.

Digital systems increasingly converge and coincide, and are often commercially driven. They make it all the more important to support, underpin and challenge (where necessary) these accelerating changes in everyday life through independent, publicly funded research. Without such research, we would lose the capacity to drive the digital transition in the directions we want, independent of commercial interests. The more the digital transition is driven by commercial actors, the more crucial it is to invest in publicly funded research that focuses on digital research as a public good (See recommendation 2.2).

Given the overwhelming societal challenge of environmental sustainability, it is clear that the green transition must affect the digital transition of society, while digital solutions must in turn support environmental sustainability.

In the face of the green transition, we also have to reduce the energy footprint of the digital solutions themselves, including their underpinning infrastructures. In this picture it is necessary to reduce energy consumption on a broad basis from where data are collected, via data transport and storage to high-performance computing facilities. Equally important is how we develop socially acceptable digital solutions that support the green transition, hence social sciences, arts and humanities (SSAH) have to play an important role. In fact, we have to overcome major challenges caused by the digital transition, for instance the evolution of cryptocurrencies, and how social media store and use data. Put simply, the digital part of the world has to become greener while at same time enabling a green, climate-resilient society.

In turn, the green transition of society will also accelerate the digital transition. Its impact may well exceed that exerted on digital technologies by large global businesses, medicine and healthcare, and military activities. Digital research and technologies offer solutions to monitor, adapt and reduce the impact of climate change. Indeed, the complexity of the green transition is also at a level that requires fundamental research both disciplinary within the digital domain and interdisciplinary where digital research plays an important role. Energy informatics is a typical example of where core computer science is coupled with a deep understanding of the evolving energy systems. Moreover, high-performance computing, data management and advanced visualisation have been and are crucial to understanding climate change and its effect on nature. The need to address climate change will become an ever more important driver for the kind of digital transition we want to see.

The European Green Deal targets climate neutrality by 2050, with a 55% reduction in greenhouse gas emissions by 2030.[6] These are ambitious goals, and it is far from clear how they can be achieved.

The green transition of society is about reducing greenhouse gas emissions, preserving and restoring nature, reversing environmental degradation and ensuring that the majority of energy comes from renewable sources.

Global warming, with all its severe consequences[2], has occurred in step with the world's growing population and increasing consumption of fossil resources. The green transition is therefore strongly linked to the reduction of greenhouse gas emissions.

At the same time, the green transition must go further, and address the conservation and restoration of nature – on land and in water. Demographic growth and enormous consumption of the Earth's resources have over the past decades caused environmental degradation and severe loss of biodiversity across the globe. The Earth's total amount of biological resources and biodiversity has fallen sharply. This development is well documented and broad actions are needed.[4]

At present, research and innovation are integral to the Green Deal. In particular, they have been ascribed an important role in "accelerating and navigating the necessary transitions", "deploying, demonstrating and de-risking solutions", and "engaging citizens".[10] However, this is a very reductionist view of research and innovation, focusing, at its most ambitious level, on an acceleration of known solutions.

It is nevertheless inconceivable that societal transformations on the necessary scale can come about without new knowledge across all parts of our lives, from energy production to use of energy throughout the society, from environmental protection to individual and societal behaviours, etc. This paper aims to demonstrate, by discussing a range of research challenges, that simply instrumentalist approaches to research that focus primarily on innovations to known solutions will not do for the digital and green transitions – the twin transition.

The term "twin transition" stems from the work with the European Green Deal and the understanding that the two transitions, digital and green (the twins), are everywhere and for everyone. They are umbilically linked, even if they also have their own individual dynamics and trajectories.

The twin transition is about how the dynamics and strength of the digital transition of society affect the green transition of society, and how these two transitions mutually influence each other and should be combined in the coming years.

The time perspective for the twin transition will be many decades ahead, and the twin transition will, most likely, transform our lives. But the umbilical connectivity between the two transitions cannot be postulated, it must be established and translated into action. What exactly is the relationship between the green and digital transitions in practice? How do they affect each other, and how could they be made to reinforce each other in optimal ways? And, finally – what research do we need to ensure that we bring these transitions together, and that the digital transition reinforces the green transition optimally? Without more research, neither goal will succeed on its own: research is all the more important if we wish to 'twin' the twins.

We are not covering education and teaching in this paper. However, as research and higher education are closely linked it is important to also develop twin transition content in education programmes and appropriate pedagogies so that the workforce of tomorrow get twin transition knowledge and skills (See recommendation 1.3).[11] For the same reason, it is important to expose students in computer science, data science and computational science to important green challenges, both challenges imposed by the digital solutions themselves and the challenges that can be solved by the next generation of digital solutions. Conversely, those studying green challenges should be given the opportunity to learn about computer science, data science and computational science, both as means to contribute to the green transition and as disciplines which should further integrate the sustainability perspective in the development of energy-efficient digital solutions.

3. A climate-friendly digitised society

The global digital infrastructure and all digital solutions, large and small, account for more than 10% of all energy consumption in the world. Around 30% of this is used by ordinary computers, mobiles and other equipment, 30% by data centres and 40% by the digital networks (Internet) transporting data around the world.[12] Recent estimates also tell us that the world produced 74 zettabytes (2^{70}) of data in 2021 and that 90% of all data stored was produced over the last two years. Furthermore, it is indicated that the annual production of data will double by 2025.[13] A large proportion of this enormous data collection is carried out by global tech companies. The large generative language and image models that have been launched during the past year are recent examples of digital solutions that consume huge amounts of energy, both when the models are generated and when they are used. Governmental bodies are also huge producers and consumers of data. There is, of course, a certain degree of uncertainty associated with these estimates, but the numbers are nevertheless disturbingly large. The consequence is that digital infrastructure and all digital solutions, including data production and distribution, contribute to greenhouse gas emissions at the level of the aviation industry.

Europe must make sure that the digital transition itself approaches climate neutrality. This requires a strong and dedicated research agenda for the creation of new and more energy-efficient processors, climate-resilient high-performance computing and data storage, edge computing based on local energy harvesting, re-use of materials and in particular rare minerals, and extensive data sharing across institutions, sectors and countries. It is important to ensure that the most energy-intensive tasks use renewable energy and are located close to power plants producing renewable energy in order to reduce energy loss. Moreover, energy-intensive tasks such as high-performance computing produce heat that should be re-used by appropriate consumers of heat, e.g. district heating or land-based fish farming. Clearly, we need the green transition for the digital transition itself.

To help achieve the green transition of digital and information technologies (IT), various actions are needed:

- **Establish green computing facilities:** For many good reasons European national and regional governments as well as the EU are investing in high-performance computing facilities. These investments should be optimised with respect to greenness and location is particularly important. High-performance computing facilities should therefore be built at locations with direct access to renewable energy and at locations where there are opportunities for re-use of surplus energy. Short distance transportation of energy also reduces loss of energy. Therefore, it is crucial that the decisions for public investment in digital infrastructures (e.g., as part of the Digital Europe programme or by the European High-Performance Computing joint undertaking) are based on thorough environmental impact assessments. Public funding bodies must also require that those infrastructures that benefit from their financial support have in place strategies and actions to prevent or mitigate their negative environmental impacts (See recommendation 3.2).

EXAMON

The main objective of the EXAMON project is to develop and deploy a scalable infrastructure for performance and energy monitoring of high-performance computing facilities. The monitoring infrastructure is implemented as a digital twin of the actual high-performance computing system using artificial intelligence techniques to improve management, performance, reliability and energy consumption of the system. The artificial intelligence techniques used range from machine-learning methods automatically detecting faults and anomalies in the high-performance computing system to the generation of more sophisticated scheduling mechanisms and allocation policies aimed at reducing energy consumption.

The project is conducted at the University of Bologna and CINECA.

- **Develop more energy-efficient algorithms and software:** Large calculations using powerful computers have been important for many decades and are increasingly used to understand and solve new challenging tasks, e.g. within artificial intelligence. We must ensure that the algorithms that are developed are implemented so that they are as energy-efficient as possible. An algorithm activating fewer operations will, in principle, consume less energy when implemented. Fundamental research is necessary to develop more energy-efficient algorithms (See recommendation 2.5). Moreover, it is also important that universities should enhance their institutional capacities and become better at rationalising with computer power, especially for the most energy-consuming calculations (See recommendation 1.1).

- **Store and transport less data, share more data:** Data storage requirements and transport of digital information across the world are huge and increasing. Can this trend continue? Strictly speaking, no one really knows how to reduce the amount of data stored and transported across the world. However, if we want to do something, different measures at many levels in society can be implemented. Not only universities but also governmental bodies, units in the public sector and companies should develop data storage strategies that reduce data production and minimise the use of active storage media. Attitude campaigns aiming to reduce unnecessary use of messages (e-mails, SMS, etc.) and the comprehensive use of mail-boxes as archives should also be carried out. Last but not least, researchers and research-performing organisations have to share more data in joint repositories. There are many research questions connected to data sharing, e.g. what kind of data and system architectures are needed for efficient and sustainable data sharing? In line with its Strategy for Data and relevant ambition to accelerate the development of a single market for data in Europe[14], the European Commission should pursue its efforts to establish "common data spaces", including the European Open Science Cloud, and remove the existing regulatory obstacles to data flows (including companies imposing unfair conditions to the data they collect). EU policy initiatives and actions should similarly promote and enable altruistic-based data sharing while ensuring sufficient protection of individuals' privacy (See recommendation 2.6).

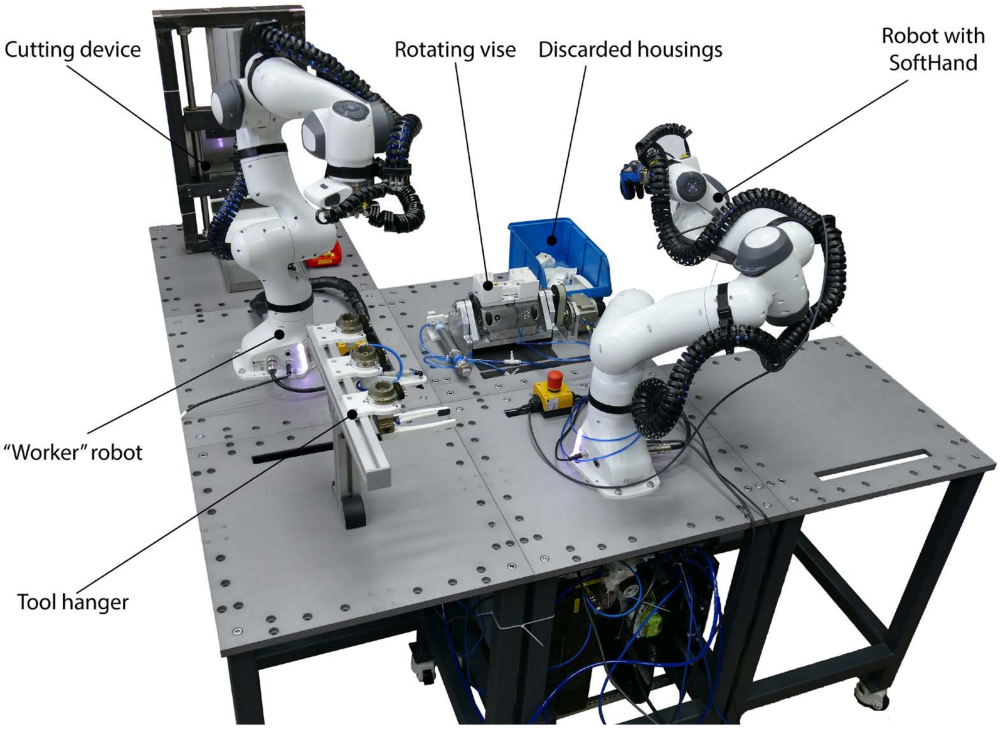
- **Reduce data volumes as early as possible – edge computing:** The purpose of edge computing is to clean and remove data close to where data is produced, mostly produced in sensors that are located at the edge of some suitable network. Successful edge computing will in general help reduce data volumes. However, as more and more sensors are put into operation we also need to work with many sensors at the same time, hence do edge computing across networks of sensors. As for the creation of efficient algorithms for high-performance computing (see above), software engineering skills are important when developing efficient algorithms for edge computing. Since artificial intelligence solutions are an important part of edge computing this area of research is also referred to as "edge intelligence".

- **Make plans for digital waste disposal and recycling of digital equipment:** The handling of digital garbage is becoming increasingly important and it is becoming ever more important to re-use old equipment and valuable materials, including rare minerals. Even here we need to invest in far more research to ensure that we find optimal ways to re-use and recycle valuable materials.[15]

Reconcycle - Self-reconfiguration of a robotic work-cell for the recycling of electronic waste

This project investigates how to automatically recycle electronic waste. Electronic waste often contains explosive, poisonous or otherwise harmful components. Those are commonly removed manually, which is slow, dangerous and unhealthy for the workers. The main goal of the project is to improve output and reduce risk by using robotic automation. In particular, the project addresses the problem that electronic waste comes in many variants and many degrees of "brokenness", which creates a very hard problem for automatic disassembly because robots need to "understand" the situation in front of them and to react flexibly to different types of device and their state. The project investigates the appropriate sensor mechanisms for this and designs relevant robotic control hardware and software, which is compatible with and non-harmful to humans working together with the robot in a disassembly process.

The following institutions are involved in the project: Jožef Stefan Institute (coordinator), University of Göttingen, Technical University of Munich and Electrocycling GmbH, Istituto Italiana di Tecnologia, and qbrobotics srl.



- **Producing more energy-efficient computer chips and quantum computing might solve a few problems:** Computers are constantly improving at the micro-level, including in their use of energy. However, as long as the growth in the use of computers is as large as it is, the total consumption of energy will not be reduced. It is difficult to predict precisely, but there is reason to believe that, within 10–15 years, the world will have quantum computers solving certain types of computational problems. These computers can, most likely together with conventional computers, potentially provide significant gains with respect to energy use when solving certain tasks.

Neuromorphic Computing

To achieve a substantial reduction in the energy consumption of computers, new computer architectures need to be developed. Neuromorphic computing uses the human brain as inspiration for the development of new architectures. The objectives are to explore new materials for computer hardware that share the energy-efficient properties of the brain. The research is multidisciplinary, involving i) investigation of how new material can form the basis for a new chip design that mimics synaptic connections in the brain, ii) research in artificial intelligence/machine learning for learning and adaption purposes, and iii) mathematics for the investigation of computational properties of networks. How can memory and computing be located together, and how can more energy-efficient information transport be achieved, are two out of many questions in this work.

The project is conducted at the University of Groningen with partners from ETH Zürich, IBM, University Twente, Technical University Eindhoven, and University of Waterloo.

ADOPD - Adaptive Optical Dendrites

This project investigates how to use mechanisms known from neuronal processing in conjunction with ultra-fast optical computing hardware, using optical fibres and other components, to speed up calculations and at the same time reduce energy consumption. Dendrites in neurons are known to be highly condensed and adaptable "processors" in the brain. This project transfers some of the dendrites mechanism into optical hardware. The goal of the project is to demonstrate that selected operations in computers can be replaced by these optical solutions and improve speed and efficiency of calculations. The environmental impact of the project is a massive reduction in energy use compared to conventional computers.

The following institutions are involved in the project: University of Göttingen (coordinator), CSIS, University of the Balearic Islands, Graz University of Technology, and Weinert Industries in Germany

It is an open question whether the capacity to "green" data handling and computing can ever keep up with the global demand for increased use of data and computing. Acknowledging this important tension is the first step in recognising the scale and importance of the task we face. Creating a climate- and nature-friendly digitised society, therefore, requires far more sustained investment in research, including fundamental research, in core computer science, data science and computational science (See recommendation 2.3). This is necessary for making "the digital part of the world" as green as possible and for optimising the twinning of the twins.

Fundamental research especially will be crucial in developing cutting-edge digital technologies that, while ensuring a human-centered digitalisation, can contribute to building a green digital world. Europe must strengthen its capacity to anticipate, address, mitigate and solve present and future (sometimes unforeseen) public emergencies caused by the climate change and the environmental degradation. To achieve this, it is crucial to foster further fundamental, curiosity-driven and high-risk high-reward research that will allow for the development of the needed game-changing breakthrough innovations. For instance, investment in fundamental research will enable research organisations, including universities, to explore possible alternatives to materials for which supply is limited or whose supply chain is uncertain and vulnerable to geopolitical contingencies. These alternatives are still unknown, but this is the very reason why Europe needs support for free, curiosity-driven and frontier research and a balance between core institutional funding and challenge-oriented funding instruments: to explore the unknown (See recommendations 2.4 and 2.5).[15]

4. Digital research enabling the green transition

The scale of the challenge of aligning the digital transition with the green transition is apparent through the challenge of 'greening' digital solutions alone. But we also need to ask how digital research and solutions can enhance the green transition of society more broadly.

Fundamental long-term research in the breadth of sciences is needed to meet future challenges and create a sustainable future for all (See recommendation 2.5). In the past, investment in open, free and independent research has provided breakthrough knowledge that has been indispensable for Europe's green transition. Thus, the European Research Council, for instance, has made essential contributions to the Green Deal[16] by funding breakthrough research that has developed new computational models to simulate sea level changes, articulated legal frameworks to enhance environmental compliance, and improved green energy production by making solar cells more efficient. It is critical to keep funding frontier research in an open way, not least because it allows scientists to identify cross-disciplinary challenges that can expand our boundaries of critical knowledge – far more effectively than any politician can (See recommendation 2.4).

That said, there are some important research areas in the digital domain that point directly to the green transition, hence being central in the twin transition of society. This study seeks to identify some of the key areas, to alert policymakers to the rich array of research domains that need support to foster a successful green transition.

Data science and computing are central, as the green transition is largely about understanding natural and human-made phenomena, extracting knowledge from data, and using this understanding and knowledge as a basis for actions. Our understanding of climate change is based on huge computational models capturing numerous physical phenomena that show how the Earth's atmosphere behaves and develops based on natural and human-made impact. Major findings and recommendations from the IPCC are based on extensive data analysis and high-performance computing.

We constantly need to understand more, hence more fundamental research is important to understanding and predicting human impact on ecosystems, both locally and globally. We are living in a complex world in constant change. Fundamental research has been and will be the most important tool for understanding changes and resolving complexities (See recommendation 2.5).

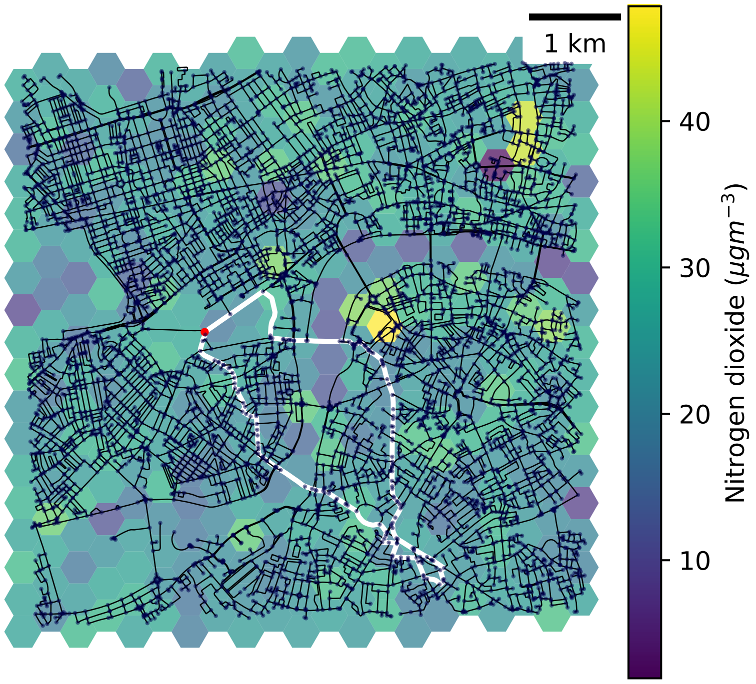
In order to better understand climate change, its short and long-term effects, and the actions it requires, it is important for research organisations as well as government bodies to collect and evaluate vast amounts of data, for example, data about climate, weather, atmosphere, soil, forests, natural resources, pollution, etc. Combined with deep knowledge in many disciplines within natural sciences, progress in data science and computing will be of crucial importance in the coming decades.

Machine learning and artificial intelligence are increasingly used to support the green transition of society, e.g. to understand environmental data, increase efficiency of weather-dependent energy production, and to make climate predictions more accurate. Equally important as developing and using machine-learning algorithms and artificial intelligence are basic issues related to how knowledge should be efficiently and correctly represented. Moreover, data management covering aspects such as data curation and structuring huge data sets should be prioritised. Progress in computational mathematics, information modelling, digital twin technologies, robotics and quantum computing will play a role in shaping the green transition in coming decades. As machine-learning algorithms and artificial intelligence systems are increasingly used, we must also pay closer attention to questions about uncertainty, explainability and ethics.

London Air Quality

Air quality in London has improved in recent years as a result of policies to reduce emissions, primarily from road transport; however, further improvements are critical to public health. By utilising city-wide air quality sensors this project is developing machine-learning algorithms, statistical methodology and data science platforms to understand and improve air quality across London. Data and air pollution measurements from various heterogeneous sources are integrated in order to better estimate and accurately forecast air pollution across the city of London. The project is developing state-of-the-art machine-learning models for high resolution air quality forecasting and change-point detection. This will help establish the most effective places to site future sensors, inform citizens about air quality and help design and evaluate government policy targeting interventions that reduce the levels of pollution in key areas and at key times.

The following institutions are involved in the project: University of Warwick, The Greater London Authority (GLA), The Alan Turing Institute, Microsoft, and Transport for London (TfL).



London Air Quality*

Connectivity sciences is the collective term for research topics within computer science that cover mechanisms for transport and distribution of data/information in digital networks, and how distributed digital solutions work across nodes in these digital networks. This is critical because our lives are increasingly reliant on the interplay between different complex systems. Typical examples of systems with such complexity include global payment systems and their connection to digital and physical retail, all sorts of written and oral remote communication systems, and systems for controlling and steering transport of people and goods. Resilience, security issues, communication mechanisms and distributed system architectures are important parts of the connectivity sciences.

Energy informatics has its origins within connectivity sciences and, put simply, energy informatics is about applying principles from the development and management of the Internet into the electricity grid. The ongoing electrification of "everything" in society is not only about connectivity, but also about the development of robust and secure energy distribution systems with enhanced control and steering mechanisms. Central in this research is the design and management of energy grids and energy systems ranging from micro-solutions in buildings to macro-solutions across continents.

Another important research topic is how to place and utilise new energy storage solutions across energy grids. This is particularly important as more and more weather-dependent energy (solar, wind) is integrated into the energy mix. There is ongoing digital research addressing these challenges; however, it is clear that more investment in research is required to understand and resolve complexity and to guide Europe and the rest of the world into cost-efficient investments in future energy systems (See recommendation 2.3).

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* - An example of a 10km route in London that minimizes the total air pollution exposure of a runner. The route starts and ends at Buckingham Palace (red dot). Yellow cells indicate high air pollution. Blue cells indicate low air pollution.

SPATUS - Spatio-Temporal Uncertainty in Energy Systems

The project aims to develop energy systems while taking into account the uncertainty of weather and climate across time and geographical space. Future energy demands must be met with intermittent renewable production from wind and solar in order to reach emission goals, and this creates a strong interplay between weather, climate, production and demand. The main objective is to find optimal capacity allocations and transmission lines in order to meet the demand and emission targets in an optimal manner. The focus is on cost optimality and stability in energy production across Europe. The project focuses on time-space random field models, which are stochastic models of future uncertainty over time and geographical space. In particular, the relationship between clouds, solar irradiation and wind fields will be better understood. Moreover, new insight into how spatial allocations can smoothen production of intermittent energy will be obtained.

The following institutions are involved in the project: University of Oslo (coordinator), University of Vienna, and University of Reading in the United Kingdom.

Sensor technologies is here a collective term for disciplines in technology and natural sciences that contribute to the development of all types of sensors, i.e. devices that in one form or another capture data and measure conditions in nature or in human-created constructions. Sensors are all around us, from smartphones to a huge number of sensors tailored to measuring single features such as temperature, pressure, speed, humidity, current flow, heart rate, etc.

Edge computing or edge intelligence refers to calculations done – in many cases – through machine-learning algorithms, where, or close to where, data is captured, mainly for the purpose of selecting relevant data from high-performance data-producing sensors and reducing data overload. This is considered to be particularly important for the green transition since edge computing/intelligence, in addition to contributing to the reduction of data volumes, also requires the development of energy-efficient hardware and algorithms since many of these sensors are and will be fuelled by batteries. When sensors are connected in networks a clear connection to connectivity sciences also appears. The development of energy-efficient (low voltage) sensors and sensors harvesting energy from the local environment can also be an important contribution to the green transition. More research, including fundamental research, is needed both for making/producing sensors that are as green as possible and for better utilisation of data from sensors and networks of sensors. Indeed, future developments in edge computing/intelligence are regarded as particularly promising with respect to the green transition. Key subject areas for the development of sensors are materials science and (nano)electronics. Moreover, advanced software engineering skills are important to ensure optimal use of the sensors and the data from sensor networks.

Digital governance consists of management structures and work processes that ensure that digital infrastructures and solutions have the desired quality, are treated properly, and are made available for practical use. The development of good digital governance relies heavily on research areas that study various aspects of how digital solutions should be implemented and used in society, in organisations and in individuals' everyday life. In addition to computer science, topics within political sciences, economics, law, pedagogics, psychology, sociology, design, and numerous other SSAH disciplines contribute to this area (See recommendation 3.1).

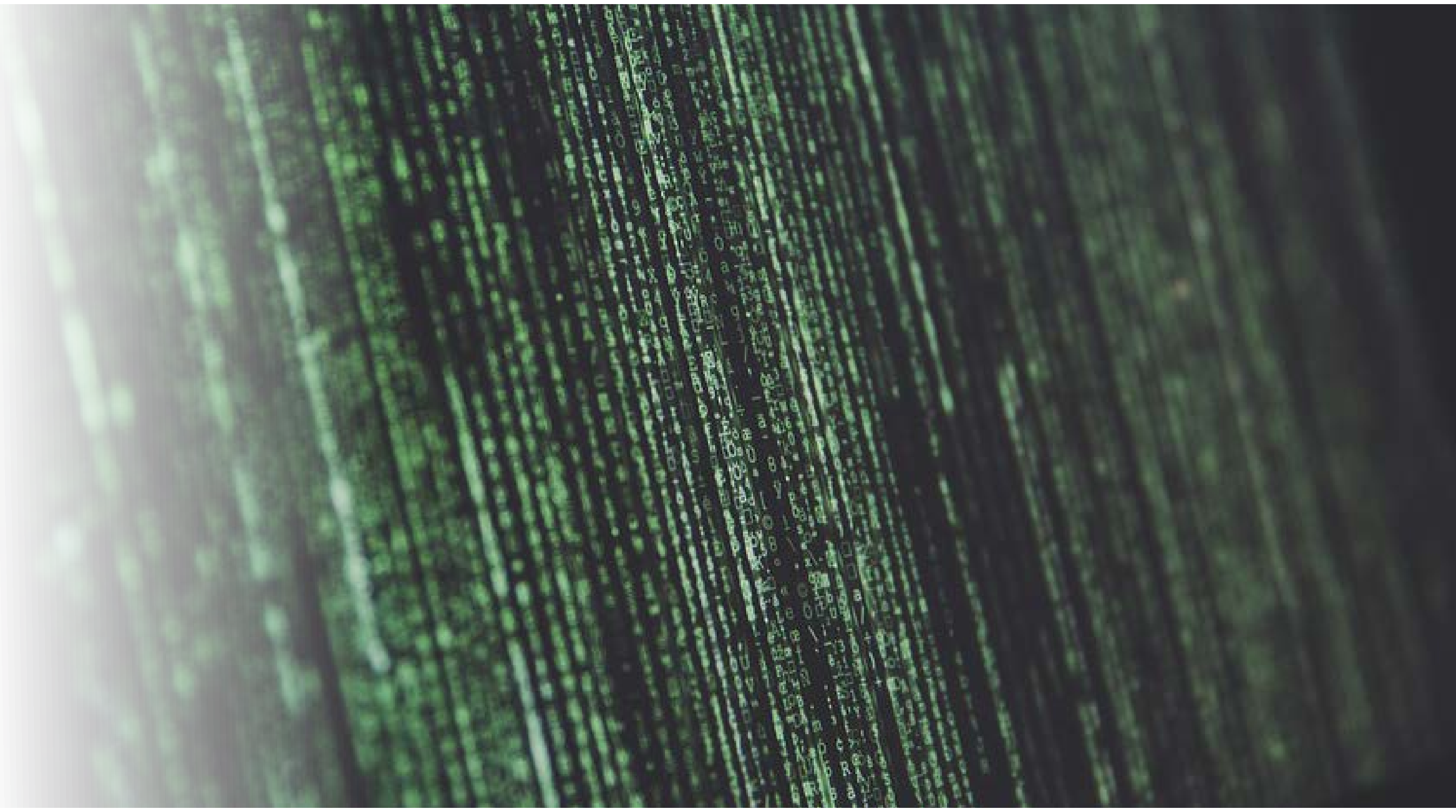
Within or closely related to digital governance we find questions related to the development of participatory platforms, human-machine interfaces, universal design and ethics. Europe should also support research that strives to understand the socio-economic drivers of, and obstacles to, the combined green and the digital transitions. Indeed, policymakers need to ensure as full an understanding as possible of the psychological, societal, economic and cultural implications of the twin transition.

The understanding of societal acceptance mechanisms and human behaviour must be an important part of the twin transition. Among other things, this involves research on how attention occurs, how opinion changes and meaning is ascribed, and how behavioural changes should be fostered in order to secure a sustainable future. This is important because new scientific insights on the digital transition and its effects on climate change should only lead to innovation if there is clarity that changes are desirable from an individual or societal perspective, and that negative effects can be addressed.

Attention studies

Taking attention as the object of study it is important to understand how we actively shape our experiences of the world and how experiences shape us. The major objective of attention studies is to enable more self-aware choices around modes of attention in order to enhance our own experience of life and increase our potential as empowered citizens. In a world dominated by short-term gains, with digital media and apps running our lives, attention studies can support necessary actions, including long-term measures, to achieve a sustainable future for all. The transition to a sustainable future needs self-aware and empowered citizens making the right choices.

Attention studies are an initiative at King's College London.



The green transition is, to some extent, also driven by individuals' expectations, preferences and aspirations for a better environment. Social sciences should not only focus on how to mitigate societal resistance to changes and solutions for the twin transitions, but also on how to encourage user-driven green innovations. Digital technologies can empower individuals and groups of individuals to contribute to the design of solutions for the green transition.

Given the challenges facing policymakers in ensuring that the two transitions are closely linked, achieve their goals, and are societally accepted, it is critical to highlight the need for interdisciplinary research approaches, as the twin transition relates to wider societal challenges.

5. Twin transition interdisciplinary actions

In this section we cover some major interdisciplinary topics where digital research plays an important role, now and in the foreseeable future – the need for a comprehensive energy transition across the whole world, actions needed in order to restore and save nature on land and in water, and necessary action to make the twin transition a just transition for everyone everywhere.

5.1. THE ENERGY TRANSITION

A substantial increase in the production of renewable energy is of crucial importance to reach the overall climate goals, but the amount of renewables that can be injected into the energy mix fluctuates, and depends on a range of factors. Except for some forms of hydroelectric power, new renewable energy is heavily weather-dependent and variable, which challenges the current energy systems. Long periods of drought also have an impact on access to the most stable renewable energy, e.g. from big hydroelectric power systems or energy-producing facilities dependent on access to biological materials.

Digital solutions can empower energy systems to absorb more power from intermittent energy sources, and they can also help to better balance supply and demand. Digital solutions will also be an important factor in designing future energy grids and systems.

As China, the EU, the United States, and other national and regional governments embark on major investments in renewable energy, it is important not to forget that building more windfarms or installing more solar panels will not be enough: we need a major renewal of the entire energy system. Several actions have been already taken, and digital solutions exist. However, more research, both fundamental and translational, are needed to guide Europe into cost-efficient investments in the next generation of energy systems (See recommendation 2.3).

Digital research and new digital solutions will play an important role in bringing the energy system of today into what is needed in the future, particularly obtaining fair distribution of energy at affordable prices. An important part of this picture is also the extensive electrification of society and the need for optimal energy storage solutions throughout the energy grid. Flexible energy storage solutions are key enabling technologies for extensive utilisation of renewable energy. Fundamental and applied research in the realm of digitalisation is necessary to secure equitable access to renewable energy (See recommendation 2.3).

The tense energy situation in Europe, which has increased due to the war in Ukraine, will change the way Europe produces, distributes and consumes energy. The repowering of

Europe has started[17], but the process will go on for decades. However, Europe is not alone, and for Europe, Africa will be particularly important. Alongside addressing critical storage and transport issues, it is important to develop close partnerships with African countries, as Africa can produce huge amounts of renewable energy, both to cover their own needs and societal progress, and for export.

At the same time, it is clear that the EU cannot impose its own needs on another continent, but that a common vision for research and innovation, articulated in the draft African Union (AU) – European Union Innovation Agenda[18], can be implemented as part of the EU's Global Gateway strategy.[19] This requires the development of common research priorities, that are owned in equal measure by partners in the EU and the AU. In order to succeed it is critical for both parties to invest in the capacities of the African research and innovation ecosystem.

The EU, for all its desire for a speedy green transition, must prioritise sustainability rather than speed in its partnerships with other global players, including Africa. And this must be a partnership based on equity, that invests in local knowledge production, higher education capacity and innovation needs, in the pursuit of common objectives.

By investing in Africa, the AU and EU together can discover how to maximise the green as well as digital transitions on both continents. The twin transition, in short, has significant opportunities not just for the EU, but also for its global partnerships. And it raises acute questions about how we best prepare societies, from Cape Town, South Africa, to Svalbard, Norway, for the renewable power age.

Smartness in things, buildings, cities and regions is very much about optimal and efficient use of energy. Huge efforts are already being put into creating energy-efficient environments and numerous digital solutions have been developed. In particular, this is the case when it comes to understanding and obtaining optimal energy consumption. However, there is still a huge potential in making houses, buildings, cities and regions more energy-efficient.

A more energy-efficient future requires research efforts in many different areas, including digital research topics ranging from sensor technologies to connectivity issues, as well as architecture, urban planning and design (See recommendation 3.1). The development of smart cities is important and European cities are collecting large amounts of data related to many different activities. How can such data be utilised to create more energy-efficient and greener cities? A couple of key scientific challenges might be to find architectures for robust and sustainable data management and using machine learning/artificial intelligence to improve logistics operations.

Moving people and goods around requires energy. Doing it smart is very much about logistics, both when it comes to transporting goods and how people can and should move around. These transport and mobility challenges can be found at all scales from global transport of goods and people to "the last mile challenge", which is about transportation of goods and people in local neighbourhoods. We buy more and more products, including food, over the Internet and the number of parcels delivered directly to private consumers is growing fast. This has environmental consequences, but it also contributes to a decline of local production, trade and consumer behaviours. This is an important example that illustrates that the digital and the green transition are not natural twins, but can also be antagonistic. A fundamental challenge, in this case, is how we can prevent the growth of consumer actions enabled by the digital transition from also increasing our carbon footprint. We need basic research, not only of technical solutions but also into legal frameworks, social systems and individual behaviours, to ensure that the twin transitions really are compatible (See Recommendations 2.5 and 3.2).

It is important to ensure that the numerous digital solutions that guide transport and mobility at most scales are optimised to reduce our carbon footprint. At the same time, more research is needed to develop new solutions for energy storage (batteries, hydrogen), as well as on how infrastructure and transportation units (cars, truck, ships, planes, etc.) should be constructed to obtain zero-emission mobility.

A broad range of measures is required to secure equitable production, distribution and use of renewable energy, the development of smart energy solutions, and green mobility. We propose a stronger focus on research in Europe seeking:

- new digital solutions for optimal production, distribution and use of weather-dependent renewable energy
- new knowledge representations and advanced algorithms for the construction of the future energy system
- new multi-scale digital solutions that support an energy-efficient society with smart environments and green mobility solutions
- systems and data architectures providing secure and scalable access to high quality energy and mobility data
- smart and innovative solutions to ensure that the digital transformation does not lead to a homogenisation of our communities and their ways of life

Given the ambitions, but also the complexities of the European Green Deal stating that Europe shall be the first climate-neutral continent by 2050, we consider it essential that an EU Mission is created that focuses on research and innovation on the development of the next generation energy system in Europe. An energy transition mission like this must be underpinned by a powerful digital research agenda with strong interdisciplinary components. This presupposes that such a Mission will add, rather than divert, investment in research and innovation, and that it would be distinguished by a core concentration on research and innovation (See recommendation 3.3).

PRITEM - Privacy-preserving Transactive Energy Management

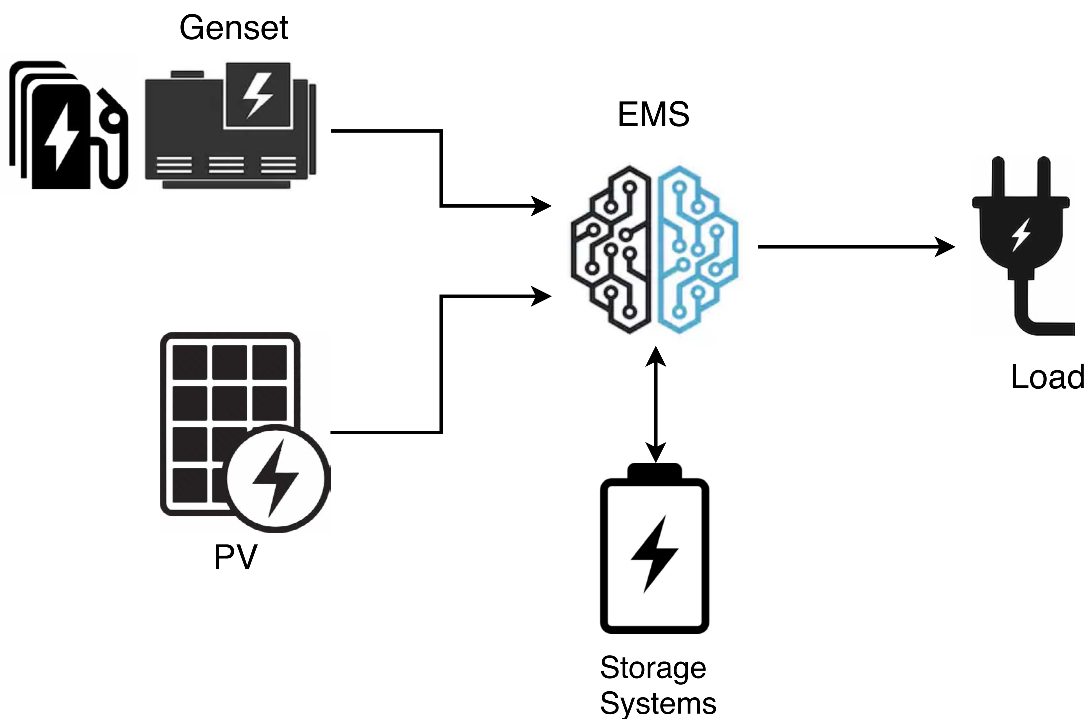
The main objective in this project is to design distributed and trust enhancing mechanisms for realising optimised approaches for transactive energy management. The research entails privacy preservation and secure data sharing for decentralised energy trading in future energy systems with access to green energy alternatives provided by local prosumers. The project will develop a new concept for peer-to-peer energy trading that has the potential to create a truly participatory and distributed energy market with increased deployment of renewable energy through active participation and contribution from local prosumers as key stakeholders in the energy ecosystem. Understanding aspects related to prosumers is crucial for acceptance and adoption of a new energy trade paradigm. Regulatory and policy aspects will play a vital role in the transition. The interdisciplinary project team behind this project addresses both technical and societal challenges towards realising the vision of zero-emission communities and smart cities.

The project is conducted at the University of Oslo.

DELTA - Dynamically Evolving Long-Term Autonomy

Many complex autonomous systems repeatedly select actions with the aim of achieving given objectives. Reinforcement learning offers a powerful framework for acquiring adaptive behaviour in such systems. From a decision-making perspective, the key to achieving long-term autonomy is the ability to adapt to changing situations. If the decision strategy is not adaptive enough, it will always select the same action in a given situation, even after it should have discovered that another action choice is superior. In this project novel reinforcement learning algorithms are developed and evaluated in two realistic scenarios; active network management for electrical distribution networks and microgrid management. The simulators developed as part of the project have made it possible to test the autonomous system for long periods while switching between objectives and introducing changes to the environment.

The project is funded by the CHIST-ERA programme and coordinated by Pompeu Fabra University with participation from Université de Liège, INRIA, and Montanuniversität Leoben.



Sustainable energy management

The main objective of this research is to integrate long-term decision-making with short-term operational activities in future energy systems. Among other things, artificial intelligence techniques and digital twin technologies are used to balance efficiency and reliability in energy systems that are increasingly dependent on distributed production of weather-dependent renewable energy. Optimisation of storage systems is also considered, which is important to achieve high penetration of locally produced renewable energy. The project aims to reach a progressive decarbonisation of energy systems by promoting the use of renewable energy sources. Moreover, the project aims to promote a progressive decentralisation, generating energy close to where it is used. In this perspective, aggregation of distributed energy resources can effectively improve the overall efficiency of an energy system.

The project is conducted at The University of Bologna.

5.2. SAVING NATURE

Environmental degradation and loss of biodiversity – the nature crisis – and the climate crisis are together arguably the largest crises humanity has ever faced. It is our common responsibility towards future generations to do what it takes to restore nature at a state where it is as clean and fruitful as possible and to protect the environment. Local and global actions for the conservation of nature, the reconstruction of lost biodiversity and the restoration of clean environments are therefore critical. By definition, these actions must be supported by comprehensive interdisciplinary research that includes central topics from the realm of digital research.

Through digital solutions, geospatial data have become more accessible, and cost-effective equipment such as drones combined with satellite data are used to measure current situations and understand the impact of future events. Typical examples are the impacts of rising ocean levels, landslides due to heavy rainfall, the removal and restoration of rainforests, etc. New digital solutions will support government agencies, humanitarian organisations, companies and citizens in making decisions by providing timely and effective information. Real-time monitoring, data analysis using machine learning and efficient communication links provide great benefits in the assessment and management of effective early warning and enhanced disaster management. Once again, the 'raw data' thus gathered will be important, and we increasingly need to scale up our analytical, predictive and monitoring capacities. But even if we do this, such investment into research and research infrastructure will only provide a full picture to policymakers if it is complemented by perspectives of the societal, cultural and economic consequences that particular scenarios and actions will have. Likewise, it is crucial that researchers and research-performing organisations have the opportunities and resources to engage with international, national and local communities and policymakers to share their insights into the environmental problems and their possible solutions (see Recommendation 1.4).

Key digital contributions to achieving a more comprehensive understanding of climate change and biodiversity loss from the digital domain are:

- sensor technologies with edge computing/intelligence facilities for green monitoring of nature and the environment
- sharing of data and digital services describing nature and the environment at many scales and across the globe
- understanding changes in nature and the environment through simulation and analysis
- using digital twin technologies for proposing optimal and fair action for restoring nature and clean environments

ForestCare

Over the past years forest quality has declined. Examples are droughts induced by climate change, and severe bark beetle infestations. The main objective of this project is to enable automatic large-scale forest monitoring for protecting tree vitality and biodiversity. Research on topics such as characterisation of trees and their vitality and automatic data processing are performed, for example using machine-learning algorithms for classification of tree species and their vitality. The data used in this process comprises lidar data, multispectral images, chemical information satellite imagery, and manual collection of data used as ground truth. Through early detection of vitality threats automatic forest monitoring enables stronger protection of biodiversity. Moreover, visualising forest vitality and biodiversity builds awareness and increased caring about the environment and protection of a vital ecosystem.

The project is conducted at the University of Göttingen, in collaboration with the University of Freiburg, GISCON Systems GmbH, and Conterra GmbH.

5.3. A JUST TRANSITION

One of the major goals of the European Green Deal is that the green transition should cover everyone everywhere. In order to achieve this a deeper understanding of societal consequences of the green transition is needed. As pointed out earlier, such an understanding also depends on the digital transition of society. Hence, the twin transition must be socially acceptable, which imposes huge challenges on policymakers. Difficult choices must be made – choices that need democratic legitimacy. It is no accident that the US Inflation Reduction Act of 2022 places such strong emphasis on benefiting the consumer. However, given that current interventions by governments to foster the twin transitions are unprecedented, in every country policymakers will need researchers to ensure they have as much information as possible about the interconnection between technological change, innovation and popular appeal, to deal with the uncertainty of their decision-making.

In order to obtain a just twin transition of society, Europe must be distinguished by stronger investment in interdisciplinary research, including:

- addressing questions connected to the twinning of the digital and the green transition and its governance
- reshaping of digital information channels to secure democratic spaces for debate on the green and digital transition
- reducing the digital and green divide across generations, social differences, abilities and skills
- developing new (digital) solutions supporting the creation of green profitable jobs and green lifecycle value chains

All forms of re-use of goods and materials, in particular rare minerals, will be central in the green transition. A key question is how digital research can play an important role in the development and management of life cycles for goods and materials. There is great potential in this, but it also requires digital and green governance (twin governance) at a level we probably have never seen, e.g. understanding and implementing a transparent and efficient circular economy across economies, sectors, countries and continents.

Transdisciplinary research faces many challenges that go beyond those facing only research aimed at the twin transition. It requires moving away from an assessment of research excellence solely against the number of publications in prestigious and often mono-disciplinary journals. Organisations funding and carrying out research must encourage researchers to collaborate, where relevant, with colleagues from other disciplinary fields as well as non-academic actors. It is crucial that research assessment systems, including the evaluation of research proposals, recognise and appropriately evaluate high-risk high-reward and multidisciplinary research. Likewise, we urge universities and research-funding organisations to provide support for the early exploration of multidisciplinary research. This implies giving researchers the resources (including financial support) to co-create excellent research proposals, which will maximise the respective contributions of each discipline (see Recommendations 1.2 and 3.1). Research-intensive universities must, at all times, cultivate the delicate balance between research deep in the disciplines with multidisciplinary research.

6. Concluding remarks

In sum, it is clear that, as policymakers recognise and reinforce the urgency of the digital transition, we must also ensure that the digital transition supports and accelerates Europe's green transition. Both processes, and their interaction, need to be carefully guided to secure outcomes that will benefit our societies, and that respond to public concerns and priorities. It is essential that Europe's twin transition is done in close collaboration with partners such as Africa, and that its direction is not imposed upon society by commercial interests. Our future must be for the public good.

For this reason, it is essential that policymakers at all levels recognise the essential role of research and innovation in order to achieve a successful twin transition. This paper explains why research is essential to drive the digital transition in the direction we want. Research is indispensable to ensure that the growth of data and computing we can foresee will be environmentally sustainable. There is no doubt that research is critical to ensure that the digital transition enhances the green transition, and vice versa.

It is essential, then, that the EU and European countries significantly increase their individual and collective investment in research and innovation as integral to the twin transition. This investment must be world-leading in size and quality. It must focus on bottom-up instruments such as the European Research Council or the Marie Skłodowska-Curie Actions as well as on challenge-led instruments. And it must foster inter- and transdisciplinary research, including the Social Sciences, Arts and Humanities. We need more investment not only in research related to the twin transition, but also to the other key challenges of Europe such as democracy, health and social justice, which are closely interrelated.

This paper has articulated the need to avoid a prioritisation of short-term innovation projects over long-term breakthrough research. Instead, we need a careful balance of investment across the entire research and innovation spectrum from fundamental curiosity-driven research to applied research and the scale-up of twin transition solutions (see Recommendation 2.4). Only if we employ the full potential of European research and innovation can we do justice to the challenges of the twin transition, and meet these challenges to the benefit of the European society.

We have demonstrated that, while the digital transition could make a significant contribution to the green transition, it could also slow it down. Digital technologies consume resources and may enable behaviours that accelerate the degradation of our environment. Twinning the transitions requires therefore research on how the two transitions could be (better) intertwined (see Recommendation 3.2). It also calls for policy coordination to ensure that the instruments aiming to accelerate the digital transition of our society and economy contribute to the objectives of the European Green Deal. The two policies must reinforce one another. A single strategy for the twin transition – that would include (among other things) a strong research component – might be a simpler solution than having distinct strategies for each of the two strategies, strategies that would then need to be coordinated by complex and possibly uncertain governance mechanisms in order to ensure they serve the same vision. At the level of the European Commission, one might, for instance, consider whether the implementation of this strategy should be entrusted to a single body or department thereof, similar to the European Health and Digital Executive Agency (HaDEA) but focused on the twin transition, possibly by means of a single funding instrument (see Recommendation 3.1).

The challenges discussed in this paper are huge. Long-term thinking and hard work over several decades are necessary to find and implement the best possible solutions. It is critical for policymakers to appreciate the significant investment that is necessary to face these challenges, and to integrate an understanding of the necessity of research in their long-term planning. Research funders will need to develop the necessary funding instruments that strengthen the capacities of Europe's research and innovation sector to meet the challenges of the twin transitions, without weakening the overall capacity of Europe's research sectors to meet so many other interconnected challenges. In the meantime, universities are embracing the twin transitions as research organisations distinguished by a unique capacity for carrying out research across the disciplinary range, at all levels, from fundamental to applied research. Besides carrying out the necessary research, their role in enabling and accelerating the twin transition is to give researchers incentives for high-risk high-reward, long-term and multidisciplinary research; resources, including infrastructures, to handle digital research in the most environmentally sustainable way; and, support to engage with policymakers and communities to share their research-derived insights into environmental problems (such as their nature and magnitude) and their appropriate solutions in terms of effectiveness, relevance and societal acceptability (Recommendation 1.4).

Throughout this paper we have included some examples that show that researchers across Europe are at the front line of tackling major challenges emerging from the digital and green transitions. With these experiences in mind and our understanding of future challenges comes one certainty: as researchers, we need to do much more!

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Rue du Trône 98, 3rd floor
B - 1050 Brussels, Belgium

+32 (0)2 274 05 00
office@the-guild.eu
www.the-guild.eu

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