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ERP Annual Report 2025

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ERP Annual Report 2025

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1 Introduction

1.1 TNO’s Exploratory Research Programme

The Exploratory Research Programmes (ERPs) constitute TNO’s exploratory research activities. Through these programmes, TNO establishes robust technological positions and collaborates with knowledge partners and stakeholders to address societal challenges and generate economic impact. In addition, the ERPs open up new domains of work with strong potential to be further developed and valorised together with industry and government partners into impactful innovations. This ensures continuous portfolio renewal within TNO and creates new market opportunities for companies and public organisations. The ERPs account for approximately 30M EUR in total.

ERP projects are strategic endeavours where TNO aims to develop expertise and positions for the Netherlands in emerging research and technology areas, addressing gaps and fostering economic fand social value for Dutch society. Despite the iterative nature and unpredictability of exploratory research, TNO focuses on mitigating risks along two primary axes: scientific and technological risks to establish a competitive position within international innovation ecosystems, and economical and societal value to enhance the applicability and impact of new technologies and methodologies. In 2025, TNO initiated the rollout of the new ERP framework, introducing sharpened selection criteria aligned with these two axes; in 2026 this framework will be further implemented, including an expansion of Seed ERPs and a steeper selection funnel, growing from 12 Seed ERPs in 2025 to 15 in 2026 and ultimately 20 by 2027.

In 2025, TNO further developed the ERP toolbox (introduced in 2024) to guide exploratory research projects, ensuring comprehensive planning of both scientific activities and outcomes, thereby reducing risks and maximizing economic and social value.

This document outlines the results of ERP projects in 2025 and summarises the anticipated outcomes of ongoing projects.

Figure 1.1: *TNO's Exploratory Research Programmes serve as the incubator for innovative technologies and methodologies, driving value for Dutch society and the economy.*

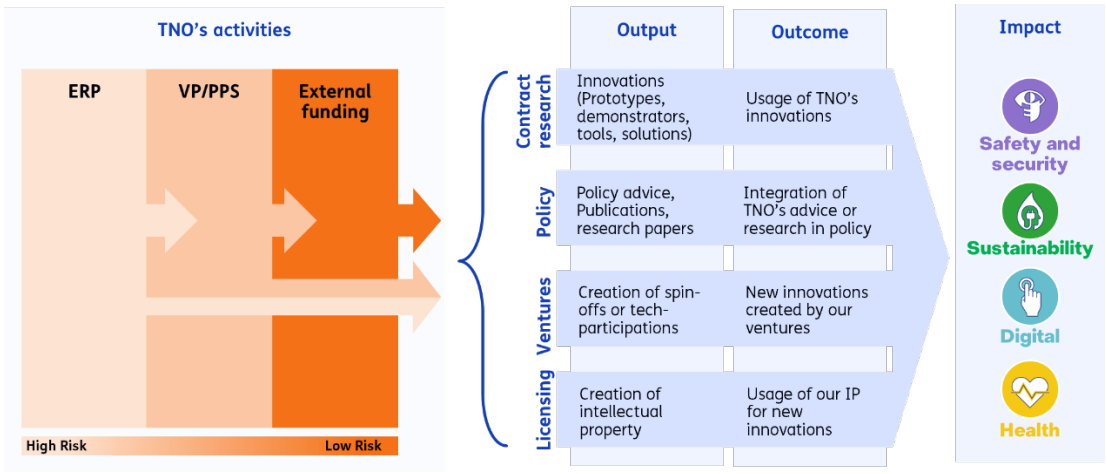


Figure 1.2: *Growing from Seed to impact – a visualisation of how TNO's ERPs contribute to achieving impact.*

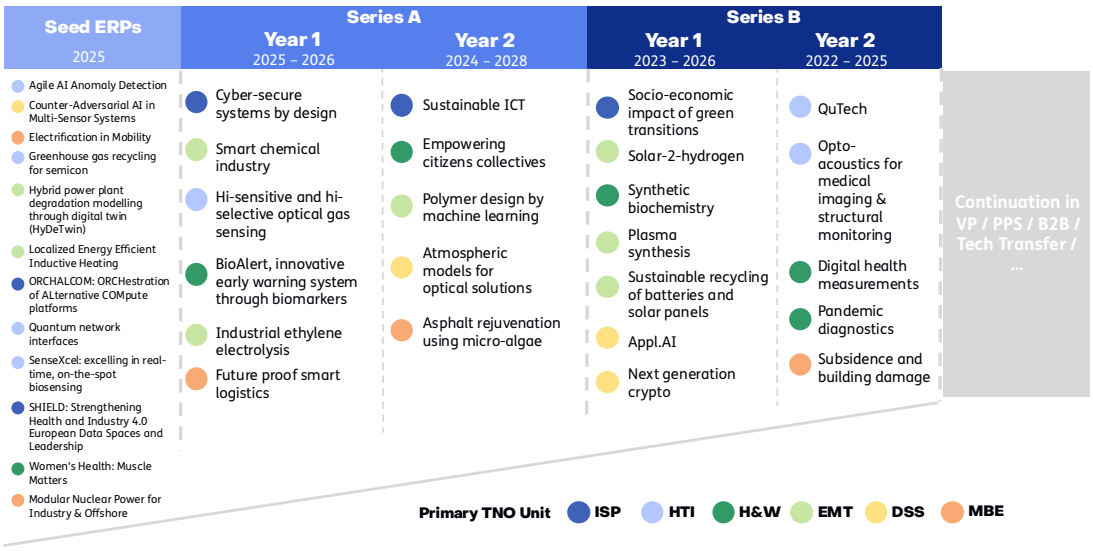


Figure 1.3: The ERP funnel in 2025

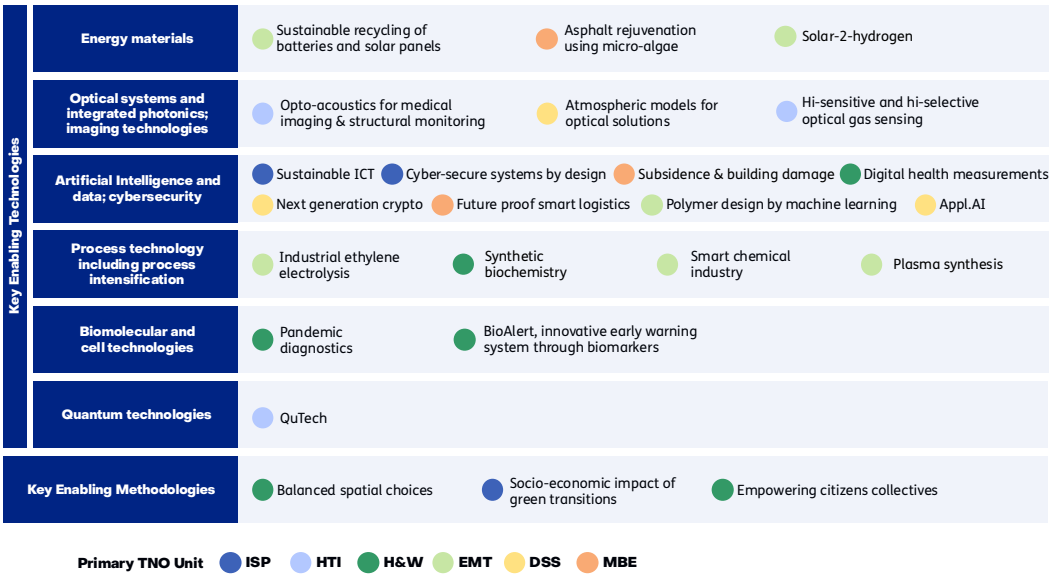


Figure 1.4: ERP projects mapped to key technologies in the national technology strategy (NTS) as well as those ERPs focussing on key enabling *methodologies*.

1.2 Results of the ERP Portfolio in 2025

- A total of 23 Full ERP and 12 Seed ERP projects were conducted in 2025. Five Full ERP projects were successfully concluded: “QuTech”, “Opto-Acoustics for Medical Imaging & Structural Monitoring”, “Digital Health Measurements”, “Pandemic Diagnostics”, and “Subsidence and Building Damage”. An internal output and impact report was produced at TNO for these five completed ERP projects, not just to present the results and outcomes, but also to promote effective follow-up within TNO in collaboration with industry and government, aiming for valorisation and impact.
- We organised an “ERP Afternoon event”, to connect ERP teams both with each other and to relevant market directors and other management. ERP teams appreciated the chance to network, share their results, and exchange best practices. The market

directors and managers were enthusiast to discuss the potential outcome of the projects and to give suggestions on the research directions from the perspective of industrial partners.

- On the scientific side, the ERP projects published a total of 86 peer-reviewed scientific publications and submitted 16 patent first filings. Almost all ERP projects (including Seed ERPs) developed proof-of-concepts, protypes, or demonstrators.
- In 2025, we selected 7 new four-year Full ERPs to commence in 2026. To do so, we analysed projects and their plans along the criteria of right-to-play and market attractiveness. Additionally, a selection of 15 single-year Seed ERPs to be executed in 2026 will be finalized by April 2026 – with 10 Seed ERPs already selected in 2025. This staggered selection approach increases the agility of the ERP portfolio to react on new developments.
- We consider a 50% success rate for Seed ERPs transitioning to Full ERPs as optimal, balancing quality promotion and minimising wasted proposal efforts. The overall quality and relevance of proposals were high, requiring us to differentiate between ‘good’ and ‘even better.’
- The selected new Full ERPs are “Agile AI Anomaly Detection”, “System-level platform for adversarial robustness testing and analysis (SPARTA)”, “Electrification in Mobility”, “Greenhouse gas recycling for semicon”, “Hybrid power plant degradation modelling through digital twin (HyDeTwin)”, “ORCHALCOM: Orchestration of alternate compute platforms”, and “Women’s Health: Muscle Matters”. All these concern domains with clear scientific challenges and high societal and economic relevance. The topics were selected out of the Seed ERPs of 2025.

2 Seed ERPs

- In 2025, TNO conducted 12 Seed ERP projects to analyse scientific and market risks associated with innovative new ideas. Of these 12 projects, the following were selected for follow-up in 2026:
  - **Agile AI Anomaly Detection** aims to develop physics-informed, data-efficient AI technology that drastically reduces required training data for anomaly detection, enabling accurate, scalable diagnostics across complex industrial, semiconductor, defense, and medical systems.
  - **System-level platform for adversarial robustness testing and analysis (SPARTA)** aims to create a system-level adversarial testing platform that uncovers unknown vulnerabilities in multi-sensor autonomous systems by generating meaningful, optimized scenarios through differentiable simulation and semantic control.
  - **Electrification in Mobility** aims to develop a high-performance large-scale agent-based simulation platform that enables accurate, fast and cost-effective system-level decision-making for electrification in mobility and future cross-domain applications.
  - **Greenhouse gas recycling for semicon** aims to increase the sustainability of the semiconductor industry by reducing the fluorinated gas impact in the full chain through (cryogenic) separation and recycling of F-gases.
  - **Hybrid power plant degradation modelling through digital twin (HyDeTwin)** aims to enhance the resilience and lifetime profitability of hybrid power plants by informing operational decisions with long-term asset degradation and reliability insights through advanced modelling and a flexible digital twin architecture.
  - **ORCHALCOM: Orchestration of alternate compute platforms** aims to develop a unified, application-aware orchestration framework that seamlessly integrates HPC, quantum, and neuromorphic computing to optimize workload placement, accelerate innovation, and democratize access to advanced computational technologies.
  - **Women's Health: Muscle Matters** aims to reduce the health gap by developing a three-pillar platform that advances sex-specific knowledge, early diagnosis, and effective interventions to improve female muscle health, performance, and employability.
- The following Seed ERPs are not continued in 2025 as Full ERP but the topics are further developed through other means:
  - Localized Energy Efficient Inductive Heating
  - Quantum Network Interfaces
  - SenseXcel: excelling in real-time, on-the-spot biosensing
  - SHIELD: Strengthening Health and Industry 4.0 European Data Spaces and Leadership
  - Modular Nuclear Power for Industry & Offshore

3 Cyber-secure systems by design

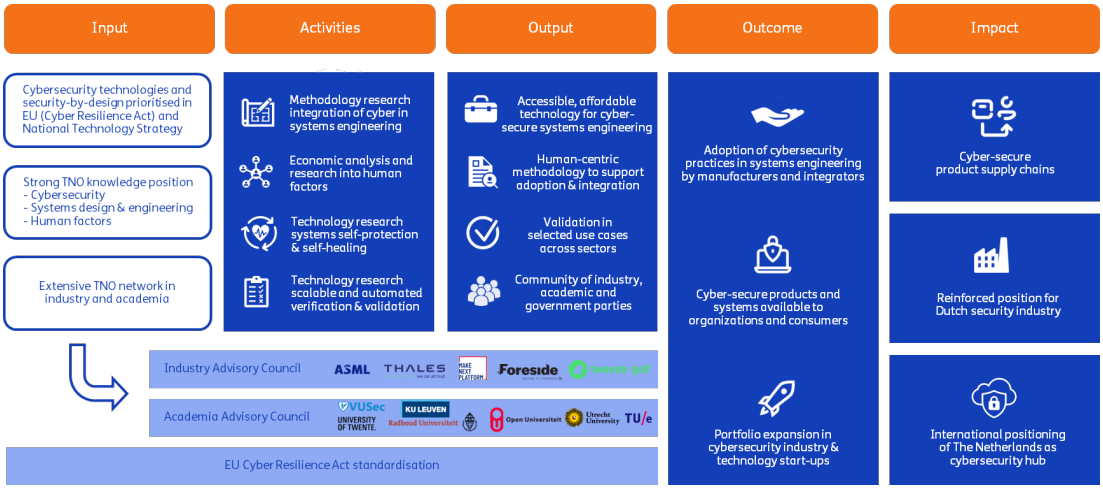
Ambition. Transforming product development by embedding cybersecurity throughout engineering processes, establishing inherently cyber-resilient systems that are secure, reliable, and prepared for future digital and regulatory demands.

Impact. Enabling a national transition toward cyber-secure products and systems, strengthening resilience of critical infrastructures and empowering industry to meet upcoming cybersecurity-by-design regulations.

Results 2025. The ERP achieved significant progress in its first year. Technology innovations were demonstrated that will make cybersecure systems engineering more feasible. We gained valuable insights in the human and economic incentives and barriers for adopting and integrating these technologies. The ERP invested in strong relationships with industry parties through our Industry Advisory Council, interviews with industry parties from multiple sectors and keynotes and presentations to share and discuss our results.

Thomas Rooijakkers (Lead Scientist), **Bert Jan te Paske** (Project Manager), **Omar Niamut** (Director of Science ISP), **Christa Hooijer** (Director of Science DSS), **Helen Kardan** (Director of Science HTI).

1st year in 2025. Running 2025 – 2028, continuation beyond 2026 dependent on ERP Series B selection.



4 Smart Chemical Industry

Ambition. Enabling autonomously adaptive, electricity-driven chemical processes by establishing an integrated toolbox that optimizes process flexibility, robustness and dynamic operation within fluctuating sustainable energy systems.

Impact. Transforming the EU chemical industry by improving energy efficiency, lowering infrastructure costs and strengthening competitiveness through flexible e-powered production that matches renewable electricity supply.

Results 2025. We developed first versions of dynamic process models established by combination of fundamental principles and data-driven approaches, to support autonomously adaptive chemical production. A series of suited ageing tests were established to assess the robustness of catalysts in adaptive chemical processes, and initial assessment of flexibility and robustness of selected demonstrator processes was performed. Furthermore, we have developed an electricity market model and projection on chemical processes.

Herbert Zondag (Lead Scientist), **Jurriaan Boon** (Lead Scientist), **Pascal Buskens** (Lead Scientist), **Nicole Meulendijks** (Project Manager), **André Faaij** (Director of Science EMT), **Helen Kardan** (Director of Science HTI), **Omar Niamut** (Director of Science ISP).

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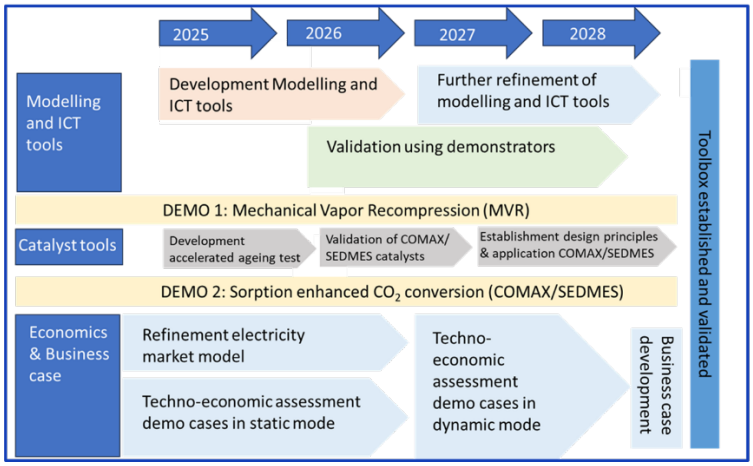


Development targets:
- Toolbox required for design and development of autonomously adaptive chemical processes established and demonstrated for ≥ 2 e-powered processes on large lab/small pilot scale (TRL=5).
- Economic advantage and energy efficiency of autonomous adaptation quantified for selected demonstrators.

Key stakeholders:
- Chemical industry: Brightlands Chemelot Campus / Fieldlab Rotterdam
- High tech Industry: High Tech Campus, Brainport Industry Campus
- University partners: UU, UvA, TUE, Max-Planck-Institut für Chemische Energiekonversion, RWTH Aachen University

5 Hi-sensitive and hi-selective optical gas sensing

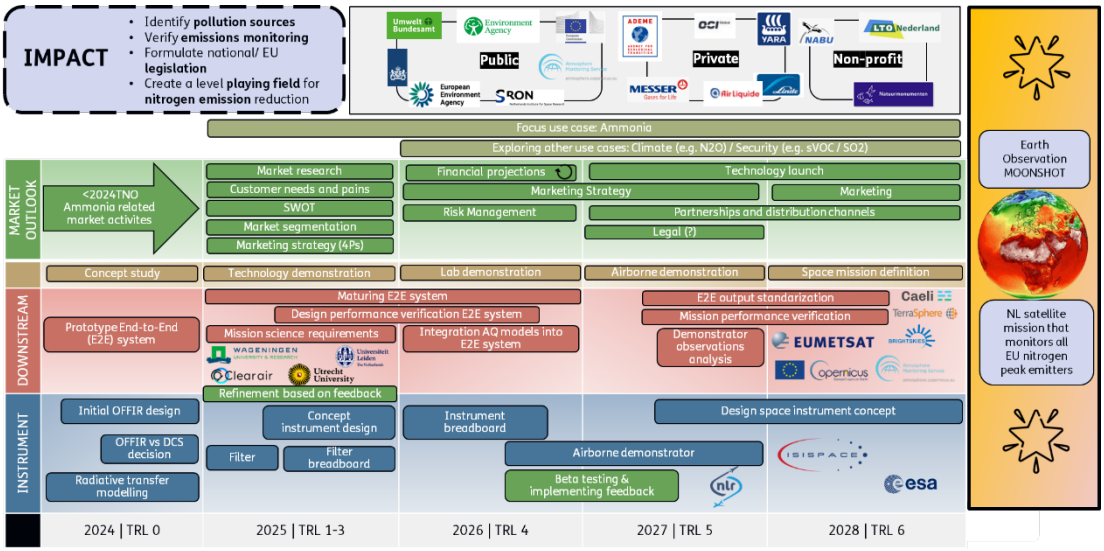
Ambition. Developing highly sensitive and highly selective thermal-IR remote sensing architectures capable of detecting trace NH_3, N_2O and VOC emissions at fine spatial scales, establishing a scalable and deployable multi-platform gas sensing capability.

Impact. Enabling early detection and reduction of nitrogen emissions and illicit chemical activities by providing precise atmospheric gas mapping, improving environmental quality and strengthening public safety and law-enforcement effectiveness.

Results 2025. The HISENSE ERP project high level results by the end of 2025 are an improved end-to-end model, the design of 2 OFFIR instrument concepts for a demonstrator, and the design of dedicated test setup to characterize OFFIR instrument demonstrator performance.

Enrico Dammers (Lead Scientist), **Gerard Otter** (Lead Scientist), **Martijn Brouwer** (Lead Scientist), **Tim Luijkx** (Project Manager), **Helen Kardan** (Director of Science HTI), **André Faaij** (Director of Science EMT).

1st year in 2025. Running 2025 – 2028, continuation beyond 2026 dependent on ERP Series B selection.



6 BioAlert, innovative early warning system through biomarkers

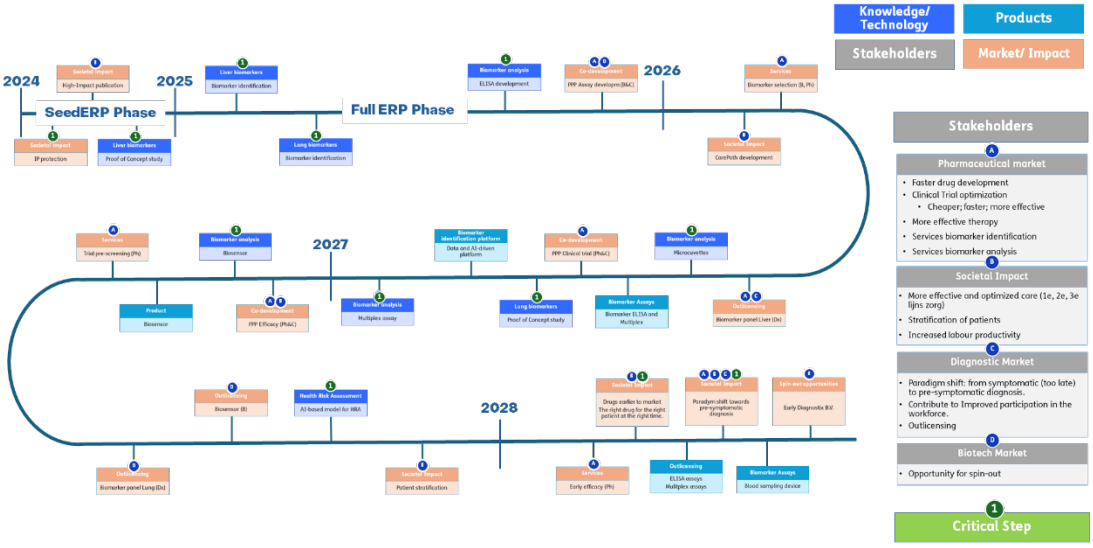
Ambition. Establishing a versatile pre-symptomatic biomarker platform enabling early identification of individuals at risk of chronic lung and liver disease, and forming a foundation for broader early-diagnostics applications across chronic conditions.

Impact. Transforming healthcare by enabling earlier, more targeted prevention and intervention, reducing disease burden and healthcare costs, and unlocking significant societal, economic and commercial value across the health ecosystem.

Results 2025. A proof of concept was realized and published in Liver International showing the high value of prognostic biomarkers for presymptomatic liver disease detection. This liver-centered approach is extended towards biomarker discovery in chronic lung disease and analysis of key dynamic disease mechanisms needed for the identification of early biomarkers. In addition to prognostic biomarker identification, techniques for robust blood sampling in a non-clinical environment, reliable assays have been developed and validated which is important for robust analysis of biomarkers.

Alex Cornelissen (Lead Scientist), **Lars Verschuren** (Lead Scientist), **Roeland Hanemaaijer** (Lead Scientist), **Jasper Kieboom** (Project Manager), **Robert Kleemann** (Director of Science H&W), **Christa Hooijer** (Director of Science DSS).

1st year in 2025. Running 2025 – 2028, continuation beyond 2026 dependent on ERP Series B selection.



7 Industrial ethylene electrolysis

Ambition. Advancing CO_2-to-ethylene electrosynthesis from materials to pilot-scale, integrating modelling, novel electrodes, and reactor design to enable the world's first multi-kW demonstration and accelerate industrial scale-up.

Impact. Enabling a cleaner chemical industry by creating pathways to defossilise ethylene production, reducing emissions, supporting renewable energy integration, and positioning TNO as a leader in upscaling electrochemical CO_2 conversion.

Results 2025. This first ERP year focused on developing strategic knowledge at all levels to advance the electrochemical process for conversion of CO2 to ethylene. In particular, the following activities and tools have been achieved: i) a 2D modelling framework to guide the design of the reactor; ii) benchmarking membranes and fabricating novel electrodes, iii) preliminary scale-up testing under controlled conditions. iv) first techno-economic analysis, including downstream processing; v) several activities on dissemination and stakeholder engagement across the whole value chain.

Francesc Sastre Calabuig (Lead Scientist), **Mark Sassenburg** (Lead Scientist), **Simone Dussi** (Lead Scientist), **Michele Tedesco** (Project Manager), **André Faaij** (Director of Science EMT), **Helen Kardan** (Director of Science HTI).

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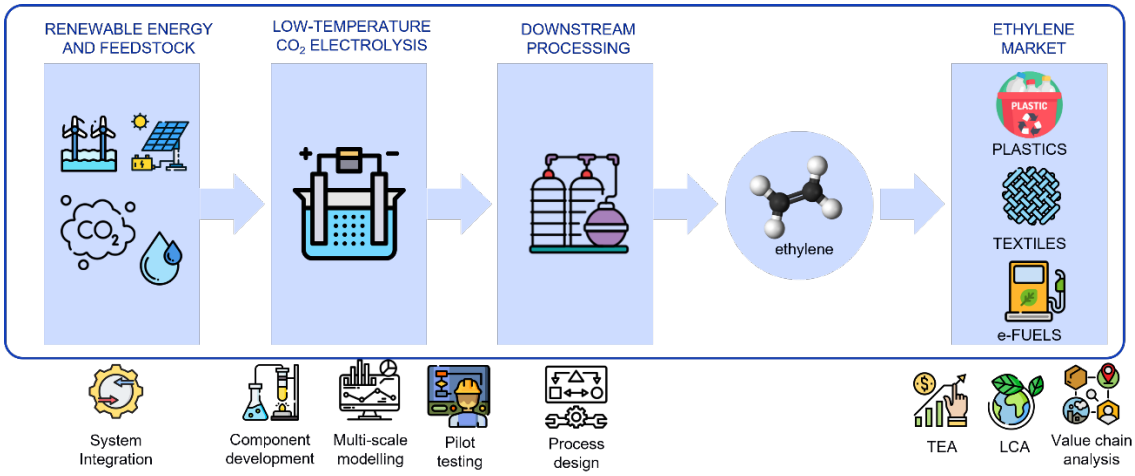

8 Future proof smart logistics

Ambition. Enabling major gains in logistics efficiency, reliability and sustainability by demonstrating trusted asset-sharing solutions that reduce emissions, optimise capacity use and strengthen the resilience of connected logistics networks.

Impact. Establishing a scalable, trusted, decentralised planning and data-sharing ecosystem that drives the system change towards collaborative logistics and accelerates the transition to the Physical Internet.

Results 2025. The project made steady progress across all five research lines, advancing work on collaborative business models, trusted data-sharing solutions, decentralized planning approaches, system integration, and stakeholder engagement. Key achievements included defining the first steps of a collaborative business model process, selecting a promising architecture for secure data sharing, exploring decentralized planning concepts with early demonstrations, delivering an initial integrated system demo, and strengthening the wider ecosystem through new partnerships, international recognition, and long-term research capacity building.

Jaco van Meijeren (Lead Scientist), **Ruben Fransen** (Lead Scientist), **Björn de Jong** (Project Manager), Arjen Adriaanse (Director of Science MBE), Christa Hooijer (Director of Science

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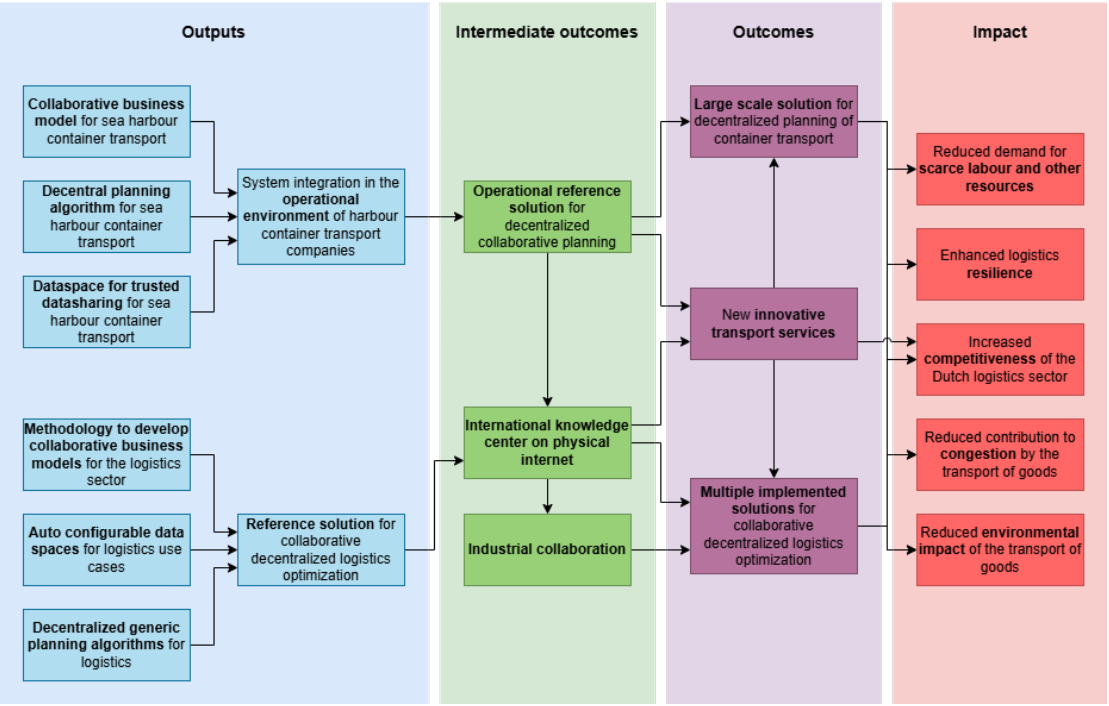


9 Asphalt rejuvenation using micro-algae

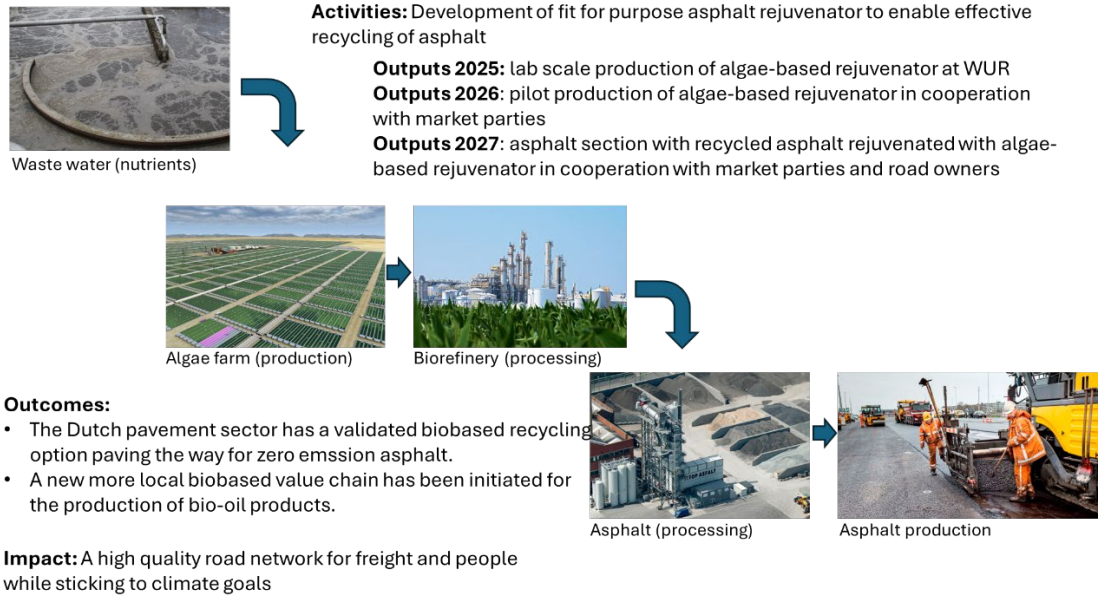
Ambition. Developing a fit-for-purpose asphalt recycling agent based on wastewater grown micro-algae at an industrial scale to keep the Dutch road network operational in a new circular value chain.

Impact. Enabling environmentally friendly maintenance approaches for a sustainable road network. This is essential for achieving at least 5 of the 17 Sustainable Development Goals.

Results 2025. The selected freshwater microalgae strain shows stable fast growth with no contaminations and a high lipid content after starvation. The hydrothermal extraction process is effective at relatively low temperatures, increasing potential value of side streams. The solvent type influences the chemical composition of the rejuvenator, which is expected to catalyse the rejuvenation effect. An approach has been formulated to assess rejuvenator effectiveness based on the aging resistance. Stakeholders for all parts of the value chain have been approached and indicate the following key elements for success: (1) clear view on costs, (2) service life benefits, (3) a stable supply chain.

Greet Leegwater (Lead Scientist), **Tim Dijkmans** (Project Manager), **Arjen Adriaanse** (Director of Science MBE), **André Faaij** (Director of Science EMT).

2nd year in 2025. Running 2024 – 2027.



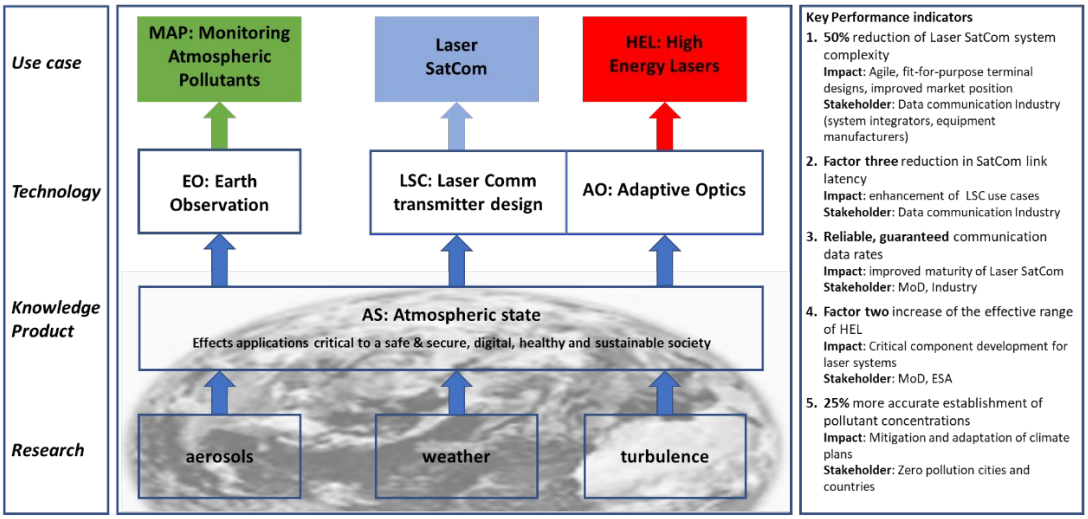
10 Atmospheric models for optical solutions

Ambition. Mastering the impact of the Atmospheric State (AS) on Adaptive Optics (AO), Optical Communication Terminals (OCT) and Earth Observation (EO). This strengthens our position for Laser Satellite Communication (laser SatCom), High-Energy Lasers (HELs) and Monitoring Atmospheric Pollutants (MAP), resulting in effective communication, successful military operations and accurate monitoring of climate and pollution.

Impact. Enabling the verification of the Paris Agreement through extremely accurate monitoring of climate and pollution, highly reliable communication through laser SatCom, and more effective military operations by mastering the performance of the high-energy laser.

Results 2025. ATMOS continued and extended TNO's capability to accurately assess the atmospheric state and utilize this in the three use-cases mentioned before. Specifically, tools have been developed and optimized to assess the impact of the atmospheric state on end-user performance indicators, such as link budgets (SatCom) or range (HEL). Results are discussed in publications and reports. Furthermore, an impact and valorization plan has been created which provides guidance for outreach activities.

Lex van Eijk (Lead Scientist), **Janot Tokaya** (Lead Scientist), **Niek Doelman** (Lead Scientist), **Heather Young** (Project Manager), **Christa Hooijer** (Director of Science DSS), **Helen Kardan** (Director of Science HTI), **André Faaij** (Director of Science EMT).
2nd year in 2025. Running 2024 – 2027.



11 Digital Health Measurements

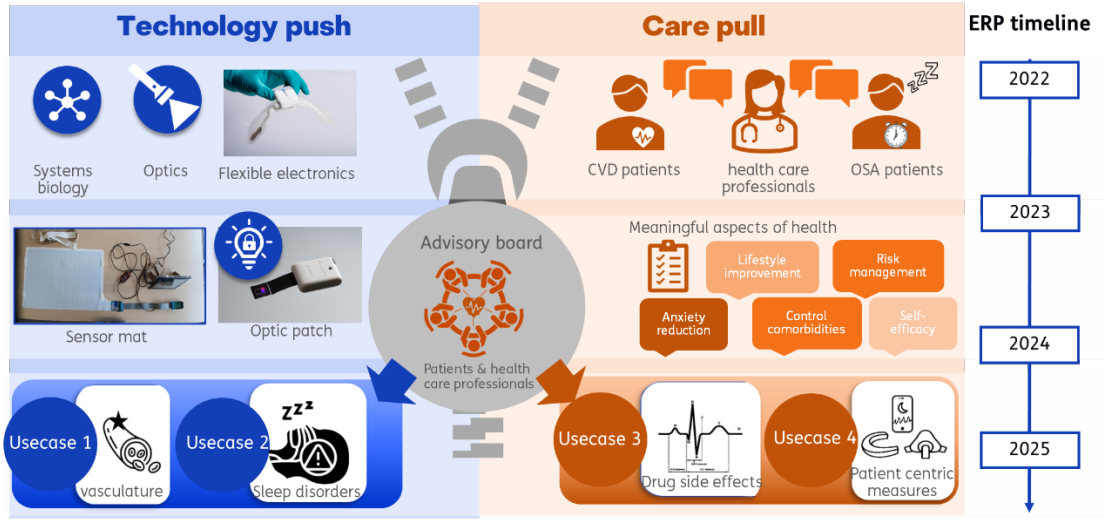
Ambition. Developing tools and methodologies for meaningful, inclusive, digital health measurements, which are a cornerstone in the upcoming transitions of healthcare.

Impact. The Generic Digital Health Measurement lab will facilitate seamless development of meaningful and inclusive digital health measurements with lead applications in CVD and sleep apnoea.

Results 2025. This ERP has resulted in the development of meaningful digital health measurements for remote patient monitoring by validating TNO's health patch, sleep mat and photonics to support the health care transition by focusing on cardiometabolic health derailments and preventive interception by research of chronobiology for sleep improvement.

Suzan Wopereis (Lead Scientist), **Sanne Kuijper** (Project Manager), **Robert Kleemann** (Director of Science H&W), **Helen Kardan** (Director of Science HTI).

4th year in 2025. Running 2022 – 2025.



12 Empowering citizen collectives

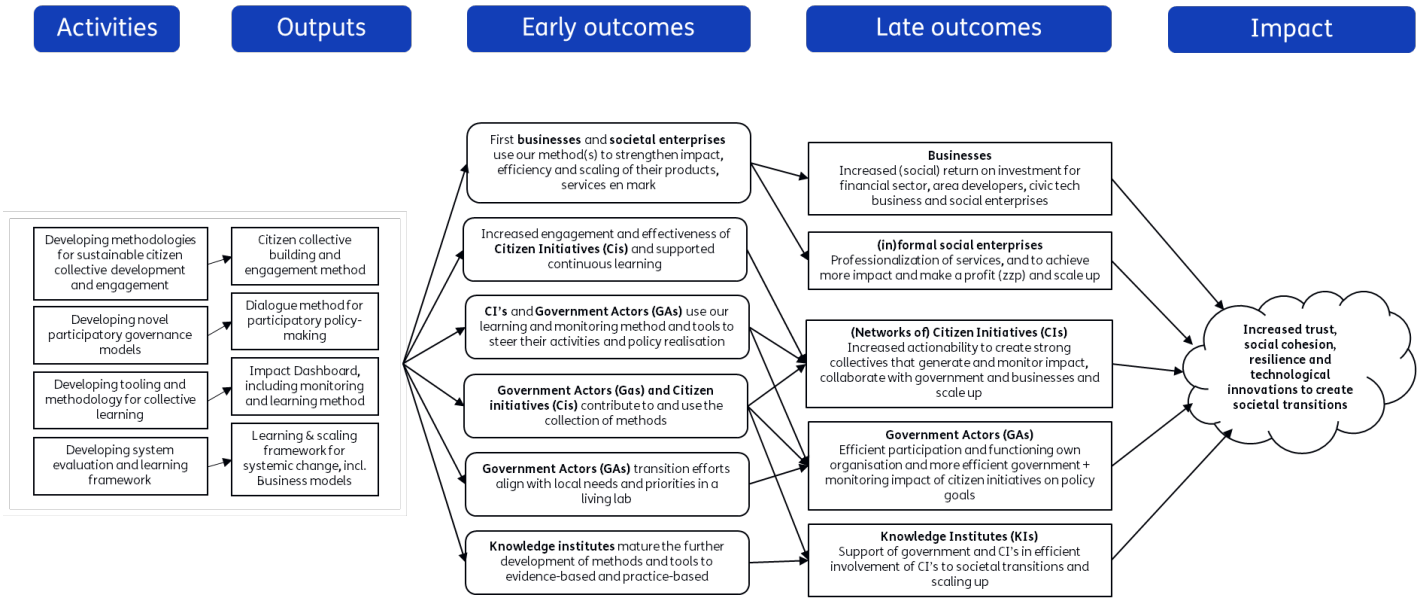
Ambition. Empowering citizen collectives by developing an evidence-based method to accelerate and scale societal transitions in neighbourhoods. This will be achieved by improving the agency of citizen collectives at neighbourhood level and engaging them in participatory policy making.

Impact. Increasing trust, social cohesion and support for governmental decisions that are needed for every societal transition.

Results 2025. In 2025 we 1) focused on the further development of tools for community engagement and governance strategies for empowering citizen collectives and applied and evaluated these tools in living labs, 2) co-designed, implemented, evaluated and improved a quantitative monitoring, evaluation and learning impact dashboard in living labs 3) defined and evaluated the impact- and scaling pathways for citizen collectives, societal change and the developed key enabling methodologies We maintained close contact with our advisory board of relevant (private) stakeholders.

Wessel Kraaij (Lead Scientist), **Pepijn van Empelen** (Lead Scientist), **Geiske Bouma** (Lead Scientist), **Eline Vlasblom** (Project Manager), **Robert Kleemann** (Director of Science H&W), **Omar Niamut** (Director of Science ISP), **André Faaij** (Director of Science EMT).

2nd year in 2025. Running 2024 – 2027.



13 Next-Generation Crypto

Ambition. Bringing secure analysis of distributed data to the next level (automatic validation, big data, real-time, quantum-safe).

Impact. In 2028, secure data sharing solutions can be engineered, validated, and subsequently exploited, for applications that use large amounts of data, and require real-time output.

Results 2025. We built a proof-of-concept for secure collaborative tracking, important for military radar, and a secure solver that helps logistic providers to work together on reducing costs and environmental pollution. We further improved our solution to check integrity of travel documents, stimulating international collaboration. We extended tools for automated protocol verification to enhance security and production costs. Technologies were developed that support the reliability and trustworthiness of AI by mathematical verification. To ensure adoption of PETs we developed governance models that include legislation.

Thijs Veugen (Lead Scientist), **Sjoerd-Jan Wiarda** (Project Manager), **Christa Hooijer** (Director of Science DSS), **Omar Niamut** (Director of Science ISP).

3rd year in 2025. Running 2023 – 2026.

14 Opto-Acoustics for Medical Imaging & Structural Monitoring

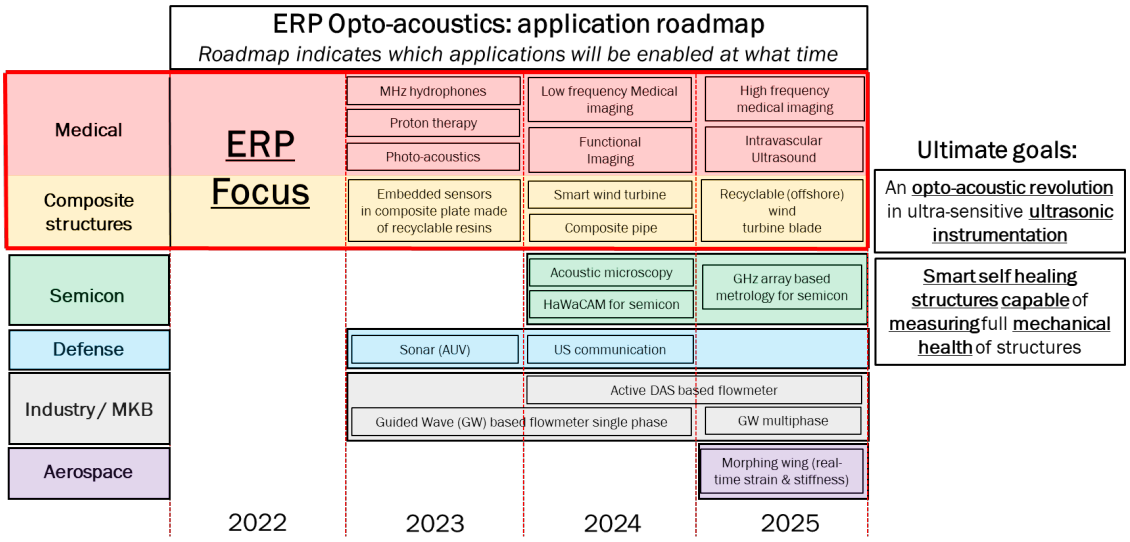
Ambition. Creating a next generation acoustic platform, using optical means only, to generate and receive acoustic waves. Such a system will radically outperform existing systems and can be miniaturized or multiplexed to cover large structural areas and long distances.

Impact. Increasing patient health and well-being by providing high quality images resulting in earlier, better and specific diagnoses. Speeding-up the clean energy revolution by extending lifetime of light-weight composite structures and accelerate material developments in re-use or recycling.

Results 2025. In the first two years of the ERP Optoacoustics (2022 & 2023), we focussed on the creation of predictive models for PUT design and the improvement of the efficiency of the PUT platform technologies on a component level. In 2024, the predictive model was further refined and steps were taken towards a prototype proof-of-concept. This included investigations into material platform dependencies and manufacturability. In 2025, the aforementioned avenue of research has been further expanded, resulting in an excellent match between PUT models and experiments (error 0 - 24%).

Paul van Neer (Lead Scientist), **Rob Jansen** (Project Manager), **Helen Kardan** (Director of Science HTI), **Christa Hooijer** (Director of Science DSS), **Robert Kleemann** (Director of Science H&W).

4th year in 2025. Running 2022 – 2025.



15 Pandemic Diagnostics

Ambition. Developing a bio-surveillance system for non-targeted identification of pathogens at pandemic hotspots (e.g. airport), a platform for on-site pathogen detection for contact tracing and a pandemic diagnostic platform for population level molecular testing.

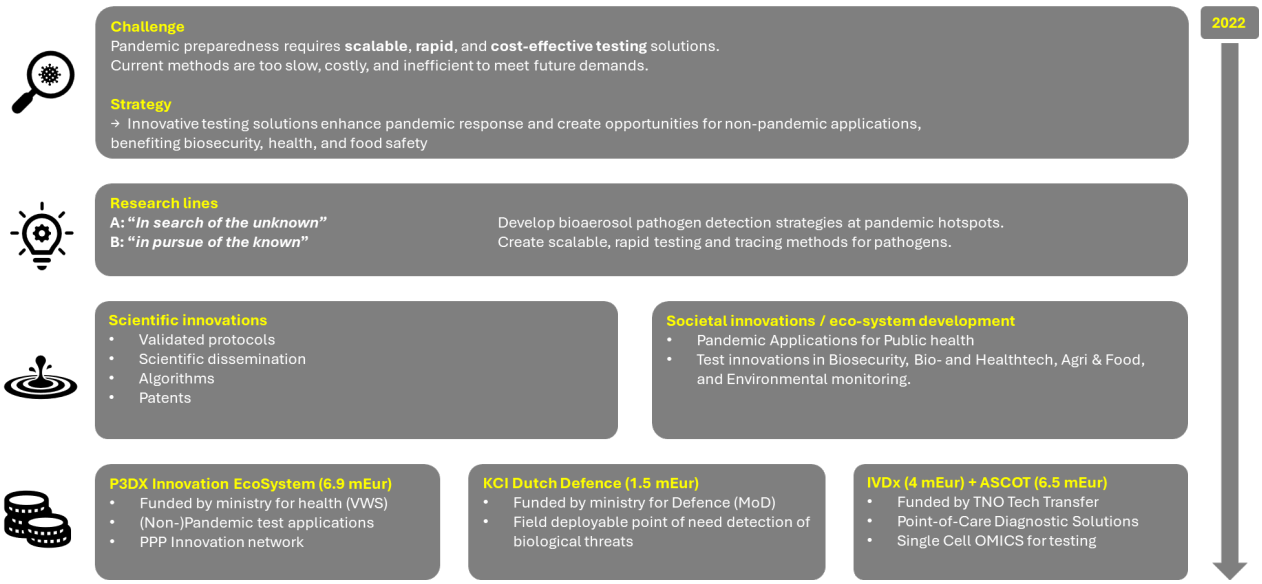
Impact. Protecting our society against the impact of future pandemic outbreaks by developing a scalable and multilevel testing strategy, optimally aligned with the needs during different phases of a pandemic outbreak.

Results 2025. The ERP Pandemic Diagnostics aims to establish innovative testing methods for future pandemic threats. In Research Line A, a water-soluble filter and proteomic mass spectrometry demonstrated feasibility for identifying viral pathogens. Additionally, a sequencing-based approach was deployed at a wastewater treatment site, demonstrating feasibility and allowing comparative evaluation of aerosol collectors.

Research line B is dedicated towards improved detection methods of pathogens expanding on isothermal detection by LAMP and/or CRISPR Cas. We established a novel method for multi target detection using the LAMP assay, with CC-LAMP tests for efficient single target detection. Methods were further implemented on point-of-need devices to evaluate lab independent applications. We explored possible methodologies for simplified sample treatment, but this was shown to require more work.

Bart Keijser (Lead Scientist), **Jasper Kieboom** (Project Manager), **Robert Kleemann** (Director of Science H&W), **Christa Hooijer** (Director of Science DSS).

4th year in 2025. Running 2023 – 2025.



16 Plasma synthesis / Plasma enhanced chemical conversion

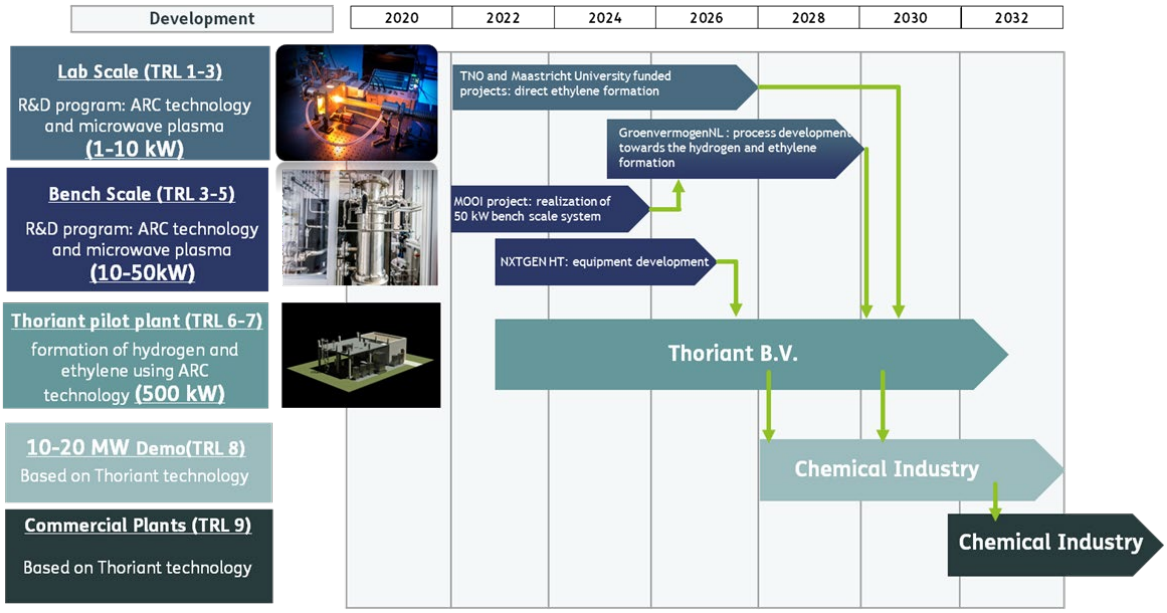
Ambition. Facilitating the electrification of the chemical industry by focussing on direct production of Ethylene; an important large volume, high value chemicals (HVC) for the polymer industry. Electrification of the chemical industry is crucial to reduce CO2 emissions. Plasma synthesis is employed for electrically converting methane to value added chemicals.

Impact. Enabling a zero-emission Naphtha cracking process and a circular chemical industry.

Results 2025. The programme focused on integration of the 5 different work packages, with the goal of obtaining better estimates of the economic viability of scaling up the process. During the first 1.5 year initial results were obtained in modelling, experiments, LCA, and TEA. Ultimately all this work is coupled, meaning that the output of one is the input for the other.

Dirk van den Bekerom (Lead Scientist), **Nicoleta Voicu** (Project Manager), **André Faaij** (Director of Science EMT), **Helen Kardan** (Director of Science HTI).

3rd year in 2025. Running 2023 – 2026.



17 Polymer design by machine learning

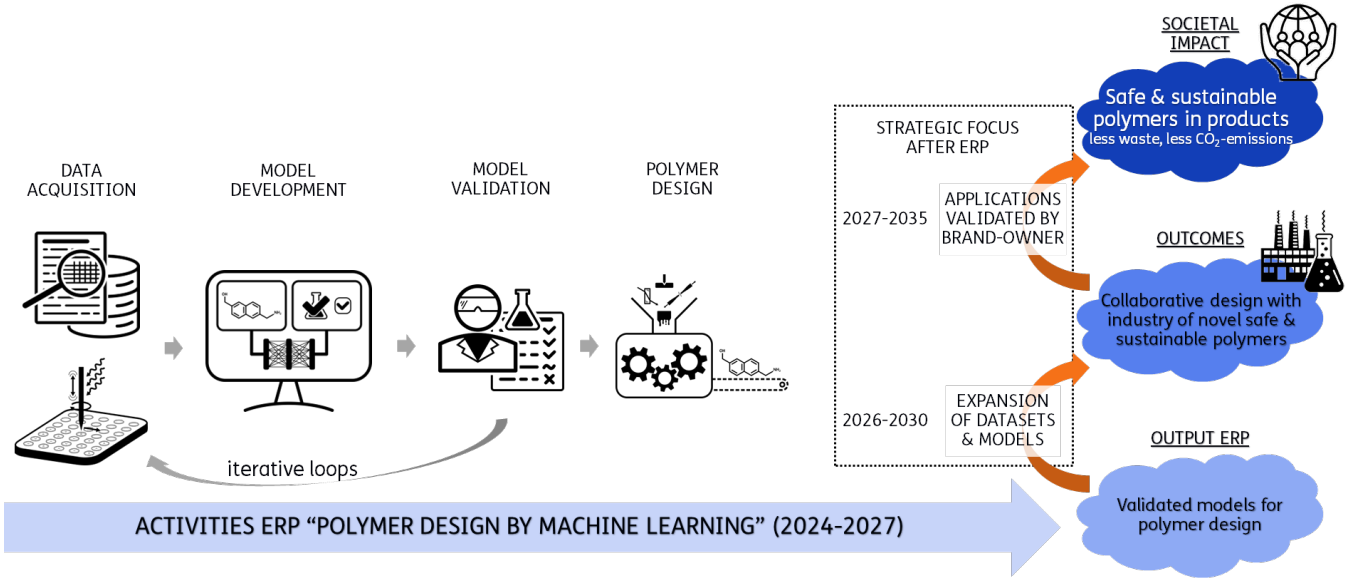
Ambition. Developing and validating a Polymer Informatics engine that realistically captures the complexity of polymers to design novel candidates that match with requirements for safe & circular plastics.

Impact. Accelerating design of polymers that are needed for future-proof plastics that are safe & sustainable by design, circular, sourced from CO2 & biomass to decarbonize industry, whilst reducing systems' complexity.

Results 2025. This ERP has resulted in three data acquisition pipelines (experimental, literature, theoretical simulations), an up-to-date database for biobased polymers and corresponding data management tools. Furthermore, the ERP has delivered algorithms to adequately describe the complexity of polymers through BigSMILES-based fingerprinting. Also, multi-task property prediction and confidence-based modelling were integrated into the AI-workflow. Finally, algorithms for high-level screening of polymer toxicity and biodegradability (end-of-life) have been explored and integrated into the AI-workflow. Various experimental results have been generated, in reasonable agreement with the predictions – as such validating our approach for AI-powered design of safe and sustainable polymers and plastics.

Jan Harm Urbanus (Lead Scientist), **Lina Rambausek** (Project Manager), **André Faaij** (Director of Science EMT), **Omar Niamut** (Director of Science ISP).

2nd year in 2025. Running 2024 – 2027.



18 QuTech

Ambition. Building scalable prototypes and underlying technology for Quantum Internet and Quantum Computing. QuTech is a multi-year collaboration, where the TNO contribution focuses at specific parts of the entire stack, at raising TRL of specific promising technology solutions, and at the systems engineering aspects of the entire stack.

Impact. Quantum technology harnesses the properties of quantum (superposition and entanglement), to achieve exponential improvements in calculation power for problems that are hard to solve using conventional computers, and by realizing inherently safe communication. Envisioned applications range from design of materials and medicines to logistics, finance and climate change models.

Results 2025. For Quantum Computing, we produced and brought online a upgraded spin qubit NISQ system with full functionality for NISQ algorithms, based on direct spin readout. This work was partially completed in 2024 but finalized in 2025 within project QLSI2.

For Quantum Internet, we have detailed the Systems architecture of our scalable quantum repeater and proceeded to key component validations (namely a micro-cavity for NV enters).

For Quantum Sensing we further developed quantum magnetometers available in our testbed to improve their capability, and identify metrology techniques enabled by quantum sensing that apply to quantum computing chips and to the semiconductor industry for failure analysis.

Finally with Quantum Devices and Materials, new processes were developed for fabrication of novel devices and we tested our final version of a TWPA.

Richard Versluis (Lead Scientist), **Jeremy Veltin** (Project Manager), **Helen Kardan** (Director of Science HTI), **Christa Hooijer** (Director of Science DSS).

4th year in 2025. Running 2022 – 2025 (second phase).

From 2026 onward the activities are valorised via the TNO proposition of Quantum Technologies with the ambition to:

- Establish the industrialization backbone of the Dutch quantum industry by engaging major OEM partners.
- Position the Netherlands as a strategic player in the international quantum supply chain.
- Accelerate adoption of quantum systems in mature industries (e.g., Defence, Space) through concrete, user driven use cases.

More information: https://www.tno.nl/en/digital/semicon-quantum/quantum-technologies/

19 Socio-economic impact of green transitions

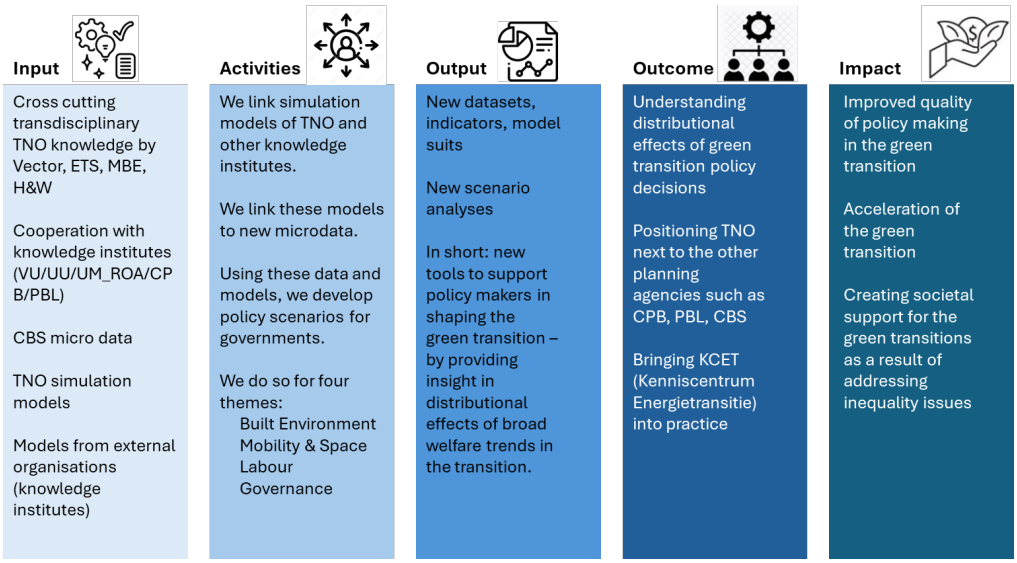
Ambition. Developing a comprehensive microsimulation approach to quantitatively assess the integral impact of the energy and mobility transitions on households' economic well-being. A grand societal challenge is to implement the transition to a sustainable and green society while maintaining and redefining societal welfare ('Brede Welvaart'). We work together with CBS, CPB, PBL and academic partners.

Impact. Providing decision-makers with the necessary information to design well-targeted and cost-effective policy measures to promote an inclusive green transition and create societal support.

Results 2025. We developed and operationalised three geo-coded microdata microsimulation modelling frameworks that enable detailed assessment of the distributional impacts of the energy and mobility transitions on households, firms, and workers. These frameworks integrate large-scale CBS microdata on income, vulnerability, skills, energy use, housing characteristics, transport behaviour, emissions, and firm dynamics, and were implemented across the built environment, mobility, labour, and governance domains. Alongside these tools, we established a broad and active user and development network—including TNO, CBS, CPB, PBL, universities, and multiple ministries—and applied the models in concrete policy use cases, ranging from housing decarbonisation and district heating to transport infrastructure, labour-market transitions, energy poverty, and green skills. Together, these activities resulted in multiple published and submitted academic and policy-oriented studies, delivering new empirical insights into how the costs, benefits, and risks of the energy and mobility transitions are distributed across households, regions, firms, and workers.

Peter Mulder (Lead Scientist), **Caroline Schipper** (Project Manager), **Anne Fleur van Veenstra** (Director of Science TNO Vector), **André Faaij** (Director of Science EMT), **Arjen Adriaanse** (Director of Science MBE).

3rd year in 2025. Running 2023 – 2026.



20 Solar-2-Hydrogen

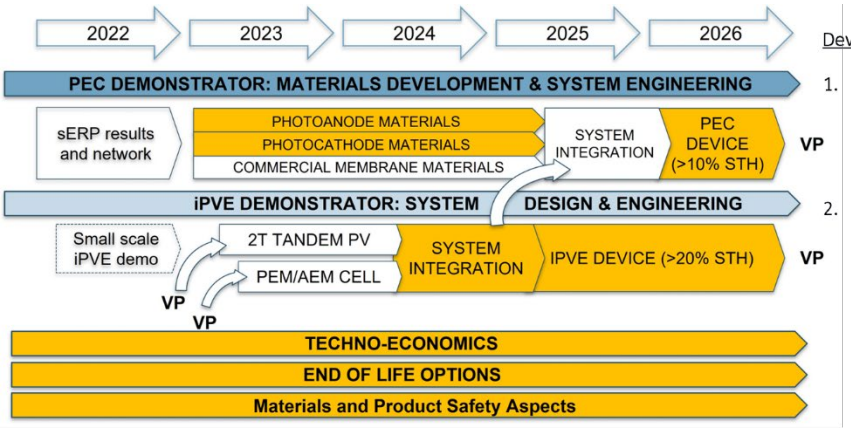
Ambition. Developing and demonstrating devices for water splitting that use sunlight as sustainable energy source and yield green H2 at a levelized cost of H2 (LCOH) comparable to green H2 from electrolysis.

Impact. Based on commonly accepted scenarios for the energy transition in NL and EU, there will be a large demand for green hydrogen (H2) that is unlikely to be fully covered by large scale electrolysis. We will research alternative technologies with the potential to produce green H2 at similar or lower costs.

Results 2025. Integrated iPVE solar-to-hydrogen devices have progressed from system design to lab and pilot demonstrators, expected to reach 21.5% efficiency and planned for validation in 2026, with a patent in preparation. Studies show these devices have lower environmental impact than conventional PV-powered electrolysers, with similar land use. We improved coatings and silicon photoanodes, enabling PEC devices up to 13.5% efficiency. Collaborative tests with UvA and UAntwerp are ongoing, with publications planned for early 2026.

Pascal Buskens (Lead Scientist), **Nicole Meulendijks** (Project Manager), **André Faaij** (Director of Science EMT), **Helen Kardan** (Director of Science HTI), **Robert Kleemann** (Director of Science H&W).

3rd year in 2025. Running 2023 – 2026.



Development targets:

1. Concept developed for solar water splitting according to the PEC approach with solar-to-hydrogen efficiency >10%. Individual device components (e.g., photo-electrodes) developed and tested on lab scale (TRL 3).
2. Pilot scale S2H panel (~196 cm^2) for solar water splitting, according to the iPVE approach, with solar-to-hydrogen efficiency >20%, validated using (concentrated) artificial sunlight (TRL 5)

Key Stakeholders:

- Government: Province N-Br, EZK, co-funding Interreg project FOTON.
- Companies: DCL, Soltech, Azteq involved via Interreg project FOTON.
- User and advisory committee for Interreg FOTON (> 10 company partners; current partners: Ankerpoort, PhotonFirst, BrainPort, Agfa, Brusche, SparkNano, Festo)
- WaterstofNet members.

21 Subsidence and building damage

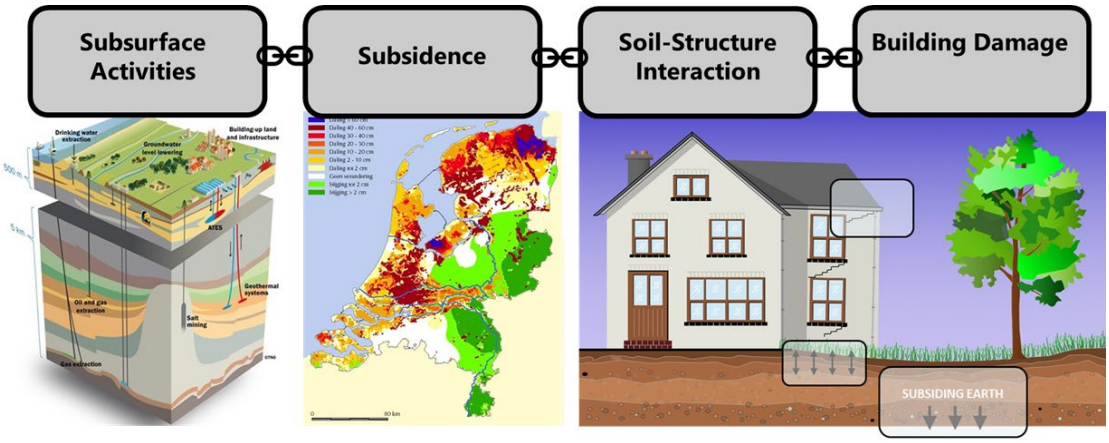
Ambition. Developing, integrating and implementing knowledge to guarantee a society where damage to the built environment caused by subsidence can be prevented or mitigated. We will build a chain of models applied to assess the causal relationship between subsidence and damage to the built environment.

Impact. Reducing the huge costs for subsidence induced damage, while enabling the safe continuation of pre-existing and future subsurface activities.

Results 2025. In the last year of the ERP existing functionality was consolidated and a working and tested model chain at TRL 4 with two sources of subsidence was delivered. Furthermore, internal and external stakeholders meetings were held to ensure the use and further development of the ERPs knowledge and network after conclusion of the project.

Chris Geurts (Lead Scientist), **Thibault Candela** (Lead Scientist), **Andreas Höllbacher** (Project Manager), **Joop Hasselman** (Project Manager), **Arjen Adriaanse** (Director of Science MBE), **André Faaij** (Director of Science EMT), **Anne Fleur van Veenstra** (Director of Science TNO Vector).

4th year in 2025. Running 2022 – 2025.



22 Sustainable ICT

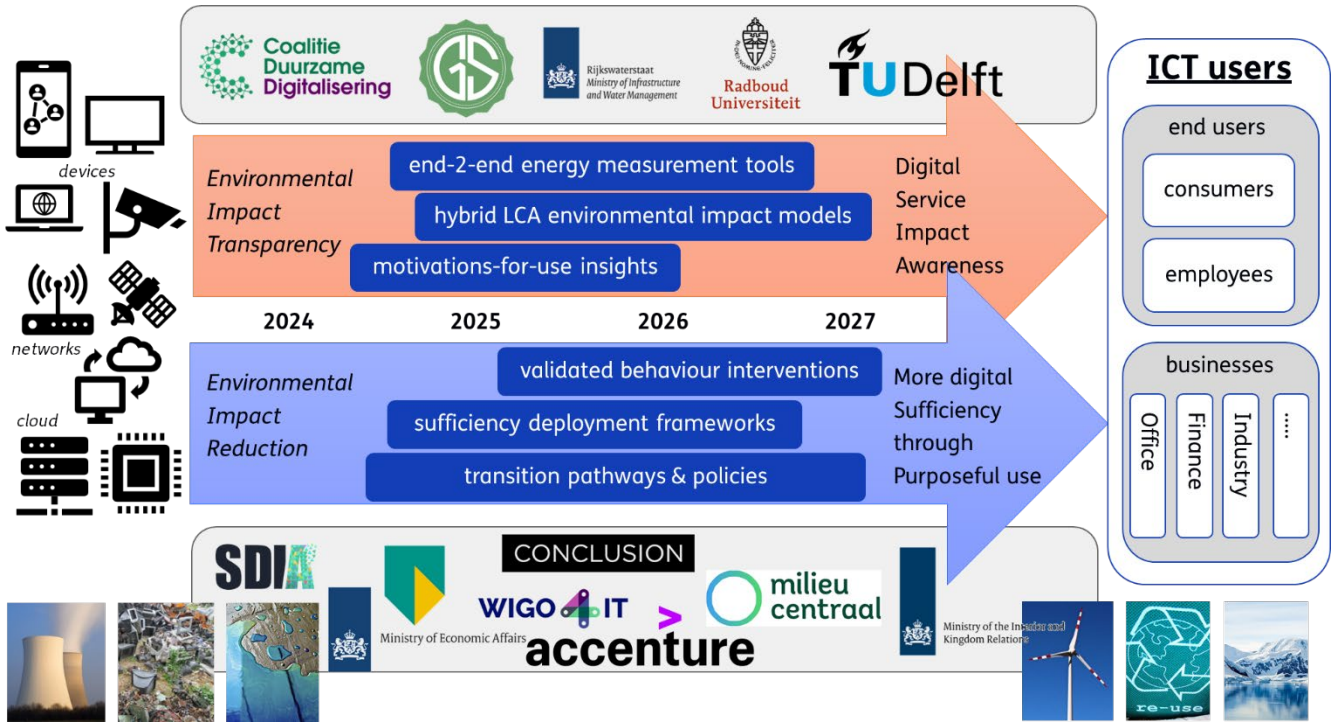
Ambition. Facilitating policy makers in comprehending the environmental impact of the ICT sector and enable ICT companies to react to governmental policy.

Impact. Improving the sustainability of the ICT sector and limit its greenhouse gas emissions by creating action perspectives for policy makers and ICT companies.

Results 2025. We defined our methodology to calculate environmental impact of ICT usage and applied this to both video streaming and company IT services. From this we derived the main areas for improvement and defined pathways for change, based on digital sufficiency and high R-ladder solutions as focus areas.

Hans Stokking (Lead Scientist), **Julie Cammell** (Project Manager), **Omar Niamut** (Director of Science ISP), **André Faaij** (Director of Science EMT), **Anne Fleur van Veenstra** (Director of Science TNO Vector).

2nd year in 2025. Running 2024 – 2027.



23 Sustainable recycling of Batteries and Solar panels

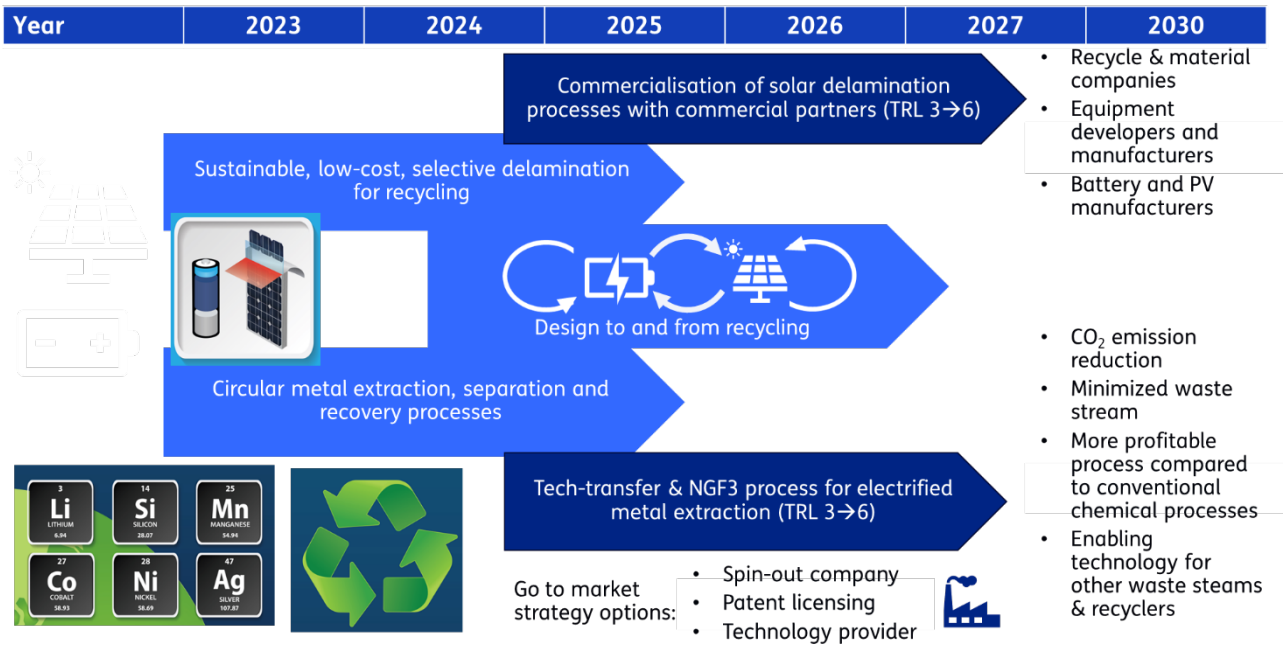
Ambition. Developing new sustainable technologies to promote strategic materials independence of the Dutch industry by recycling of electronic products and their design from and to recycling. Our focus will be on batteries and PV panels as primary use cases.

Impact. Closing material loops by design from and to recycling by developing sustainable technologies for recycling of batteries and solar panels within a system level approach. These sustainable technologies are of generic relevance to utilize (electronic) waste streams.

Results 2025. The selective delamination process for solar panels was further optimized towards a scalable process. Sustainable metal extraction for Li-ion batteries was patented, this process is currently being modified to metal extraction from PV waste. The design to and from recycling activities was kicked-off by mainly exploring the feasibility of using the recovered materials in various applications.

Mirjam Theelen (Lead Scientist), **Devin Boom** (Lead Scientist), **Ahmed Fawzy** (Project Manager), **André Faaij** (Director of Science EMT).

3rd year in 2025. Running 2023 – 2026.



24 Synthetic Biochemistry

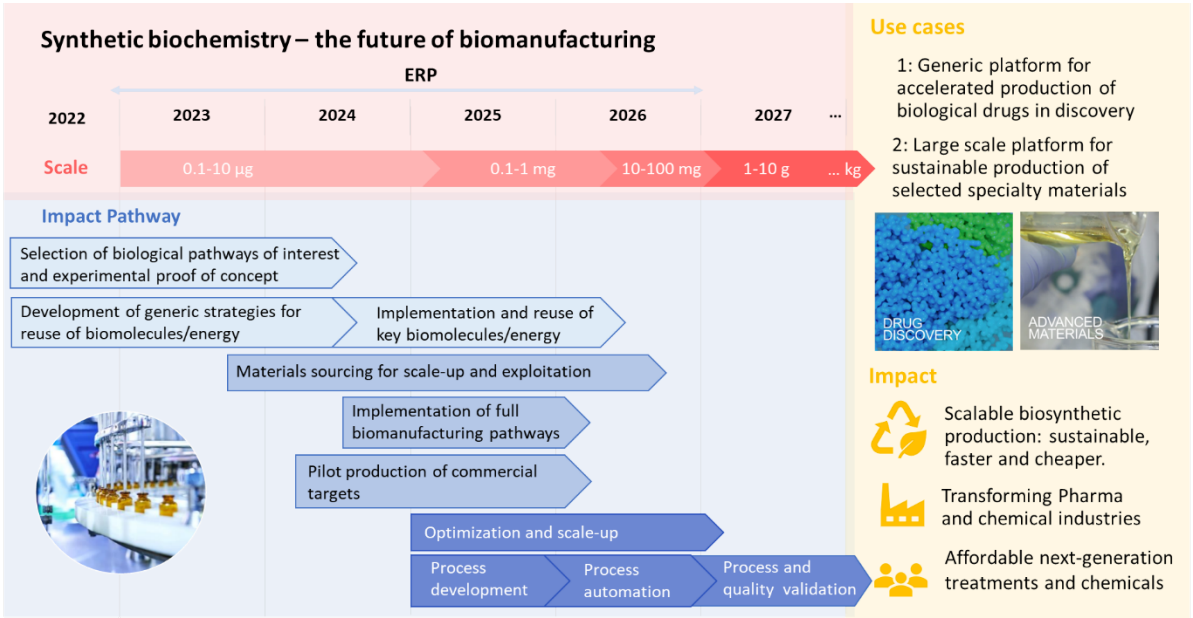
Ambition. Developing the world's most sustainable biosynthetic version of a biomaterials and biopharmaceuticals production platform with process efficiencies >90% enabled at 10-20% of current production costs.

Impact. Accelerating R&D timelines in pharma, biotech, chemical and energy carrier industries. Lowering the cost of goods while increasing technical success and achieving sustainability goals. Initiating a paradigm shift through bottom-up biological production instead of isolation of by-products from mainly waste.

Results 2025. The programme showcased its optimised and scaled-up biosynthetic approach to produce therapeutic proteins and bulk chemicals and energy carriers (BCECs) of commercial interest. Following external validation of its envisioned business case and technology strategy, this ERP has now set the path towards valorisation by consolidating its IP position and exploring additional funding opportunities.

Olaia Álvarez Bermúdez (Lead Scientist), **Niamh Whelan** (Project Manager), **Robert Kleemann** (Director of Science H&W), **André Faaij** (Director of Science EMT).

3rd year in 2025. Running 2023 – 2026.



25 Appl.AI

Ambition. Building new AI capabilities into Autonomous Systems and Federated Decision Making and to integrate AI into System Engineering and Lifecycle Management.

Impact. Solving societal problems by combining our domain knowledge, multidisciplinary expertise and our knowledge of AI technology. For this, AI systems need to have capabilities that are flexible, trustworthy, and engineered for lifetime validity.

Results 2025 per flagship.

FATE advanced trustworthy AI with tools for individualized interaction and integrated fairness, confidentiality, and explainability. It demonstrated privacy-preserving counterfactuals over distributed data and produced scientific publications, new stakeholder leads, and several valorisation-driven use cases.

GRAIL developed tools and methods, in cooperation with stakeholders, to translate theoretical responsible Generative AI aspects into practical frameworks. This includes tools to facilitate critical reflection for professionals when using GenAI, methods for assessing GenAI, including Dutch bias evaluation and new decision focused metrics.

SNOW advanced and evaluated, robust stackable AI modules providing autonomous capabilities for robotic platforms. The modules can be flexibly combined, reused across diverse platforms and use cases, and support extensibility for partners needing additional autonomous functionalities.

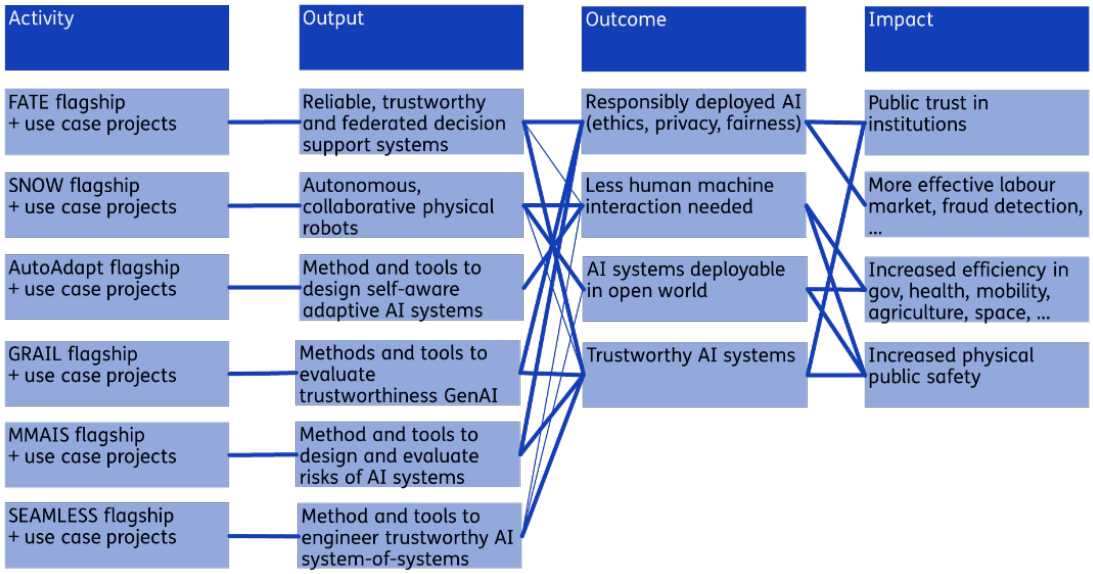
MMAIS advanced tools and methods for specifying, developing, and monitoring high-risk, morally sensitive AI systems. Results include tools that facilitate specification of desired AI behaviours, uncertainty-aware moral decision-support technologies, and a monitoring framework preventing unacceptable behaviours such as inappropriate profiling.

SEAMLESS advanced systems engineering and lifecycle methods for AI-based cyber-physical systems, raising its system-analysis approach to higher TRLs and demonstrating design, V&V, monitoring, and diagnostics methods. Results were validated with partners and showcased at major automotive industry events.

AutoADAPT integrated awareness-with-learning, short-horizon GA optimisation, and RL-based constraint policies into a unified self-adaptive concept demonstrated on a cloud-connected HIL battery system. Real-world and simulation showcases for laser satellite communication and vehicle battery management validated its potential and initiated discussions for follow-up industry projects.

Cor Veenman (Lead Scientist), **Frank Benders** (Lead Scientist), **Johan Janssen** (Project Manager), **Christa Hooijer** (Director of Science DSS), **Omar Niamut** (Director of Science ISP), **Arjen Adriaanse** (Director of Science MBE).

3rd year in 2025. Running 2023 – 2026.


Activity
Output
Outcome
Impact
FATE flagship + use case projects
SNOW flagship + use case projects
AutoAdapt flagship + use case projects
GRAIL flagship + use case projects
MMAIS flagship + use case projects
SEAMLESS flagship + use case projects
Reliable, trustworthy and federated decision support systems
Autonomous, collaborative physical robots
Method and tools to design self-aware adaptive AI systems
Methods and tools to evaluate trustworthiness GenAI
Method and tools to design and evaluate risks of AI systems
Method and tools to engineer trustworthy AI system-of-systems
Responsibly deployed AI (ethics, privacy, fairness)
Less human machine interaction needed
AI systems deployable in open world
Trustworthy AI systems
Public trust in institutions
More effective labour market, fraud detection, ...
Increased efficiency in gov, health, mobility, agriculture, space, ...
Increased physical public safety

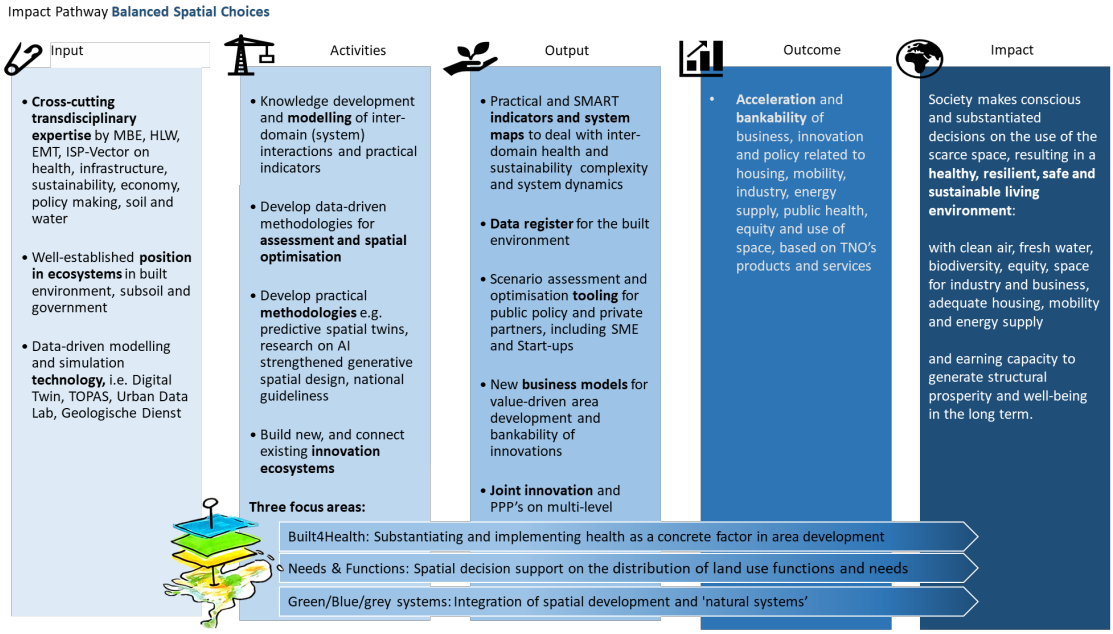
26 Balanced spatial choices

Space is scarce. Especially in the Netherlands, while the demand for space keeps on increasing and several transitions are transforming the living environment and use of space. Social, environmental and economic needs and requirements like health, biodiversity, inclusiveness, climate change, competitiveness, safety, mobility, housing, autonomy, social cohesion and inclusion influence how we use, preserve and adapt the space around us. We need to integrate all these claims, functions and needs when making balanced spatial decisions. The leading question for the Balanced Spatial Choices program (BSC) is therefore: how can we drive, support and substantiate integrated spatial decision making, by balancing social, environmental and economic needs?

Results 2025. The Balanced Spatial Choices programme has implemented three main programme lines – health and inclusive urban areas, balanced needs & functions for regions, and transforming green, blue, and grey systems – by developing and concretising roadmaps in the first quarter, launching new projects and continuing current ones throughout the year, and fostering collaboration both internally across TNO units and externally with partners and stakeholders.

Marloes van der Klauw, Tanja Vonk, Heleen de Kraker (Project Manager).

2nd year in 2025. From 2026, this programme will no longer be positioned within the ERP portfolio. Its activities will, however, continue on a cross-unit basis.



Strategy

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