TNO innovation for life

ERP Annual Report 2024

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ERP Annual Report 2024

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1 Introduction

1.1 TNO's Early Research Programme

The Early Research Programmes (ERPs) constitute TNO's early 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. The ERPs account for approximately 5% of TNO's turnover, while the remaining 95% is directed by TNO's stakeholders, including industrial and public clients, 'Topsectors', ministries and governmental bodies (via consultation and/or task financing).

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 and social value for Dutch society. Despite the iterative nature and unpredictability of early 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 2024, TNO introduced 'impact pathways' to guide early research projects, ensuring comprehensive planning of both scientific activities and outcomes, thereby reducing risks and maximizing economic and social value. The impact pathways are under continuous further development but already show a great diversity of intended impact.

This document outlines the results of ERP projects in 2024 and summarises the anticipated outcomes of ongoing projects.

Figure 1.1: TNO's Early Research Programmes serve as the incubator for innovative technologies and methodologies, driving value for Dutch society and the economy. In 2024 we realised the first 'ERP day' were teams presented their results and discussed how to maximise projects' outcome.

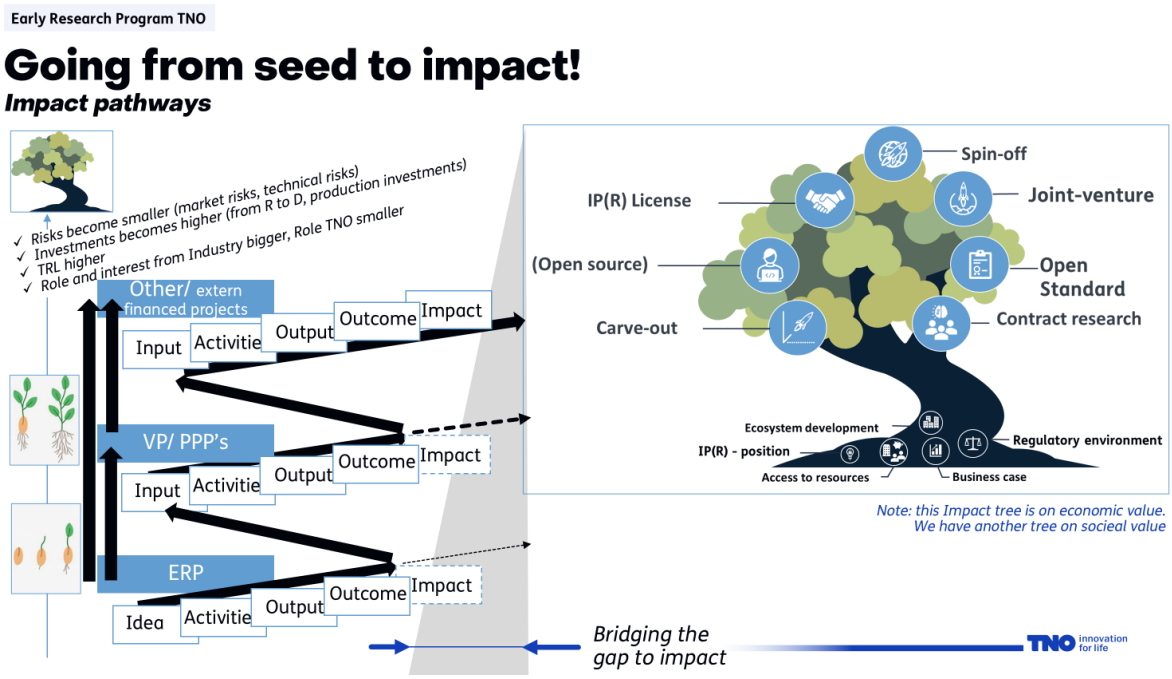


Figure 1.2: Growing from Seed to impact – a visualisation of how TNO's ERPs contribute to achieving impact.

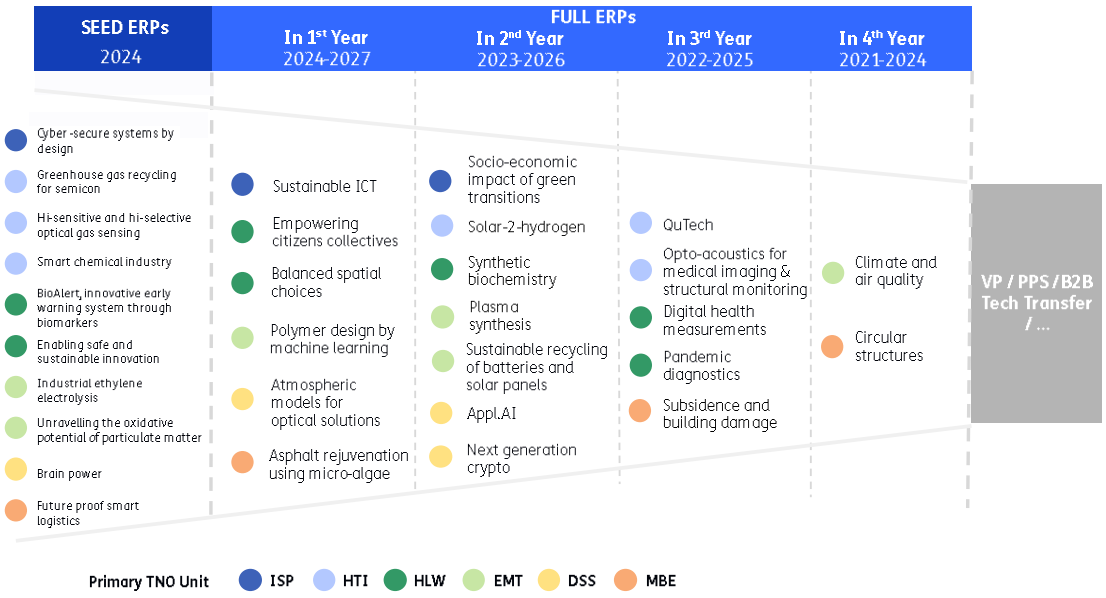


Figure 1.3: The ERP funnel in 2024

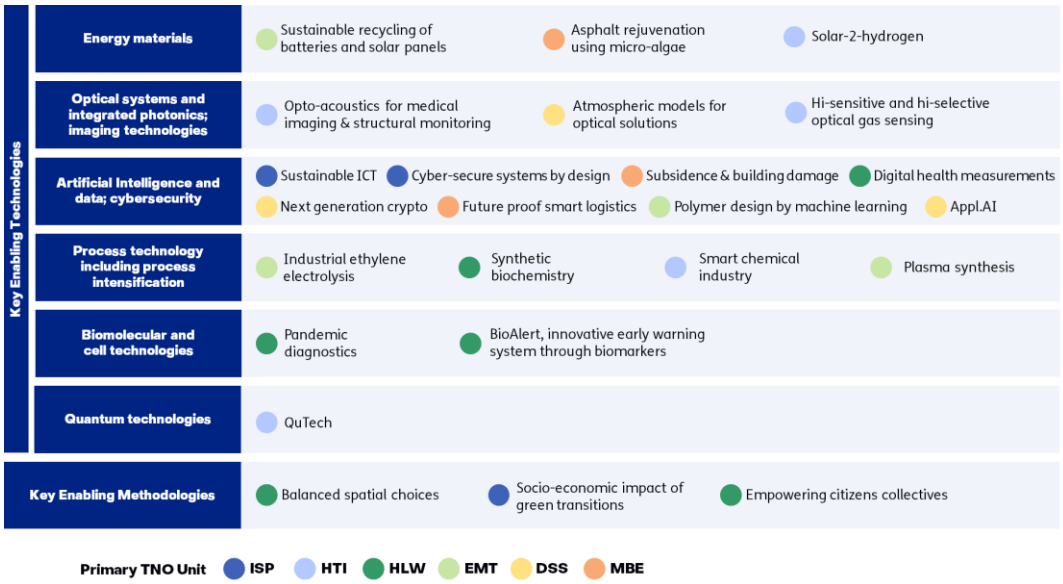


Figure 1.4: ERP projects mapped to key technologies in the national technology strategy (NTS) as well as those ERPs focussing on key enabling *methodologies*.

1.2 Results of the ERP Portfolio in 2024

- A total of 20 Full ERP and 10 Seed ERP projects were conducted in 2024. Two Full ERP projects were successfully concluded after 4 years: Circular Structures and Climate Air Quality.
- We organised a 2-day event, the 'ERP Days', 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. A rich programme of workshop was offered, including workshops on intellectual property (IP) strategy, innovation orchestration and potential forms for follow-up funding.
- On the scientific side, the ERP projects published a total of 96 peer-reviewed scientific publications and submitted 17 patent first filings. Almost all ERP projects (including Seed ERPs) developed proof-of-concepts, protypes, or demonstrators.
- A selection of results and ongoing work is highlighted below to illustrate notable developments and impact potential within the portfolio:
  - Both ERP projects finished in 2024, "Circular Structures" and "Climate and Air Quality" show a strong valorisation outlook, as evidenced by the successful acquisition of several million euros in follow-up funding, underscoring their attractiveness for further development and societal or economic impact.
  - In the context of the Seed ERP BioAlert, the paper "Development of a novel non-invasive biomarker panel for hepatic fibrosis in MASLD" was published in Nature Communications.
  - Several ERP projects have started discussions with TNO Tech Transfer towards valorisation as spin-outs. This includes the ERPs "Pandemic Diagnostics", "Sustainable Recycling of Batteries and Solar Panels", "Synthetic Biochemistry" as well as "Asphalt rejuvenation using micro-algae".

  - The ERP projects also resulted in new programmes within several joint innovation centers (JICs). For example, as part of the ERP 'Plasma Synthesis,' TNO collaborates within the Brightsite knowledge center. Brightsite focuses on key challenges such as replacing fossil-based energy and feedstocks with renewable electricity, advancing plastic waste recycling, and fostering the next generation of researchers and professionals. Another example is our collaboration with LUMC within the context of several ERPs of the unit Health & Work.

- In 2024, we selected 6 new four-year Full ERPs to commence in 2025. To do so, we analysed projects and their plans along the criteria of right-to-play and market attractiveness. Additionally, a selection of 11 single-year Seed ERPs to be executed in 2025 was finalized by the end of 2024. 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 “Industrial ethylene electrosynthesis”, “BioAlert innovative early warning system through biomarkers”, “Future proof smart logistics”, “Cyber-secure systems by Design”, “Smart Chemical Industry” and “HiSensitive and HiSelective Optical Gas Sensing”. All these concern domains with clear scientific challenges and high societal and economic relevance. The topics were selected out of the ten Seed ERPs of 2024.

2 Seed ERPs

- In 2024, TNO conducted 10 Seed ERP projects to analyse scientific and market risks associated with innovative new ideas. Of these 10 projects, the following were selected for follow-up in 2025:
  - **BioAlert, innovative early warning system through biomarkers**, aims to achieve a paradigm shift from diagnosing diseases after symptom manifestation to detecting them pre-symptomatically by developing a unique and versatile biomarker technology platform.
  - **Cyber-secure systems by design** aims to transform product development by integrating cybersecurity at every stage of the process, ensuring inherently secure and reliable cyber-physical systems.
  - **Future-proof smart logistics** aims for a system change in logistics for urgent improvements in efficiency, sustainability and resilience by developing new methods and decentral algorithms for trusted scalable collaborative planning solutions for asset sharing in systems of connected logistics networks.
  - **Highly-sensitive and highly-selective optical gas sensing (HISENSE)** aims to develop a remote sensing system with enhanced spatial resolution, adaptive spectral-range selectivity and radiometric sensitivity using a model-based instrument and end-to-end system simulator and data-processing approach resulting in a prototype that can acquire, detect and quantify very low concentrations of target gas species located in challenging operational environments.
  - **Industrial ethylene electrolysis** aims to position TNO as a worldwide leader in industrializing electrochemical CO2 conversion, with multidisciplinary expertise on material science, modelling, electrochemical engineering, leveraging unique testing infrastructures.
  - **Smart Chemical Industry** aims to support and guide the EU chemical industry in its transition towards climate neutrality by enabling optimum use of sustainable electricity, thereby maintaining a competitive and sustainable position in Europe.
- The following project was granted another Seed ERP phase:
  - **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.
- The following Seed ERPs are not continued in 2025 as Full ERP but the topics are further developed through other means:
  - Brain power
  - Enabling Safe and Sustainable Innovation
  - Unravelling the oxidative potential of particulate matter

3 Asphalt rejuvenation using micro-algae

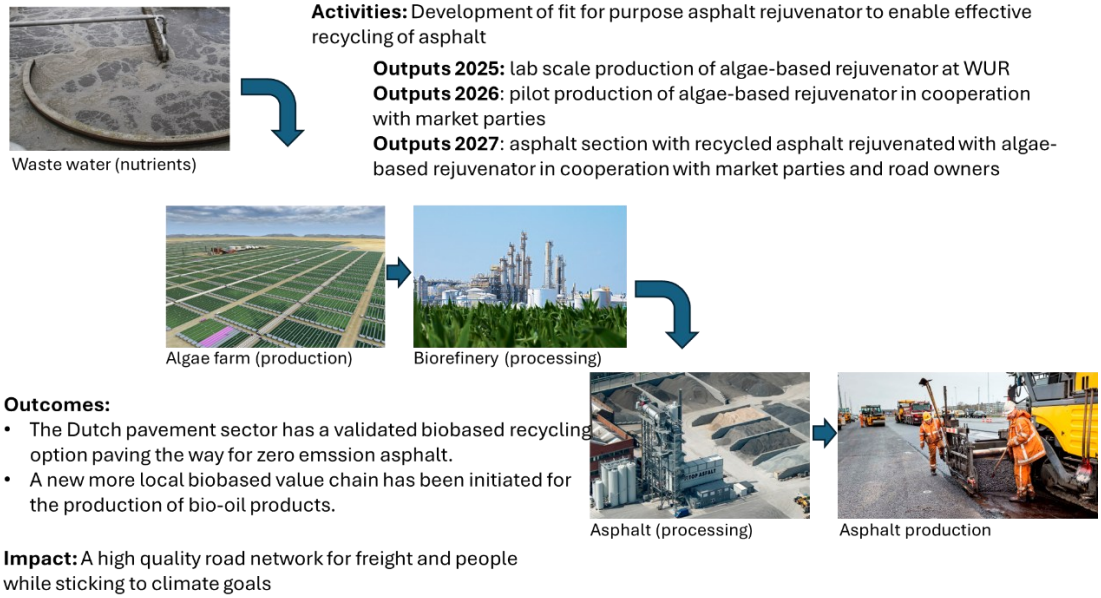
Ambition. Developing a fit-for-purpose asphalt recycling agent based on wastewater grown micro-algae at an industrial scale to keep the Dutch road network operational in a new circular value chain.

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 2024. During the first year of the ERP preparatory work was executed to enable the design of a fit-for-purpose rejuvenator; a preselection of suitable microalgae strands was made, the working principles for an asphalt rejuvenator were formulated, the cell disruption steps in the extraction process have been tested and the foundation for the techno-economic analysis that will support future assessments has been established.

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.



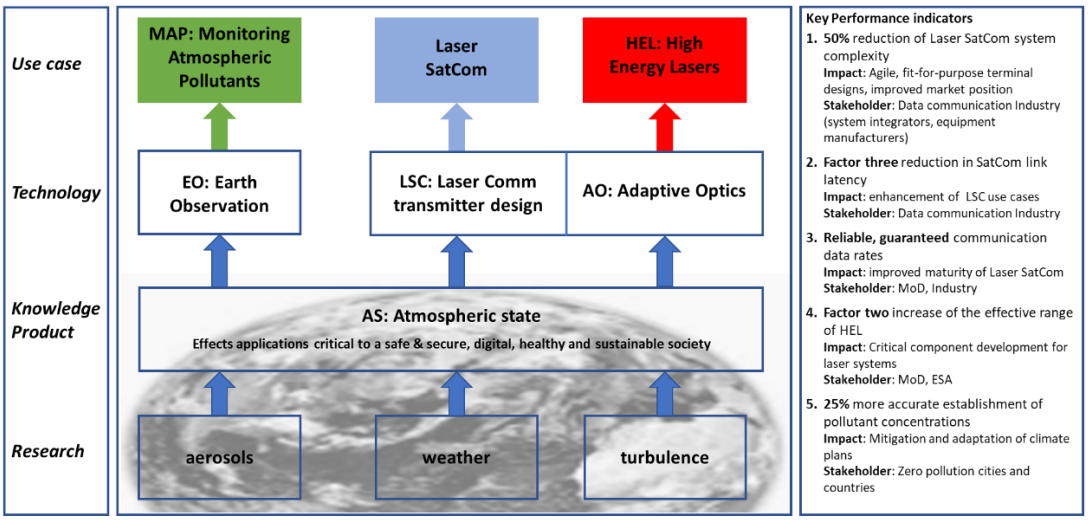
4 Atmospheric models for optical solutions

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 2024. Work has progressed on improving atmospheric state (AS) models and modelling capabilities. The Weather Research & Forecasting (WRF) model has been implemented on the TNO High Performance Computation cluster, tested for various use-cases and used to parametrise turbulence profiles. A performance model for Laser Satellite Communication has been built, as well as an expanded high-energy laser (HEL) propagation codeto assess the impact of AS on HEL weapon performance. Aerosol modelling within LOTOS-EUROS\ORACLE has been expanded in terms of distribution and size.

Lex van Eijk (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.



5 Circular Structures

Ambition. Enabling sustainability-oriented and material-quality-based multi-objective design of concrete structures and support decision-making in simultaneously reaching optimum in social wellbeing (incl. structural reliability), environmental impact & economic performance for non-traditional concrete solutions.

Impact. Integrating multi-objective optimization into structural engineering, thereby enabling the development of advanced parametric models for circular concrete structures that use construction and demolition waste (CDW). By targeting structural integrity, environmental sustainability, and economic performance simultaneously, the project not only redefines traditional design paradigms but also paves the way for a more circular construction economy. Moreover, by designing and characterizing CDW-based binders as a viable cement replacement, it addresses the dual challenge of reducing carbon emissions and promoting resource efficiency in the building industry.

Results 2024. We developed knowledge and technology that enables a shift from traditional specification-based design strategies for concrete structures to new design approaches driven by an integration of material quality and performance demands. We successfully introduced a new engineering design method for concrete structures, driven by multi-criteria optimization. It incorporates advanced models for predicting the performance of non-traditional solutions, including the recycling of construction and demolition waste and the reuse of reclaimed structural components, and enables safe, cost-efficient and environmentally-optimal use of construction and demolition waste (CDW) in structural applications.

Agnieszka Bigaj van Vliet (Lead Scientist), **Siska Valcke** (Lead Scientist), **Francesco Cinquini** (Project Manager), **Arjen Adriaanse** (Director of Science MBE), **André Faaij** (Director of Science EMT).

Concluded in 2024.

6 Climate Air Quality

Ambition. The overall goal is to develop a globally applicable atmospheric modelling system with resolution down to 25m to fully exploit the emerging observation capacities of satellites and sensors. In this final year the aim was to consolidate and integrate the emission modelling concepts and quantify their added value for air quality modelling applications. For hyper local scale modelling (DALES) we aimed to complete the budget of reactive nitrogen (with particulate matter formation). By disseminating the added value, we aimed to ensure a lasting impact beyond the ERP lifespan through a project portfolio in the following years.

Impact. This research project enhances environmental policy by providing hyper-local air quality and nitrogen assessments, enabling more targeted mitigation strategies. It moves beyond national average emission factors to offer detailed insights into pollutant sources, supporting more effective regional and local interventions. By integrating air pollutants, greenhouse gases, and nitrogen compounds, it helps identify policy co-benefits. Open-access tools like TOPAS and the LOTOS-EUROS model support policy development across Europe, while improved air quality forecasting benefits public health.

Results 2024. During 2024 new parameterizations for agriculture, road transport, inland shipping, landfills and small combustion sources were developed and tested in air quality simulations. The largest improvement is seen for ammonia for which we were able to improve the explained variability from 38% to 58%. New developments on grassland application emissions may improve this further. Simulations with chemistry in DALES show that the contribution of secondary compounds is important at several kilometres from highways. Based on the demonstrators a project portfolio of similar size as the ERP was secured for the years to come.

Martijn Schaap (Lead Scientist), **Rianne Droge** (Project Manager), **André Faaij** (Director of Science EMT), **Arjen Adriaanse** (Director of Science MBE), **Helen Kardan** (Director of Science HTI).

Concluded in 2024.

7 Digital Health Measurements

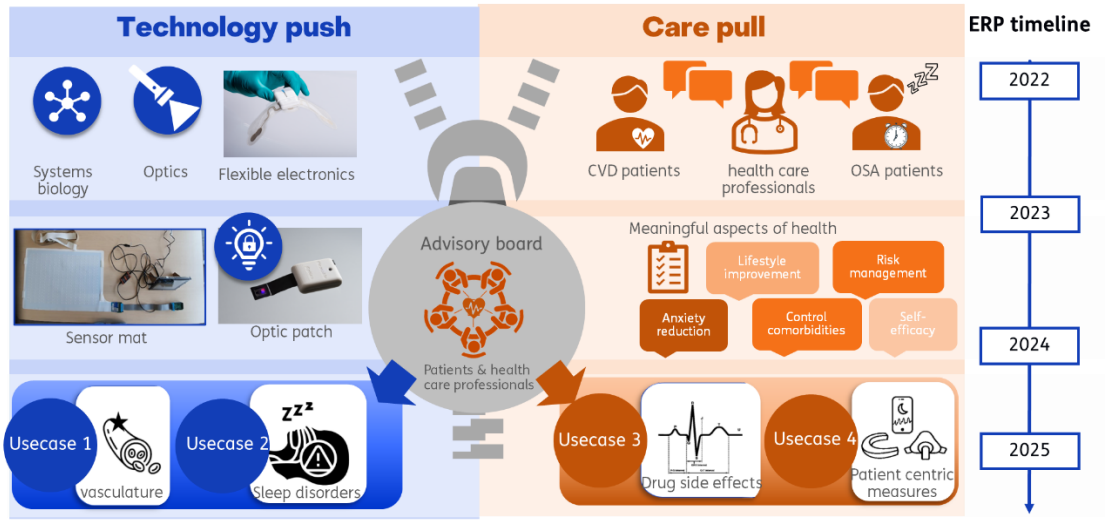
Ambition. Developing tools and methodologies for meaningful, inclusive, digital health measurements, which are a cornerstone in the upcoming transitions of healthcare.

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 2024. The ERP has continued the developments of meaningful digital health measurements for remote patient monitoring by TNO's health patch, sleep mat and photonics that 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), **Paulien Bongers** (Director of Science H&W), **Helen Kardan** (Director of Science HTI).

4th year in 2025. Running 2022 – 2025.



8 Empowering citizen collectives

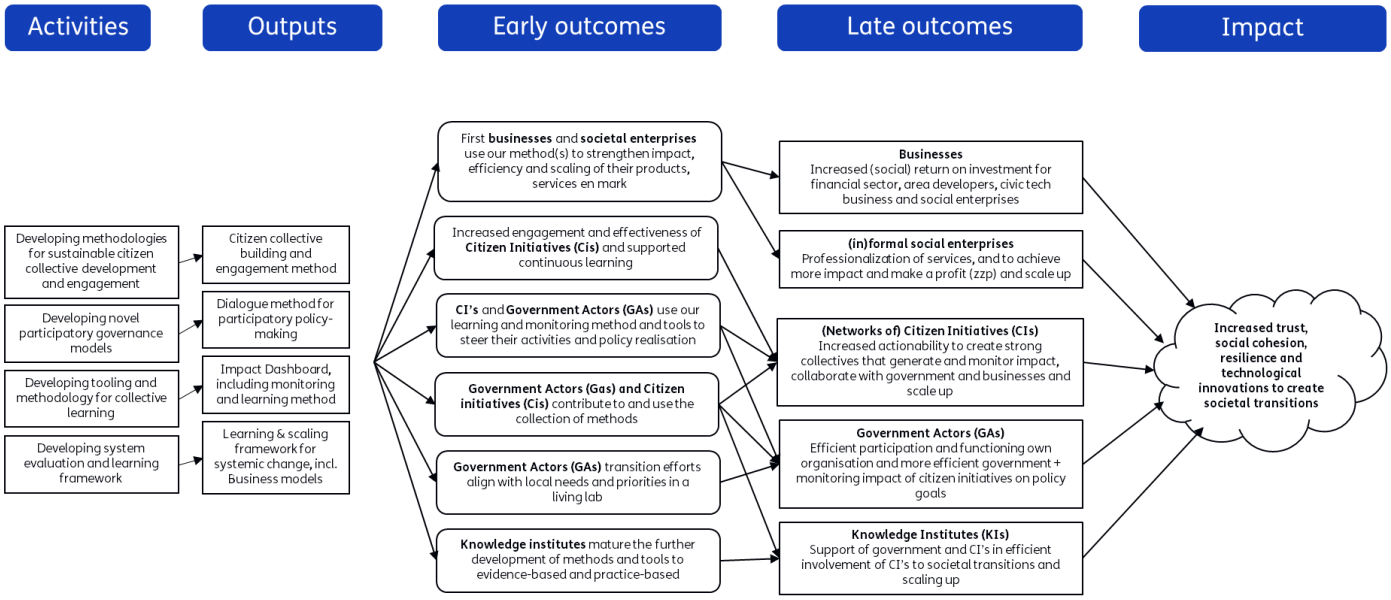
Ambition. Empowering citizen collectives by developing an evidence-based method to accelerate and scale societal transitions in neighbourhoods. This will be achieved by improving the agency of citizen collectives at neighbourhood level and engaging them in participatory policy making.

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

Results 2024. Our activities were focused on developing our knowledge beyond state-of-the-art regarding community building and development and transformative governance. We have for instance collaborated on methods regarding joint goal setting, outreach, asset mapping (photovoice) activity with our external local partners. We have co-designed a prototype architecture for monitoring, evaluation and learning with Energiek Noordveen. We have strengthened cooperation and build up trust with our external partners in living labs, launching our participatory action research. This also resulted in a NWA proposal focussed on new forms of collaboration.

Wessel Kraaij (Lead Scientist), **Pepijn van Empelen** (Lead Scientist), **Geiske Bouma** (Lead Scientist), **Ellian Lebbink** (Project Manager), **Paulien Bongers** (Director of Science H&W), **Omar Niamut** (Director of Science ISP), **André Faaij** (Director of Science EMT).

2nd year in 2025. Running 2024 – 2027.



9 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 2024. We continued fruitful collaborations within and outside of TNO, extended first technical results. In our work with stakeholders, focus shifted from ethical implications in two use cases to legal issues and business models. For the logistics use case, we focussed on the assignment problem of the "talking trucks" planning problem: packets are distributed over collaborating trucks (from competing logistic providers) by securely computing for each packet the extra delivery costs per truck and choosing the cheapest option. This use case is generically applicable in various domains.

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.

10 Opto-Acoustics for Medical Imaging & Structural Monitoring

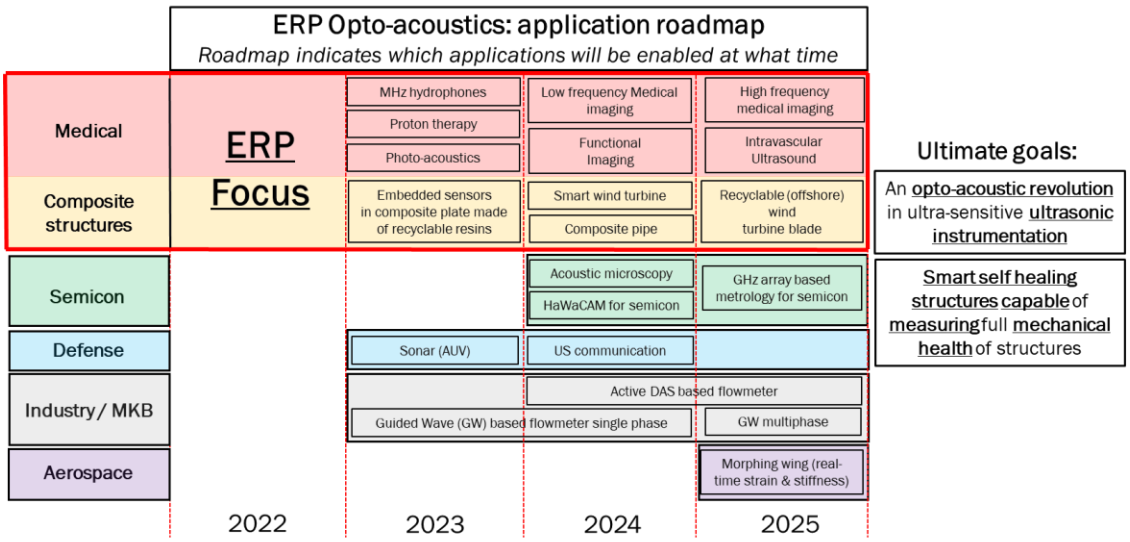
Ambition. Creating a next generation acoustic platform, using optical means only, to generate and receive acoustic waves. Such a system will radically outperform existing systems and can be miniaturized or multiplexed to cover large structural areas and long distances.

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 2024. In the first two years of the ERP Optoacoustics we focussed on improving the efficiency of the Photonic Ultrasound Transducer (PUT) platform technologies on a component level and having a model for both technologies, Integrated PUT (IPUT) and Fiber Optic PUT (FOPUT), to transmit and receive an acoustic wave. In 2024, the focus shifted from component proof-of-concept towards proof-of-concept for the Minimum Viable Product (MVP), including research on material platform dependencies and manufacturability.

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

4th year in 2025. Running 2022 – 2025.



11 Pandemic Diagnostics

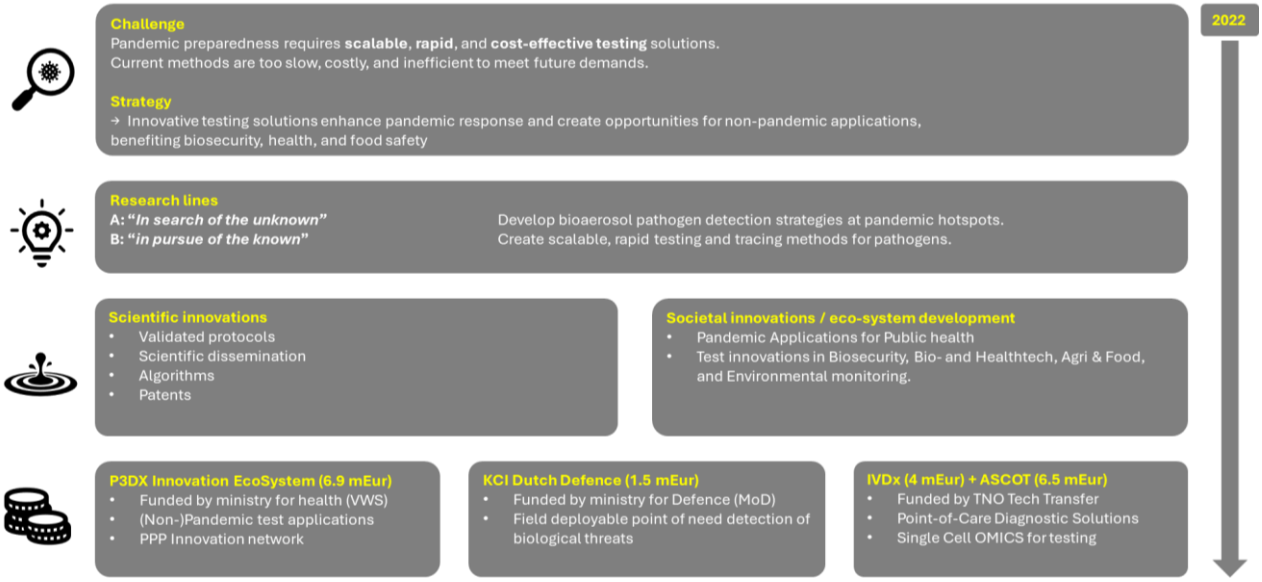
Ambition. Developing a bio-surveillance system for non-targeted identification of pathogens at pandemic hotspots (e.g. airport), a platform for on-site pathogen detection for contact tracing and a pandemic diagnostic platform for population level molecular testing.

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 2024. The ERP Pandemic Diagnostics aims to establish innovative testing methods for future pandemic threats. Work is performed along two research lines. In Research Line A, a water-soluble filter and proteomic mass spectrometry demonstrated feasibility for identifying viral pathogens, though filter efficiency requires improvement. Additionally, a sequencing based approach was deployed at a wastewater treatment site, demonstrating feasibility and allowing comparative evaluation of aerosol collections. 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), **Paulien Bongers** (Director of Science H&W), **Christa Hooijer** (Director of Science DSS).

4th year in 2025. Running 2023 – 2025.



12 Plasma synthesis / Plasma enhanced chemical conversion

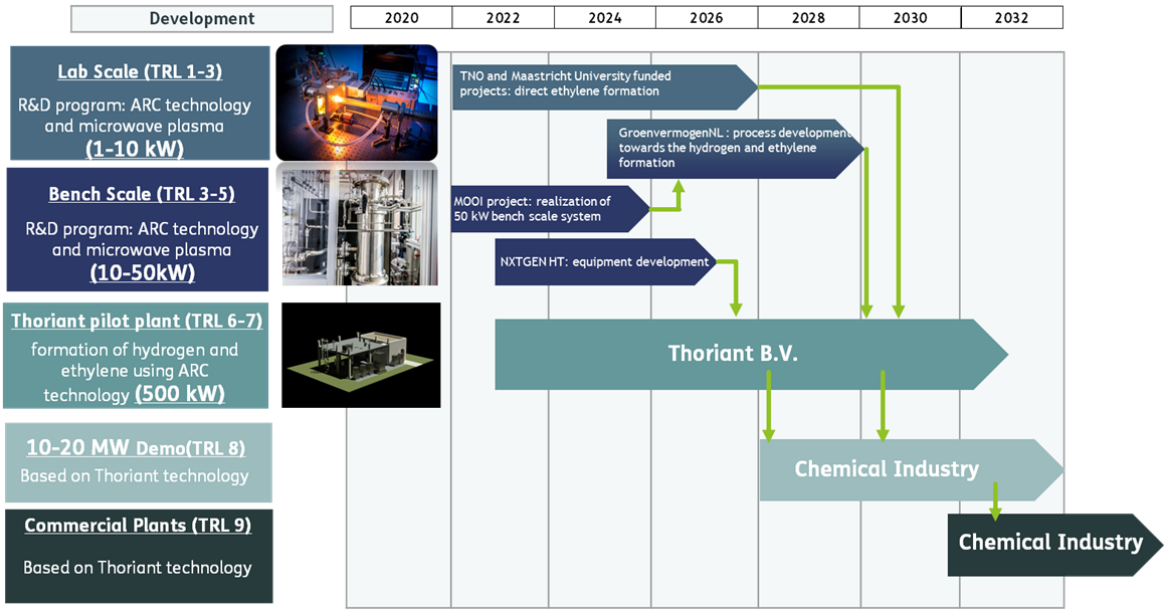
Ambition. Facilitating the electrification of the chemical industry by focussing on direct production of Ethylene; an important large volume, high value chemicals (HVC) for the polymer industry. Electrification of the chemical industry is crucial to reduce CO2 emissions. Plasma synthesis is employed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

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

Results 2024. The results for 2024 solidified understanding of the methane plasma-pyrolysis reaction mechanism, which includes the plasma pyrolysis in the reaction zone as well as the quench. Whereas the 1st half year (2023) focussed on starting up and "initial" efforts, 2024 focussed on expanding on and refinement of existing efforts. A first version of validated kinetic model was delivered. An initial Techno-economic analysis (TEA) was performed including sensitivity matrix.

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

3rd year in 2025. Running 2023 – 2026.



13 Polymer design by machine learning

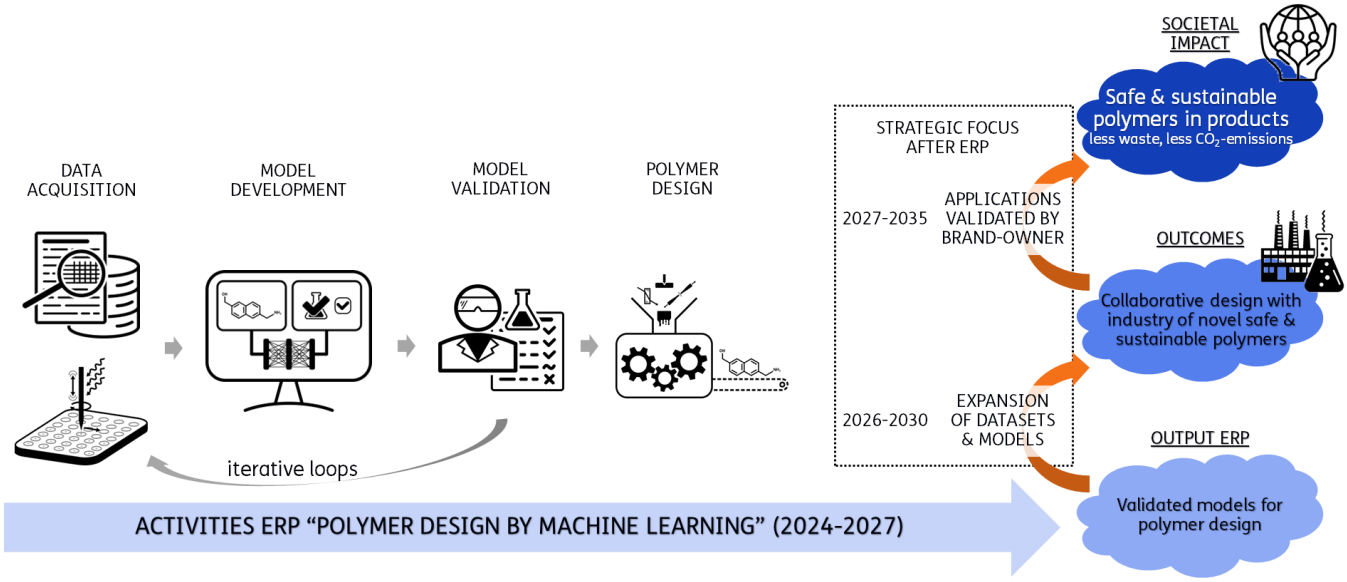
Ambition. Developing and validating a Polymer Informatics engine that realistically captures the complexity of polymers to design novel candidates that match with requirements for safe & circular plastics.

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 2024. We developed an effective database infrastructure and corresponding data-collection protocols. Manually, >5000 polymers and their properties were added to this database from over 2000 scientific papers. Furthermore, a first prototype for a protocol was developed that automatically collects data from scientific papers. With respect to machine learning, 2024 resulted in the selection of effective fingerprinting techniques and algorithms that allow for the accurate description of structure-property-function relationships of polymers, as a basis for further development. The first models using our proprietary database show considerable improvement in predictive power compared to the state-of-the-art.

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.



14 QuTech

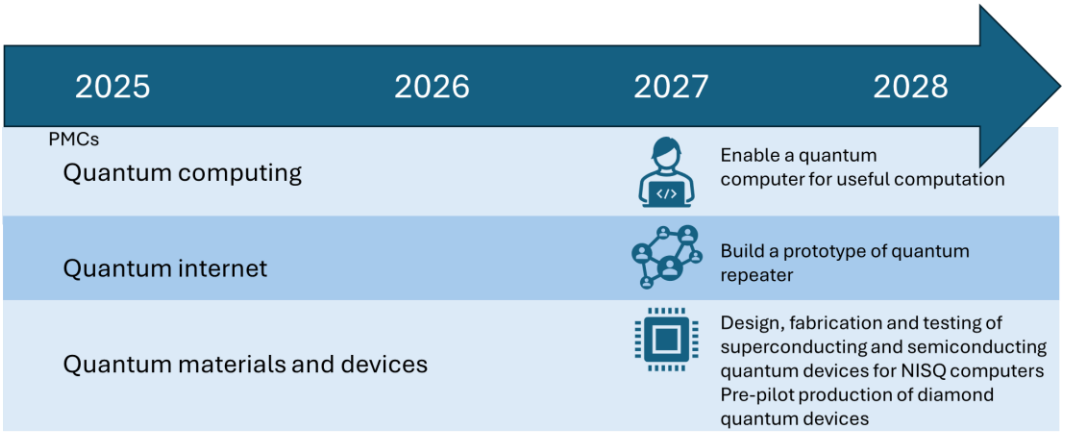
Ambition. Building scalable prototypes and underlying technology for Quantum Internet and Quantum Computing. QuTech is a multi-year collaboration, where the TNO contribution focuses at specific parts of the entire stack, at raising TRL of specific promising technology solutions, and at the systems engineering 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 2024. For Quantum Computing, we delivered a first version of a TWPA device. We intended to bring online a 10-spin qubit NISQ system with full functionality for NISQ algorithms, based on direct spin readout but fell slightly short on that goal on the chip side, with a 8 qubit system instead. For Quantum Internet, we realized an improved node with control of an additional 13C qubit and made two NV-based nodes available online via the QNE web interface. These have since then been dismantled from the demonstration location (Den Haag) to be relocated in Delft. We also created a detailed design of a scalable quantum repeater archtiecture, which is the core of one of our PMC. For Qubit Research, we worked on the fabrication of a state of the art fluxonium qubit and a 3 dots channel Kitaev chain.

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

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



15 Socio-economic impact of green transitions

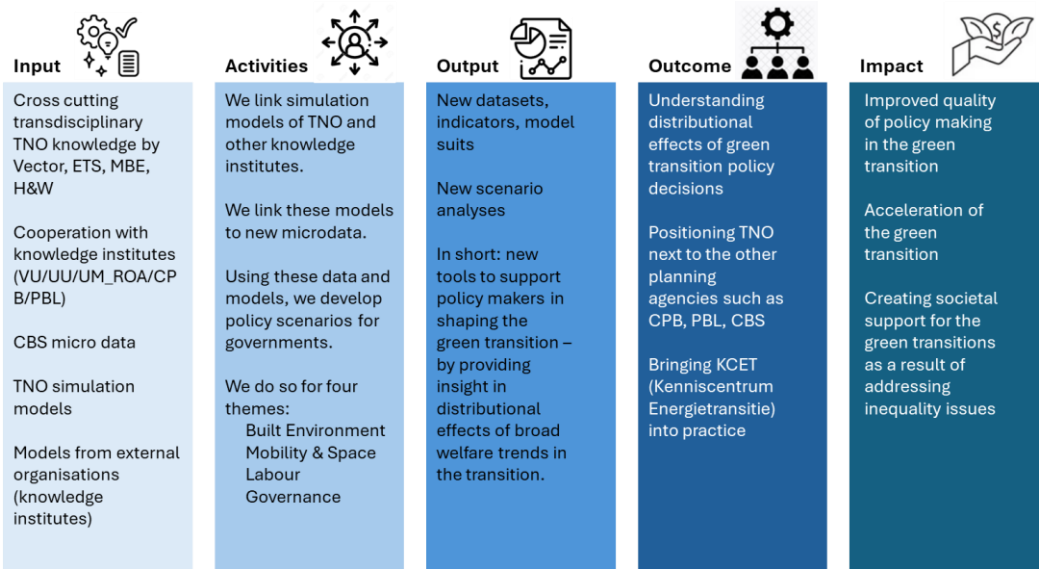
Ambition. Developing a comprehensive microsimulation approach to quantitatively assess the integral impact of the energy and mobility transitions on households' economic well-being. A grand societal challenge is to implement the transition to a sustainable and green society while maintaining and redefining 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 2024. We realized three newly developed geo-coded microdata-microsimulation modelling tools that allow for assessing the impact of the energy- and mobility transition on households. This includes big data-tooling that links microdata at the household and firm level on economic vulnerability, income, skills, energy use, housing characteristics, transport behaviour and emissions. In addition, we established a network of stakeholders that develop and use these tools, including TNO, CBS, CPB, PBL, universities and Ministries. Finally, we developed several use cases. Together this led to a couple of published and unpublished novel calculations and insights on the distributional impact of the energy- and mobility transition on households.

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.



16 Solar-2-Hydrogen

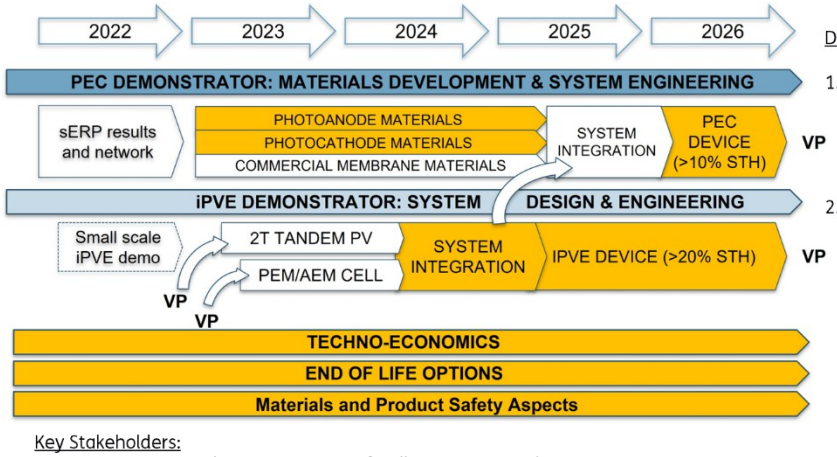
Ambition. Developing and demonstrating devices for water splitting that use sunlight as sustainable energy source and yield green H2 at a levelized cost of H2 (LCOH) comparable to green H2 from electrolysis.

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 2024. Activities result in a validated iPVE 1st generation (ca. 196 cm^2) silicon based and 2T Per/Si based (>5 cm^2) integrated iPVE device with a STH efficiency ≥ 15%. The test results of the 1st generation devices were used to generate an updated techno-economic analysis, and updated iPVE panel design serves as the blueprint for the pilot scale iPVE panel. Based on the updated design a pilot iPVE panel development and realization strategy and plan were defined. Furthermore, an optimized design for PEC devices was delivered including a lab scale PEC device demonstrator consisting of a photocathode with a minimum STH efficiency of 4% under AEM conditions. Emphasis in 2024 was on validation of the developed toolbox, and on optimization of demonstrator efficiency. Interreg project FOTON, with a.o. strategic partners IMEC and UHasselt, started Q1 2024. Updated reports on techno-economic, sustainability analyses and required health and safety measures for solar water splitting targeting the end deliverables of the full ERP were delivered at the end of 2024.

Pascal Buskens (Lead Scientist), **Nicole Meulendijks** (Project Manager), **André Faaij** (Director of Science EMT), **Helen Kardan** (Director of Science HTI), **Paulien Bongers** (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.

17 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 2024. In 2024 the V1 Python-based model chain was further developed towards version V2 streamlined for calculation performance and including an updated downscaling accounting for both lithologies and engineering knowhow on material properties.

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.

18 Sustainable ICT

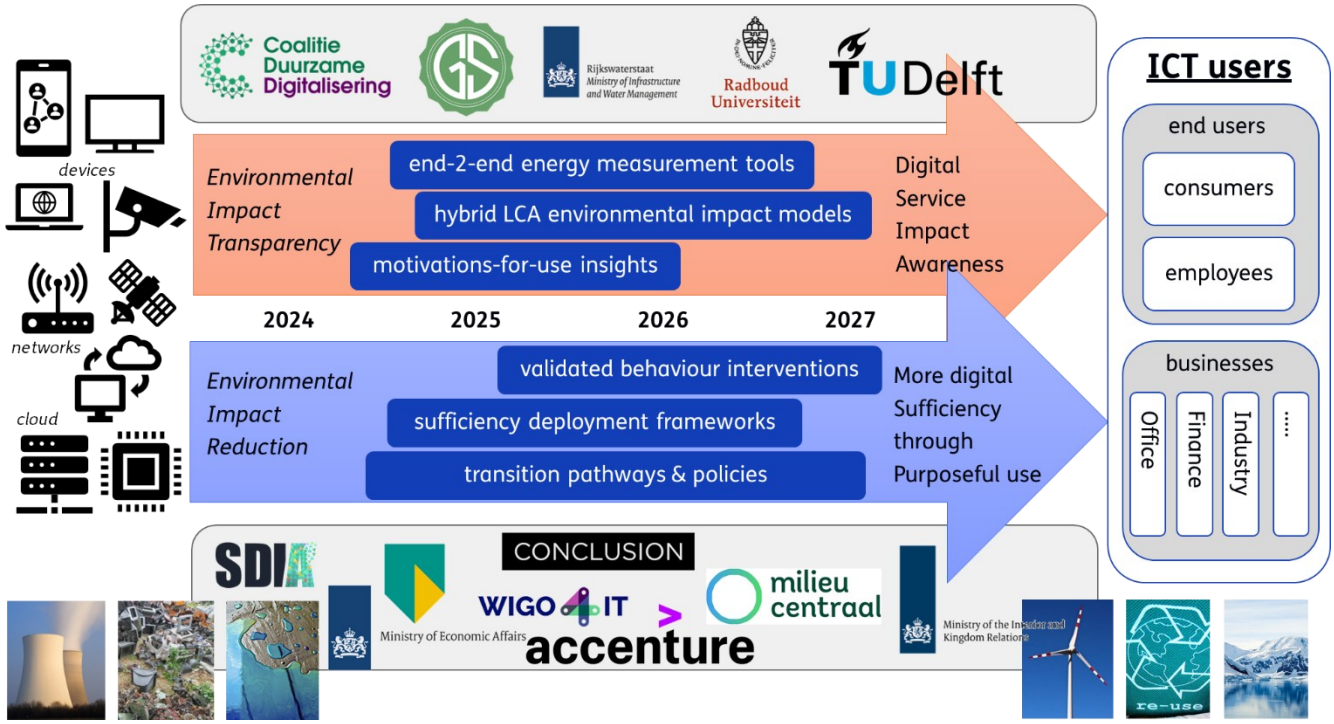
Ambition. Facilitating policy makers in comprehending the environmental impact of the ICT sector and enable ICT companies to react to governmental policy.

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 2024. We gained insight in the broad problem scope of sustainable ICT, identified Jevons Paradox as main hurdle and developed 3 action perspectives for real change. We developed a first prototype for measuring energy use of ICT services, we have insight in the environmental impact of one ICT service (video streaming), we have insight in the motivators for use of such service and insight in the business and policy ecosystem for this domain. These insights, together with the developed action perspectives, have shaped the ERP plan for the coming years.

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.



19 Sustainable recycling of Batteries and Solar panels

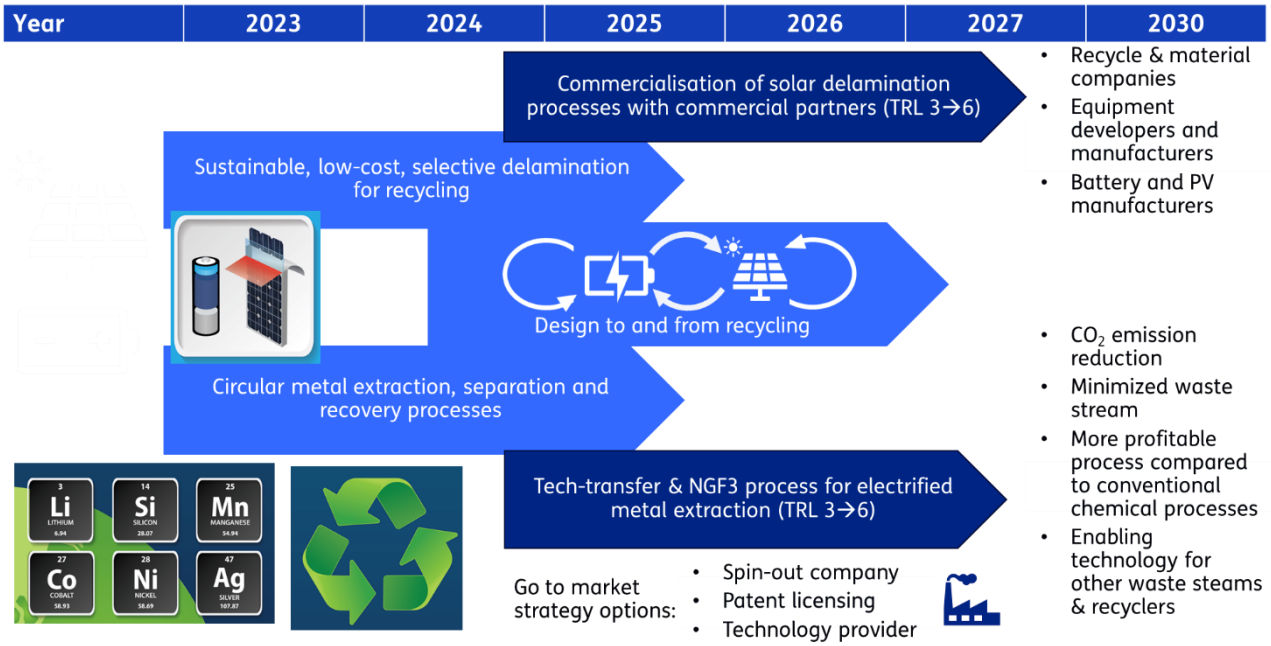
Ambition. Developing new sustainable technologies to promote strategic materials independence of the Dutch industry by recycling of electronic products and their design from and to recycling. Our focus will be on batteries and PV panels as primary use cases.

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 2024. Commercial PV modules were opened up by our laser process, allowing sustainable and clean separation and collection of the glass and silicon wafers. Subsequently, silicon wafer parts were cleaned by mild chemicals to bare silicon without contacts or contamination. Based on these successful results, TNO will work towards application of this technology with industrial stakeholders in 2025. A fully regenerative electromechanical process has been developed for the leaching step in Li-NMC cathode materials. A new electrochemical separation technique for battery-relevant metals, as well as sustainable synthesis of battery-grade metals salts is further developed.

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.



20 Synthetic Biochemistry

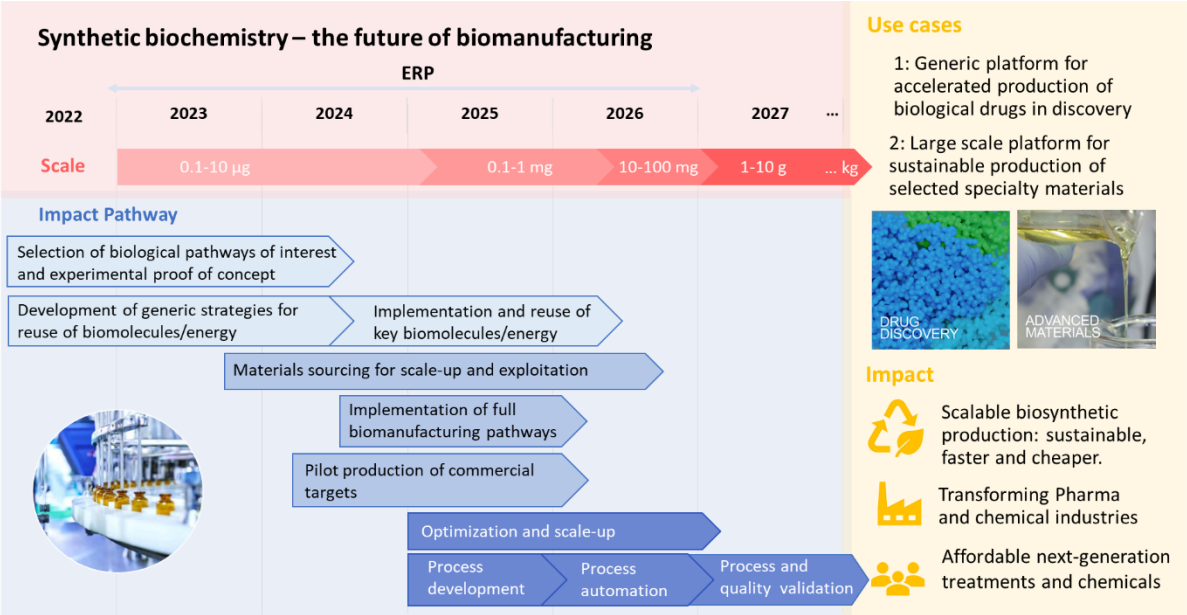
Ambition. Developing the world's most sustainable biosynthetic version of a biomaterials and biopharmaceuticals production platform with process efficiencies >90% enabled at 10-20% of current production costs.

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 2024. In 2024, SYNBIO showcased innovative biosynthetic approaches in both the therapeutic proteins (TPs) and bulk chemicals and energy carriers (BCECs) sectors. Supported on the definition of individual valorisation strategies, executed IP protection and enhanced collaborations, the stage for an inaugural demonstrator study was set.

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

3rd year in 2025. Running 2023 – 2026.



21 Appl.AI

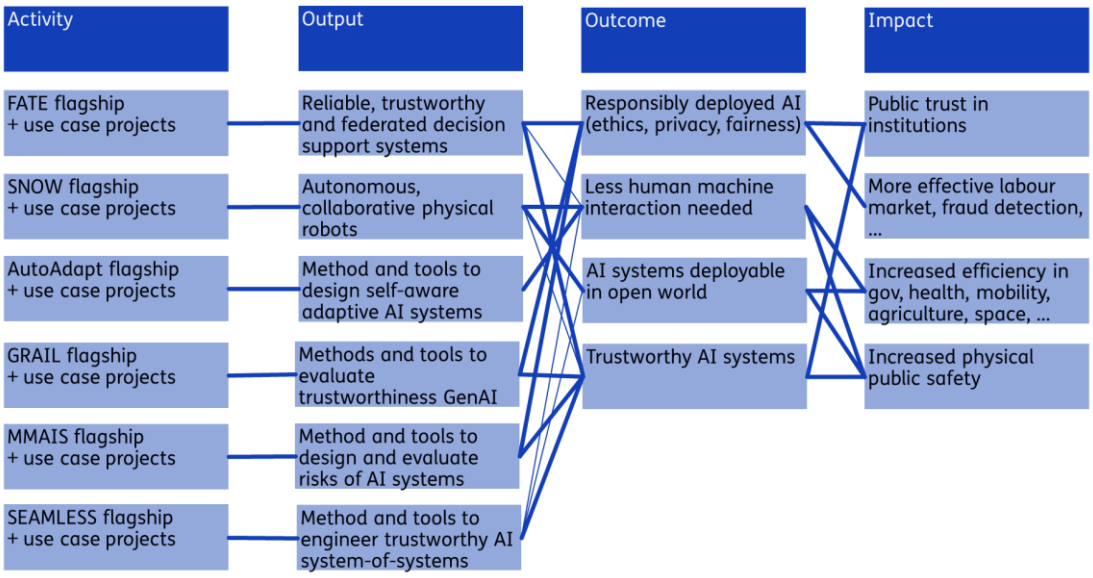
Ambition. Building new AI capabilities into Autonomous Systems and Federated Decision Making and to integrate AI into System Engineering and Lifecycle Management.

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 2024. In 2024, the Appl.AI programme made significant advancements in developing responsible generative AI ecosystems, enhancing autonomous systems, and ensuring trust in AI-based systems. The flagship GRAIL focused on user-LLM collaboration, creating over 20 support function concepts, a comprehensive GenAI evaluation framework, and a prototype tool for metric selection, while also experimenting with regulatory alignment tools. FATE used Diabetes Mellitus Type 2 as a showcase, exceeding expectations through additional projects and collaborations. SNOW advanced (semi-)autonomous systems' interaction capabilities and closed the OODA loop on a robotic platform. SEAMLESS introduced a novel approach for AI-embedded systems, linking computational models with Digital Twins and automating modelling processes to ensure lasting system fitness and trust. MMAIS project equipped organizations with innovations to develop AI applications aligned with societal values, including a workshop methodology for value identification, technologies for value-based behaviour and assessment, and a dashboard for auditors to manage value conflicts. AutoADAPT developed two novel adaptation loops with self-learning components. For vehicle energy management, a battery life-aware energy management strategy is developed; for laser satellite communication, adaptation approaches to optimize the downlink communication channels are developed

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.



22 Balanced spatial choices

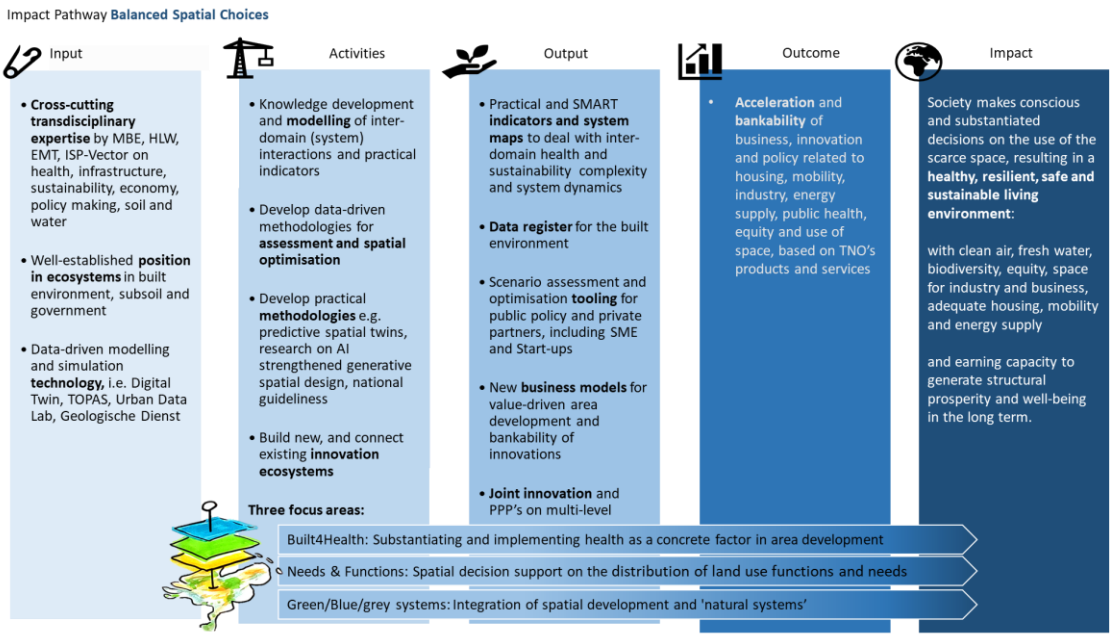
Balanced Spatial Choices is an ERP of *status aparte* as it is funded through the ERP portfolio but governed through the usual business processes in the units.

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 2024. A broad programme outline for the 4-year programme was formulated, including the proposed governance, the way of working and a more detailed plan and intended results. Governance has been implemented, among which the constitution and execution of the Regieteam, Programmaraad and Partnerraad.

Heleen de Kraker (Project Manager).

2nd year in 2025. Running 2024 – 2027.



Strategy

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