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TNO EARLY RESEARCH PROGRAMS

Annual Report 2021

TNO-report: TNO 2021 R12745

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Date 1 maart 2022

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Results 2021 of TNO's Early Research Programs

In this report we present the 2021 progress of TNO's Early Research Programs (ERP) portfolio; see the funnel in Figure 1. The plans corresponding to the results reported here were described in 'TNO Early Research Program Annual plan 2021' (reference TNO 2020 S083, dated October 5th, 2020).

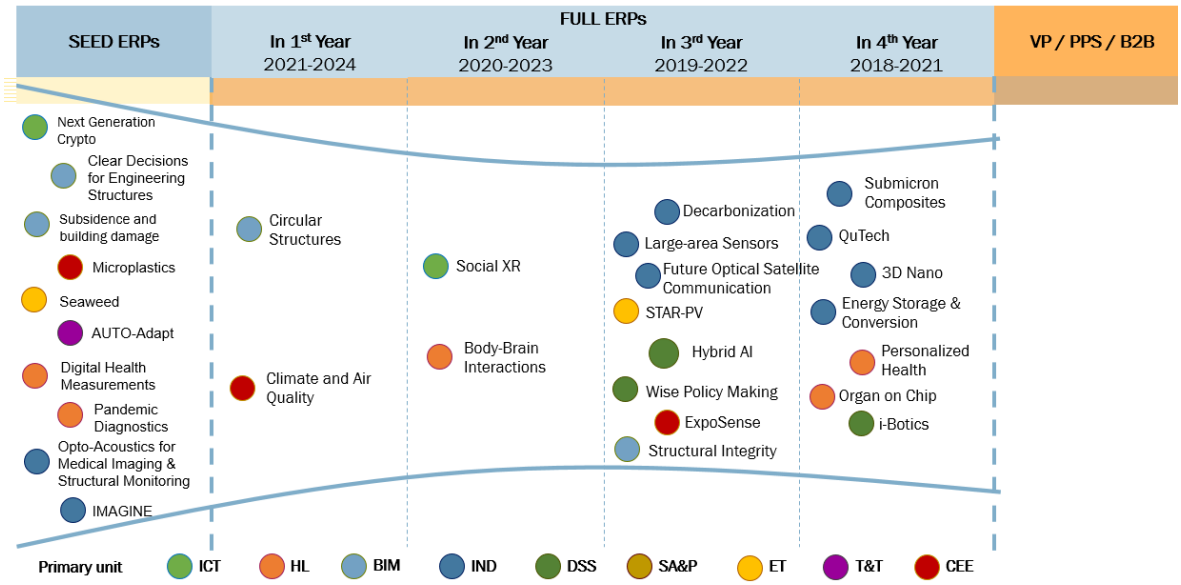

Figure 1 Funnel TNO Early Research Programs 2021

In total 19 Full (four-year) ERPs were being carried out (see Table 1), focused on societal and economical challenges requiring a concerted effort of fundamental and applied research, to be succeeded by future private development. We continued our use-case-inspired research approach with emphasis on generating *cutting edge knowledge and technology* together with research partners from academia, and on *building research ecosystems* with stakeholders and sponsors from industry and public organizations. Table 1 lists these Full ERP's and provides for each of these a (few) 2021 highlight(s). Figure 1 shows that the ERP numbers are not equally distributed over the years. This is an historical effect related to the original start of TNO's ERP portfolio which we are gradually reducing towards a portfolio in which every year approximately five new Full ERP's can start.

In addition to the Full ERP programs we executed 10 Seed (single-year) ERP projects (see Table 2). Our policy is to yearly execute a set of such Seed ERP's, of which a selection based on quality and outlook is promoted to Full ERP's for the four years thereafter. It is a deliberate choice to yearly award twice as much Seed ERP's as can be promoted to Full ERP in the consecutive year, thus promoting quality by a fair amount of competition. In the course of 2021 the Seed ERP's "Subsidence and building damage", "AUTO Adapt", "Digital Health Measurements", "Pandemic Diagnostics" and "Opto-Acoustics for Medical Imaging and Structural Monitoring" have been promoted to Full ERPs starting in 2022.The Seed ERP 'Clear Decisions for Engineering Structures' has started in 2021, but has been paused due to capacity problems and will be restarted as Seed in 2022. The Seed ERP Microplastics was granted with a 2-year Full ERP status. For Seed ERP topics not promoted to Full ERP status, alternative ways to proceed are explored and regularly also found.

In the frame of the described ERP programs opportunities to publicize and to patents results were actively pursued. Overall the ERP programs yielded a total of approximately 110 scientific publications and a total of approximately 39 patents were filed.

In 2021, we shared our plans and results of this year and of previous years with many potential partners and stakeholders in the form of patents and other publications, conference presentations, posters and ERP dissemination events.

The ERP plans for 2022 and beyond are described in 'TNO Early Research Program Annual plan 2022' (reference TNO 2021 R11720, dated September 30th, 2021).

Table 1: Full Early Research Programs, Highlights 2021

Full Early Research Programs (four-year programs)	
ERP-title *Short overall description*	**Highlights 2021**
4th year Full ERP projects: Start 2018 – End 2021	
Submicron Composites *We develop smart, responsive materials by precisely controlling their chemical composition and micro/nanostructure. Examples are nanostructured coatings and nanocomposite polymer films for thermochromic energy efficient windows and 3D-printed fiber reinforced composites with high strength and integrated sensing functionality.*	Together with industrial partners we integrated our previously developed doped VO_2 (M) pigments in PVB films using master batches for film extrusion and used the resulting pigmented films to produce thermochromic laminated glass panes. Lab scale laminated glass samples have been prepared. Good thermochromic properties were demonstrated. The first pilot scale window demonstrators have been prepared (1 m² sized), optically characterized and integrated for performance monitoring in test buildings at SolarBeat. Furthermore, we developed materials and processing strategies for 3D printing with continuous fibers, enabling products with mechanical and thermal properties suitable for high performance (e.g. aerospace) applications with properties such as high compressive strength (>260 MPa), flexural stiffness (>25 GPa), thermal stability (>125°C) and stability in thermal cycling (-50°C to 125°C). Developments included optimization of adhesion between fibers and matrix polymer and the resistance of the material against high temperatures and the use of high temperature polymers such as PEKK, PEEK and PPS. Processing strategies addressed good interlayer adhesion, minimizing voids and obtaining good fiber alignment for 3D load cases.
QuTech *We aim to demonstrate fault tolerant quantum computing and quantum internet.*	The Quantum Computing Demonstrator was upgraded with a second 2-qubit spin device and improved spin control with up-conversion. Automatic tuning and calibration was introduced in the transmon computing system. A first Quantum Internet demonstrator was launched, based on a simulated back-end.
3D Nano Manufacturing *We create breakthrough solutions for semiconductor metrology for the next generations of chips by developing and exploiting scanning probe microscopy in all its different modalities. Additionally we facilitate innovation in neighbouring areas like bio-technology.*	In 2021 deep subsurface imaging of chips was achieved by integrating a 4Ghz piezo actuator on a custom cantilever tip. With this new device features of 2um pitch could be imaged under 5um and 9.7um deep layers. With this result alignment and overlay metrology can be improved substantially. Furthermore 3D nanowire structures were imaged making their chemical composition visible at a level of 20nm resolution. TNO's own quantum sensing Atomic Force Microscope was tested and it outperformed current commercial devices. In the Design for AI program a demonstrator was built to show the concept of "design for AI" applied to an over-constrained metrology problem.

Energy Storage & Conversion *Using renewable electricity and sunlight, CO_2 and green H_2 as a feedstock, we produce C1 chemicals and fuels providing a great opportunity to store energy, to overcome the inherent fluctuations in supply of renewable energy and the spatial and temporal mismatch between demand and supply.*	In the electrons-to-chemicals research line (using renewable electricity as energy source to drive chemical reactions) a completely new process concept for electrolysis of CO_2 has been developed. Formic acid production using this concept was demonstrated and patented. A 1 kg/hr test installation (ZEUS) has been commissioned and is now in operation. Scale-up of CO_2 and CO electrochemical conversion and sale-up of integrated CO_2 capture and conversion using capture solvents as electrolytes was demonstrated. In the photons-to-chemicals research line (using sunlight as the energy source to drive chemical reactions) strategies of commercially feasible photo(electro)chemical conversion of CO_2 to methanol and C≥2 chemicals are developed and validated. A complete lab-scale mini-factory for the conversion of CO_2 to methane and syngas has been commissioned and is now in operation. A H2020 project was started to develop and validate a photonic device and chemical process concept for the sunlight-powered conversion of CO_2 to chemicals/fuels CO and CH_4.
Personalized Health *We develop a system providing personalized advice on sustainable lifestyle habits based on biological understanding of inflammatory dynamics, dysmetabolism, AI modeling and health community support.*	In 2021, 62 volunteers started the SLIMMER+ study. The primary goal of the TNO SLIMMER+ study is to examine if personalization based on the innovative combination of biology, personality and behavior results in a more effective intervention to improve and maintain healthy behavior (as compared to the regular SLIMMER program) and if this approach is suitable for implementation in primary care. The first results include positive experiences of the participants and health care professionals, paving the way for conducting personalized interventions at scale. The study will be completed in Mach 2022.
Organ Function on Chip *With an advanced organ-on-a-chip preclinical toolbox we enable the inclusion of human diversity in the preclinical phase of drug development and the selection of the right candidate drugs and right patients for clinical trials.*	We validated our applications of gut on-a-chip and liver on-a-chip with a number of model compounds. These validation datasets show the value of the models as the obtained data are very comparable to human data from clinical studies. With respect to further technology development, we succeeded in technical coupling of liver and gut: with partners we are working towards gut-liver-kidney coupling for 'ADME' applications (concerning disposition of pharmaceutics in humans). The technology developments will continue in in several consortia that have been setup in 2021. We became a representative user in the TTW SMART project, a collaboration of several strong academic partner, technology companies and big pharma. We prepared a webinar (taking place in March 2022) that will present our models ready for applications in commercial projects and we will also present the collaboration possibilities for further development. Our gut on-a-chip advances have been published in two peer reviewed papers.
i-Botics *We focus on optimal human-robot interaction in challenging, unpredictable, dynamic situations. The focus areas are human controlled robots based on telepresence perception and manipulation capabilities for e.g. installation, maintenance, repair and emergency response; and wearable robots for human enhancement in rehabilitation and heavy work environments.*	We have built a demo of a bimanual tele-operated setup augmented with another arm (see also picture on front page). We continued our work on interpreting the VR environment and creating symbolic object representations and their transfer to live operators in a multi-sensory VR environment for situational awareness. A demonstrator of an active back support exoskeleton and a controller optimized for effectiveness and usability in practice were built, including multiple algorithms targeted to generate a real-time estimation of the bending forces in the lower back. We created a sensor-based tool which helps determine the potential for exoskeletons in heavy work.

3rd year Full ERP projects: Start 2019 - End 2022	
Decarbonisation *We target to reduce the dependency of the chemical industry (primarily at the Chemelot site) on fossil sources, by developing climate proof technologies and associated implementation strategies.*	To investigate plasma technologies, a 3D finite element thermal gas flow model for simulating the chemical conversion has been developed. Based on simulations the relations between chemical conversion, residence time and gas temperature have been retrieved. Those relations, including the effect of acetylene conversion on gas mixture composition and accompanying thermal properties, have been studied to estimate the resulting acetylene production. Additionally, we are working on a bench scale version of a plasma plant in order to test, verify and improve the process models. The opening of the Brightsite Plasmalab was in November 2021. With the enhanced and validated models and the test results of the bench scale, the design of a pilot plant can be optimized.
Large-Area Ultrasound *We develop technology for large area, flexible ultrasound imaging/monitoring systems enabling to bring medical care to the home environment. Our essential approach is to build printed ultrasound transducers using cost effective display fabrication technologies.*	As a result of better device processing and understanding ~16x improvement in pulse-echo efficiency was realized with our flexible polymer ultrasound technology. Prototypes of 128-channel linear arrays were realized. Acoustic crosstalk was negligible. Ultrasound images of tissue phantoms were recorded using image capture times of 0.1-1 ms, which is a factor of 106 improvement over our last year's imaging results. We tested several versions of wearable ultrasound patches. A study with healthy volunteers gave important information on comfort and wearability aspects.
Future Optical Satellite Communication *By using laser light instead of radio we aim to greatly enhance communication between satellites, ground stations and airplanes, providing ultra-high data throughput and ultra-secure and multi-point communication.*	In 2021 we established a system concept of a ground communication terminal capable of transmitting data at 200 Gigabit/s to a LEO satellite to contribute to the ultra-high data throughput future needs (also see picture on front page). To support the ultra-secure communication development, we designed a narrowband and adjustable spectral filter to reject background radiation. This will contribute to future daylight BB84 QKD links. Finally, a consolidated design and analysis of multiple optical concepts for an optical telescope with an extreme low volume is now in place, to enable multi-point GEO/MEO communication terminals.
STAR-PV *By gaining insight in and by developing improved control of basic degradation mechanisms we enable improved reliability and sustainability and lifetime extension (e.g. beyond 20 years) of integrated thin film devices (photovoltaic and other opto-electronics) integrated in building components and products.*	Novel in-situ fiber sensor technology was developed and installed for field monitoring of multiple stress factors in integrated solar modules, providing detailed information to study basic degradation mechanisms and to define more realistic accelerated lifetime test methods. TNO experts on circular economy and photovoltaics jointly published a position paper on the sustainability of photovoltaics, which was presented in a webinar attracting >600 attendants. Reliability research on stretchable printed electrical interconnection lines resulted in commercial application in wearable electronics (TNO spinoff).
Hybrid AI *This ERP, our largest, consists of a coherent set of program lines, two of which being the 'flagships' of the program: SNOW (AI capabilities for self-aware autonomous systems that can operate safely and effectively in an open world) and FATE (AI to provide fair advices by continuous learning from multiple potentially confidential and biased data sources). These two flagships form the actual ERP and are surrounded by a set of use case projects.*	A main characteristic of the Appl.AI program is its integral approach. The knowledge development branches out to concrete applications in different domains. In 2021 we developed a multi-year Strategic Research Agenda to focus the research in the flagships and use case projects of the program. In SNOW, we developed AI capabilities related to situation-awareness, user-awareness and self-awareness. These capabilities have been implemented on the SPOT robot (see picture on front page) and tested with specific KPI's. In FATE, we developed AI capabilities on the topics Fair AI, Explainable AI, Co-learning and Secure Learning. These capabilities were tested and demonstrated in the AI4Justice use case. Knowledge on AI, its characteristics, technologies, limits, etcetera are acquainted in all of the projects. All research combined strengthens TNO's knowledge position on AI.

Wise Policy Making *We develop a suite of instruments and methods to support policy makers to assess the impact of policy options on wellbeing (ex-ante) and to engage in unbiased and well-informed dialogue leading to decisions that prioritize sustainable societal wellbeing.*	We developed a prototype of the Wise Cube (a tool to analyse expected impact of alternative policies on wellbeing), including a quantitative model and interactive dashboard (see picture on front page). To support the identification and avoidance of biases in policy making, we developed a Neuro-evolutionary Bias Framework that provides insights into the neuro-evolutionary origin and underlying working mechanisms of cognitive biases. This Bias Framework has been published and has been included in the prestigious Encyclopedia of Behavioral Neuroscience.
ExpoSense *We develop solutions for personalized promotion of health based on non-invasive assessment of external and internal exposure profiles to Particular Matter (PM), by developing accurate, reliable and calibrated PM sensors and by predicting and interpreting personal external and internal exposures by quasi real-time modelling*	In 2021 we demonstrated how a combination of (sensor) measurements and modelling can quantify personal and population exposure within our living environment. Within this overall context: (1) We have built a new version of the ERP developed sensor for chemical identification of PM and tested this in an environmental setting. (2) We have integrated data from the Regionaal Meetnet Zuid-Oost Brabant and other sensor data into a LOTOS-EUROS based data assimilation model for dynamic high resolution air quality monitoring. (3) We merged dynamic population data with dynamic air quality data for assessments of population exposure levels on postcode-4 level in Eindhoven.(4) We performed a pilot on using sensors for personal exposure assessments to identify both local emission sources as well as personal influence on exposure levels.
Structural Integrity *We develop digital twins (simulation models fed with sensor data) mimicking the behaviour of macro-structures and guiding the design and management of these structures. Main challenges are multi-scale modelling, advanced sensing techniques, high speed computing and AI learning capabilities.*	Components of the DT (Digital Twin) Steel Bridge were successfully integrated and tested on the IJsselbrug. It was agreed with RWS that the Moerdijkbrug will be used as a field site in 2022 (final year of the ERP) and beyond: RWS will participate actively. A lab demo has been built for the DT Bolted Connection and successfully used for the first tests. A demo of the DT Loadmap has been given to the city of Amsterdam and resulted in plans for follow-up cooperation. Our BridgeWiM system achieved part of the requirements. Blast resistant composite material development was sufficiently mature to hand it over to projects with budget for higher TRL levels.
2nd year Full ERP projects: Start 2020 – End 2023	
Social XR *We create a shared XR (eXtended Reality) environment, where participants get an enhanced feeling of being in the presence of, and interacting with, other persons at a remote location.*	We have developed technology to improve eye contact and eye gaze awareness, such as gaze tracking and Head Mounted Display removal. We have generated key insights into the placement and scalability potential of the media functions, and – based on the output of cross-layer orchestration – a decision where to place Social XR workloads conditioned on bandwidth and latency budget and constraints like availability of GPU accelerators. We have determined the functional and technical requirements for selected cues that make and break the experience of social presence, and performed an evaluation for XR meetings. We have integrated research results from 2020 into a first update of the social XR platform, resulting in a system that was rated significantly higher on all factors compared to 2019.
Body-Brain Interactions *We improve life-long health, performance and mental strength via mechanism-based understanding of the connections between body and brain, realized into a Brain-Body Interaction technology platform.*	We have developed a new way of sampling small aliquots of human blood (using a preclinical technology known from research with mice) to enable human profiling and characterization. We will use this technology with the human volunteers in the human Body-Brain platform on molecular level. An METC-approved experimental design was made for the study on sleep deprivation as an acute stressor.

1st year Full ERP projects: Start 2021 – End 2024	
Circular Structures *We develop knowledge and technology that enables for concrete structures a shift from traditional design strategies to a new engineering design method driven by supply quality-demand integration.*	In 2021, two use cases have been analyzed to demonstrate the feasibility of multi-objective design optimization of sustainable concrete structures: (i) using recycled concrete aggregates to replace aggregates from primary resources in new structures and (ii) re-use of an existing, reclaimed (precast) hollow core slab for optimized design of a new building. A review of circularity indicators has been performed and the design tool indicators were selected and parameterized to enable their implementation in 2022. A unique combination of measurement tools was tailored in-house to show that performance of construction and demolition wastes can be interpreted in relation to its key characteristics as well as its specific combination with additives. Collaboration was established with UTwente. Results from 2021 enabled launching projects with industry aimed at formulating an RWS research roadmap for enabling non-traditional solutions for sustainable concrete transport infrastructure.
Climate and Air Quality *We develop a globally applicable, multi-scale atmospheric modelling system with resolution down to 25m to fully exploit the emerging observation capacity from satellites and sensors.*	In 2021, we have developed several components of the modelling system: (1) Emission models: Development of local emission models using advanced techniques (deep learning and data mining) of households and restaurant emissions. Research on vehicle emission based on actual acceleration patterns per vehicle type. (2) Atmospheric modelling: Increased resolution of LOTOS-EUROS modelling to 1km. Increased accuracy of DALES modelling by taking into account a mosaic of land use types and its effect on atmospheric dispersion.(3) Evaluation and data assimilation: Development of a dynamic model evaluation strategy, complemented by indicators on time scale dependent cycles and sensitivity to meteorological parameters. Demonstration of the TROPOMI assimilation scheme with LOTOS-EUROS.

Table 2. Seed Early Research Programs, Highlights 2021

Seed Early Research Programs (single-year projects)	
ERP-title *Short description*	**Highlights**
Seed ERP's 2021 → promoted to Full ERP, Start 2022 – End 2025	
Subsidence and building damage *We develop a concept of workflow and a preliminary model chain to predict subsidence resulting from human subsurface activities and to translate this into potential for damage to the built environment.*	In 2021 we combined and improved modeling approaches for shallow-cause and deep-cause subsidence prediction, for subsidence-induced damage modelling on a pre-selected buildings with certain foundation type and realized an interface to translate a spatiotemporal subsidence pattern into an appropriate input matric for damage modeling. These results are connected and integrated as a Proof of Concept to access the risks of subsidence.
AUTO Adapt *We develop self-learning adaptive methods to maximize overall system performance and dramatically reduce development time and costs by automatically adapting the controlled system behaviour and configuration.*	In 2021, we defined the full technology concept and architecture for self-adaptive systems. This was essential input to create the full ERP project plan. The potential of self-adaptive systems is demonstrated for the leading use case: energy management of plug-in hybrid electric trucks. Also, contacts have been initiated with potential partners, which resulted in 3 letters of support.
Digital Health Measurements *We aim to develop a generic (implementation) framework aimed at validation, security, data governance and utility of digital health measures.*	In this Seed ERP, technical innovation was combined with social innovation with a focus on sensors for digital health measurements related to sleep. Pilot volunteer studies showed that objective monitoring of sleep using sensors shows better correlation to sleepiness experienced after a work shift, while comparison against polysomnography is still warranted. Also, not only sleep duration, but also parameters related to sleep quality should be investigated in their integrated relation to health and work performance. Stakeholder meetings and workshops generated perspectives, perceived benefits and risks on application and implementation of the health patch (as sensor platform for sleep) or other wearable technologies in the clinical setting and in the work setting. We learned that it is important to intertwine social innovation with technological innovation as part of the development process because it enables adaptation of technology to user wishes and context and steering technological innovation. It also enables one to adapt the context of usage to the technology, and orchestrate implementation and ecosystem development.
Pandemic Diagnostics *We will establish generic analytical strategies to identify novel, pandemic infectious agents and to establish efficient strategies for diagnostics and population-level surveillance.*	For Research Line 1 "Improved bio-surveillance of (respiratory) viruses based on mass spectrometry" we have developed an approach to use mass spectrometry for the identification of common viruses, including the isolation of virus particles from relevant matrices. For Research line 2 "Targeted point-of-care analysis for respiratory viruses", we have been able to establish the design for LAMP-based detection of four key respiratory pathogens and evaluated the performance of two in a clinical pilot. Furthermore, in collaboration with WUR, we have published a novel LAMP- CRISPR assay in Nature Communication

Opto-Acoustics for Medical Imaging and Structural Monitoring *We develop an acoustic platform, using optical means only, to generate and receive acoustic waves. Such a system will radically outperform existing (often piezo based) acoustic systems. Another advantage is that this system can be miniaturized or multiplexed to cover large structural areas and long distances.*	We established two clear applications to further develop the opto-acoustic sensor system, one focusing on medical (ultrasound) imaging and the other one on smart and recyclable composites structures where an (offshore) wind turbine blade is targeted as the case where this system can make the biggest impact. We are proud that we demonstrated, using a Photonic on Integrated Chip, that we have the same performance as state-of the art, piezo based sensor. Our opto-acoustic design tools, although very basic, showed to be helpful and reliable. We also performed a successful test with an opto-acoustic emitter fiber based emitter array, provided by the University of Lowell from the US, to get good insight in state of the art performance of fiber based opto-acoustic systems.
Seed ERP's 2021 → special cases which will proceed in 2022	
Clear Decisions for Engineering Structures *We develop a tool to discuss scenarios that include deep uncertainties towards the future, but still require decisions now regarding engineering structures and systems*	On this topic our experts are massively over-asked. As this is such an important topic, in 2021 we have been able to use this Seed ERP to create extra capacity by hiring new people as well as finishing some big projects that freed-up our key-experts. Hence in 2022 this Seed ERP will kick-off in full swing.
Microplastics *We develop mitigation strategies for microplastic based on knowledge on the formation and release of microplastic.*	We established a first correlation between Microplastic formation and polymer characteristics. This is the basis for future microplastic mitigation strategies. Furthermore, we connected to relevant academic and industrial stakeholders to evaluate several opportunities for future collaboration.
Seed ERP's 2021 → will not proceed as Full ERP in 2022	
Next Generation Crypto *We develop building blocks for quantum-secure analysis of distributed data.*	Together with experts from health and Police & Justice, we listed a number of interesting use cases for secure analysis of distributed data. And we developed a proof-of-concept to aggregate the local model parameters within federated learning, in an active-security model.
Seaweed *We develop use cases where integral and system thinking, essential for the seaweed industry, to maximise the impact of seaweed.in the transition to a just, circular, energy neutral, biobased society.*	We have identified and selected representative extracts and seaweed components. They were evaluated using TNO screen tool for potential positive human health effects of the human microbiome. Several compounds showed a positive effect and the dose effect relationship was established.
IMAGINE *Design, manufacturing and testing of 3D structured electrodes for the efficient, sustainable and low-cost electrochemical production of hydrogen from water and chemicals from CO2.*	We have carried out an IP scan and we have identified the performance targets for a system to be developed in a Full ERP program. Proof of concepts of structured electrodes were designed, manufactured and tested leading to promising results.