Electrochemical Conversion & Materials

Towards a CO_2-neutral energy supply in 2050

TOPSECTOR ENERGIE
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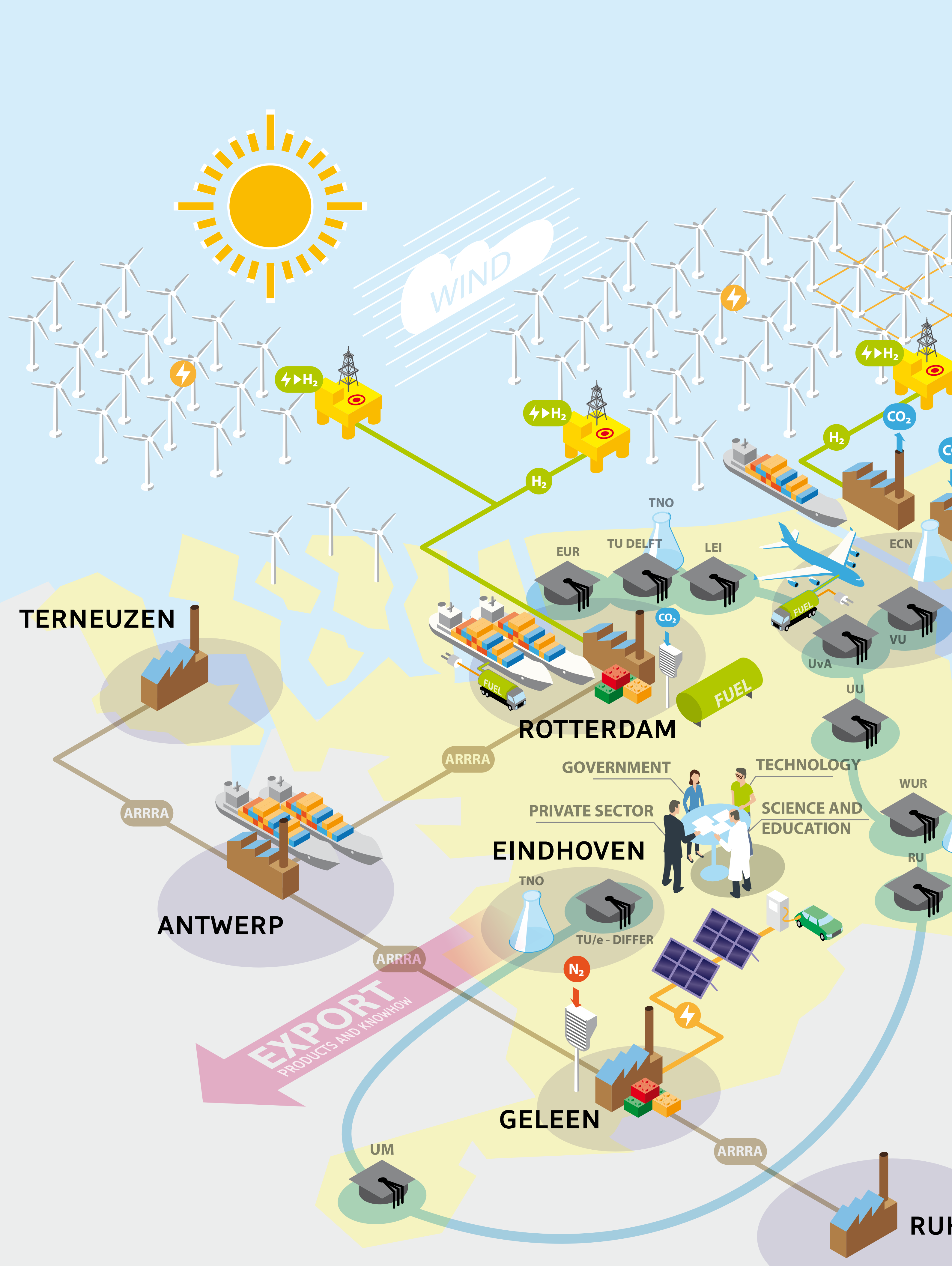

RRRA = industrial cluster Antwerp-Rotterdam-Rijn-Ruhr-area

www.creative projects.nl amsterdam

The Hague, april 2018

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Introduction

It is clear that in our future energy system, renewable electricity will play a major role in the transition towards a low carbon energy supply. This transition will be facilitated by the CO_2 objectives established by the Dutch government (CO_2-neutral by 2050). This requires far-reaching electrification. In the future, however, there will be a continued need for fuels (for flight, shipping and heavy goods transport over road) and for chemical products and materials. These activities and the associated production processes are currently responsible for more than 35% of worldwide CO_2 emissions . We now face an enormous challenge in manufacturing these fuels and chemical products through the use of renewable electricity and on the basis of biomass and/or CO_2. This can be realised using electrochemical conversion.

In addition, solutions are needed to tackle the problem of the imbalance between production and consumption of electricity, which is also termed intermittency (both oversupply and undersupply). These solutions lie in connecting networks and production capacity (interconnection), organising an optimal balance between supply and demand through flexible production and consumption, and in direct storage of electrical energy. For that last aspect, storage of electricity in batteries or similar systems is an option, as is the electrochemical production of chemicals as an energy carrier. Electrochemical conversion is the most promising option for the long-term storage because this technology can easily be scaled according to the quantity of energy.

Research into Electrochemical Conversion & Materials, see Figure 1, will become an important branch of science and technology development because electrochemical conversion contains the key to storing renewable electricity in chemical compounds. This lays a foundation for future sustainable, synthetic energy carriers that will be able to contribute to a sustainable energy supply in various ways. They offer a solution for the future problem of a time- and place-dependent imbalance of electricity and mitigate a structural shortfall of sustainable fuels that are produced via other routes (primarily from biomass). Additionally, renewable resources for the chemicals sector can be produced via electrochemical conversion. Electrochemical Conversion & Materials (ECCM) is the key technology to make the electrification of processes possible.

[1]. United States Environmental Protection Agency (EPA)

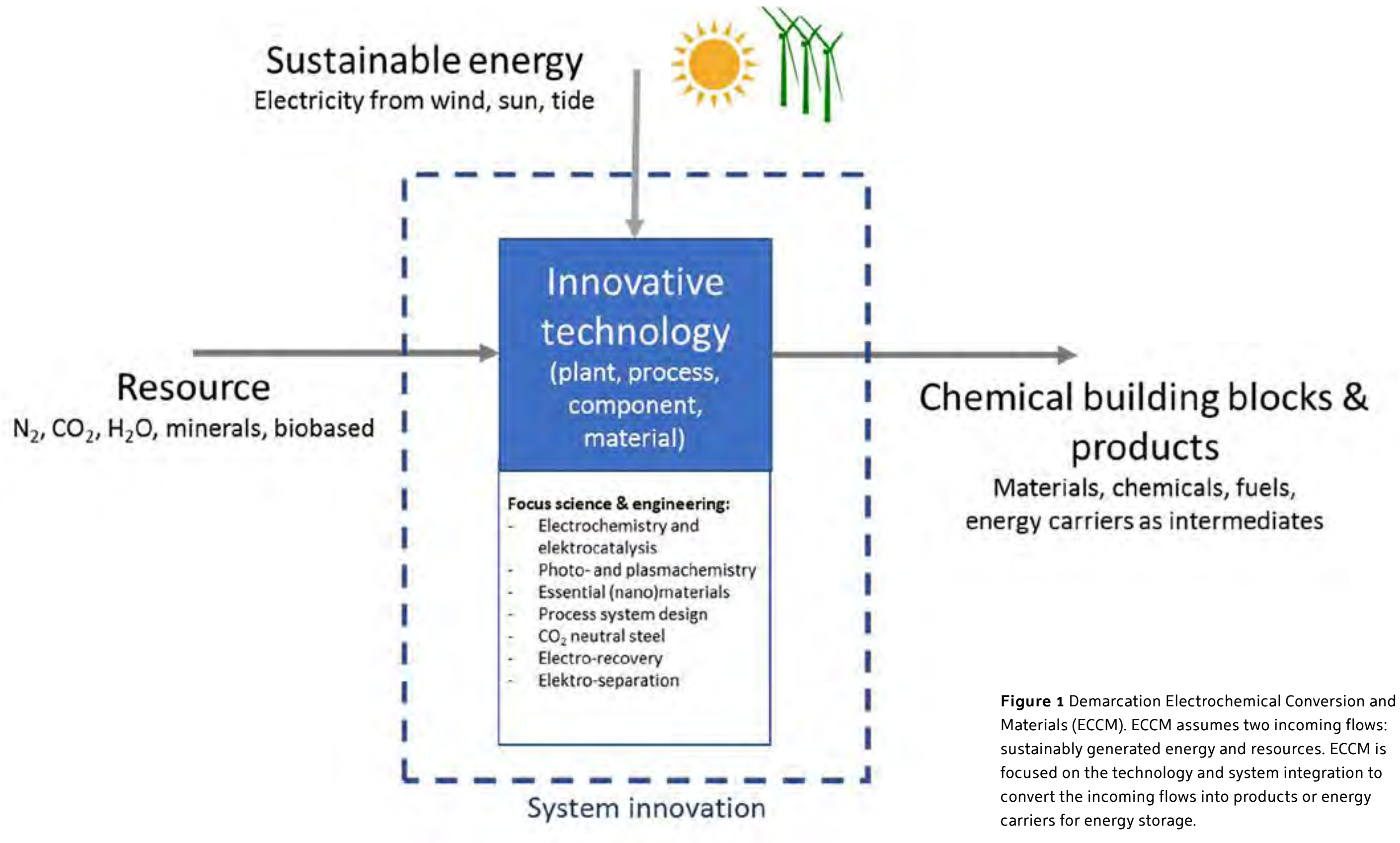

Figure 1 Demarcation Electrochemical Conversion and Materials (ECCM). ECCM assumes two incoming flows: sustainably generated energy and resources. ECCM is focused on the technology and system integration to convert the incoming flows into products or energy carriers for energy storage.

From a strategic interest, the Netherlands does not want to be dependent on other countries for the implementation of this new technology in vital infrastructure. Furthermore, the Netherlands has the ambition of playing an important international role in the global energy transition by means of its own research and development activities, in close collaboration with other countries. The top sectors Energy, High Tech Systems & Materials (HTSM) and Chemistry have noted that a lot is already happening at the interface of these sectors, especially regarding the conversion of electricity and sunlight into products, but that there is also a need to realise a joint approach to bring the use of electrochemical conversion and materials a step closer. The theme requires collaborations between various disciplines, new alliances between companies (Annex A) and institutions from various sectors, and collaborations across the boundaries of the top sectors. To bring this national approach one step closer, the top sectors Energy, HTSM and Chemistry have appointed an advisory committee which is to realise a joint vision on behalf of a wide range of stakeholders made up of companies and scientists, see Annex B.

The committee set to work with a broad administrative mandate from the top sectors involved and a strong thematic embedding in the Dutch National Research Agenda Routes Energy Transition, Materials, and Circular Economy. The committee has compiled its vision in consultation with the the top sectors involved as well as a broader group made up of various innovation, management and governance experts.

After an extensive consultation with experts from industry and the knowledge field, the advisory committee Electrochemical Conversion & Materials has come up with the following objectives:

- By 2030, hydrogen will be produced in a CO_2-poor manner at a price of no more than € 2/kg, and by 2050 at a price of € 1/kg.
- By 2030, at least 20% of the hydrogen and ammonia will be produced without CO_2 emissions.
- By 2050, at least 40% of the industrially produced CO_2 will be used as a resource in the transition to a circular carbon cycle.
- Mobility: by 2050, the entire transport sector will be CO_2-neutral.

[2] The Dutch government wants to further strengthen the international position of the so-called top sectors for innovation. The government identified **nine top sectors**: Horticulture & Propagation Materials, Agri-Food, Water, Life Sciences & Health, Chemistry, High Tech Systems & Materials, Energy, Logistics, and Creative Industries.

[3] **The Dutch National Research Agenda** is a source of inspiration for those interested in science. The agenda presents 140 overarching scientific questions and is the result of a unique bottom-up initiative, driven by the general Dutch public and a vast number of organisations in the Netherlands. The questions reveal the complexity of the issues challenging Dutch society today, and provide a glimpse into the areas where Dutch scientific research plans to focus on in the coming years.

According to the committee, the following three focus areas are necessary to achieve these objectives:

1. Integration of electrolysis and sustainable hydrogen in the energy system and large-scale chemical processes (Section 2);
2. Large-scale development of innovative electrochemistry and materials science (Section 3);
3. Applying focus and mass in education and knowledge exchange (Section 4).

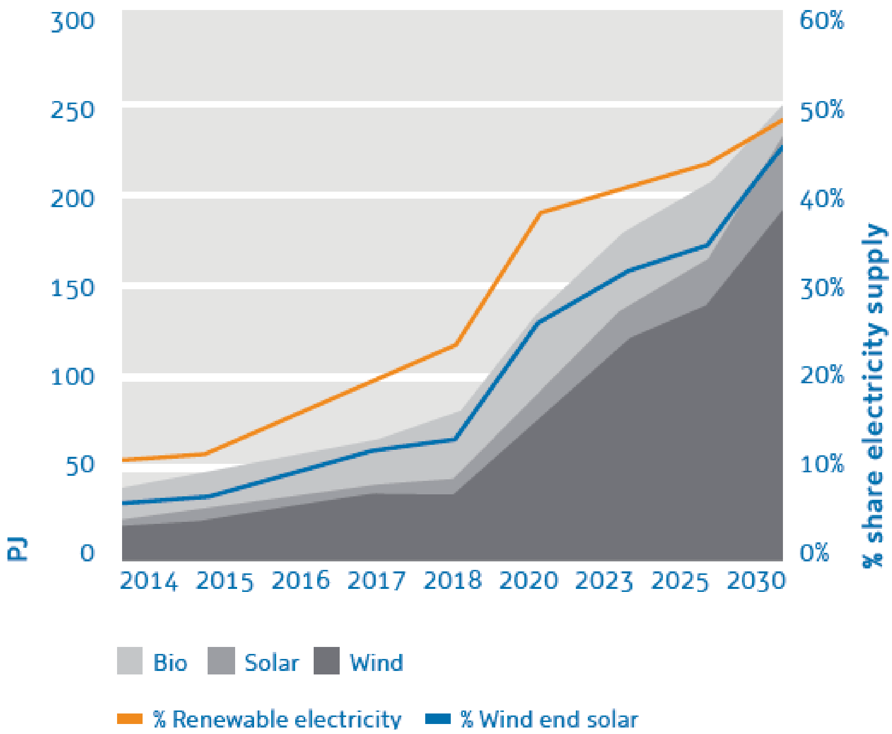

Figure 2 Development of the supply of renewable electricity in the Netherlands.
Source: Electrification in the Dutch process industry. Berenschot, 2017

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Integration of electrolysis and sustainable hydrogen in the energy system and large-scale chemical processes

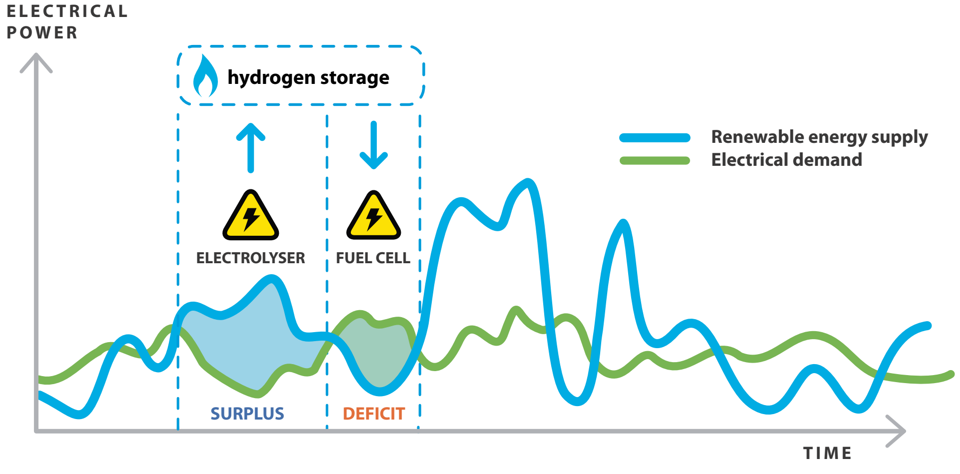
The electrolytic "splitting" of water into hydrogen and oxygen using electricity is currently the most developed and most efficient (~70% for commercial electrolysers) way of using electricity to produce hydrogen as a fuel. Major advantages are that electrolysis is scalable and can be used flexibly. The technique for fuel cells is also highly developed and can be used to convert the hydrogen produced back into electricity.

The Netherlands has a high concentration of industrial clusters and a high population density. It is therefore ideally suited to the system integration of electrolysis. A unique factor is that the Netherlands has a highly advanced national distribution network for natural gas. The natural gas network could eventually be used as a future hydrogen network in the form of a mains supply throughout the Netherlands for the connection of hydrogen production.

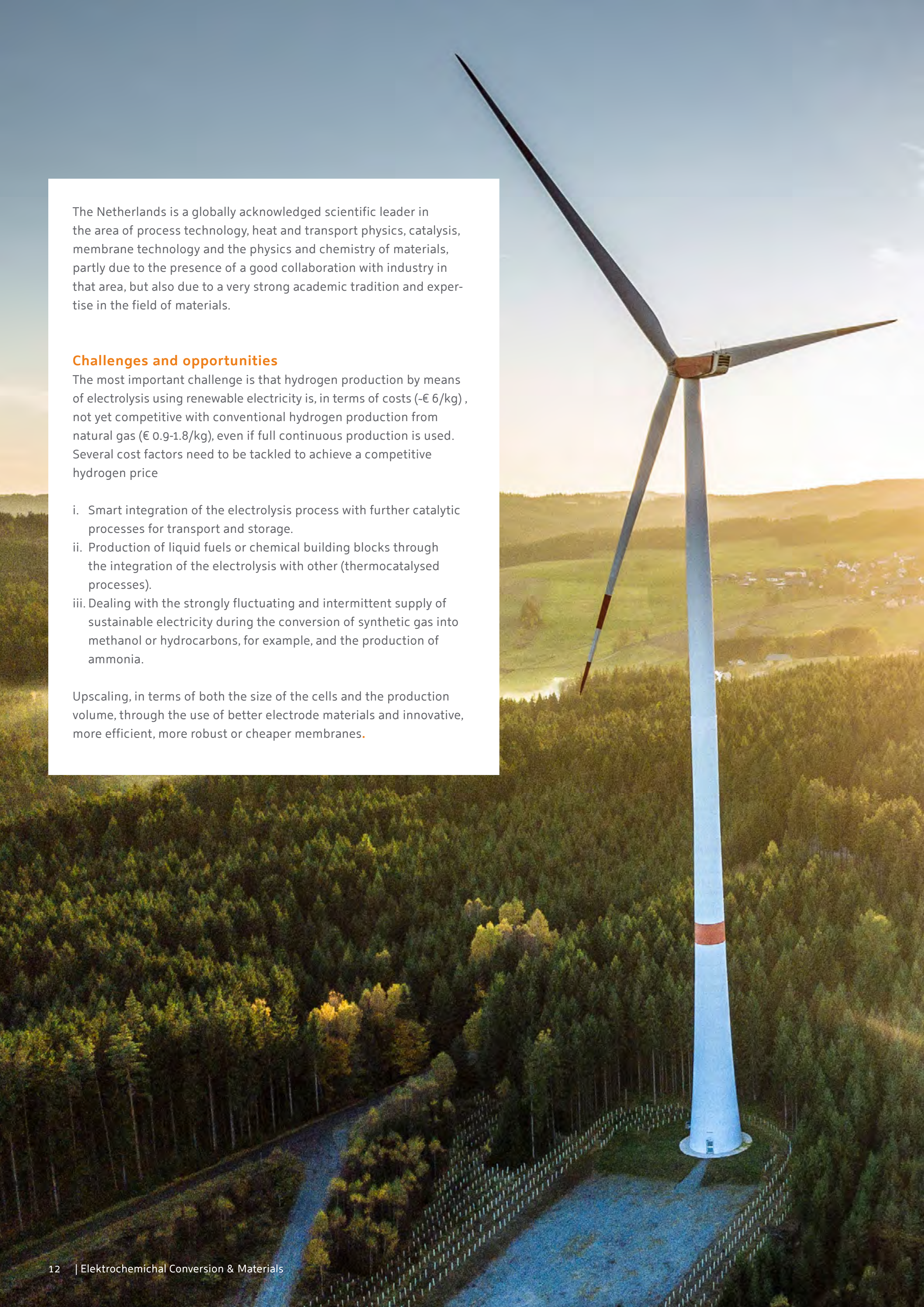
Several multinationals with considerable infrastructure and R&D activities are located in the Netherlands, such as Shell and AkzoNobel. In addition, the Netherlands has small, specialised companies that are active at the intersection of hydrogen, electrochemistry and energy. Collaboration with the high-tech sector is required in the area of system integration (for the connection of ECCM to smart grids, to allow companies to smartly connect with and disconnect from the energy grid) and equipment construction (CO_2 capture installations, including the necessary nanomaterials, (micro)reactors and electrolysis equipment).

Showcase: Hydron energy

Hydron Energy is a start-up that develops and implements innovative water electrolysis (and fuel cell) technology on the basis of Polymer Electrolyte Membranes. Together with specialised strategic partners, Hydron Energy produces renewable energy installations based on hydrogen technology. Through the application of flexible and modular electrochemical technology, Hydron energy can provide solutions that range from several watts to MW in scale.



Source: Hydron Energy



The Netherlands is a globally acknowledged scientific leader in the area of process technology, heat and transport physics, catalysis, membrane technology and the physics and chemistry of materials, partly due to the presence of a good collaboration with industry in that area, but also due to a very strong academic tradition and expertise in the field of materials.

Challenges and opportunities

The most important challenge is that hydrogen production by means of electrolysis using renewable electricity is, in terms of costs (-€ 6/kg) , not yet competitive with conventional hydrogen production from natural gas (€ 0.9-1.8/kg), even if full continuous production is used. Several cost factors need to be tackled to achieve a competitive hydrogen price

i. Smart integration of the electrolysis process with further catalytic processes for transport and storage.
ii. Production of liquid fuels or chemical building blocks through the integration of the electrolysis with other (thermocatalysed processes).
iii. Dealing with the strongly fluctuating and intermittent supply of sustainable electricity during the conversion of synthetic gas into methanol or hydrocarbons, for example, and the production of ammonia.

Upscaling, in terms of both the size of the cells and the production volume, through the use of better electrode materials and innovative, more efficient, more robust or cheaper membranes.

3

Large-scale development of innovative electrochemistry and materials science

Electrochemistry is the branch of chemistry that is concerned with the conversion of electricity using building blocks like nitrogen, water, carbon dioxide, minerals or biomass, into chemicals, fuels or materials. Photoelectrochemistry, which uses direct sunlight, has a special place in this. The committee has high expectations of new innovative forms of electrochemistry in which electricity will be directly used for the manufacture of products and molecular building blocks in an electrochemical reactor. Electrochemistry is a broad discipline in which various fields come together, such as thermodynamics, catalysis, analytical sciences, organic chemistry, materials science, process technology and nanotechnology. The research field is developing rapidly, and the challenges mainly lie in the area of selectivity and kinetics. A combination with light or other forms of radiation (with electricity being used to generate this radiation, for example microwaves, plasmon excitation, et cetera) to improve process intensification and/or selectivity is a topic of research.

The public interest in renewable energy has once again made photochemistry a priority in recent years at the universities in Leiden, Delft, Eindhoven, Twente, Wageningen, Amsterdam, Utrecht and Groningen, as well as the research institutions DIFFER, TNO and ECN. This has in part been supported by the NWO programmes CO_2-neutral fuels and Solar2Products, the applied innovation programme VoltaChem, and the programmes BioSolar Cells, Solardam, Solar2Products, Materials4Sustainability, MCEC and the Chemical Building Blocks Consortium (ARC CBBC).The Dutch processing industry has a long tradition of activity in the field of electrochemistry, which includes Tata Steel (steel production), Nyrstar (zinc refining) and AkzoNobel (chlorine production), but there are also numerous smaller high-tech companies active in the area of hydrogen or electrode development. Shell and Avantium are currently making considerable investments in building up electrochemical expertise. Furthermore, the Netherlands is renowned in the area of developing electrochemical measuring equipment (Metrohm Autolab, Ivium, PalmSens).

Challenges and opportunities

One of the main challenges is the development of selective catalysts to convert CO_2 and biomass into useful products. Cell, electrode and catalysis design, downstream product purification and applications, business case development and Life Cycle Analysis (LCA) will also require significant research efforts for commercial application. Challenges within photochemistry include the development of sufficiently stable photoelectrodes. Additional interaction between the photoelectochemistry and photocatalysis communities will support this.

The development of innovative electrochemical processes depends on the development of new, advanced materials that are produced from nonscarce elements (such as iron or silicon) and that can be implemented on a large scale:

- Thin-film techniques to apply catalysts to electrode surfaces with atomic precision;
- Analysis of charge transfer processes in the electrolyte across solid-liquid interfaces;
- Structure characterisation at the nanoscale;
- Correlation of the structure of advanced electrodes to gas bubble formation (growth dynamics);
- 3D-printing of electrodes and cells;
- Production of large surface nanostructured materials.

[4] Hinkley et al. (2016) Cost assessment of hydrogen production from PV and electrolysis. CSIRO, Australia


4

Applying focus and mass in education and knowledge exchange

With the societal challenge related to climate change and CO_2 reduction in combination with a high concentration of activities and interest at the academic, technical and industrial levels in the Netherlands, an unmistakable momentum is now present in the Netherlands to further put Dutch electrochemistry on the map. Both geographical and informal lines between the various public and private partners are traditionally short in the Netherlands. However, there is no coherent national community in the area of electrochemistry and electrochemical engineering yet, and only a limited number of new people are being trained.The committee therefore advises investing in new educational programmes (educational modules) in the area of electrochemical conversion at universities and universities of applied sciences. These include the development of a multidisciplinary BSc and MSc in electrochemical conversion and materials, and introducing new professorships and tenure-track associate professorship appointments at universities as well as lector positions at universities of applied sciences so as to encourage the broad knowledge base and knowledge acquisition and to increase the capacity of knowledge institutions to train and supervise new talent. Furthermore, the training of professionals at universities of applied sciences and in vocational education should be encouraged to ensure that the necessary upscaling and implementation can occur in the near future.

Knowledge exchange should be facilitated by setting up a knowledge community that brings together expertise in the areas of material technology, materials science, reactor engineering, catalysis, heat and transport studies, power electronics, smart grids and the necessary high-tech and low-tech engineering for application in the infrastructure.

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The Flying Dutchman
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Governance

A long-term, mission-driven programme is necessary to create a well-functioning ecosystem in the area of electrochemical conversion in the coming years. This programme will involve the parties with the right knowledge and expertise, develop and exchange new fundamental and applied knowledge, show leadership and entrepreneurship, bring together supply and demand, train people and encourage talent, and give direction to achieving the objectives set (roadmap). Due to the complexity of the energy system, it is clear that individual market parties are not able to realise a collective objective without coordination. The government should take the lead by facilitating, establishing centralised coordination and demonstrating longer-term commitment.

This cannot be realised without economic and social innovations, such as the development of new business models and understanding how to deal with this new technology. Demand-Side Management is necessary to further reduce the seasonal dependency. The systematic analysis of limiting and facilitating financial stimuli and legislation are an essential aspect of the programme. During the programme, it is important to invest in life-cycle analysis.

Governance and coordination

An ECCM steering group, appointed by the government, provides coordination at national level by ensuring the interaction within the knowledge community and the realisation of the joint objectives. It also has the mandate to make choices. The government has a facilitating role in this process. An ECCM advisory council made up of international experts will advise the steering group about the specific choices and strategy. Finally, the Dutch strategy cannot be viewed independently from that of the joint EU Member States and European policy and legislation.

Funding

Due to the urgency, the advice is to start with a research and development budget of at least 20 M€/year for applied mission-driven research for implementation in 5-10 years (TRL3-6) with a limited private matching (<10%) in addition to in-kind contributions. At least M€ 4 per year of this budget is for fundamental mission-driven research with a horizon of more than 10 years (TRL1-3). Furthermore, the committee proposes reserving M€ 200 per year for large-scale investments in small-scale living labs and large-scale open access pilots and demos, so that existing technologies can be demonstrated in the short term (<5 years, >TRL7-9). This amount will be supplemented with private contributions (M€ 150-200 per year).

Recommendations

The committee has reached the following recommendations with respect to governance, legislation, education, and research and development:

Governance

- Develop a national approach in the area of ECCM focussed on international collaboration and targeted innovation. This requires stating strengths and paying attention to blind spots, governance and coordination, a good overview of bottlenecks and potential solutions in the Netherlands and abroad, and increasing the deployment of people and resources.
- Appoint an expert steering group that can realise the coordination with a national mandate. Due to complexity of the energy system, individual market parties are not capable of realising a common goal without coordination. The steering group is responsible for the convergence and prioritisation of options, monitoring, feedback, learning and evaluation, and will organise a knowledge platform in which partners with knowledge and expertise can participate. The steering group will be advised on these topics by an international advisory board.
- Connect use-inspired research with further development and investment budgets for large-scale pilots and demos. Earmark budgets for research into ECCM by universities, by universities of applied sciences and by institutes for applied research, but also for demos and pilots so that the aforementioned link between use-inspired research and further development can actually take place.
- Focus on convincing business cases and on national strategic importance. For example: in Germany, the strategic interest (e.g. in hydrogen technology) often weighs heavier in the decision for incentives than the actual business case, such as in the Kopernikus programme.
- Appoint a national figurehead to be the face of ECCM for a large diversity of stakeholders. The national figurehead can act as the independent chair of the national committee, serve as an administrative point of contact or engage his or her network to connect parties in the area of ECCM.

Legislation

- Focus on the long-term uncertainty concerning legislation in the area of CO_2 and a level playing field in the international context. Encouraging the reduction of CO_2 emissions requires more instruments than merely subsidies. Pricing CO_2 emission as a supporting mechanism is desirable.
- Set standards for CO_2 reduction and for CO_2 emissions for goods transported by vehicle (per km or tonne). This could also apply to other sectors besides the mobility and transport sectors. Examples include standards such as a percentage of the transported electricity with a sustainable footprint or a given percentage reduction of the CO_2 footprint for bulk industrial products such as chemicals by 2050.

Education

- Invest in electrochemistry programmes at universities and universities of applied sciences.
- Encourage the training of professionals at universities of applied sciences and in vocational education to ensure that the necessary upscaling and implementation can occur in the near future.
- Develop multidisciplinary BSc and MSc programmes in the area of materials for electrochemistry and electrochemical conversion systems.

[5] In 2016, four Kopernikus programmes were started in Germany that must realise breakthroughs in the Energiewende (energy transition). The focus is on four 'problem corridors' without fixed final objectives, to allow the various possible solutions to remain open during the programme duration of 10 years. See: **www.kopernikus-projekte.de**

Research and development

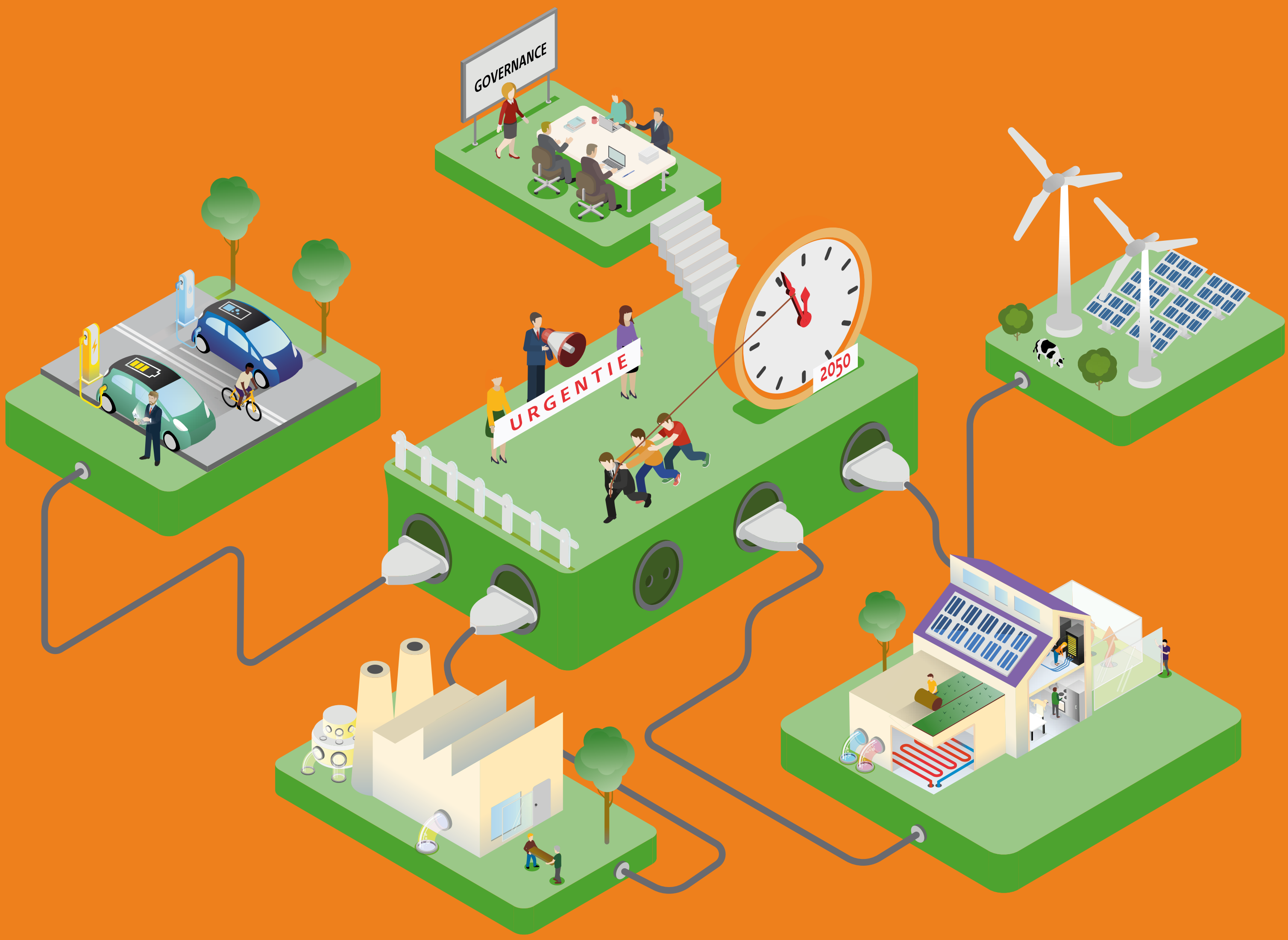
- Introduce a national approach in the form of a long-term mission driven programme (Technology Readiness Level, TRL, 1-6) to generate impact and to counteract the current fragmentation into smaller-scale initiatives. The realisation of this programme can connect with existing initiatives and structures, but the financial and government mandate should lie with an independent committee. The programme must also clearly facilitate (applied) research with a long time horizon as well as fundamental engineering; this is usually difficult to fund, but both are essential. Space should also be provided for exploring new subjects within the theme.
- Introduce new professorships and tenure-track associate professorship appointments at universities and lector positions at universities of applied sciences to encourage knowledge acquisition and to increase the capacity of knowledge institutions for the training and supervision of new talent.
- Support necessary investments for pilot plants so that innovations can be tested and developed under realistic process conditions.
- Encourage the formation of a coherent "community".
- Seek collaboration with leading players abroad; with targeted investments in the area of electrolysis and fuel cells, the Netherlands can become part of the international state-of-the-art in ECCM.
- Start with a research and development budget of at least M€ 20 per year for the further development of existing knowledge and technology (applied mission-driven research for implementation in 5-10 years, TRL3-6) with a significant but limited private matching (<10%). Earmark at least M€ 4 per year for fundamental mission-driven research with implementation in more than 10 years' time (TRL1-3) and the strengthening of the knowledge base. This M€ 4 consists of M€ 3 for programmatic research and M€ 1 for new senior research positions at universities (assistant and associate professorships) and universities of applied sciences (lectors).
- Reserve M€ 200 per year for matching with private funds for investments in small-scale ECCM living labs and large-scale open access pilots and demos. In the short term (<5 years, >TRL7-9), this will lead to existing technologies being demonstrated as cost competitive for the first time.

[6] **Oppakken en doorpakken. Durven kiezen voor energie-innovatie (AWTI)**

Table 1: Examples of short- and long-term opportunities and challenges in Electrochemical Conversion and Materials.

	Short-term (0-10 years): until 2030	Long-term (10-30 years): until 2050
System integration	• Integration of heat and power (steam recompression, electrical boilers and heat pumps). • Replacing steam with electrical propulsion. • Demo and first implementation electrolysis (water into hydrogen).	• Value chain development new resources and energy. • Large-scale electrolysis. • Incorporating electrolyser into multi-commodity network. • Infrastructure for hydrogen, CO_2 and electricity. • Using hydrogen for chemistry and fuels. • Using CO_2 sources (CCU) for electrochemical conversion (e.g. Port of Rotterdam).
Electrolysis	• Intensified electrolysers. • Cheap and sustainable subcomponents. • Dynamic use. • Economic scalability.	• Electrolysis for the production of chemicals and fuels from renewable sources (CO_2, N2, biomass). • Decentralised vs. centralised production.
New electrochemistry and materials science	• Selective oxidations for efficient conversions and high-value applications as a stepping stone to a larger scale. • Materials for efficient and sustainable electrolysis. • Use of nonscarce metals as electrocatalysts. • Electrochemical purification and recycling.	• Smart integration of the electrolysis processes with thermocatalytic processes. • Electrochemical CO_2 capture and further chemical reactions. • Photoelectric chemistry and direct sunlight conversion. • Glass fibres for converting H_2O into H_2 and O_2 using (sun)light.
Integrating fuel cells	• Electrochemical compression. • Integration with hydrogen.	
Redox-flow energy storage	• Incorporating redox-flow systems in the power grid.	• Redox-flow with separate anolyte and catholyte for conversion.

Attachments



Annex A

Commercial Activity Dutch Electrochemical Conversion and Materials

Energy

Distribution
Alliander
Greenpoint
Stedin
TenneT

Production
Eneco
Engie /laborlec
Nuon
RWE
Uniper

Gas sector
GasTerra
Gasunie
Operators North Sea
Shell

Chemistry

Air Liquide
Air Products
AkzoNobel
Albemarle
Antecy
Arkema
Avantium
BASF
Coval Energy
Criterion
Dow
DSM
Huntsman
ICL Terneuzen
Linde
Nyrstar
OCI Nitrogen
Praxair
RWB
Shell
Total
Vopak
Yara

High tech and materials

Airborne
Ampleon
Chemtrix
Elestor
E-Trucks
Evoqua
Holthausen
Hydron Energy
HyET
Hygear
Ivium
Flowid
3M
Ligal
Metrohm Autolab
MTSA Technopower
Nedstack
PalmSens
Pitpoint
Stork (system integration)
Tata Steel
Team Fast
Teesing
VDL

There is considerable potential for equipment builders and suppliers in the high-tech sector who can respond to a market demand if the government embraces ECCM as a transition route.

Water

A. Hak Industrial Services
Aquabattery
Evides
Fujifilm
Lenntech
REDstack
Van der Knaap
Vitens
Voltea
Waternet
Waterschap de Dommel
W&F Technologies

Logistics

Port of Rotterdam

Annex B
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Prof. Bernard Dam (Delft University of Technology), Materials for Energy Conversion & Storage
Dr Earl Goetheer (TNO), Principle scientist Sustainable Process & Energy Systems
Prof. Gert-Jan Gruter (Avantium), Chief Technology Officer
Prof. Petra de Jongh (Utrecht University), Inorganic Chemistry & Catalysis
Prof. Marc Koper (Leiden University), Electrochemistry
Prof. Guido Mul (University of Twente), Photocatalytic synthesis
Dr Alexander van der Made (Shell), Principal Scientist Future Energy Technologies
Dr John van der Schaaf (Eindhoven University of Technology), Chemical reactor engineering
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President Executive Board European Center for Climate Change Solutions)
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High-tech Solutions for Global Challenges

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Global Challenges, Smart Solutions

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