ElectroChemical Conversion & Materials

ECCM National Agenda

A Dutch *Research, Development & Innovation Agenda* for a CO_2-neutral industry based on renewable energy

ENERGY INNOVATION NL Powering a sustainable future
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NL Holland High Tech Global Challenges, Smart Solutions

The Hague, the Netherlands – November 2021

The **Advisory Committee for ElectroChemical Conversion & Materials, ECCM**, was established in 2017 by the Dutch government with the support of three Top Sectors: Chemistry, Energy and High Tech System and Materials, HTSM. The reason for this initiative was the common realisation that many promising activities towards a CO_2-neutral society were taking place at the interface of these different sectors. Yet a coordination effort between activities in the field, summarised as ECCM, to bring focus, avoid replication and make the Netherlands a frontrunner in the energy transition was missing. This was one of the assignments of the ECCM committee: to develop a joint R&D agenda towards the ambitious target of CO_2-neutrality by 2050.

At present, the ECCM committee brings together 16 members: national experts from industry, government and academia. Committee members reflect on the national interests in the international context, not on the vested interest of their employers. It is a way to strengthen the existing network of stakeholders, stimulate collaboration and prevent duplication. Furthermore, the committee serves as a platform to coordinate and facilitate national R&D activities on the theme of ECCM and to organise the requisite funding.

Since 2017, the Committee has coordinated the R&D and innovation efforts of companies and knowledge institutes in the Netherlands in the field of short-term hydrogen and system integration and longer term electrochemical conversion. The ECCM has also initiated new collaborations and adopted initiatives within the scope of its 2017 advisory report, building up a broad portfolio of research programmes and demonstration projects (TRL 1 to 8), see also Annex 1. Important efforts that illustrate this are the involvement in drafting *GroenvermogenNL*. a large National Growth Fund proposal on green hydrogen and green chemistry, and the launching of the first international collaborative actions to establish cross-border joint programming, in particular between Germany and the Netherlands.

Furthermore, the ECCM committee is keen to connect with existing infrastructures and programmes that fit within the vision of the committee. For instance, in 2019-2020 the ECCM committee sparked the RELEASE consortium on reversible energy storage. Other examples are the MW test centre HydroHub, established by ISPT, and the Field Lab Industrial Electrification established by the VoltaChem programme and partners.

Within the Netherlands, the committee is building an ECCM community of knowledge institutes, companies, governments and NGOs. To this end, the committee organises conferences/ workshops in the field of ECCM, an annual Graduate School and from winter 2021 onwards a Research Day to bring together all major ongoing R&D programmes in the Netherlands in the field of ECCM.

The ECCM committee works closely with the government (e.g. the Ministry of Economic Affairs and Climate Policy, EZK; the Ministry of Education, Culture and Science, OCW; the Top Sectors and Mission Teams) and the knowledge sector (NWO and TNO). The committee aims to bridge sectors, missions, disciplines and agendas to achieve the objectives for upscaling, cost reduction and innovation for green hydrogen and green chemistry, as stated in the National Climate Agreement of the Netherlands, the knowledge and innovation agendas of the Mission-driven Top Sector and Innovation Policy and the ECCM advisory report.

For more information:
www.co2neutraalin2050.nl

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Executive Summary

The Advisory Committee for ElectroChemical Conversion & Materials,[1] ECCM, advises the Dutch government on how to make the transition to a CO_2-neutral industry based on generation, storage and conversion of renewable energy/electricity. The Committee promotes a cross-sectoral approach to achieve a CO_2-neutral industry in the next few decades and its advice spans the entire innovation chain (TRL 1-8).

The ECCM Advisory Committee coordinates efforts in the field of ECCM at the national level, by initiating new collaborations and by adopting initiatives that fit within the scope of the advisory report published in 2017. Important efforts that illustrate this are: the involvement in the drafting of GroenvermogenNL, a large National Growth Fund proposal on green hydrogen and green chemistry, the launching of the first international collaborative actions to establish cross-border joint programming between Germany and the Netherlands, and the organisation of many events to build an ECCM community of knowledge institutions, companies, government representatives and NGOs.

Four years later, the ECCM committee is presenting an update of its initial advisory report to take into account the changes in the landscape of the energy transition and the raw material transition. The recommendations of the ECCM committee in this National Agenda are organised along **four action lines** covering the entire innovation chain from technology development to system integration and implementation in society.

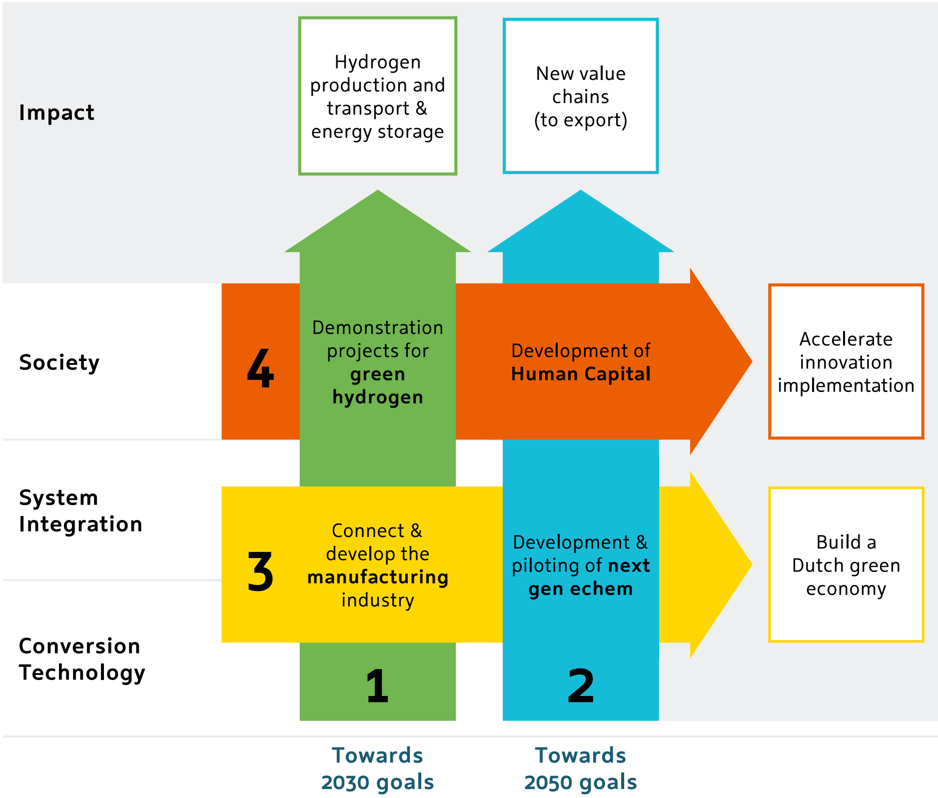
1 More information: www.co2neutraalin2050.nl

Line 1. To work **towards the 2030 goals**, the ECCM committee advises **pilot and demonstration projects for green hydrogen (scale 1-100 MW) and its applications for green chemistry**.

Line 2. To work **towards the 2050 goals**, the ECCM committee advises **the research, development, innovation and piloting of the next generation of green electrochemical conversion processes**, using renewable energy/electricity, to realise the deep decarbonisation of the (chemical) industry. This includes novel technologies for **green hydrogen** as well as **new electrochemical conversion processes**.

Line 3. **Strengthen and develop the high-tech manufacturing industry** to produce and export systems and materials, building a green economy Made in NL.

Line 4. **Develop and implement a Human Capital Agenda** by training and educating students (at the MBO, HBO, and WO levels) and retraining/upskilling the existing workforce in the area of ECCM, building a solid knowledge and skill base for companies to innovate, grow and strengthen themselves.



Within these four action lines, and especially where the lines connect, the ECCM Committee identifies **strategic focus areas**:

- New electrochemical conversion concepts and materials
- Field labs, co-creation, pilots
- Made in NL
- System integration
- Vocational and higher education
- Multi-annual coordination and perspective

leading to the following recommendations:

- Develop **New electrochemical conversion concepts and materials**
  - Low TRL programmes for H_2 - fundamental technical science, system integration & socioeconomic research;
  - Low TRL programmes for next-generation electrochemical conversion - fundamental technical science & socioeconomic research.
- Set up **Field labs, co-creation projects, pilots**
  - Cross-sectoral (energy, chemistry, HTSM) field labs, testbeds and pilots in the 10-100 kW scale, also to be used for HCA activities.
- Support **Made in NL**
  - High TRL programmes for innovation in the supply chain for electrolysers and electro-conversion processes;
  - High TRL programmes for demonstration in the supply chain for electrolysers, allowing for size diversifications (*scale-up and also number-up).*
- Invest in **System integration** projects
  - Innovation of system integration;
  - Demonstration projects on H_2 storage and buffering, and on flexibility and heat coupling in the chemical industry.
- Develop **Vocational and higher education**
  - Intensify cooperation between companies and educational institutes and develop dedicated programmes on the electrification of the industry;
  - Implement ECCM Learning communities for MBO and HBO (in regions) and develop a national programme for knowledge sharing.
- Develop **Multi-annual coordination in an international perspective**
  - Establish an overarching governance and coordination structure for all related activities to guarantee synergy, knowledge transfer, national and international alignment.

The ECCM committee underlines that **all four action lines need to be undertaken *now* to meet the 2030 and the 2050 targets**. Given the rapid developments in technology, policy and legislation around the energy transition, the committee expects that a new update of this National Agenda might be due within the next 5 years.
Finally, the Netherlands is not operating in a vacuum: our neighbours and trade partners face similar challenges and are undertaking efforts to accelerate development on these themes. The Netherlands needs to belong to the frontrunners in international cooperation. **Coordination and collaboration at the international level will therefore be crucial** for the success of this National Agenda.

Reading Guide

Chapter 1 sets out the background against which this Agenda was written.
Chapter 2 fleshes out the Agenda's recommendations to reach the 2030 and 2050 goals.
Chapter 3 gives the technological and sociotechnical information, on which the recommendations in Chapter 2 were based.

1

Why a national ECCM Agenda

1.1 Setting the stage

Pressing global challenges like climate change and severe loss of biodiversity, mean the world's economy needs to undergo a radical transformation in how we relate to energy and natural resources. The next few decades will be crucial for the transition to a CO_2-neutral society and a new circular economy (**Fig. 1**).

The EU Green Deal seals Europe's commitment to be the first fully climate-neutral continent by 2050 and sets out an ambitious plan to reach a 55% reduction in greenhouse gas emissions[2] by 2030. Important ingredients towards these targets are replacing fossil fuels with renewable energy, increased energy and resource efficiency, general reduction of energy and resource consumption, and carbon capture storage and utilisation, CCS/CCU. In the context of the energy transition, **this Agenda focuses on** the role of renewables in **the electrification of the energy-intensive industry, in particular for the chemical industry, and on electrochemical conversion technologies.**

2 Compared to 1990 values

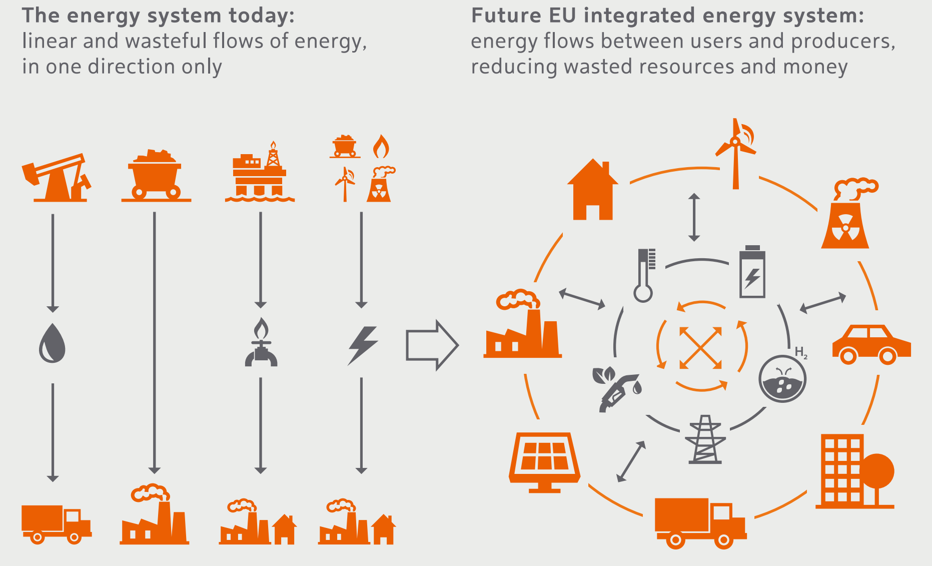
The energy transition needed for a CO_2-neutral future demands **large-scale deployment of renewable energy resources**, such as solar and wind.[3] The intermittent and seasonal nature of these resources, in turn, requires the **development of energy storage and conversion technologies at the TW scale.**[4]

At the same time, the transition to a circular economy needs **new technologies for the sustainable**[5] **production of building blocks and synthetic fuels** (e.g. for the hard-to-electrify transport, as aviation or shipping) and feedstock for the chemical, high-tech systems and materials industries. In our current linear, fossil-based economy, these activities are responsible for more than 35% of worldwide CO_2 emissions.

3 Greenhouse gases, GHGs, refer to a mixture of gases (www.ipcc.ch/sr15). Here we focus on CO_2, as it accounts for the vast majority of GHGs in the atmosphere today (ca. 76%).

4 DNV-GL report 2015 on the need for energy storage in the Netherlands

5 Fossil-free processes at first, and in the future fully circular economy, also fossil-free raw materials.



An Integrated EU Energy System will have **three main characteristics**:

- A more **efficient and "circulair" system**, where waste energy is captured and re-used
- A **cleaner power system**, with more direct electrification of end-use sectors such as industry, heating of buildings and transport
- A **cleaner fuel system**, for hard-to-electrify sectors like heavy industry or transport

Figure 1. Inspired by the Factsheet 'EU Energy System Integration Strategy'. This Agenda will mainly address the last two bullets.

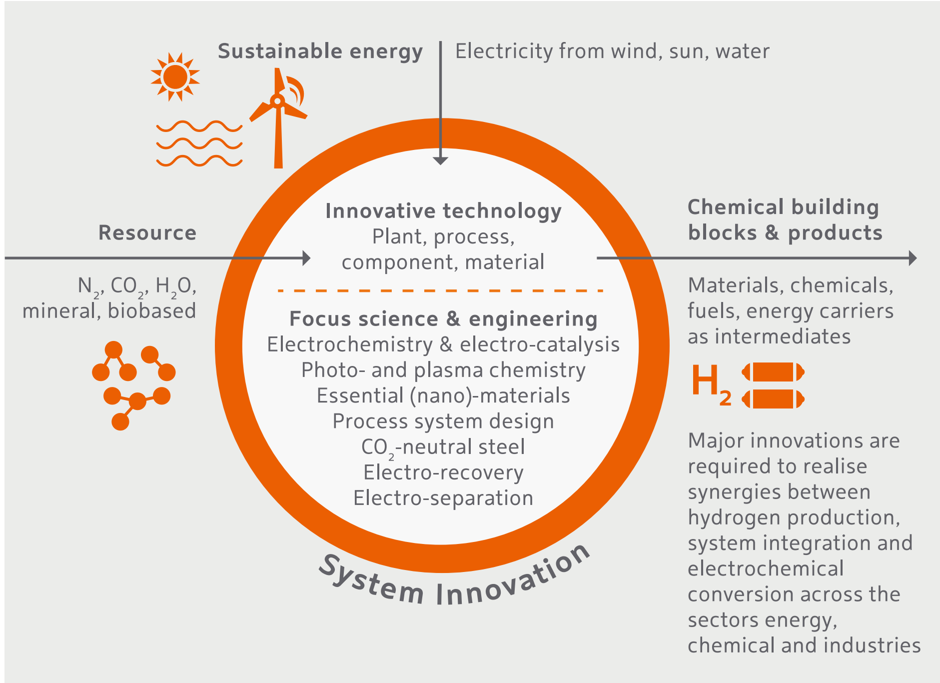


Figure 2. Electricity-driven (chemical) processes towards a CO_2-neutral industry.

Electricity-driven (chemical) conversion processes hold the key to these technological challenges (**Fig. 2**), as they enable:

- Storage of renewable electricity in energy carriers such as green hydrogen,[6] notably via electrolysis of water. The hydrogen produced in such a sustainable way can then be used in chemical synthesis or in fuel cells to buffer the energy demands;
- Direct conversion of renewable energy and non-fossil feedstock into higher value chemicals, such as instance electrochemical nitrogen reduction into ammonia, or CO_2 reduction into hydrocarbons.[7]

As a result, the resources of the future will be based on widely available, non-toxic feedstock, such as water, air –both a source of nitrogen (N_2) and carbon (CO_2) – and biomass, **and renewable electricity**. Innovative technology is needed to power this change.

The need for energy storage and CO_2-neutral production of feedstock and fuels brings together industrial sectors that have so far operated largely independently from each other (see Fig. 1). The chemical industry will become much more intertwined with the electricity sector, while the electricity and fuel sectors will become closely connected. In addition, a massive overhaul of our infrastructure is to be expected, including the challenge of making our built environment CO_2-neutral and evolving towards a fully circular infrastructure.

All this indicates that **a trans-sectoral approach is required**. Novel materials, technologies, systems and infrastructure clearly need to be developed and deployed considering TW scale of the energy infrastructure (see, for instance, the TeraWatt challenge[8]). Therefore, this aspect of the energy transition, where new disruptive approaches are needed, offers –next to the chemical and energy industry– ample opportunities for the high-tech systems and manufacturing industry to play a significant role. Transforming the industrial sector cannot be done without societal support and this, in turn, requires the early identification and monitoring of tensions created by trade-offs and the development of explicit and coherent plans for addressing such tensions (**Section 3.5**). Therefore, the trans-sectoral approach needs to include sociotechnical aspects such as public acceptance, education and decision-making (e.g. laws to help set a competitive market etc.).

Box 1 - Granular Scaling

We realise that the new technologies will need to operate at the TW scale, but right now it is less clear which specific technology will prevail and whether it will be operated in a centralised or decentralised fashion. The present economy of scale (essentially based on 3D operations) may not apply when 2D technology (e.g. PV or electrochemical processes) becomes dominant. One of the interesting challenges is to find the scale-up rules for electro-conversion technology and assess the maximum viable system size. On the other hand, the prosumer/consumer trend might propel the development of smaller sized solutions for energy conversion and storage.
A systematic study of the societal embedding of new energy technology is essential for its implementation: **the energy transition cannot be simply seen as replacing one energy carrier for another**.

C. Wilson et al., Science, 368, 36, 2020

6 Green hydrogen refers to hydrogen obtained via water electrolysis using renewable electricity.

7 By capturing atmospheric CO_2 –now in excess– these syntheses are effectively CO_2-neutral.

8 R. E. Smalley, MRS Bulletin, 30, 412, 2005 and S.R. Kurtz et al., MRS Bulletin, 45, 159, 2020

1.2 Challenges and opportunities for the Netherlands

The Netherlands is uniquely positioned to become a frontrunner in the energy transition. It intends to play a key international role in this, using its geographical advantages and innovation ecosystem in close collaboration with other countries. The National Climate Agreement of the Netherlands (Klimaatakkoord)[9] testifies to this ambition by setting out a series of targets in line with the EU Green Deal.

Our strengths

To start with, the high-density population and the **high concentration of energy-intensive industry clusters** in the Netherlands makes it an outstanding candidate to develop new climate-neutral technologies and ideally suited to system integration of electricity-driven conversion processes. Several multinationals with considerable infrastructure and R&D activities are located in the Netherlands, such as Shell, Nobian, Tata Steel, and a number of chemical clusters (e.g. Rotterdam, Geleen, Zeeland, Moerdijk and Delfzijl). Moreover, an established high-tech manufacturing industry (VDL, HyET, Nedstack, Hauzer technocoating, Frames, Bosch, Vonk, etc.) is present, alongside a rich ecosystem of start-ups and SMEs, with specialised companies active at the intersection of H_2, electrochemistry, energy and manufacturing. In general, the Dutch chemical industry, agricultural sector and high-tech manufacturing are recognised worldwide. This is due to two main factors: the unique geographical location and infrastructure, allowing trading of goods via our main ports (such as the Port of Rotterdam and Schiphol airport); and our innovative industry, where strong entrepreneurship has close ties with knowledge institutions.

A unique factor for the Netherlands is that it has a highly advanced national distribution network for natural gas. This **existing infrastructure** could eventually be converted and used as a connected network **to supply green H_2 throughout the country**.

Finally, the Netherlands is a **global leader in scientific research and technological innovation**, with a network of 13 (technical) universities, 36 universities of applied sciences, and applied research organisations (TO2s) like TNO. Particularly strong areas are process technology, heat and transport physics, catalysis, membrane technology and the physics and chemistry of materials. This is due to a very strong academic tradition and expertise in the field of materials, the presence of a good collaboration with industry on this topic and recently established field labs in the area of electrochemical conversion (e.g. EnTranCe in Groningen, Rotterdam Harbour field lab, etc.).

Challenges & Opportunities

The energy flows in the Netherlands are huge (in the order of thousands PJ/year): we currently import large amounts of fossil carbon (gas, oil, coal) and convert these to high-value products (chemicals, specialties, etc.) that are then sold worldwide. **Fig. 3** gives an overview of these energy flows in 2018. This picture must change quickly if we are to usher in a CO_2-neutral society: to reach the European and Dutch 2050 climate goals, we have to become CO_2-neutral as soon as possible. Big questions lie ahead: *How are we going to embrace the energy transition while keeping our role as an advanced economy, with a thriving industry that keeps adding value to its flows? What is needed to keep our knowledge basis and technological development up to standard under the changing landscape?*

Part of the answer lies precisely in our geographical location and infrastructure. While local H_2 production has the advantage of lowering international energy dependence and enhancing supply security, import of H_2 will still be needed in the long term in (Northern) Europe. For the Netherlands, this translates into the prospect of being both a major local producer of green hydrogen based on offshore wind energy as well an important import/export hub of hydrogen from other parts of Europa and other world regions. In other words, we are in an excellent position to become a hydrogen hub for Europe,[10] and the hydrogen hub for North-Western Europe, see also **Section 3.5 (Box 5)**.

However, this is not enough on its own. **To keep our advanced industry thriving, we will also need to provide economic added value in a CO_2-neutral landscape. This means, we must transform our current industry by developing new chemical conversion and processing technologies and by creating new opportunities for the manufacturing sector.**

Only if we succeed at this challenging task will we still be able to generate business worldwide in a renewable energy future, keeping exporting technology Made in NL. This is an incredible opportunity for the Netherlands, especially as in the coming years large-scale electrochemical activities will likely move to areas where renewable energy is cheaply available on a large scale (e.g. the Middle East). However, we can only succeed in this area if we invest in **building up knowledge and skills in electrochemistry and related areas** (i.e. chemical conversion and synthetic technology, which use renewable energy/electricity as the primary source of energy), thereby creating innovative key technologies and the related business activities that characterise the Dutch knowledge-based economy.

9 https://www.government.nl/documents/reports/2019/06/28/climate-agreement

10 See Outlines of a Hydrogen Roadmap by Top Sector Energy 2020.

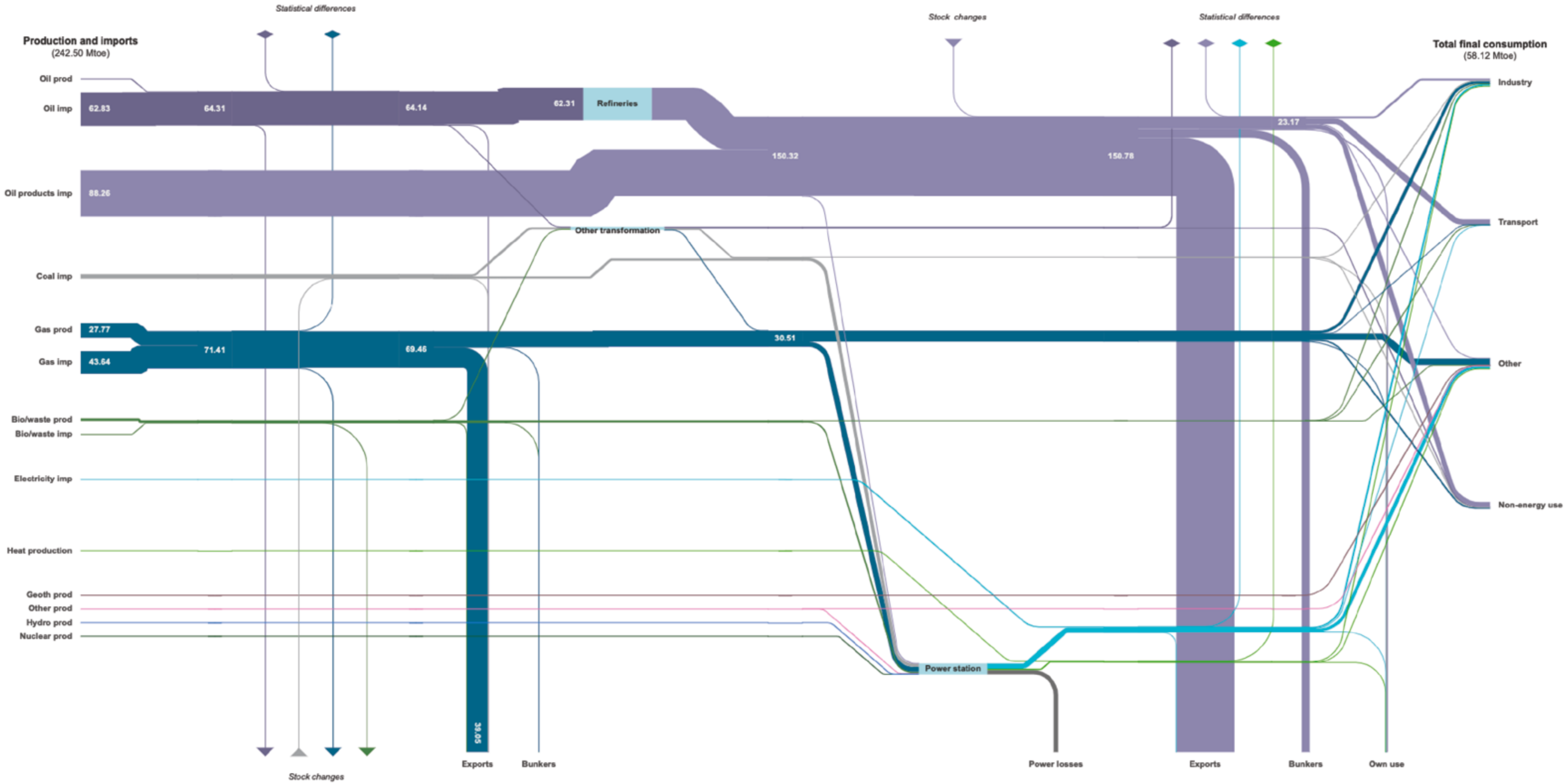


Figure 3. Energy flows in the Netherlands. Graph from IEA (data from 2018). This shows our vast current earnings from import & export: renewable alternatives are needed in the decarbonised industry of the future.

At the same time, *because* of the limited geographical area of the Netherlands, it will be probably challenging to produce enough sustainable energy to fulfil the internal demands and those of the countries we export to. Given the cost of long-distance electricity transport, energy will mostly be imported in the form of H_2, NH_3, methanol or synthetic hydrocarbons, albeit at substantial transportation fees. These imports will also cover the large-scale (TWh) storage needs and will be partially exported (with or without added value) to non-coastal European regions. This scenario implies that **the more complex industrial conversion processes** (based on both electro- and thermochemical conversion) **will likely be the basis for the local Dutch chemical industry**. Nevertheless, there is increasing evidence for optimistic upscaling settings: large-scale green hydrogen production in the Netherlands can be cost-competitive with alternatives from abroad (see also **Section 1.4** for Groenvermogen II).[11]

In any case, we will need to align our local electricity demands with the intermittent nature of the renewable electricity that we produce, which requires smart energy conversion and storage technologies and a robust energy infrastructure.[12] The chemical industry can play a key role in this. Therefore, **a national industry policy should aim to support the de-fossilisation of industrial processes and feedstock by fostering the development of both complex and simple electrochemical conversion technologies.** Exporting technology for the latter may generate enormous opportunities for the high-tech industry, such as manufacturing, system integration, balance of plant, etc. Looking at **Box 2** it is clear that becoming a world leader in (a part of) the manufacturing process can be quite profitable.

Box 2 – Chances for the manufacturing industry in NL

Companies like Philips and ASML have realised a completely new value chain, with huge impact for the Dutch economy, leading the development of high-volume, high-precision technologies. Integration of software-driven electronics allows products to be improved in short innovation cycles. Nowadays, this has become the key knowledge of the High Tech Technology cluster in the South of the Netherlands. This provides a fast track for technology scaling for high-power electro-conversion technologies like electrolysis: **creating such local value chains and businesses in the Netherlands really is an opportunity for the field of ECCM**. We already have promising companies like HyET, HyGear, Nedstack, Hydron Energy, Frames, Elestor, etc. that have expertise in building electrochemical equipment and parts of it. Keeping these business in the Netherlands (HyGear recently has been bought by the Canadian company Xebec) is important. Local innovation and demonstration projects where these companies can scale up their innovative technologies are important for keeping them in the Netherlands and increasing their export potential. The industrial systems targeted will need to be a factor of 100-1000 larger than the demonstration technologies available now.
In addition, integration with large power infrastructures as well as the need to integrate such technologies in large systems will drive the introduction of integrated systems. Likewise, companies like high-tech development and manufacturing system suppliers, such as VDL, Demcon, Prodrive, Bosch, NTS and Sioux, etc. are well positioned to move in this new domain and support scaling of the Dutch new technology companies as well build global markets on their own in this domain, based on their extensive experience in high-tech systems. For the ECCM domain, **the intrinsic business scaling potential of electro-conversion technologies including the mass production of membrane-based products and the production line technologies is considered a huge Dutch industrial growth opportunity**.

11 Klimaatneutrale energiescenario's 2050 (Kalavasta) and Design of a Dutch carbon-free energy system (KIVI)
12 See for instance the Report from the Taskforce Infrastructure Climate Agreement Industry (TIKI)

To this end, it is essential to establish a close collaboration between industry, organisations for applied research (TO2s) and academia; in other words, along the entire value chain. This needs to be a sustained effort (>10 years) from all stakeholders, where the government should be committed to creating the appropriate boundary conditions. In line with arguments as outlined by Mazzucato,[13] companies and governments need to share the risk and the rewards. This creates a strong ecosystem and economy, as we have seen in the past for other major societal challenges in the Netherlands, such as the Delta Plan to protect the country against the threats of the North Sea, or the reshaping activities in the South of the Netherlands that resulted in the establishment of the Royal Dutch State Mines (DSM) and the seed for the present-day Chemelot site.

To summarise, **we are about to experience a reboot of the three industrial sectors – the chemical, energy and high-tech manufacturing industrial sectors. Accordingly, the associated R&D, upscaling and cost reduction is multidisciplinary in nature and should have a long-term (> 30 years) perspective.** While in general, the Netherlands benefits from strong collaborations between industry and academia, the challenges at hand advocate for an even tighter and better-coordinated interaction of all stake-holders across sectors and across the TRL scale to unlock innovative technology, upscaling and cost reduction along the entire value chain.

13 See for instance Mariana Mazzucato's 2021 book "Mission Economy"

ECCM
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At present, the ECCM committee brings together 16 members: national experts from industry, government and academia. These committee members reflect on the national interests in the international context, not on the vested interest of their employers. It is therefore a way to strengthen the existing network of stakeholders, stimulate collaboration and prevent duplication. Furthermore, the committee serves as a platform to coordinate and facilitate national R&D activities on the theme of ECCM and to organise the requisite funding.

The ECCM committee works closely with the government (e.g. the Ministry of Economic Affairs and Climate Policy, EZK; the Ministry of Education, Culture and Science, OCW; the Top Sectors and Mission Teams) and the knowledge sector (NWO and TNO). The committee aims to bridge sectors, missions, disciplines and agendas to achieve the objectives for upscaling, cost reduction and innovation for green hydrogen and green chemistry, as stated in the National Climate Agreement of the Netherlands the knowledge and innovation agendas of the Mission-driven Top Sector and Innovation Policy, and the ECCM advisory report. For the past achievements of the ECCM committee, please see **Annex 1**.

1.3 Developments in the Energy Transition landscape - Higher urgency and higher ambitions for the ECCM National Agenda

The landscape has changed significantly in the past few years owing to: the European Green Deal and the National Climate Agreement of the Netherlands, together with the recent provisional agreement of the **European Climate Law, which makes the 2050 target of net-zero GHG emissions legally binding**;[14] a new mission-driven programming by the Top Sectors; the formulation of an ambitious proposal for the Dutch National Growth Fund for a complete ecosystem connecting green hydrogen and green molecules initiatives/investments in various ecosystems and proposing an accompanying research and development programme.

14 European Climate Law

These developments have led to the emergence of:

- A clearer agenda for H_2 as an energy vector, both nationally as well as internationally[15]
- The recognised role of H_2 as a feedstock for the chemical industry
- A clearer need for technology to make synthetic fuels and chemicals directly for storage purposes and as base chemicals[16]
- Increased urgency to couple shorter term hydrogen to longer term direct electrochemical solutions (a synergy recommended by PBL for the National Climate Agreement of the Netherlands)
- The need to couple the innovation agenda with the human capital agenda, to train and educate the workforce for the future green economy
- A refill of all parts of the innovation funnel is needed at all TRLs and implementation levels (technology, manufacturing, new business cases) and across the energy, chemistry and HTSM sectors
- An urgent need for coordination and collaboration at the regional and international levels.

Against this backdrop and to be able to realise the ambitions described in the next chapter, a number of **boundary conditions** need to be in place:

- A prerequisite is the influx of renewable electricity and the system ability to bridge intermittency. The ECCM industry is part of

15 See Outlines of a Hydrogen Roadmap by Top Sector Energy 2020.
16 Klimaatneutrale energiescenario's 2050 (Kalavasta) and Design of a Dutch carbon-free energy system (KIVI)

the solution for dealing with intermittency (**Box 3**). However, the vision set out in this Agenda no longer takes the availability of green electricity for granted. As the ECCM committee, we will therefore systematically emphasise the coupling of projects and programmes with the required supply of green electricity.

- Ensure the adequate influx of CO_2, biomass, and recycled resources, essential for direct conversion. This is a crucial step as it ties together two big transitions needed in our time: the transition to renewable energy and the transition to renewable materials and a circular economy.
- Realise a level playing field for fossil-based products/technologies, via regulatory measures such as a CO_2 tax. The industry needs clarity on how this will develop in the coming decennia.
- Have the Dutch government act as the key mitigator of risks for the large investments needed to bring ECCM technologies to an industrial scale. For example, by realising the necessary electrical infrastructure for the electrochemical conversion plants. This has previously been a key success factor in offshore wind.
- Examine the geographical location of the various industrial clusters in the Netherlands: the chemical industry in Rotterdam, Geleen, Zeeland, Moerdijk and Delfzijl have different access to renewable energy and renewable feedstock. This has implications for (short-term) technology development and demonstration and for the realisation of the necessary infrastructure (e.g. the Hydrogen backbone infrastructure). Each region could have its own niche and focus – connections and collaborations between the regions can result in a true national ecosystem with intensified international collaborations.

1.4 ECCM National Agenda and GroenvermogenNL

In 2020, the ECCM committee initiated and helped coordinate the development of a large research and innovation proposal for the National Growth Fund based on green hydrogen and green chemistry, entitled 'Groenvermogen van de Nederlandse Economie', or GroenvermogenNL. This proposal received a conditional funding of M€ 338 in April 2021: the ECCM committee is currently involved in the ongoing preparations to start up the programme and its coordination. The overlap of GroenvermogenNL with the present ECCM Agenda is considerable. The conditional funding is focused on low TRL research, small H_2 pilots (up to 50 MW), Human Capital and national coordination (see **Section 2.2 Focus areas - recommendations**).

At the same time, the ECCM committee has invested in pushing forward other focus areas described in the ECCM Agenda and is involved in the development of other proposals for the National Growth Fund. Two proposals were submitted in autumn 2021, carrying contributions from the ECCM committee and covering crucial topics of this Agenda: Groenvermogen II,[18] focused on scale-up (100 MW plants) and system integration; and NXTGEN HIGHTECH,[19] in which an energy chapter is devoted to the manufacturing industry for electrolysers and electrochemical conversion and system integration.

It should be noted that while these research and innovation proposals are organised around 5- to 8-year-long programmes, **the recommendations set out in this Agenda are based on a vision of social, economic and technological developments towards 2030 and 2050**.

18 Groeiplan GroenvermogenNL 2
19 Groeiplan NXTGen high-tech

Box 3 – How much renewable energy does NL need to be CO_2-neutral by 2050?

In the ECCM Agenda, we present our strategy for a successful energy transition in the NL. There is one big BUT, though: availability of the right amount of renewable energy is essential to power the transition.

The Climate Agreement[17] indicated the required availability of renewables:

- 84-120 TWh by 2030 - of which 49-80 TWh offshore wind energy and 35-45 TWh renewable on land (large scale);
- 205-550 TWh by 2050 - 50-320 TWh offshore and 155-230 TWh onshore.

Production costs are pivotal in this regard. They will be monitored and are projected to reach 30-40 €/MWh by 2030 and significantly lower in 2050. (Source: Klimaatakkoord, Noordzee Energy Outlook 4 December 2020).

Finally, market price is more than just production costs. Storage and transport of large amounts of (electrochemically stored) renewables ultimately adds to the final market price, so this impact also needs to be monitored.

17 https://www.government.nl/documents/reports/2019/06/28/climate-agreement

2

Future Agenda

2.1 ECCM National Agenda

The Netherlands aims to be CO_2-neutral by 2050. To achieve this, we have to move away from fossil fuels as an energy and feedstock source. This requires large-scale electrification, using renewable electricity to make fuels, fertilizers, materials and other products from renewable feedstock such as water, biomass, waste and CO_2.
This demanding target requires the concerted development, demonstration and implementation of new technologies, new regulatory measures and social innovations: with the present Agenda, the committee for ElectroChemical Conversion & Materials (ECCM) strives to provide a path towards these ambitions. This Agenda addresses the actions to be taken and developments needed in the disciplines and sectors relevant to ECCM.

In this chapter, **we outline the underlying route towards achieving the 2030 and 2050 climate targets, the technological developments needed, and in parallel the socioeconomic developments required** as described in Chapter 3, **to strengthen the Dutch economy.**

National Agenda - framework along 4 action lines

The ECCM committee advises the Dutch government to consolidate and strengthen the themes within ECCM by following the framework presented here, along 4 action lines. In this way, the Netherlands can work towards achieving CO_2 neutrality by 2050 while simultaneously building a leading position in sustainable technology that will strengthen its green economy.

While 2050 might seem a target far in the future, the ECCM committee underlines that all four action lines need to be undertaken *now*. We also expect that given the rapid developments in technology, policy and legislation around the energy transition, an update of this National Agenda might be due in the next 5 years.

Finally, the Netherlands is not operating in isolation: our neighbours and trade partners face similar challenges and undertake similar efforts. For this, optimal coordination and collaboration at an international level will be crucial for the success of this National Agenda.

The ECCM committee recommends two technology-driven action lines to work towards the climate goals using ECCM technologies:

- **Line 1**. To work **towards the 2030 goals**, the ECCM committee advises **pilot and demonstration projects for green hydrogen (scale 1-100 MW) and its applications for green chemistry**, to learn what is needed to bring **green hydrogen to large-scale deployment**.

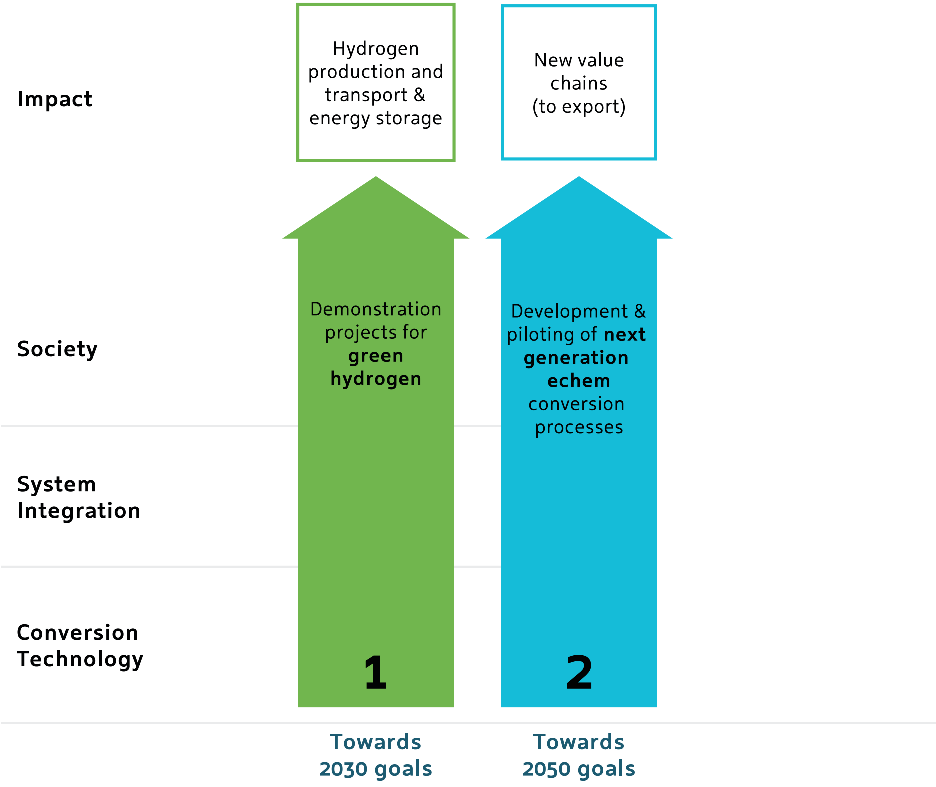

Figure 4. Primary action lines as advised by the ECCM committee to reach the climate goals.

- **Line 2**. To work **towards the 2050 goals**, the ECCM committee advises **research, development, innovation and piloting of the next generation of green electrochemical conversion processes**, using renewable energy/electricity, to achieve the deep decarbonisation of the (chemical) industry. This includes **novel technologies for green hydrogen** as well as **new electrochemical conversion processes**.

These two lines should cover the entire innovation chain from R&D to implementation and governance (**Fig. 4**), as explained in detail in Chapter 3. **Line 1** will enable large-scale hydrogen production and storage, and applications in the energy-intensive industry, facilitating storage of renewable energy and thus contributing to the solution of congestion and intermittency of renewable electricity. Crucially, **Line 1** leads to large-scale availability of green hydrogen for a wide range of applications and technologies that utilise H_2 for conversion and buffering purposes or as a feedstock for the industry to produce (high-value) chemicals with a significantly lower CO_2 footprint. In addition, green H_2 might be utilised to produce synthetic fuels for difficult to defossilise mobility by combining it with CO_2 (e.g. synthetic kerosene) or nitrogen (NH_3).

Line 2 will unlock radically new, disruptive electrochemical conversion technologies and favour their implementation in the Netherlands and abroad, effectively establishing our country as a leader in the export and valorisation of chemical conversion technologies for the future green industry. The expected impacts include novel conversion processes with increased energy efficiency and reduced waste, effectively lightening the burden of the currently energy-intensive (chemical) industry on the demand for green electricity.

Line 1 focuses especially on R&D at the materials, component and system level (needs for industrialisation and high-volume scaling, such as precision, reliability, safety, etc.).

On the other hand, **Line 2** promotes explorative R&D and focuses on lower TRLs.

Nevertheless, there are strong synergies between **Line 1** and **Line 2**. Some of the demonstration projects described under **Line 1** will also create spillovers for the technology development of **Line 2**, while radically new concepts and technologies on green hydrogen arising from **Line 2** will need to be tested in **Line 1**. In addition, the innovation on the system engineering and integration in **Line 1** needed for green hydrogen deployment will most probably be of use in the development of **Line 2**.

The rationale upon which **Line 1** and **Line 2** are built is based on the representation of the entire **conversion and integration chain** for the new energy landscape given in **Fig. 5** (for a more elaborated version of this scheme, see **Fig. 8** in **Chapter 3** and **Annex 2**). This gives an idea of the different technological layers involved in converting sustainable energy/electricity into either hydrogen or other chemicals.

The entire production chain spans different technological hierarchies, i.e. conversion and integration:

- Starting from the **conversion devices** (these are all the materials and components involved in the conversion reaction);
- moving onto functional modules for conversion (these result from the assembly of the various basic units), such as **stacks** for electrolysis or fuel cells;
- and to all the technology needed for **power and control** of these stacks.
- The next layer covers the fully-integrated operational plants, i.e. the **conversion systems** (these result from the assembly of stacks and the power & control architecture).
- Finally, the top layer represents the technology needed to enable users applications, i.e. **transport, storage, distribution** of the product.

Let us zoom in on the example of green hydrogen, in **Line 1**, whereby renewable electricity is used for water electrolysis into H_2 and for which the Netherlands is considering deploying large-scale demonstration projects (100-200 MW). It needs to be realised that for such projects, *at the moment*, we need to import the required high TRL technology (electrolysers) from the few leading, foreign OEMs, as these businesses are currently not present in the Netherlands. While in the short term, this is not a big problem, in the long term, this represents a real risk: without swift action, Dutch companies might not be in the position to further develop and improve the innovative materials and technology needed for water electrolysis. This can create a gap in the value chain, i.e. we would be doing research at our universities in the area of water electrolysis and be leading in demonstration projects for green H_2 production and H_2 transport, but we would lack the national high-tech manufacturing industry to develop, build and export the electrochemical conversion systems, materials and technology needed. This is at odds with the current situation, where Dutch companies are leading in the international market as suppliers of innovative technology, especially at the integration level (e.g. ASML, VDL, Prodrive), but not yet in the industry of energy-related

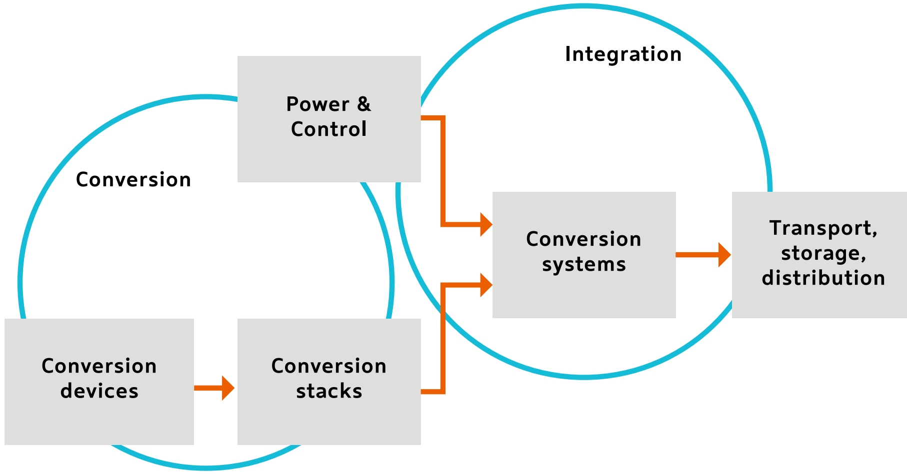

Figure 5. The entire production chain for the conversion of sustainable energy/electricity.

technology. A similar risk holds for **Line 2**. Two socioeconomic action lines are needed **to ensure that the Dutch economy reaps the benefits** from **Line 1** and **Line 2**, completing the Agenda's framework, as shown in **Fig. 6**.

Line 3. Strengthen and develop the high-tech manufacturing industry to produce and export systems and materials, building a green economy Made in NL. **Line 3** is essential to ensure that the knowledge generated in the Netherlands from **Line 1** and especially **Line 2** will also be valorised in the Netherlands to its full extent.

Last but not least: human capital is a critical success factor for achieving the ECCM Agenda's innovation goals. New technological processes can only be developed, implemented and deployed on scale if there are enough well-trained professionals over the full technology chain, from low to high TRLs. We therefore need a fresh workforce that can deal with the new challenges presented by **Line 1**, **Line 2** and **Line 3**. These challenges include H_2 deployment, new chemical conversion technologies, innovative high-tech manufacturing, and the development of a 'common language' to translate chemical requirements into successful devices & systems. Also, at the same time, some of the existing workforce will need to be retrained/upskilled to handle the changes posed by the transition. An example is the professionals in the big petrochemical industry or working in our ports, where LNG will soon be replaced by (or traded alongside) H_2. This is a crucial aspect to preserve these jobs, also in light of our export role. This last line completes the framework (**Fig. 6**):

Line 4. **Develop and implement a Human Capital agenda** by training and educating students and retraining/upskilling the existing workforce in the area of ECCM, building a solid knowledge and skill base for companies to innovate, grow and strengthen themselves.

The framework described above is composed of four fully intertwined lines; strategic investments in all lines are needed for the Netherlands to be successful in the ECCM field. **Line 1 and Line 2 are crucial to reach the energy and climate targets:** without innovations, without piloting those innovations, and without bringing these technologies to implementation and large-scale deployment, we will not be able to make the transition to a sustainable (chemical) industry and ensure the earning capacity and a leading role in the new green economy. **Line 3 is crucial to build a competitive Dutch green economy:** currently, we are using/transporting much more (fossil) energy and feedstock than we produce in the Netherlands; i.e. we are a net importer of energy and resources. Most likely, this will remain so when shifting towards a society/economy fully based on renewable energy. This means that we will need to also partly import green hydrogen and other intermediate products created abroad using ECCM technology. Note that the Netherlands will, in this sense, remain a country with an important hub role in the import of green chemicals for our European neighbours, such as Germany. It also means that we have the opportunity to globally export our innovative technology, systems and materials developed by our high-tech manufacturing industry. **Line 3** will connect research at our knowledge institutes in the area of electrochemical conversion to a high-tech manufacturing industry to develop, build and export the systems, materials and technology. Without this line, we could only briefly be a leading country in demonstration projects for green hydrogen production and application, but not structurally integrate this know-how and expertise in our economy. Finally, with the **Human Capital development in Line 4**, we ensure the connection of education, research and business, as only then can we fill the new jobs that will be created and preserve those jobs that will inevitably change, with people who have the right skillset.

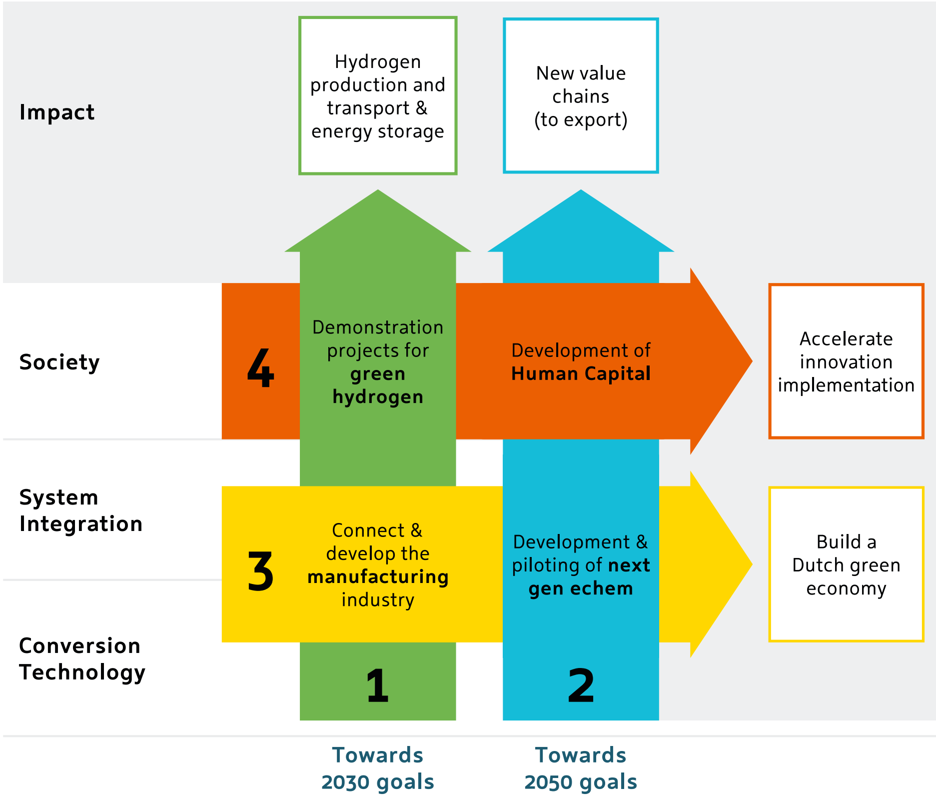

Figure 6. The development of a manufacturing industry in the ECCM field as well as the development of human capital, are crucial for a sound deployment of Lines 1 and 2 in the Netherlands.

Cover the entire value chain

The framework recommended above should cover the entire value chain from electricity generation; electricity and hydrogen infrastructure, large-scale energy storage; electrochemical conversion technologies through to full chemical plants. Fostering the creation of such a new business requires research, development and scale-up along this entire value chain and with the network of knowledge institutes and companies: the system for electricity-driven conversion, the required supplies, peripherals and components.

We distinguish three levels of implementation of ECCM technology.

1. **New concepts (TRL 1–4):** New electrochemical conversion technologies are being developed in labs worldwide. Examples are water electrolysis, nitrogen reduction and CO_2 conversion.
   - When assessing the potential of new concepts (based on new materials or new system geometries), scalability to MW-GW systems in terms of cost, materials availability and design is key.
   - It needs to be appreciated that this early-stage research has a distant application horizon.
   - The development of new concepts from TRL 1 to 4 is a long-term effort and therefore requires persistent (mostly public) funding before it can be taken up by industry and lead to new business.
2. **Pilot projects (TRL 5-6):** Any new electrochemical conversion technology will need to be tested under industrially relevant conditions to demonstrate its feasibility. For CO_2 electrolysers, for instance, this includes integration with the purification of the feed and separation of the products. For water electrolysis, integration with, for example, a subsequent chemical process needs to be tested under intermittent conditions.
   - These facilities will be crucial to prevent the insidious innovation gap between research and industry. Such facilities will present the academic world with new research challenges while providing industry with insights about the feasibility of a particular technology for their process. In addition, these facilities can be used in the context of the Human Capital Agenda.
   - Until recently, significant funding for demonstrating and testing of newly designed systems at the TRL 5-6 scale was severely lacking; **GroenvermogenNL (Section 1.4)** will give an important one-time boost to piloting; however, structural funding in the coming years is essential.
   - Pilot systems will create new business over the entire value chain and foster the emergence of start-up companies.
3. **Demonstration projects at industrial sites (TRL 7–8):**
   - These will help the commercialisation of new electrochemical conversion technologies and their scale-up: this brings new technology to a higher level.
   - These will provide insight into the challenges involved in integrating these systems in a large-scale industrial environment, taking into account the intermittent nature of sustainable electricity sources. These projects will therefore lead to new challenges on process systems and control, the development of new peripherals and components and will stimulate new local business in these areas.
   - These may lead to the development of new industrial processes for which a green hydrogen feed can be used and may therefore help a certain industrial sector to survive.
   - At these scales, the availability of renewable energy is increasingly important, both from a production capacity as well as an intermittency perspective.
   - These will also be needed to investigate the economic and related regulatory boundary conditions that are required to make such projects viable for industry. For example, green NH_3 will probably be more expensive compared to grey NH_3 from outside the EU. If no equal level playing field is created, the green option will not take off.

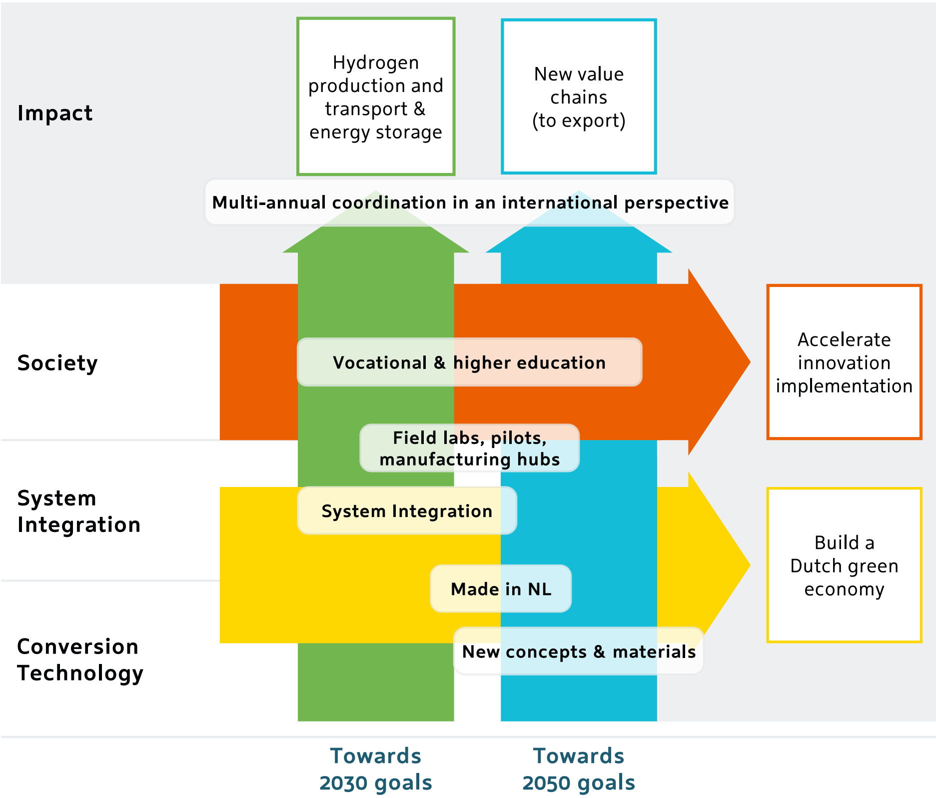

Figure 7. Focus areas (white ellipses) recommended by the ECCM committee that require sustained efforts.

Financing this ECCM cluster of technologies is a complex matter. It should be realised that innovation is a continuous process with many feedback loops, which does not stop with the industrial implementation of a certain technology.
The scale-up, steady improvement in efficiency as well the required cost reduction, require research on all three aforementioned levels (TRL 1–8) and that will continuously allow for the creation of new businesses.
In other words, the framework described needs to be fully interconnected.

2.2 Focus areas – recommendations

Along the framework, and especially where the lines connect, the ECCM committee has identified six key focus areas that require a sustained effort. These are shown in **Fig. 7** and described in the tables below. The specific needs and challenges for each line are further described in **Chapter 3**.

New electrochemical conversion concepts and materials

Focus area & potential	Challenges & needs	ECCM Advice
By improving green hydrogen technology and by developing electrosynthetic processes to convert, for instance, CO_2 and N_2 –to reduce the number of process steps– we can develop a unique knowledge base in the Netherlands.	A lot of materials development is ongoing, but more focus is needed on the application of these materials under industrial conditions, e.g. high current densities, long lifetime, higher efficiencies and lower costs. Moreover, long-term industrial needs such as process integration, product diversification and system integration still need to be designed.	• A **strong research programme** connecting Dutch knowledge institutes that should lead to **breakthrough inventions in the field of electrochemical production of hydrogen**. Not only electrochemistry, but also polymer science, gas-fluid dynamics, materials science, corrosion science, power electronics, safety sensors and electrical engineering should be studied. Implementing green hydrogen feedstock with, for example, CO_2 or N_2 conversion, requires the integration of intermittent electrolysis with thermochemical conversion. Connection with societally-related research should be sought (e.g. ethical questions, fair governance, technology adaptation). • The development of **disruptive electrochemical conversions** (e.g. of N_2 and C-feedstock): it is a **long-term effort** and therefore requires persistent, mostly public financial support. The research needed to study these conversion processes ranges from electrocatalytic studies, materials development and reactor engineering to system integration & control and should cover the entire range of process steps from feedstock purification to product separation. Additionally, these fundamental studies should always keep in mind the aim of a large-scale integrated system. Research consortia should involve partners from the entire knowledge chain (universities, universities of applied sciences, applied research organisations and companies).

Field labs, co-creation, pilots

Focus area & potential	Challenges & needs	ECCM Advice
Field labs and co-creation: this is where innovation happens, where fresh and experienced human talent gets the chance to work with new technologies, where companies co-develop innovation. Pilots are needed to bring new technologies to scale-up and commercialisation and to test the feasibility of new technologies under industrially relevant conditions (process integration, intrinsically safe processes, etc.).	Proving new technologies and creating supply chain increase.	**Piloting: Pilot activities at around 10-100 kW scale** are needed to test, integrate and demonstrate the new conversion technology at a scale at which further upscaling potential can be assessed.Substantial investments in lab space, equipment and support staff are required. These piloting activities are often (too) expensive for the start-ups developing the innovations and therefore proper support is needed to overcome this "valley of death". Close collaboration with HTSM companies is essential to develop key manufacturing competences in NL. **Co-creation:** The development of new technologies requires a multidisciplinary approach and consortia where the end users are directly involved. Co-creation should go beyond the obvious sectors (energy, chemistry) and include Dutch companies with, for example, expertise in power conversion, electronics and corrosion. **Field labs, testbeds, manufacturing hubs:** Regional field labs and testbeds are needed for experimental development in real industrial settings (>TRL5). At these locations, companies and research institutes can jointly develop, test and demonstrate new technologies and systems. Also, in these field labs and testbeds, demonstrations can be done at a small scale (up to 25 kW), allowing fast innovation cycles at lower costs/risks. A direct link with MBO, HBO, and WO should be made to directly train students on relevant topics. Besides these field labs and testbeds, a dedicated Dutch innovation & production hub for manufacturing companies is needed where companies and research institutes can build competencies together and test new technologies for membrane-electrode assemblies (MEAs). It is important to have a diffuse, decentralised system in place: but also an overarching national coordination of these activities will be needed to guarantee synergy and knowledge transfer while avoiding unnecessary duplication.

Made in NL

Focus area & potential	Challenges & needs	ECCM Advice
Development of a strong Dutch supply chain for electrolysers and electrolyser-related systems (e.g. electrochemical reactors and GWh flow batteries). This innovation is essential to accelerate technology scale to GW levels. This requires risk-controlled upscaling of the technology and development and testing new materials, stack and system designs.	Currently, there are only a few companies in the world that can build electrolysers at large scale, mostly based on conventional technologies. The Netherlands can, in principle, develop its own electrolyser, but to be competitive –i.e., to offer a strong export product that can be protected and can serve a large market– this only makes sense if such a development is based on a fundamentally different technology made in the Netherlands. In addition, the system integration competences present in the Netherlands will allow the development and manufacturing of a product with a high degree of functional integration, supporting performance, scalability and efficiency comparable to what has been achieved in semiconductor technology. Equally compelling, **the Netherlands is in a unique position to develop the novel technology required for the entire supply chain of electrolysers and electrolyser-related systems** (see e.g. **Fig. 5**), covering all critical competencies, and improve efficiency of existing electrolysers systems and components. We can achieve this by drawing on our rich manufacturing industry and especially on our leading role in system integration.	**Innovation & piloting:** To develop a Made in NL supply chain for green hydrogen and electro-conversion, strong collaboration within innovation lines is needed: these new systems need to be developed, tested and scaled up. For electrolysers this requires that we **bring industry, technology developers, equipment engineers and manufacturing industry together**, via 1) field labs, 2) Electrolyser Manufacturing Platform 3) innovating and standardising together and in parallel, 4) governance and 5) investing in an international proposition of the Netherlands.[20] We should reduce the risk of developing and scaling up the supply chain Made in NL by setting up multiple projects over time and at different size ranges according to their TRLs. This approach will avoid the situation where risk-averse investors only invest in proven technology (from abroad). To realise this we should **incentivise the adaptation of national innovations in projects that receive public support**. **Demonstration:** Parallel to innovation, there is a need for demonstration projects, both with large-scale centralised systems and smaller scale decentralised systems. These projects are needed to study the behaviour of these systems under intermittent operation, improve their reliability and learn lessons on smart scaling or numbering up. **We should not directly build a GW factory, but gradually increase scale, for instance in the order 20, 100, 200, 500 and 1000 MW**. For the smaller decentralised systems, it is important that there are many (parallel) projects to enable the manufacturing industry to move from custom-made systems to mass-manufactured systems. Proper scaling choices should be based on integral system modelling and simulation, whereby modelling can draw from the rich expertise available in the Netherlands in multidisciplinary model-based development and engineering. Given the power levels, transport and storage required, the involvement of key players such as electricity transmission system operators and energy network operators (TenneT and Gasunie) is essential and requires central coordination from the government. Such investments require a strong collaboration between the public and the private sectors, in which both share risks and rewards. **The government should be a key mitigator of risks and a facilitator**, for example by realising the necessary electrical infrastructure for the electrochemical conversion plants. This has also been a key success factor in offshore wind. **Scaling up:** the scaling up of the manufacturing of electrochemical systems is a combination of "numbering up" and "sizing up", so the size of the demonstrators should be diversified.

20 See for instance 'Electrolysers: opportunities for the Dutch manufacturing industry', FME-TNO, 2020

System integration

Focus area & potential	Challenges & needs	ECCM Advice
Redesign chemical plants and chemical clusters using renewable energy and renewable feedstock. Model-based design and optimisation of interfaces, modules, module sizing, etc.	There is a significant challenge to integrate the very high energy and power needs of the process industry to align with the energy delivery and transport via the public grid infrastructure. An optimal solution requires close collaboration between technology manufacturers, system integrators, system operators, and power companies, which is enabled by multidisciplinary system-based design, engineering and manufacturing workflows. Also, an integrated grid infrastructure is essential, with a full power, data and product coupling between users in the grid, which needs to operate under variable energy supply. For real system integration, upscaling of ECCM technology needs to go hand in hand with sustainable energy production.	**Innovation:** Develop dedicated technology solutions for the transition (e.g. combination with battery systems and infrastructure with hydrogen storage). **Demonstration of:** • H_2 storage and buffering • flexibility and heat coupling in the chemical industry Several demonstration projects at different scales can support the development of different solutions and bring new technology demands to the electrolyser companies and research community. We have to examine the geographical location of the various industrial clusters in the Netherlands: the chemical industry in Rotterdam, Geleen, Zeeland, Moerdijk and Delfzijl have different access to renewable energy and renewable feedstocks. This has implications for (short-term) technology development and demonstration.

Vocational and higher education

Focus area & potential	Challenges & needs	ECCM Advice
Human capital is a critical success factor to acquire a leading knowledge position in ECCM technology.	We currently have insufficient trained human capital to build and operate demonstration plants for electrochemical conversion. Without enough well-trained professionals, new technological processes cannot be implemented at a large scale. There is a need for both training schemes directed at a fresh workforce to deal with the challenges presented by the new jobs that will be created, and for retraining and upskilling of the existing workforce, to preserve current jobs in the (chemical) industry under the inevitable changes these will undergo.	Develop a Human Capital Action Agenda, aligned with the Human Capital initiative described in GroenvermogenNL (see **Section 1.4**) and the national Human Capital Strategy of the Top Sectors. The ECCM Human Capital Action Agenda should contain the following HC lines: • **HC Line 1: Labour Market for ECCM.** E.g. Map jobs and (future) skills, and analyse shortages and possibilities relevant for the energy transition, together with industry; Quantify HC needs between now and 2030; Promote ECCM and related topics among students. • **HC Line 2: Education and Training.** E.g. Analyse ECCM knowledge in education and training; Develop ECCM curriculum elements for all three education levels in the Netherlands (universities, HBO and MBO); Evaluate graduate schools/advanced courses in the ECCM field, establish needs of companies and develop required programmes; Integrate ECCM in talent programmes of Top Sectors Chemistry, Energy and HTSM; Perform international benchmark and inventory of international courses (MOOCs). • **HC Line 3: Knowledge Dissemination between Companies and Education Institutes.** E.g. Map and develop ECCM-related public-private partnerships for all three educational levels; Implement ECCM Learning communities for MBO and HBO (in regions).

Multi-annual coordination in an international perspective

Focus area & potential	Challenges & needs	ECCM Advice
The framework presented needs coordination to align activities, promote synergy, identify weaknesses and potential, and avoid unnecessary replication.	The nature of this global problem and the chances for the Netherlands to assess itself as a market leader in innovation means that international collaboration is paramount for the success of the Agenda. The governance therefore needs to take place in an international perspective. Finally, while the single projects and programmes will be limited in time (3 to 5 or 8 years), the whole coordination of the Agenda will have a long-term vision to realise of the goals for 2030 and 2050.	A strong **overarching coordination** of all related activities is needed to guarantee synergy, knowledge transfer, national and international alignment. The goal of this overarching coordination is to: • Connect and harmonise all national research and innovation efforts around ECCM, with an outlook to international developments • Develop an adaptive system model with economic, behavioural and technical knowledge • Coordinate a national HCA approach to educate and retrain staff • Increase public acceptance of the new technologies • Be a clear contact point from an international point of view. **Actors and roles:** The actors of this overarching coordination are (see also **Fig. 9, Annex 1**): • **National Hydrogen Programme, NWP** – develops/makes available green hydrogen offer, develops the required infrastructure, promotes the use of hydrogen via intersectoral collaboration, and facilitates existing initiatives and projects; • The **thematic team Energy and Sustainability** as the 'meeting of shareholders' for the integration of the recommendations into the broader mission-driven innovation policy; • The cross-sectoral, high-level **Round Table on 'Hydrogen and Green Chemistry'** has an advisory role towards GroenvermogenNL and a supporting function for NWP, by jointly defining development directions and by translating sector ambitions into commitments; • **GroenvermogenNL**, an imposing M€ 300+ RDI national programme set to be running in the next 8 years (see **Section 1.4**); • **RVO** and **NWO**: funding and implementing institutions for RDI programmes, also evaluating the implementation. For this, RVO focuses on the investment programmes and NWO on the research and development programmes; • The **ECCM committee** is the 'innovation leg' of the national green hydrogen and green chemistry strategy in the long term. The ECCM committee connects existing RDI initiatives, identifies innovation hiatuses, develops new activities and strengthens the (inter)national community.

2.3 Take action

Below we indicate for each recommendation the actors involved from the triple helix and how they can take action.

Recommendations	Government & Policy	Industry	Knowledge Institutes
Multi-annual low TRL programmes for green H_2. Technical/Fundamental science, system integration & socioeconomic research	Develop, Fund	Develop, Co-fund, Research partner	Develop, Research partner
Multi-annual low TRL programmes for explorative research and disruptive electrochemical conversion. Fundamental technical science & socioeconomic research	Develop, Fund	Develop, Co-fund, Research partner	Develop, Research partner
Cross-sectoral (energy, chemistry, HTSM) field labs, testbeds and pilots in the 10-100 kW scale, also to be used for HCA activities	Subsidise, Co-create	Subsidise, Co-create, Research partner	Co-create, Research partner
High TRL programmes for innovation in the supply chain for electrolysers and electro-conversion processes	Develop, Fund	Develop, Co-fund	Research partner
High TRL programmes for demonstration in the supply chain for electrolysers, allowing for size diversifications (scale-up and number-up)	Develop, Fund, Coordinate	Develop, CO-fund	Research partner
Innovation at the system integration level	Invest	Invest, Develop	
Demonstration of H_2 storage and buffering, and of flexibility and heat coupling in the chemical industry	Invest	Invest, Develop	
Intensify cooperation between companies and education institutes and develop required programmes	Facilitate	Develop	Develop
Implement ECCM learning communities for MBO and HBO (in regions) and develop a national programme for knowledge sharing	Facilitate, Fund	Develop, Implement	Develop, Implement
Establish an overarching governance and management structure for all related activities to guarantee synergy, knowledge transfer, national and international alignment	Facilitate	Participate	Participate


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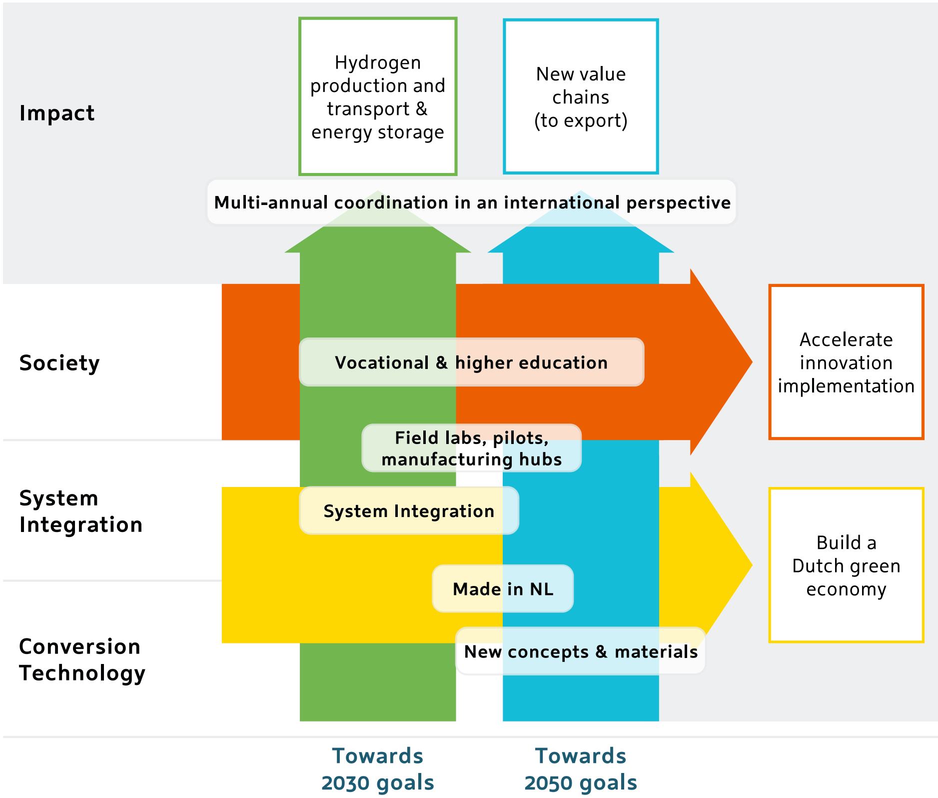
3

Dutch ECCM landscape: what is needed, what are the challenges

In this chapter, we consider in greater depth the needs and challenges of research, development and innovation for each of the four action lines as advised in Chapter 2, at the different levels (conversion technology, system integration, society) and including the challenges for the multi-annual coordination of the ECCM landscape.



3.1 Needs and Challenges for the production of green hydrogen - Line 1

Introduction

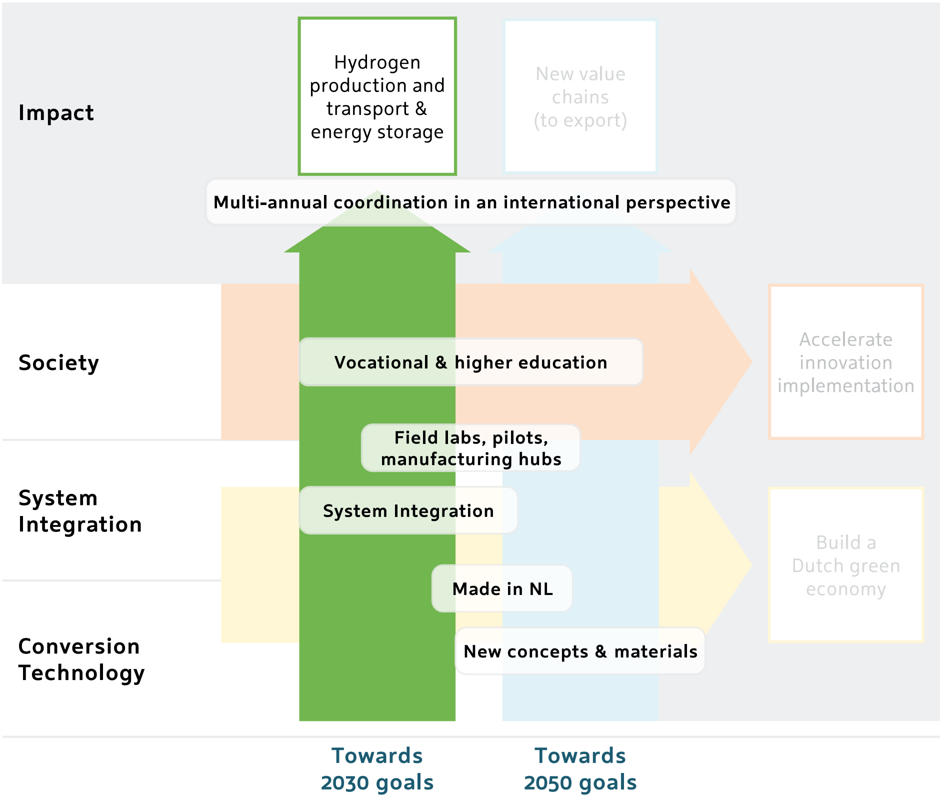
Electrolysis of water into hydrogen and oxygen, H_2 and O_2, is the easiest way to convert and store electricity in the form of a chemical bond. Water electrolysis is a well-known technology with a century-old history, but it is yet to be developed at large scale and at an affordable price, as both design and materials issues still need to be solved. Simple but essential building-block molecules such as CH_4, C_2H_4, NH_3, etc. can be produced by reacting electrochemically produced H_2 with N_2 or CO_2 from air or green sources using classical thermochemical methods. This route is often called the indirect route because hydrogen is produced as an energy carrier and feedstock for the chemical industry.

The challenge again is the upscaling, especially in conjunction with an intermittent source of hydrogen since the latter is produced from intermittent sustainable resources. The optimisation of such a combined electrochemical/thermochemical process poses interesting challenges in terms of process control and system integration: Can we design thermochemical processes which operate under fluctuating process conditions? How much storage of an intermediate is possible? How can we make use of the process heat? In addition, in the thermochemical processes the heat source needs to be electrified. Clearly, this involves a substantial redesign of an intensified and efficient (chemical) industry, in which current waste heat from traditional industrial processes is re-used on a large scale.

Several national and international studies have recently appeared on green hydrogen, which is hydrogen produced by water electrolysis powered by renewable electricity sources.[21, 22, 23,24] These studies show that green hydrogen can play a vital role in the energy transition. This agenda focuses on the different water electrolysis technologies and the specific role the Netherlands should play in the research, development and demonstration of these technologies.

Hydrogen production by water electrolysis has been around for over a century. In the twentieth century, 100 MW+ size plants were operational in, for example, Norway, Egypt and Zimbabwe, where cheap hydropower was used to produce renewable hydrogen for fertilizer production. With the advent of cheap natural gas, these plants were no longer economically viable and closed in favour of fossil-based alternatives such as steam methane reforming (SMR) and autothermal reforming (ATR). Hydrogen production through water electrolysis is currently only used for small-scale applications (up to a couple of MW) where high purity hydrogen is needed and accounts for less than 0.7% of global hydrogen production. Most electrolysers are being manufactured and sold in China.

21 Waterstof voor de energietransitie, TKI Nieuw Gas, 2019
22 The Future of Hydrogen, IEA, 2019
23 IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition
24 Green Hydrogen for a European Green Deal, a 2x40 GW initiative, 2020



A key difference between the large-scale plants that were built in the past and the planned new-generation water electrolysis facilities is that the new plants will be operated using wind- and solar-based renewable electricity, which means that the water electrolysis technology needs to be flexible to account for the intermittent availability.

In the following sections, we summarise what is needed to bring green hydrogen to large scale deployment from the perspectives of technology, system integration and societal implementation.

Conversion Technology - Overview of water electrolysis technologies and their development potential

Several water electrolysis technologies exist, the most developed ones being alkaline technology, polymer electrolyte membrane (PEM) technology and solid oxide technology. Other technologies such as anion-exchange membrane electrolysis (AEM) and proton-conducting ceramic electrolysis (PCC) still require more development. In addition, new systems are being developed such as the Battolyser, (combining battery storage with electrolysis) and alternative electrochemical routes to produce hydrogen. Here, we only briefly describe the main proven technologies and indicate their development potential. For detailed KPIs regarding the costs and performance of these technologies towards 2030, we refer to a roadmap developed by Hydrogen Europe.[25]

- **Alkaline electrolysis:** this technology makes use of a porous diaphragm membrane and nickel-based electrodes in combination with a strong alkaline electrolyte. The operating temperature is 70-90 °C. This is the technology that was used for the large water electrolysis plants of the 20th century.
  - Advantages: low capital costs due to low-cost materials
  - Disadvantages: low current density resulting in bulky electrolysers, not designed for flexibility
  - Development potential: increased current density through improved electrodes and diaphragms, more flexible operation (higher ramp rates), increased operating temperature to valorise heat
- **PEM electrolysis:** this technology makes use of a proton-exchange membrane with noble metal electrodes and pure water. The operating temperature is 50-70 °C. The technology has been piloted at the MW scale in the last decade.
  - Advantages: compact design due to high current density, flexible
  - Disadvantages: high capital costs due to noble metal use (iridium, platinum) and expensive polymer membrane
  - Development potential: reduced noble metal loadings, reduced cost of membrane, increased cell area, increased lifetime, increased operating temperature to valorise heat
- **Solid Oxide electrolysis:** this high-temperature technology operates at 500-850 °C and makes use of a ceramic membrane. Electrode materials typically consist of nickel combined with oxides based on rare earth metals such as yttrium and lanthanum. Piloting is currently being carried out up to 100 kW scale with first examples in the MW range.[26]
  - Advantages: very high efficiency, potential to operate reversibly (in fuel cell mode)
  - Disadvantages: high capital costs, high degradation rate, complex heat management, less flexible
  - Development potential: improved stability, pressurised operation, increased cell area, selectivity, throughput, lower costs

There is a clear need to reduce the costs of hydrogen produced by water electrolysis, since it is still significantly more expensive than fossil-based production methods such as SMR and ATR. Commonly expressed targets for 2030 and 2050 are respectively 2 €/kg and 1 €/kg.[27] Achieving these targets will require a combination of reduced electricity costs, improved efficiencies and reduced capital costs. Besides the technical improvements mentioned earlier, reduced capital costs can be achieved through scaling up of the production capacity of electrolysers. Currently, the most suitable methods and materials for series production of electrolyser systems are still under development as electrolyser systems are still largely hand made. Therefore, the current electrolyser industry can be compared to the status of the photovoltaics industry in the 1990s, which suggests that a large reduction in production costs should be possible thanks to automation (**Line 3**).

Another area for cost reduction is the total system scope of a water electrolysis plant. A recent study on the design of large-scale electrolysis facilities[28] shows that the electrochemical stacks form only a small part (~15%) of the total plant costs. Other reports indicate stacks costs as 45% of the total for both PEM and alkaline.[29] At any rate, there is also a clear need to optimise the balance of plant's design, the power supply system and the downstream processing of the hydrogen produced.

Piloting and demonstration of electrolysis technologies

An important part of developing electrolysis technologies is piloting activities at 10+ kW scale, in which the TRL level of the innovations is increased up to a level required for demonstrations. These piloting activities are often (too) expensive for the start-ups developing the innovations, and so proper support is needed to overcome this “valley of death”. After a successful pilot, it will be much easier to attract commercial investors.

25 Strategic Research and Innovation Agenda, Hydrogen Europe, 2020

26 https://www.sunfire.de/en/news/detail/multiplhy-green-hydrogen-for-renewable-products-refinery-in-rotterdam

27 Gezamenlijke verklaring deelnemers 1e bestuurlijke rondetafel Waterstof en Groene Chemie (december 2020)

28 Gigawatt green hydrogen plant, state-of-the-art design and total installed capital costs, ISPT, 2020

29 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5□C Climate Goal.

There is also a need for demonstration projects, both with large-scale centralised systems as well as with smaller scale decentralised systems. These projects are needed to study the behaviour of these systems under intermittent operation, improve their reliability and learn lessons on smart scaling or numbering up. For large-scale systems, the projects will be carried out by large engineering companies that will need to go through a logical scale-up process to minimise risks and incorporate lessons learned from smaller scales. This means that we should not directly build a GW factory, but gradually increase scale, for example in the order 20, 100, 200, 500 and 1000 MW. Many projects are needed for smaller decentralised systems to enable the manufacturing industry to move from custom-made systems to mass-manufactured systems. The scaling up of the manufacturing of electrochemical systems is a combination of “numbering up” and “sizing up”. Electrolysers are made up from modular systems (stacks) and a common balance of plant. To increase the overall size of the system, the size of the stacks will increase, but mainly the number of stacks per system will increase. Cost reductions are expected from series production of these modular modules. Multiple smaller scale pilots/demonstrations or large demonstration projects can be used to support the scaling up of manufacturing. Cost reduction of the common balance of plant around the modular stacks is expected to come from enlarging the total system. These cost reductions require large demonstration projects with associated larger risks. Given the urgency of the energy transition, these demonstration projects should start as soon as possible. This implies that for the first demonstration projects, foreign electrolysers will be used. This is acceptable given the fact that the energy transition is a global challenge, which will need technological innovations from all over the world. For the same reason, comparable projects should take place in other European countries so that the supply chain can develop. In the coming decades, there should also be continuous room for new demonstrations projects of innovative technology so that future Dutch manufacturers can also scale up their products. We should avoid the situation where risk-averse investors only invest in proven technology by incentivising the adaptation of new innovations in projects that receive public support.

System Integration - The integration of green hydrogen in industrial processes

Integration of water electrolyser systems

The Netherlands is not a green field. Integration of the electrolyser systems will therefore need to happen within existing infrastructure. A significant part of the cost of the energy transition will be related to this integration (**Fig. 8**). Interaction of electrolyser systems with the surrounding infrastructure should never lead to brownouts or blackouts. Limited knowledge exists on the integration of large electrolyser systems within the existing power grid. This integration will lead to new technical requirements that need to be considered when designing the electrolyser systems. An optimal solution requires close development collaboration of electrolyser manufacturers, system integrators, system operators and power companies. The Netherlands has a strong history in such sector-coupling collaborations. Different electrolyser technologies have different advantages and disadvantages. Large integrated solutions will consist of smart coupling of different technologies. Other electrochemical solutions (solid or flow batteries, supercapacitors), can also play an important role in such optimised solutions. Demonstration projects are needed to support the development of different solutions and bring new technology demands to the electrolyser companies and the research community. It will also support the required increase of production capacity for the manufacturing supply chain, see **Line 3**.

Integration with chemical industry

The Netherlands has a large chemical industry. This industry is already a major consumer of hydrogen for ammonia, methanol and fuel production, for example, and the use of hydrogen is now also being explored as an alternative for fossil fuels in e.g. high-temperature heating and steel production. The plants are mostly located in port areas, in the vicinity of the locations where green electricity generated by offshore wind farms will come onshore. The large hydrogen demand of these industries makes them an ideal testing ground for green hydrogen demonstration projects.

An important aspect in these green hydrogen demonstration projects is flexibility. Chemical plants are typically operated baseload. Although this might still be possible in a future energy system with hydrogen storage, it would be more attractive from a system perspective if the chemical plants could “breath” with the intermittent supply of renewable electricity and green hydrogen. The extent to which chemical plants can be made flexible should therefore be investigated.

Another relevant aspect is the coupling of heat between the chemical plants and the electrolysis systems. This is especially relevant for solid oxide technology, which requires the input of high-temperature heat.

For the low-temperature electrolysis technologies such as PEM and alkaline, it needs to be explored if waste heat can be upgraded to valuable steam or alternatively can be used in applications such as residential heating.

The chemical industry is a risk-averse industry. For this industry to invest in green hydrogen, it needs to have confidence in the suppliers of electrolysis systems. It has to be demonstrated that the supply chain is healthy and strong and can support them in the future. Therefore, we need to demonstrate not only the technology but also the participation of the supply chain needed.

Hydrogen grid and hydrogen storage

In our future energy system, we will have a national grid for hydrogen, that allows for the decoupling of hydrogen production and demand, which in turn makes it easier to apply hydrogen in a diverse range of applications. Gasunie is currently actively developing such a hydrogen grid and plans to have a first grid operational by 2025.[30] Such a system will require large-scale hydrogen storage. Suitable storage solutions should be explored (salt caverns, depleted oil and gas fields) and the (bio)chemical influence of such storage on the quality of hydrogen should be investigated.

The search for the optimal system solution

Our future energy supply will likely consist of a combination of local and international supply, just as it does today. The key difference is that all these energy sources need to be renewable and so green electricity and green hydrogen are expected to be key energy carriers. This will require the development of both the electricity grid and the hydrogen grid. In general, one can say that it is cheaper to develop a gas grid than an electricity grid, but the direct use of electricity is more efficient than a power-to-gas-to-power solution. This implies that a system predominantly based on hydrogen is cheaper but less efficient than a system predominantly based on electricity. Gasunie and TenneT have already explored a number of future scenarios for both grids,[31] but more research in the optimal system solution is required. How our grids will develop will be related to the need for large-scale and smaller scale local electrolysis systems.

30 https://www.gasunienewenergy.nl/projecten/waterstofbackbone/hydrogen-backbone

31 Phase II – Pathways to 2050, a joint follow-up by Gasunie and TenneT of the Infrastructure Outlook 2050

At the intersection between System integration and Society - Capabilities in the Netherlands

Different roles are required along the complete supply chain of water electrolysis systems, where it should be noted that players can fulfil more than one role:

- Knowledge institutes - develop relevant knowledge on water electrolysis systems
- Component suppliers - make components for stack and system suppliers
- Stack suppliers - produce water electrolysis stacks
- System suppliers and system integrators - supply complete water electrolysis systems
- Engineering companies - engineer, procure and construct plants
- Operators of water electrolysis facilities - invest in and operate facilities
- Customers - procure green hydrogen

Currently, in the Netherlands, we have customers, operators, engineering companies and knowledge institutes in the field of water electrolysis, but we lack leading component, stack and system suppliers (See **Box 2**. We do have promising SMEs with the potential to fill a niche in the market. Therefore an appropriate industrial policy for these parties could lead to huge opportunities for the Netherlands). As a result, piloting and demonstration projects are often carried out with foreign electrolysers. However, since climate challenge is a global challenge requiring global technology development, the Dutch economy would benefit from the Netherlands taking a leading role in component, stack and systems production. The Netherlands is in a good position to do this because it already has a strong supply chain for large-scale and technology-intensive manufacturing processes with expertise in high-volume production and robotised system assembly. As electrolysis technologies have not yet fully matured, now is the ideal moment to enter this market and there are already some promising initiatives to mobilise the manufacturing industry.[32,33,34] This is addressed by Line 3. Human Capital is a critical element to successfully implement green hydrogen technologies in the Dutch society. This is further described in **Section 3.4**.

32 Waterstof, kansen voor de Nederlandse industrie, 2019

33 HyScaling, manufacturing for scaling up water electrolysis, 2020

34 Electrolysers: opportunities for the Dutch manufacturing industry', FME-TNO, 2020

Recommendations

In summary, we need the following actions for large-scale green hydrogen production in the Netherlands:

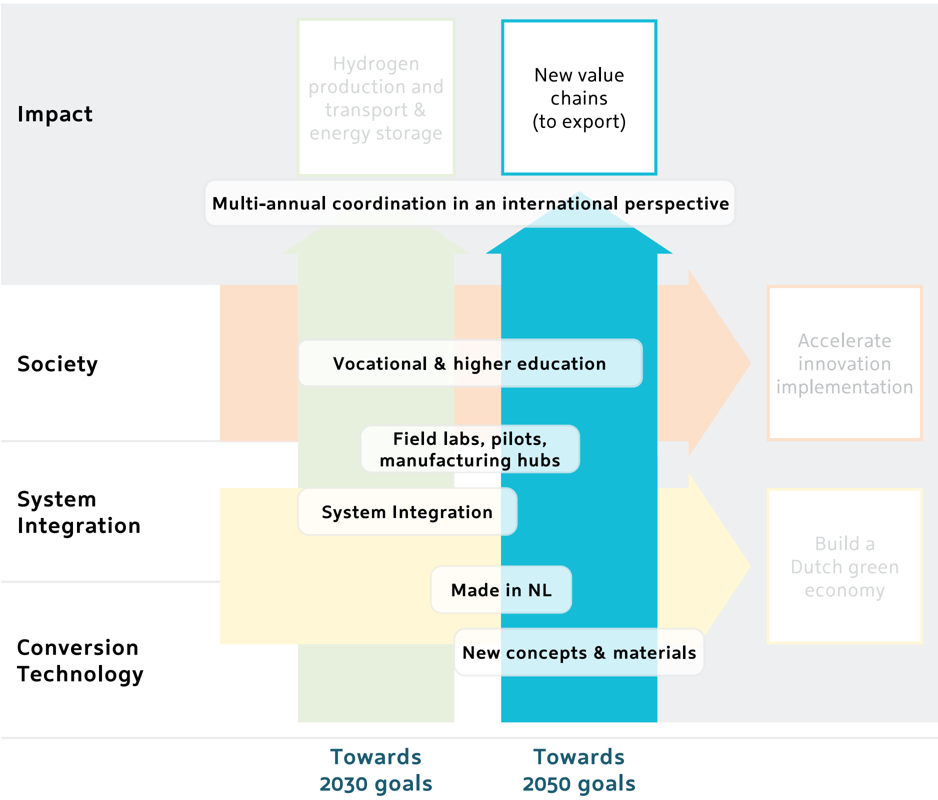
- Pilots of water electrolysis at the 10+ kW scale.
- Demonstration at >1 MW to:
  - study the behaviour of these systems under (intermittent) operation;
  - improve their reliability;
  - learn lessons on smart scaling or numbering-up;
  - reduce investment risks for larger systems;
  - optimise the balance of plant design, the power supply system and the downstream processing of the hydrogen produced.
- Demonstrate at gradually increasing scales to allow the Dutch manufacturing industry to connect and grow with these developments.
- Reduce costs by further developing and optimising the conversion technology.
- Demonstrate the building of healthy and strong supply chain for industrial users to build confidence for large investments.
- Demonstrate H_2 storage.
- Demonstrate flexibility and heat coupling in the chemical industry.
- Develop H_2 and electricity grid.
- Develop dedicated technology solutions for the energy transition (e.g. combination with battery systems).
- Develop the full value chain of water electrolysis.
- Develop Human Capital, see **Line 4**.

3.2 Towards the next generation of electrochemical conversion processes - Line 2

Conversion Technology
In this section, we describe the research challenges and needs for the development of electro-conversion technologies. This involves both:

- radically new concepts for water electrolysis to green hydrogen, and
- direct electro-conversion technologies to produce simple molecules directly from feedstocks such as CO_2, N_2 and H_2O, without the use of green hydrogen.

The direct route has the potential to reduce the number of process steps, thereby increasing the energy efficiency. Such a technology is about to get tested beyond lab scale, but its implementation typically has a long-term (>10 years) perspective.



While high Faradaic efficiencies are obtained at relevant current densities, upscaling of this process at relevant levels of reliability is needed to reach a commercial stage.
This creates the opportunity for companies in the Netherlands to develop a unique knowledge base.

At present, it is not possible to predict which process will become the most economically viable. The effect of the intermittency is tough to predict. Therefore, the ultimate challenge is developing design rules to determine which conversion process is the most economically viable given a certain product and feedstock combination. In the last decade, significant progress has been made for the production of commodity and specialty chemicals through direct electrochemical conversion. The progress has mainly focused on developing novel electrode materials, and not so much on the development of electrochemical systems. In the case of specialty feedstock, current processes are mostly based on hydrocarbons that need to be functionalised. When changing the feedstock to air and water, biomass (carbohydrates), or recycling streams, one such design rule is to keep the functionalities already available in those feedstocks. In the following sections, we give a high-level overview of the development potential for new electrochemical technologies. In this, we only briefly describe the main challenges. For detailed KPIs regarding the performance of these technologies towards 2030, we refer to the Energy-X Research Needs Report and the Sunrise Technological Roadmap, which have now been incorporated in the SUNERGY initiative.[35]

For all the new-generation conversion technologies, it should be noted that scaling by many orders of magnitude will ultimately need to take place in real-life industrial plants. Also, the electrosynthetic processes introduced will need to be integrated in complex industrial processes at the reactant, power and process control level. This requires a strong interaction between chemical manufacturing equipment industries, see also **Line 3**.

Radically new water electrolysis technologies
The development of a water electrolysis industry Made in NL should be accompanied by a strong research programme at the Dutch knowledge institutes that should lead to breakthrough inventions in the field of water electrolysis. This programme should not only incorporate electrochemistry, but also other fields of science that are relevant for the complete water electrolysis system.
These include polymer science, gas-fluid dynamics, materials science, corrosion science, power electronics and electrical and system engineering (see also **Fig. 8**, the more detailed version of the conversion and integration chain already discussed in **Chapter 2, Fig. 5**).
These different fields of science should work together to find the best system solutions.

35 Documents | SUNERGY (sunergy-initiative.eu)

An eye should also be kept open for efforts to radically redesign existing electrolysis systems as well as develop new hybrid devices such as the Battolyser, which combines battery storage with water electrolysis. Such a research programme should aim to lower the cost of green hydrogen through novel technology development.

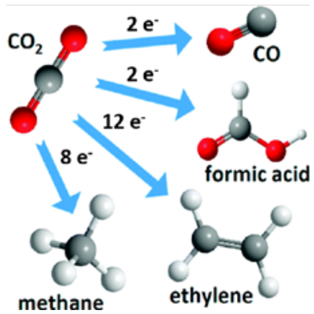
The feasibility of green hydrogen technology has to be tested in field labs and at pilot level, for example to test integration with a subsequent chemical process under intermittent conditions. Field labs are crucial to prevent the insidious innovation gap between research and industry. Pilot systems will help create new business over the entire value chain, help to cross the "valley of death", and foster the emergence of start-up companies.

Upscaling and demonstration should be done at gradually increasing scales to minimise risks and learn from the smaller scale. This will enable the manufacturing industry to move from custom-made systems to mass-manufactured systems and to create multiple sites and ecosystems in the Netherlands where new technologies can be tested and integrated.

Electrifying the carbon cycle

Directly making products from renewable organic feedstock such as CO_2 or biomass, and H_2O, without the use of green hydrogen, has the potential to reduce the number of process steps, thereby increasing the energy efficiency.

Electrochemical reduction of CO_2 at low temperatures can lead to a broad range of chemicals:



Several of these products can be made with high selectivity, but the energy efficiency and productivity is still quite low. This is due to a limited understanding of the catalytic processes in addition to severe transport limitations of the components in the reaction. In addition to C1 and C2 molecules, CO_2 can be used in the synthesis of higher value chemicals. Also, high-temperature CO_2 reduction using solid oxide electrolysers is of interest; due to the elevated temperature (500-800 °C) this can be done with high efficiency, but for this technology, a higher stability, scalable reactors, and better system integration are needed.

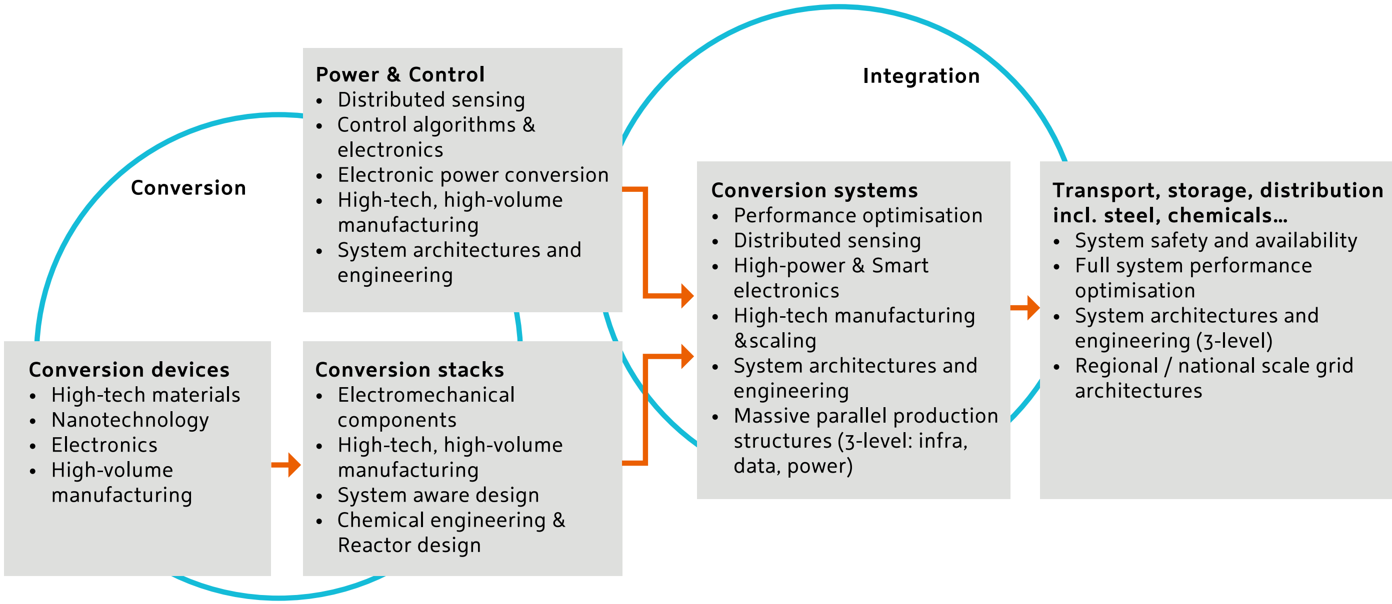


Figure 8 Conversion and integration chain for electro-conversion process development.

Another route to sustainable products is electrosynthesis: converting renewable feedstock such as carbohydrates from biomass into higher value products, using selective electrochemical hydrogenation, selective electrochemical oxidation and new electrochemical condensation reactions, i.e. C-C and C-N bond formation.

Clearly, significant challenges have to be tackled before CO_2 reduction and electrosynthesis can be used in a commercial arena at a large scale:

- Increase the efficiency, selectivity and current density of the process by developing electrodes and catalysts
- Increase the stability of the electrode-catalyst systems and develop stable ion-exchange membranes for application in electrosynthesis
- Develop a scalable reactor design that allows for high current densities (e.g. increased pressure, gas diffusion electrodes in case of CO_2 as feedstock) and improved energy efficiency
- Develop suitable feed purification and product separation processes as well as processes that can deal with intermittent operation
- For the high-temperature route: improve material stability (e.g. coke formation at the electrodes), realise cost-effective reactors which can be scaled up in a stacked configuration, and optimise and efficiently integrate system integration (e.g. use high-temperature CO_2 sources), and downstream purification technologies.

Electrifying the nitrogen cycle

The current ammonia synthesis is rooted in the Haber and Bosch process developed before the First World War. The current synthetic route requires elevated temperatures and pressures at very big scale (~1500 tons per day), starting typically from methane. This leads to a significant CO_2 footprint (~2% of the global CO_2 emission). The holy grail is to develop a green, direct route for the reduction of nitrogen and water to ammonia. The necessary research and development is currently at very low TRL levels, signalling the difficulties towards developing a green route. The challenge is related to the very strong nitrogen-nitrogen bond, which needs to be cleaved. Another interesting approach would be to develop oxidation technology to convert nitrogen to nitrogen oxide, which can be converted, for example, to nitric acid or ammonia. Moreover, other molecules based on nitrogen can be made upon further development of C-N coupling technology. The main challenges here are to develop a better understanding of the reaction mechanism, control the selectivity of the reaction, and discover new electrode and electrolyte materials.

Other emerging technologies

Access to renewable energy and renewable feedstock differs per geographical area. For some regions, this creates opportunities for other **power-to-chemicals** technologies. An example is the plasma-activated reactor, currently being investigated in Geleen. Another long-term opportunity is **direct photo-electrochemical conversion**, directly using solar energy to produce hydrogen or chemicals. This provides the opportunity to become independent from the electricity market and so independent of the electricity market price. It also avoids costs related to electricity transport. **Power-to-X-to-Power** is also a much-needed technology for energy storage. The increasing share of intermittent renewable electricity requires electricity storage for a broad range of timescales/capacities: from storage to buffer hourly wind or sun fluctuations to storage for seasonal fluctuations. This requires different solutions. For short time periods and local storage, (flow) batteries can be used. For seasonal storage, batteries are not sufficient, and storage in chemicals/fuels is needed. This also has the advantage that the energy can easily be transported. Important goals for energy storage are to maximise the energy round trip efficiency and the lifetime of the (flow) battery.

Capabilities in the Netherlands

Many knowledge institutions in the Netherlands are developing relevant knowledge on direct electrochemical conversion processes. Several companies are developing direct electrochemical conversion processes to convert CO_2 to carbon monoxide, ethylene and carboxylic acids: e.g. Avantium, Coval Energy, Shell and Siemens. HyGear as a system supplier can provide systems to produce carbon monoxide from CO_2.

Dutch companies active in the field of (flow)batteries are Leyden Jar and Elestor. Clearly, this is an emerging field with many opportunities for new value propositions for the Dutch industry.

Box 4 – The Volta Technology from Avantium

In November 2016, the Dutch company Avantium acquired Liquid Light, a Princeton 2009 start-up in which more than 35 million dollars was invested. Liquid Light had developed proprietary process technology and IP to make major chemicals from CO_2. The acquisition combined the technology of Liquid Light with Avantium's expertise in developing sustainable chemical processes and in accelerated catalyst testing. This formed the basis to develop a leading technology platform for the direct conversion of CO_2 to high-value chemicals. Using this platform and the acquired IP, Avantium is developing an integrated process for the production of carboxylic acids from carbon dioxide. Currently the technology is scaled out of the lab, and will be demonstrated at a power plant in Germany as well as a cement factory in Greece.

Recommendations

Fundamental research, TRL 1-3: In this case, a lot of research needs to be done, ranging from catalytic studies to materials development, reactor engineering and system integration (including downstream) & control. However, these fundamental studies should always keep in mind the aim of a large-scale integrated system. Hence, there should be a close interaction between materials development and reactor and system engineering. The back-and-forth design philosophy should give rise to certain product/feed combinations (being e.g. both in the liquid phase or otherwise). The fundamental studies will also provide input for the techno-economic analyses for deciding upon the viable embedding of this technology in the local ecosystems.

Applied research, TRL 4-6: The proof of the pudding is in the eating. So, in this case, pilot activities at around 10-100 kW scale are needed to test and demonstrate the integrated technology at a scale at which further upscaling potential can be assessed. The pilot plant activities should be integrated with pre- and post-treatment to be able to assess all relevant aspects. Substantial investments in lab space, equipment and support staff is required. In addition, a close collaboration with HTSM companies will prove to be advantageous to make quick progress and develop key manufacturing competencies.

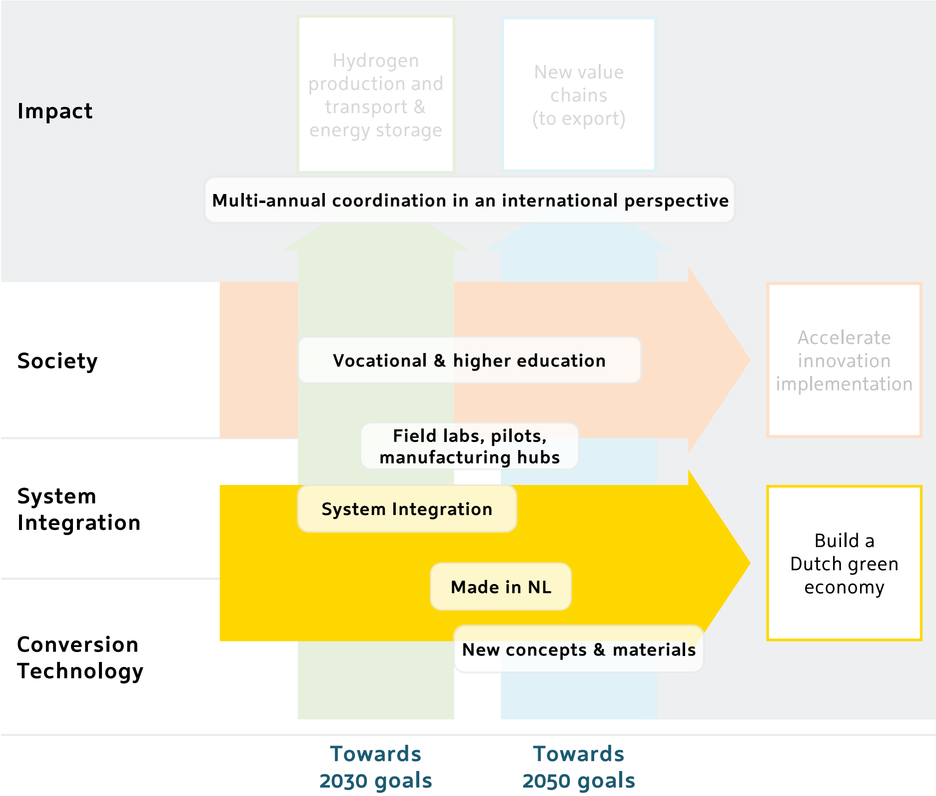
3.3 Connect and Develop the Manufacturing Industry - Line 3

Throughout the energy transition, many of the changes in industrial activities will be driven by the reduction of CO_2 emissions. With the expected availability of lower cost electricity, industrial conversion is expected to be driven by electric power, either by indirect electric heating or by direct electro-conversion methods such as electrolysis, electrochemical synthesis or plasma conversion. Most of the current thermally-driven chemical conversion routes are based on large chemical reactor designs that provide the best scaling for current processes. With the large scale introduction of membrane-based technologies, however, this approach will change. The expectation is that many of the future chemical processes will be implemented in parallel units, all made in the same way and electronically driven per unit to achieve maximum performance and safety. In addition, all units together will perform as one conversion unit driven by full system controls.

For the production of such massive parallel conversion systems, conventional single reactor engineering and production will prove inadequate. For example, membrane-based conversion like water electrolysis at GW level will require millions of membranes, ideally to be produced with high product accuracy and quality and subsequently assembled and contacted automatically to drive prices down and assure reliability and total system safety.

Designing and driving such conversion units as electronic systems and introducing advanced algorithms and software controls to drive conversion power will help optimise such units' performance under a wide variety of conditions. This will help to optimise fluctuations in the converter, in the total chemical plant or even deal with power intermittency. In addition, chemical conversion based on parallel systems is expected to drive performance improvement by short-cycled system improvement steps. The base technologies for the production of such systems or their production lines are very much related to the existing Dutch industrial capabilities for large quantity high-quality consumer goods and the large capability clusters driving the current high-tech industrial expansion in the mechatronics and semiconductor equipment industry.

Most of the ventures active in electro-conversion producing new or improved electrolysers, electrochemical converters, flow batteries or plasma-based converters need to scale their production by orders of magnitude in a short period of time. Entering the market, though, is proving to be a daunting task given all the capabilities required, the complexity of the device, and the scaled environment it needs to function in.



The Netherlands has a good starting point as it contains all required companies in the supply chain of manufacturing electrochemical systems up to the implementation and operation of these (see **Box 2**).[36, 37, 38] It covers the supply chain with electrode production, membrane production and membrane plates up to the balance of plant components and integrators (for the specifics see **Annex 2**). Some of these components are already produced at large scale, but most require scaling up the manufacturing capacity to fulfil the future demands and lead to the required cost reductions.

Many companies from the HTSM industry have expressed their interest and ambitions in electrochemical conversion systems. A common item of feedback, however, is that they can only do this if the risks are controlled. Many companies are therefore looking to set up a testbed to jointly develop, test and demonstrate systems, not only to assess the technology implementation but also to rapidly explore the technology and business scaling opportunity with new ecosystem partners.

The need is for **relatively small projects that can be executed relatively fast**. As technology development is expected to accelerate in the coming years, there will be a need to have projects with different TRLs running in parallel. The significant size of lower TRL projects will be smaller (typical 5 – 25 kW) than the size of demonstrators for higher TRL systems (typical 100-1000 kW). For demonstrators, in particular, there is a strong need to integrate the very high energy and power needs of the process industry and to align these with the energy delivery and transport via the public grid infrastructure. In both cases, **urgent involvement of the manufacturing world is vital.**

Recommendations

- Testbed for jointly developing, testing and demonstrating at a 5-25 kW scale. This will explore all aspects of electro-conversion, including conversion kinetics, efficiency, active controls, driving algorithms and software and power topologies, including optimised grid connections – overlap with **Line 2**.
- Pilot locations for 0.1- 10 MW scale demonstration – overlap with **Line 1**.

36 www.gasunienewenergy.nl/projecten/waterstofbackbone/hydrogen-backbone
37 Phase II – Pathways to 2050, a joint follow-up by Gasunie and TenneT of the Infrastructure Outlook 2050
38 ECCM@ HTSM Brainstorm-session, November 2020

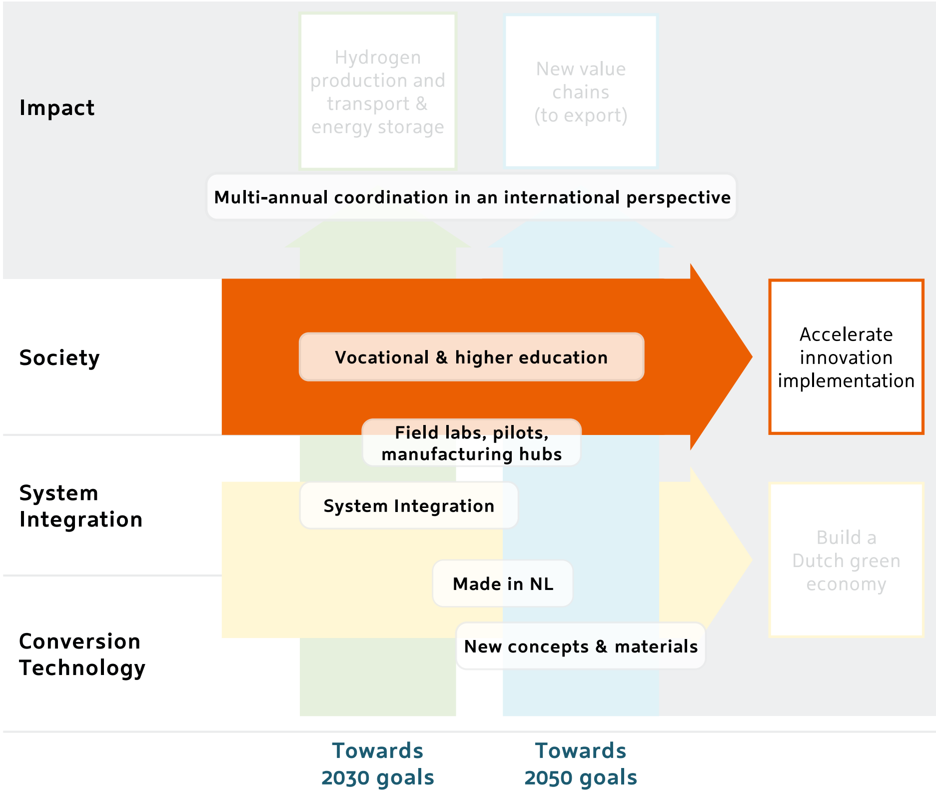
3.4 Human Capital Development - Line 4

Human capital is a critical success factor for achieving the innovation goals of the ECCM Agenda towards 2030 and 2050. At present, there is not enough trained human capital across the various TRL levels to power the required innovation, from basic research to building and operating demonstration plants for electrochemical conversion. The ECCM committee has already taken some first steps to developing the knowledge base in the Netherlands via the ECCM Graduate School (educating and creating a community of young academics and industrial researchers) and the ECCM Tenure Track programme (to establish the professors of the future), see **Annex 1**. However, more well-trained professionals are needed as soon as possible to develop and implement new technological processes at a large scale. Part of the ECCM Agenda therefore revolves around creating the right human capital, **focusing on the development of knowledge and skills of people**. In this context, Human Capital addresses all career stages and entails learning via training/schooling, learning on the job and learning to innovate.

Human Capital analysis for ECCM

Human capital management for the ECCM field is not a matter of simple plug and play of standard recruitment from existing human capital pools. For ECCM, three important human capital issues exist:

- Compared to other (chemical) domains, the **number of people** trained in the ECCM field **is limited and needs to be increased**.
- The knowledge base for ECCM is not yet mature. Knowledge and skills in the ECCM domain are subject to rapid development, both at companies and educational / knowledge institutes. **Training of students** and **lifelong learning of employees in companies are crucial** for professionals to remain up to date with the latest developments.
- **To boost ECCM knowledge dissemination on a 'practical' level**, and speed up the implementation of new technologies in companies, **cooperation between companies and esp. MBO/ HBO education institutions needs to be intensified**. Whereas the number of public-private partnerships in the ECCM domain is increasing for research universities, for MBO and HBO this is still limited (CIV, RIF, CoE, field labs).



Recommendations

To promote the targets of ECCM, a Human Capital Action Agenda is recommended. This agenda is aligned with the Human Capital initiative described in GroenvermogenNL (see Section 1.4) and the national Human Capital Strategy of the Top Sectors.[39]

The ECCM Human Capital Action Agenda will contain the following HC lines:

HC Line 1: Labour Market for ECCM

- Map current jobs, (future) skills and analysis of shortage and possibilities for job transitions between sectors[40] that are relevant in and for the energy transition (together with industry).
- Quantify human capital needs between now and 2030.
- Map "ECCM student" numbers for MBO, HBO and WO: What are the criteria? Are there minors or masters in the ECCM field?
- Promote ECCM and related topics towards students.

HC Line 2: Education and Training

- Analyse ECCM knowledge in education and training.
- Map and develop ECCM knowledge base (curriculum elements) for all three education levels in the Netherlands (universities, HBO and MBO). An overview at academic level has already been drafted by the ECCM committee, see table on Curricula elements below.
- Evaluate summer/ graduate schools/ advanced courses in the field of ECCM, establish needs of companies and develop required programmes.
- Integrate ECCM in talent programmes of Top Sectors Chemistry, Energy and HTSM.
- Perform International benchmark (especially with Germany): inventory of international online courses (MOOCs).

HC Line 3: Knowledge Dissemination between Companies and Education Institutes

- Map and develop ECCM-related public-private partnerships for all three educational levels in the Netherlands:
  - Universities/ research groups - tenure tracks;
  - HBO/ CoE / lectorates;
  - MBO/ CIV/ RIF / practorates.
- Intensify programme for implementing ECCM Learning communities for MBO and HBO (in regions) and developing a national programme for knowledge sharing, joint investment in digital learning to accelerate innovation and teach-the-teacher programmes (lifelong learning).

Fig. 9, Annex 1 also gives an overview of the academic knowledge institutions specifically focused on H_2-related research questions: e-Refinery–TUD, MCEC–UU, Solar Fuels–DIFFER, ARC CBBC, EIRES-TU/e, AMCEL-UvA, J.M. Burgerscentrum, together with institutions for applied research, like TNO and the universities of applied sciences (hogescholen, HBO), MBO and lectors' platforms.

Regional industrial clusters connected to learning communities are:

- **Northern Netherlands:** University of the North/NEC
- **Rotterdam/Moerdijk**: H_2EnergyLab (RDM Innovation Dock) & Campus Green Chemistry
- **Zeeland:** HZ University of Applied Sciences, Delta Power Lectorate. The Lectorate Delta Power conducts research in the field of Energy from Water, Energy Storage, Aquathermia and Hydrogen
- **Amsterdam/North Holland:** Department of Energy Transition; HCA VTi Amsterdam (Professional school for technical installations); and the Research Group Energy Resilience (Inholland)
- **Arnhem/Brainport:** HAN H_2Lab, Energy Vehicles Fueling Station (NeFuSta), SEECE
- **Chemelot:** Brightsite, Chill (MBO Vista, Zuyd University of Applied Sciences and Maastricht University).

39 https://www.tweedekamer.nl/kamerstukken/detail?id=2019Z21756&did=2019D45255
40 https://humancapitaltopsectoren.wijzijnkatapult.nl/corona/transitiemogelijkheden-arbeidsmarkt

Curricula elements

Area	Why relevant?
Electrochemistry	Development of electrocatalysts. Stack development.
Corrosion	Suitable material choice for both electrodes and construction materials.
Polymer chemistry	Membrane development. Suitable plastic construction materials.
Gas-Fluid dynamics	Optimise cell design based on gas-liquid flow.
Electrical engineering	Optimise transformer-rectifiers systems for electrolysers and direct coupling of renewable power systems to electrolysers.
Chemical engineering	Balance of plant development: e.g. G/L separation, drying, separation...
Civil engineering	Find optimal solutions for integration of electrolysis plants (both onshore and offshore).
Control engineering	Optimise control strategy in light of flexible operation.
Materials Science	Development of new materials for electrodes, bipolar plates and porous transport layers.
Manufacturing	Optimise manufacturing process of electrolysis systems.
System studies	Find optimal system solution.
Socioeconomic sciences	Optimal way to involve the whole society in energy transition (e.g. cost and LCA, public acceptance of new technology, legislation, geopolitical issues, governance).
Analytical chemistry	Develop optimal analytical instruments for process monitoring of flexible electrolysis plants.
Process safety	Develop optimal safety solutions for electrolysis plants.
Process automation & Industry 4.0	Development advanced concepts of operation and monitoring of electrolysis plants – expertise in both AI/digitalisation and ECCM sector.
High power electronics	To design power input to electrolysers at the GW scale.

Who do we need?

Non-exhaustive, and both on practical and theoretical training levels.

Area	Why?
Chemical engineering	Design the electro-conversion plants
Electrical engineers	Install the electrical systems
Mechanical engineers	Construct the equipment (both electrolysers and Balance of plant)
Maintenance engineers	Perform maintenance on electrochemical plants
Project managers	Coordinate the implementation of systems
Civil engineers / construction worker	Build the civil construction works
Operators	Operate the electrolysis plants
Analysts	Monitor raw material/product quality (e.g. impurity levels in demi water, hydrogen purity)
Chemical analysts	Monitor raw material/product quality (e.g. impurity levels in demi water, hydrogen purity)
Energy and utility managers	Manage and maintain the role in the energy system
Health, Safety & Environment experts, managers, legal experts	Manage and control the safety health and environment impact of EC conversion and plants
Equipment suppliers	Supply units and components
Supporting staff like HR, Finance, Communication, Logistics,	Support the core processes
Researchers	Work on next-generation processes and plants
Digital data scientists	Realise digitalisation of the processes
Digital analysts and AI experts	Create the required models for advanced process control and predictive maintenance
System architects	Create the overall energy and data systems
Economists, Behavioural scientists, experts in geopolitics, energy policy and governance	Connect the various RDI, innovation and social needs and challenges with the right policy actors

HCA management

The ECCM Agenda brings together the human capital agendas of the Top Sectors Energy, Chemistry and HTSM. The three Top Sectors share the same vision and have elaborated this in the Roadmap Human Capital.[41] ECCM recommends bringing together the human capital agenda for ECCM here in order to benefit from the experience, knowledge, networks and connection with the mission-oriented innovation programmes for industry. The execution of the HC lines requires close cooperation between companies and education. The Top Sectors can coordinate this cooperation, contribute knowledge and make connections with existing programmes. Now we need to quickly build up the knowledge base in the Netherlands to accelerate the ECCM transition agenda.

41 Roadmap Human Capital Topsectoren 2020 – 2023 'Samen aan de slag'

3.5 Multi-annual coordination in an international perspective

Electrochemistry as a catalyst for future growth

The use of H_2 and CO_2 as the main feedstock in the production of chemicals, materials, and fuels will require transformations extending beyond the factory gates, including the development of new supply chains, new infrastructure, new business models, and institutional conditions public support and geopolitical awareness. Electrochemistry could be a catalyst for new avenues of growth, allowing a redefinition of the competitive advantage of the Netherlands at a European and global scale. Strong industrial clusters in the Netherlands provide both significant challenges and major opportunities for such transformation. On the one hand, the large level of integration in industrial clusters makes decision-making more complex due to the existing interconnections and the possibility of domino effects among industrial sectors and value chains, as changes in one industry may result in unintended consequences in another. On the other hand, industrial clusters already have a governance model based on vertical and horizontal cooperation and their integration in global value chains, which can facilitate the deployment of conditions vital for enhancing the large-scale deployment of electrochemical processes.

Need for new governance models

The availability of low-carbon electricity lies at the basis of the low-carbon/CO_2-neutral electrochemical process. Therefore, the transformation of the industrial sector will require intensified sector coupling, especially between the power and industry sectors. Novel governance models will be needed to allow for better coordination and planning between sectors and stakeholders, allowing for consensual decisions and launching concerted actions that take multiple societal challenges into account. Here it should be noted that most decarbonisation strategies throughout the economy currently rely to a large extent on the (future) availability of renewable energy (e.g. strategies based on electrification of heat networks or electrification of transport). Therefore integrated planning and cooperation cannot focus on just power and industry but must cover all energy sectors, which significantly increases the level of complexity. The large deployment of electrochemical processes as a key element of transitioning towards a more sustainable society will therefore need to assess harder-to-quantify issues like system complexity, long-term risks and public acceptance in addition to more traditional cost/benefits analyses.

Various market design barriers hinder the deployment of low-carbon technologies, especially those that require a radical transformation of processes. It is particularly important to create conditions that encourage long-term investment. Such conditions, for instance policy interventions through long-term support mechanisms, will require coordination between local, regional, national and European policymakers and are likely to require a rethinking of the different roles of stakeholders for driving industrial transformation.

Moreover, as discussed in this Agenda, a successful transformation of the industrial sector will entail a fair allocation of risks and benefits between the different sectors and stakeholders. For instance, managing job losses from fossil-based industries and chains while increasing job opportunities in new areas; or driving faster replacement of stock before the end of life versus revitalisation and increase of new economic activities. Therefore the industrial sector cannot be transformed without societal support and this, in turn, requires the early identification and monitoring of tensions created by trade-offs and the development of explicit and coherent plans for addressing such tensions. Ex-ante assessments (technology, environmental, policy) are vital for generating these insights and can be used to support communication between and to stakeholders.

A radical change cannot and will not be risk-free. Managed risk-taking needs to be an integral part of the development of an electrochemistry-based industry. One of the conclusions from the first high-level round table Hydrogen and Green Chemistry of December 2020 (see **Annex 1**) pursued by the ECCM committee is to define milestones for the 2030-2050 targets. Therefore, explicit recognition and communication of the risks involved in developing new technologies and in the drastic transformation of the industrial (and power) sector are needed. Awareness, information, analysis and technology demonstrations at scale will be required by decision-makers in industry, government and civil society. Actively raising awareness of the potential impacts and benefits of electrochemical based processes is needed to create confidence in the decision-making process. Furthermore, early investments are necessary to support rapid diffusion of knowledge, including best practices, as well as strengthening human capital by investing in (re)skilling, upskilling and or (re)training workforce in companies and supply chains. Human capital management has become increasingly significant to investors as it is one of the key drivers of corporate success and sustained competitive advantage. This trend will continue and increase in importance as we move towards a new low-carbon industrial sector based on alternative energy and carbon sources.

International perspective and collaboration

The global challenges ahead of us mean that no country can operate in a vacuum. Just as national coordination guarantees optimal deployment of the various activities, a thorough international perspective and collaboration is essential to reach the EU Green Deal goals.

The Netherlands enjoys unique conditions (**Box 5**). However, if the Netherlands is to secure and strengthen a forerunner position in the electrification of industry, it must maintain a strong international visibility and engage in fruitful international collaborations. Examples of ongoing large international consortia on the ECCM theme in which the Netherlands is already involved are the European Partnership for Clean Hydrogen, Fossil-free fuels and chemicals for a climate-neutral Europe (SUNERGY), the 2x40 GW Green Hydrogen Initiative and the European Partnership Processes4Planet.

Bilateral collaborations are also an important tool. For instance, the Netherlands is an obvious strategic partner for **Germany**. Our neighbours project to import two-thirds of their H_2 demand, and for this, the Dutch infrastructure will be crucial. Collaboration with Germany is rather advanced already. In 2019, the German and Dutch governments signed a memorandum of understanding to underline the cooperation in the field of the energy transition, including research and innovation through bilateral or multilateral research projects. This provided the basis to intensify preparations towards bilateral programmes. The 'Call to Action to foster collaboration between Germany and the Netherlands on green hydrogen & green chemicals' identifies areas of relevant collaboration and sets the basis for cross-border funding instruments on ECCM (see **Annex 1**). Similar collaborations with France, Belgium and the US are currently being explored.

Recommendations

- Develop a new governance model for the multi-sector, multi-stakeholder ECCM field, where the availability of renewable energy is a key determining factor
- Create the right investment conditions
- Identify and communicate risks and benefits; share risks and benefits between the different sectors and stakeholders
- Facilitate and continue international collaboration

Box 5 – The Dutch position in the international ECCM landscape

In the international landscape, the Netherlands enjoys an extremely favourable position to become a leader in ECCM technology:

- We are home to a powerful energy-intensive industrial cluster and have an established knowledge base in chemistry, materials and chemical technologies.
- In Europe, we are the second biggest producer of H_2 after Germany and are already connected to Belgium, France and Germany via (private) hydrogen infrastructure.
- In a short time we can achieve replacement of most grey H_2 with blue H_2 via CCS (see inspiring projects such as H-Vision and Porthos).
- We have a large offshore wind energy potential (60-80 GW) for large-scale production of green H_2 via electrolysis.
- Unlike our neighbours, we have a vast gas infrastructure which we could convert/repurpose in a relatively short time for H_2 transport. We also have large-scale, cheap salt caverns for H_2 storage.
- Our coast together with our well-developed harbour infrastructure enable large-scale H_2 import and transit to Northwest Europe
- We have the relevant knowledge on gas, energy generation, geosciences, gas distribution and storage.

Notes on Hydrogen: While local H_2 production has the advantage of lowering international energy dependence and enhancing supply security, import of H_2 from other global regions will still be needed in the long-term in (Northern) Europe. For the Netherlands, this translates into the prospect of being both a major local producer of green hydrogen based on offshore wind energy, as well an important import/export hub of hydrogen from other parts of Europa and other world regions.

Annex 1
Achievements of the ECCM committee

The ECCM committee started its mandate in 2017 by publishing its first advisory report, which was presented to the DGs of EZK Sandor Gaastra and Berthold Leeftink by the three ‘Boegbeelden’, representatives of the Top Sectors Chemistry, Energy and HTSM: Emmo Meijer, Manon Janssen and Amandus Lundqvist.

The conclusions of the **2017 advisory report** were:

- **Quantified targets** for green H_2 price in 2030 and 2050, for CO_2-neutral ammonia production by 2030, for the use of CO_2 as feedstock by 2050 and for CO_2-neutral mobility by 2050.[42]
- **Short-term** focus on green H_2 production and integration in the energy system.
- **Long-term** focus on electrochemical conversion towards a green industry.
- Strengthen the **knowledge base**, bringing focus and mass in education, knowledge exchange and community building.

Since 2017, the ECCM committee has coordinated R&D efforts and facilitated upscaling activities of companies and knowledge institutes alike, with a short-term focus on green hydrogen production and system integration and a longer term focus on electrochemical conversion. During this period, it has built a portfolio of community-building initiatives, research programmes, pilot and demo projects (TRL 1 to 8).

Four years later, the advantage of bringing together an active community of researchers, industrial partners and governmental stakeholders is evident. The ECCM committee has established itself as a reliable, recognised party that is regularly consulted on matters related to electrification. It has also managed to position ECCM as a high-priority theme that needs public and private investments sustained in the long term. Perhaps one of the most significant achievements has been the role of the committee in the National Growth Fund (Nationaal Groeifonds)[43] proposal GroenvermogenNL and its alignment with the ECCM Agenda (see **Section 1.4** and below).

42 Specifically:
- By 2030, H_2 will be produced in a CO_2-neutral 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 H_2 and NH_3 will be produced without CO_2 emissions.
- By 2050, at least 40% of the CO_2 produced by industry 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.

43 The National Growth Fund focuses on public investment to boost the Dutch economy's long-term earning power. These investments are needed to tackle challenges to economic growth, including demographic ageing, climate change and the stalling of productivity growth.

ECCM portfolio from 2017[44]

The ECCM committee has initiated and launched **two Calls for Proposals** run by NWO:

- ECCM Tenure Track call to establish six young researchers in the ECCM field and to strengthen the science base in the Netherlands, with co-funding from Tata Steel, Nouryon and Shell
- A dedicated NWA call for Storage and Conversion, resulting in three public-private consortia to foster cross-disciplinary integration.

The ECCM committee advocated and initiated **RELEASE**, a large public-private consortium on Reversible, Large-scale Energy Storage, for a total size of M€ 10, where 25 companies work together with 7 universities and 4 universities of applied sciences.

Launched and adopted **higher TRLs initiatives,** such as:

- FLIE - Field lab Industrial Electrification (Rotterdam)
- Faraday Lab (Petten)
- Hydrohub (Groningen)

The annual **ECCM conference** has become the event that brings together the Dutch ECCM community. Not only is this a growing community (450 participants in 2020) but also a very diverse one, with participants well distributed along the triple helix. Launched in autumn 2021, the **ECCM Research Day** brings together all major ongoing R&D programmes in the Netherlands in the field of ECCM.

Given the importance of involving the manufacturing industry at an early stage, the committee has undertaken a number of initiatives. At the end of 2020, it organised a brainstorming session on the role of the **HTSM manufacturing industry for ECCM**. Currently, the committee is supporting efforts to establish a national Electrolyser Manufacturing Platform and has helped drafting the Energy Chapter of NXTGEN HIGHTECH, a National Growth Fund proposal (see **Section 1.4**), which focuses on the next generation of high-tech equipment for energy applications.

International collaboration is essential for the Netherlands: the ECCM committee has started this by organising a **German-Dutch bilateral committee**. The organisation of a high-level workshop (October 2020) for over 80 experts from industry, knowledge institutes, regions and governments across the Dutch-German border resulted in a **Call to Action**[45] formulating potential areas for bilateral collaboration.

The **ECCM KICkstart DE-NL** call for proposals has been drafted as a result, and a larger call for proposals (M€ 10) for cross-border partnerships in the ECCM field is being developed.

Finally, annual **ECCM Graduate Schools** on electrochemistry are organised for industry and knowledge institutes with the aim of increasing the knowledge level of all stakeholders involved.

The ECCM committee initiated and co-coordinated the development of a large research and innovation proposal for the **National Growth Fund on green hydrogen and green chemistry 'Groenvermogen van de Nederlandse Economie'** and contributed to the setup of the programme. The proposal received conditional funding of M€ 338 in April 2021: the ECCM committee is currently involved in the ongoing preparations to start up the programme (see **Section 1.4**). In autumn 2021, **Groenvermogen II** was submitted to the National Growth Fund. This follow-up proposal focuses on upscaling and integration of green hydrogen production.

The present Agenda, with a roadmap character, is a follow-up to the first advisory report and takes into account the changed landscape of the past four years.
The roadmap is adjusted to the new targets of the National Climate Agreement of the Netherlands and the ambitions set in the first **high-level round table Hydrogen and Green Chemistry**. The round table is another major achievement of the ECCM committee, which took first place in December 2020 and brought together about 30 representatives from government, industry and the knowledge sector under one common declaration.[46] Although initiated by the ECCM committee, the high-level round table was later adopted and chaired by the DGs for Climate & Energy and Industry & Innovation of EZK, and prepared in close collaboration with the secretariats of ECCM, EZK and the three Top Sectors. This round table will convene twice a year and work as a 'state of the land' moment to gauge the public and private ambitions on the ECCM theme.

As of November 2021, the members of the ECCM committees are:
Prof. Richard van de Sanden - DIFFER, chair
Prof. Bernard Dam - TU Delft
Dr. Jörg Gigler - Programmatische aanpak H_2
Prof. Earl Goetheer - TNO
Prof. Petra de Jongh - Universiteit Utrecht
Prof. Marc Koper - Universiteit Leiden
Ir. Geert Laagland - Vattenfall
Prof. Guido Mul - Universiteit Twente
Drs. Ton Peijnenburg - VDL ETG
Dr. Matthijs Ruitenbeek - DOW
Prof. John van der Schaaf - TU Eindhoven
Dr. Klaas Jan Schouten - Teijin Aramid
Drs. Marco Waas - Nobian
Dr. Hans van der Weijde - Tata Steel
Dr. Ellart de Wit - HyGear
Dr. Ronald Wolf - Shell

44 An –non-exhaustive– overview of the ECCM initiatives within the relevant landscape can be found in **Fig. 9**.

45 Call to Action to foster collaboration between Germany and The Netherlands on green hydrogen & green chemicals

46 Eerste bestuurlijke rondetafel Waterstof en Groene Chemie zet de ambities op scherp

Overview of structures, programmes and initiatives in the fields of hydrogen and green chemistry in The Netherlands

ECCM landscape H_2 and green chemistry innovation

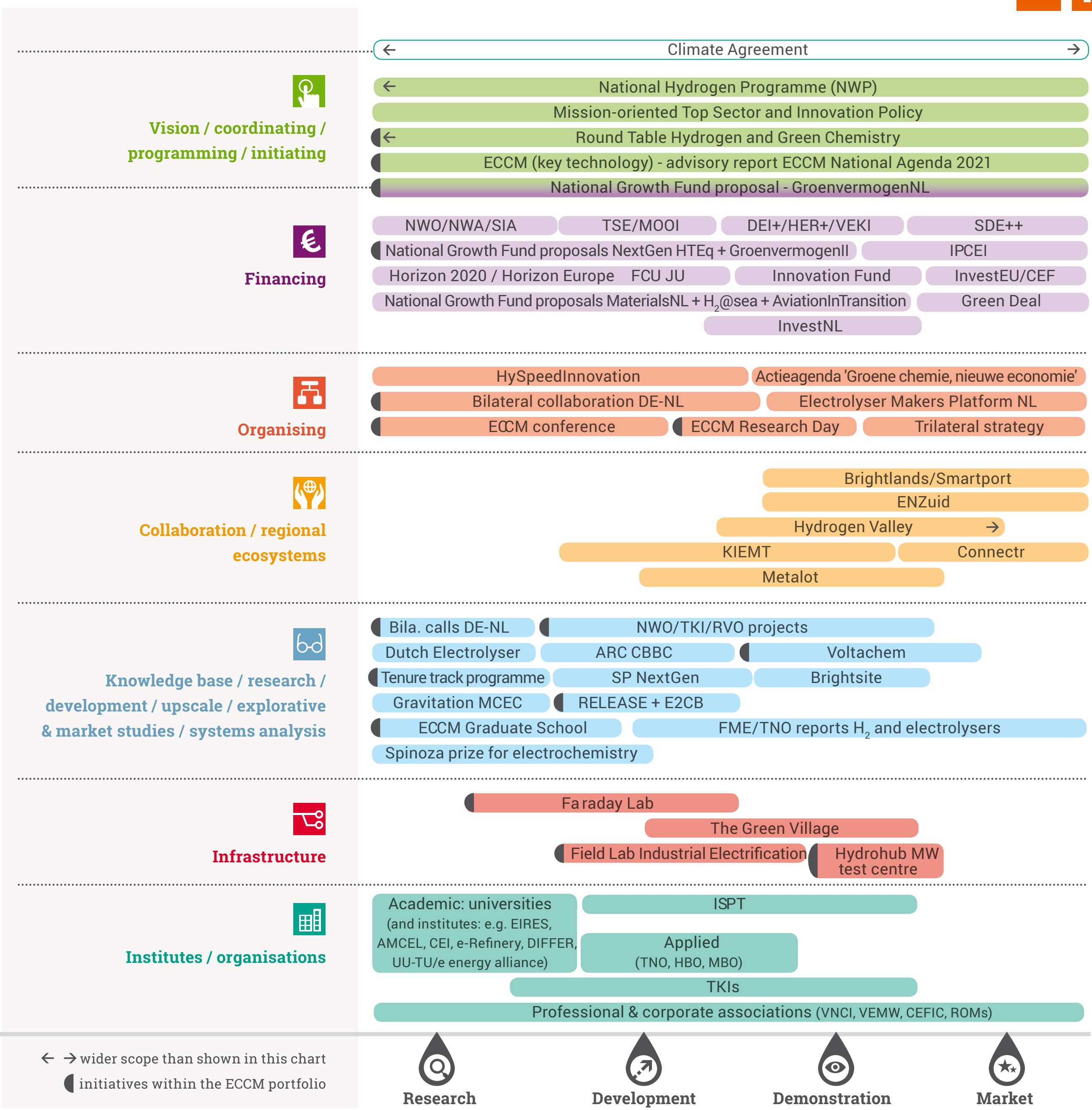


Figure 9. A non-exhaustive overview of the Dutch ECCM landscape. The half moons indicate the initiatives within the ECCM portfolio, i.e. launched or adopted by the ECCM committee. Designer: Petra Klerkx, Amsterdam

Annex 2

Power & Control

Distributed sensing
Sensors, Fieldbuses, Connectivity

Control algorithms & electronics
Conversion optimisation, stack control, safety & emergency handling, data acquisition and processing

Electronic power conversion
High power, high efficient conversion topologies

High-tech, high-volume manufacturing
Electronics manufacturing and packaging, racks, cooling, conditioning...

System architectures and engineering
Addressing power & conversion at stack and device level

Conversion

Conversion devices

High-tech materials
Membranes, Functional coatings, Thin Films, Catalysts, Materials system optimisation (electronic, chemical, properties of bulk and interface)

Nanotechnology
Nanostructured devices allowing new or superior conversion performance

Electronics
(integrated) performance sensing, power driving and distribution...

High-volume manufacturing
Function integration, (precision / high yield) / low cost manufacturing, printing, R2R

Conversion stacks

Electromechanical components
Valves, pumps, heaters...

High-tech, high-volume manufacturing
Automated precision assembly, qualification, precision mechanics, 3D-printing, design for production, etc.

System aware design
Driven by system architecture and engineering (Power & control)

Chemical engineering & Reactor design
Flow optimisation, dissipation handling, high pressure configuration, high temperature conversion

Integration

Conversion systems

Performance optimisation
Balance of Plant, system architecture optimisation given constraints, process sensor input processing, adaptive control strategies

Distributed sensing
Collect, process and store sensor information; use as input for optimisation; log offline for machine learning; use as input for condition monitoring, predictive maintenance and smart control

High-power & Smart electronics
Optimize power flow to electrolyser, adjust for grid conditions and adapt to performance optimisation demands, power response based sensing

High-tech manufacturing & Scaling
Module based strategies; functional qualification of modules, ease of assembly and service when installed;

System architectures and engineering
Multi-level system energy modelling, develop criteria, elicit requirements, boundary conditions; create architectures and compare towards criteria; propose scalable, modular architectures

Massive parallel production structures (3-level: infra, data, power)

Transport, storage, distribution, incl. steel, chemicals...

System safety and availability
Based on operating envelopes, boundary conditions, propose safety constraints for system

Full system performance optimisation
Multi-objective optimisation

System architectures and engineering (3-level)
Hybrid system modeling; multi-objective optimisation; topology optimisation

Regional / national scale grid architectures

List of abbreviations

ATR	Autothermal reforming
CIV	Centres for Innovative Workmanship
CoE	Centres of Expertise
ECCM	ElectroChemical Conversion & Materials
EZK	Dutch Ministry of Economic Affairs & Climate Policy
HBO	Higher professional education
HC, HCA	Human Capital, Human Capital Agenda
HTSM	High Tech & Smart Materials
MBO	Secondary vocational education
MOOCs	Massive Online Open Courses
NWA	Dutch Research Agenda
NWO	Dutch Research Council
OCW	Dutch Ministry of Education, Culture and Science (OCW)
OEM	Original Equipment Manufacturer
PEM	Polymer electrolyte membrane
PBL	Netherlands Environmental Assessment Agency
R&D, RDI	Research & Development; Research & Development & Innovation
RIV	Regional Investment Funds for MBO
SMR	Steam methane reforming
TKI	Top Consortia for Knowledge and Innovation
TNO	Netherlands Organisation for Applied Scientific Research
TO2	Applied Research Institutions
TRL	Technology Readiness Level
WO	University education

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