# ACCELERATING THE ENERGY TRANSITION

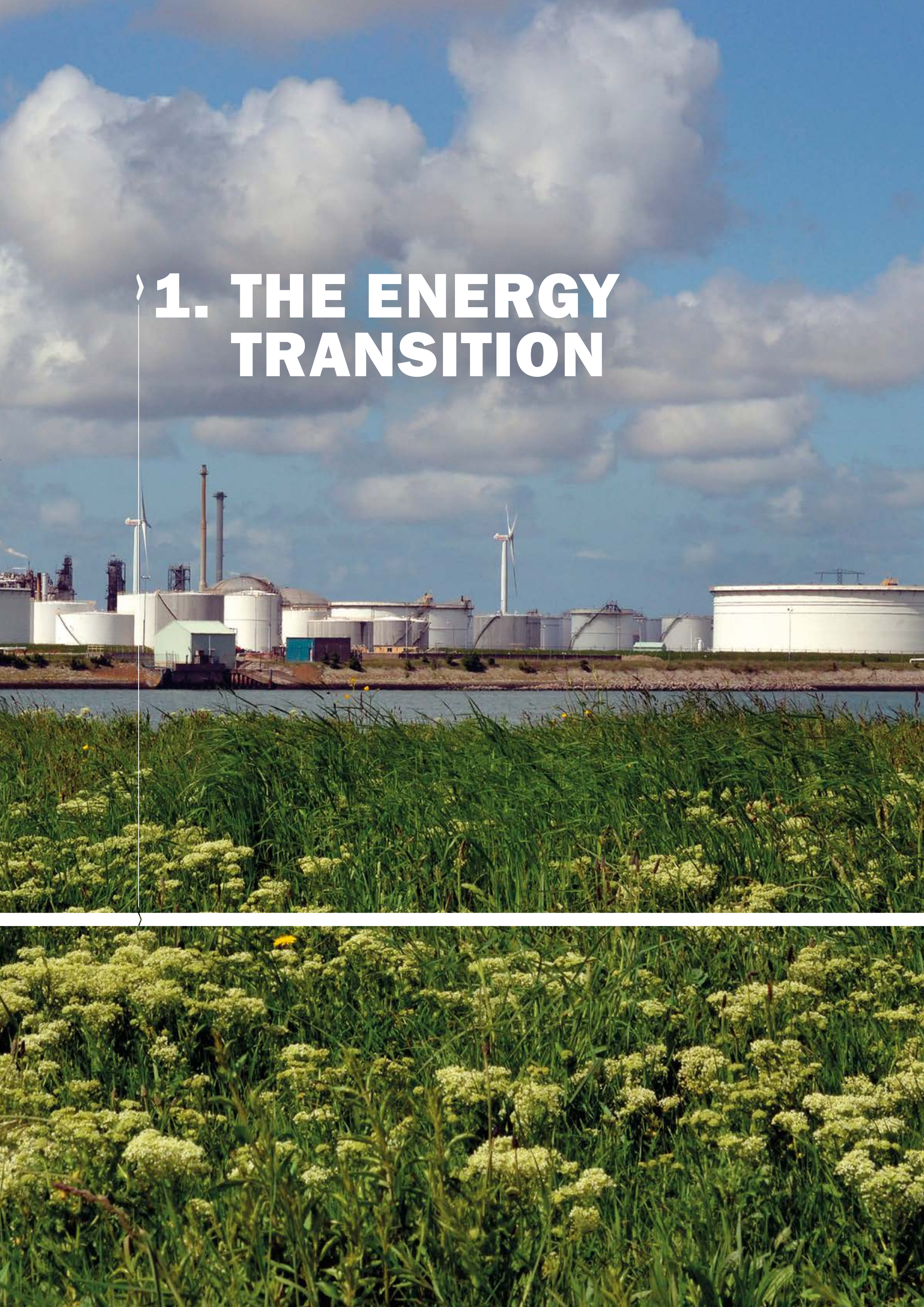
## HYBRID ENERGY SYSTEMS AS A LINK TO A SUSTAINABLE FUTURE

SEPTEMBER 2016

innovation for life

TNO ENERGY VISION 2030

# 1. THE ENERGY TRANSITION



Energy is one of the primary necessities of life and an important engine of the economy. Since the nineteenth century, we have obtained most of our energy from fossil resources. Many people have prospered tremendously from the use of these virtually inexhaustible resources. In recent decades, however, it has become clear that a major cause of global warming is the emission of greenhouse gases from the combustion of fossil resources. The potential impact of global warming includes melting glaciers, rising sea levels, ecosystem degradation and changes in the food chain. This poses a serious threat to life on our planet. Accordingly, national and international agreements have been made to limit the average increase in global temperature.

A transition to a renewable energy system is essential. At the same time, the system must remain reliable, safe and affordable. A successful transition will require tremendous effort from all sectors of society around the world. This is especially true in the Netherlands, where our current economy and prosperity rely heavily on fossil resources and fuels[1].

This document describes TNO's energy vision, which extends to 2030. Where necessary, an outlook to 2050 is provided. This vision is the basis for TNO's energy innovation programme.

## CLIMATE OBJECTIVES

The Netherlands has committed to European targets to reduce greenhouse gas emissions by 2050. By that time, emissions must be 80%-95% lower than the levels in 1990. For 2020, the EU has developed the so-called 'Europe 20-20-20' target: 20% reduction in greenhouse gas emissions, 20% improvement in energy conservation, and 20% use of sustainable energy by 2020. To achieve the Europe 20-20-20 targets, the Netherlands signed the *Energie Akkoord* – the Dutch Agreement on Targets for Sustainable Energy. The agreement outlines an average 1.5% increase in energy conservation per year, leading to energy savings of 100 PJ by 2020. In addition, energy from renewables will reach 14% in 2020, and 16% by 2023.

In December 2015, 195 countries adopted the legally binding Paris Agreement, which aims for a restriction in global warming. While the goal is to limit temperature increase to well below 2 degrees Celsius above pre-industrial levels, participants will make every effort to limit the increase to 1.5 degrees. This will lead to accelerated efforts to reduce $CO_2$ emissions.

1 Weterings et al., *Naar een toekomstbestendig energiesysteem voor Nederland* (To a future-proof energy system for the Netherlands), TNO report, TNO 2013, R10325, 1 March 2013.

# 2. THE ROAD TO INCREASED SUSTAINABILITY

Opinions and perspectives differ about precisely when the energy system can become fully renewable. Scenario studies have frequently been conducted, and these often lead to different conclusions[2]. Previous experiences clearly show that it is impossible to make reliable predictions about the nature of the future energy landscape, and about the pace of the transition. The uncertainties involved are simply too vast. What is certain, however, is that the transition will require dramatic changes, both in technology and society. The energy system will become much more decentralised. It will also become intertwined with other sectors of society, such as the built environment, transport and industry. New interdependencies and partnerships will emerge. So will new regulatory systems and new market models. There will also be new business opportunities, and new players in the energy domain who want to capitalise on them.

In principle, there are four pathways to a renewable energy system. These complement one another and must be used in combination in order to achieve $CO_2$ reduction targets. The pathways are: 1) energy conservation, 2) use of renewable energy sources, 3) cleaner use of fossil resources, and 4) nuclear energy. In the Netherlands, nuclear energy has encountered substantial societal and political opposition. The country has only one nuclear power plant. Accordingly, this pathway will be excluded from further consideration here. In the course of the transition, renewables will become increasingly dominant in the energy system. So the third pathway – cleaner use of fossil resources – will gradually become less significant.

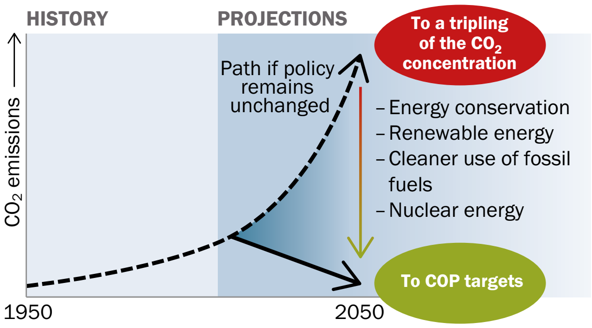



*Figure 1. Pathways to increased sustainability.*

## LARGE-SCALE ENERGY CONSERVATION

The first pathway, which is a priority in almost every scenario, is efficient energy use. In households, mobility, businesses and industry, there are abundant opportunities to conserve vast quantities of energy. The industrial sector has the additional challenge of ultimately switching to sustainably produced raw materials. To conserve energy in transport, mobility, and the built environment, the challenge is to implement measures on a sufficiently large scale.

## LARGE-SCALE INTRODUCTION OF RENEWABLE ENERGY

Sun, wind, geothermal and biomass are all promising renewable energy sources. The efficiency of energy generation is steadily improving, and the associated costs are falling. So these sources are becoming increasingly attractive. For example, the price of electricity from solar energy (PV solar energy) is falling so fast that, in some cases, it is already competing with 'fossil electricity' (see Figure 3). This is especially true in the built environment. As yet, however, none of these alternatives are mature enough to replace fossil fuels completely.

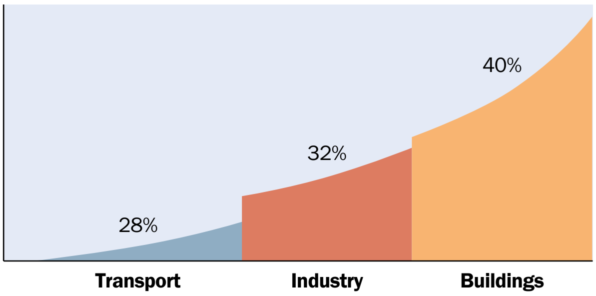



*Figure 2. Various sectors' potential contributions to energy conservation in the Netherlands.*

## CLEANER USE OF FOSSIL ENERGY SOURCES

As long as we continue to use fossil fuels, it will remain necessary to restrict $CO_2$ emissions as much as possible. One way to achieve this is to replace coal – a fuel with high $CO_2$ emissions – with natural gas. Natural gas can also be replaced by residual heat and geothermal energy. One option that has a short-term impact on $CO_2$ emissions is the capture, use, and storage of as much $CO_2$ as possible: Carbon Capture, Use and Storage (CCUS). However, we must be careful to prevent CCUS from strengthening the existing dependence on fossil energy sources and negating the incentives to transition to renewable energy.

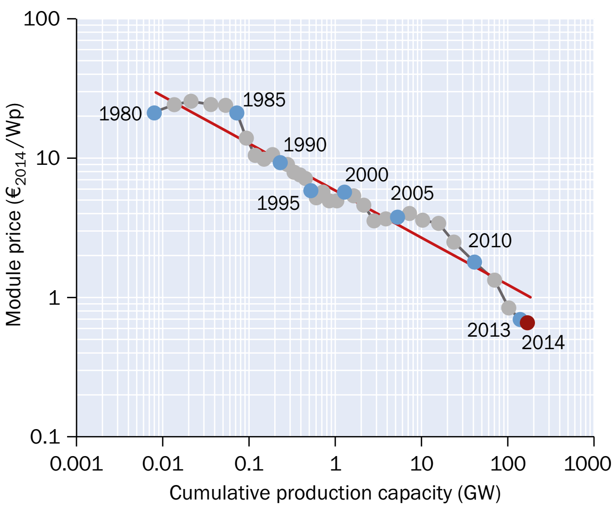
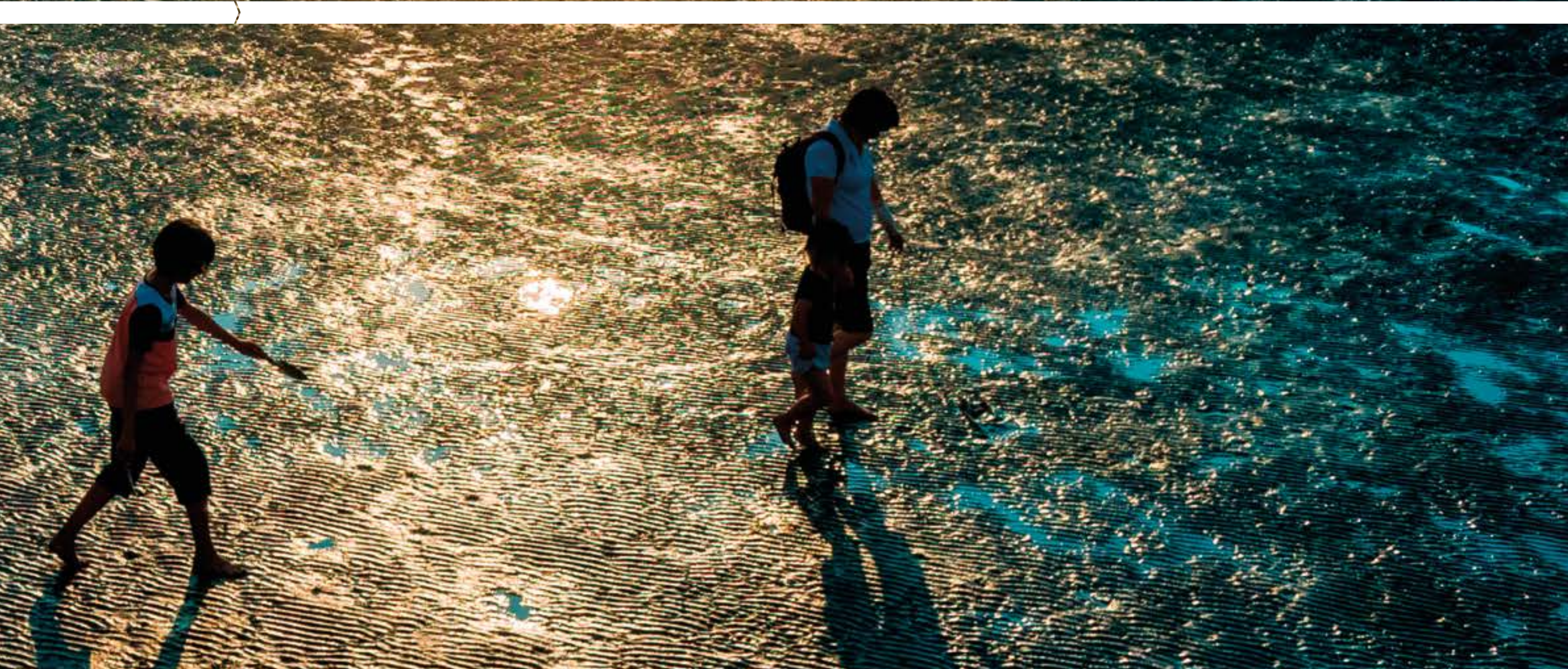



*Figure 3. Cost development PV solar*[3].

2 Weterings et al., *Naar een toekomstbestendig energiesysteem voor Nederland* (To a future-proof energy system for the Netherlands), TNO report, TNO 2013, R10325, 1 March 2013.
3 Fraunhofer ISE, Current and Future Cost of Photovoltaics. Long-term scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende, February 2015.

# 3. TOWARDS A NEW BALANCE



The pathways to increased sustainability described in the previous chapter will have major consequences for the energy system. In particular, the introduction of renewable energy has a profound effect. In 2014, renewable energy accounted for around 5.5% of the Dutch energy supply[4], which means that the Netherlands is lagging behind many other European countries in this respect. According to governmental targets, 14% of all energy use in the Netherlands must be renewable by 2020. This is a major challenge. Until renewable energy technology is sufficiently mature, safe, reliable and affordable, we will continue to make supplementary use of fossil resources. In order to accelerate the transition, we must focus on the maximum deployment of renewable sources, while switching the role of fossil energy from dominant to supportive. The pace at which this can be achieved is strongly influenced by technological change, assurance of supply, affordability, and the socioeconomic and legal embedding of renewable technology in our society. The price of renewable energy is a major factor in the speed of its introduction.

If renewable energy becomes cheaper than fossil fuels, its introduction will accelerate exponentially. Assurance of supply is equally important, since consumers are only willing to switch if energy can be delivered without any hitches.

Therefore, over the next few decades, we will be in a period of transition to a fully renewable energy system. During this period, we will use a hybrid energy system, involving both fossil fuels and renewable energy sources. In this hybrid system, renewable sources will supply a growing proportion of the primary energy demand – heating/cooling and electricity. Eventually, renewables will replace fossil sources altogether. To assure supply, these renewable sources will be integrated into the system in a controlled way. New opportunities for storage, conversion, transportation and systems integration will play a crucial role.

## HYBRID ENERGY SYSTEM

We define the 'energy system' as the combination of energy production, infrastructure (grids), energy conversion, energy storage and energy use. A combination of fossil and renewable energy (and, in some cases, nuclear energy) feed a hybrid energy system. Various infrastructures (gas and/or liquid fuel, power, heat) connect these energy sources to the demand side (see Figure 4), perhaps by means of temporary energy storage or conversion. In the run-up to 2030 (this vision's time horizon), the hybrid energy system will have to accommodate both fossil energy and renewable energy, with the goal of eventually transitioning to a fully renewable energy system. In this connection, grids/infrastructures will play a crucial role on various scales, from local to national and international. These grids must be able to receive energy generated from both fossil resources and renewables, and provide users with affordable energy, on demand.

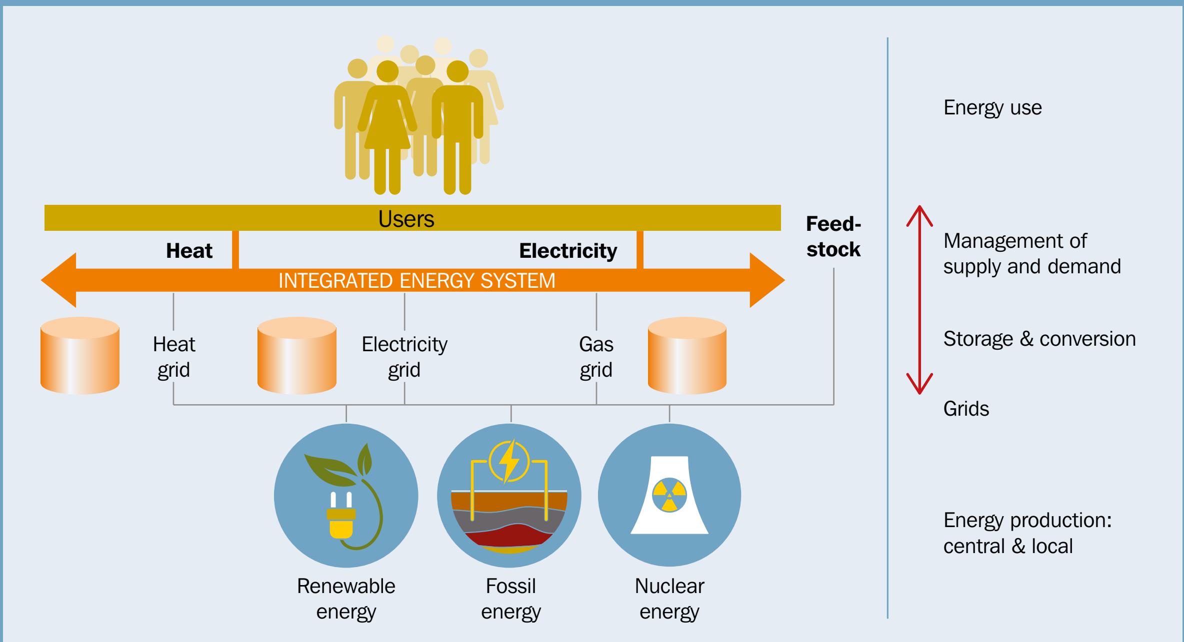



*Figure 4. Schematic representation of a hybrid energy system.*

4 Renewable energy in the Netherlands in 2014, Statistics Netherlands, The Hague, 2015.

# 4. THE CHALLENGE

The transition to a renewable, reliable and affordable $CO_2$-neutral energy system has consequences for the built environment, industry, mobility and transport sectors in particular, as well as for the energy sector itself.

## BUILT ENVIRONMENT

The number of existing buildings is significantly higher than the number of new constructions. In terms of energy conservation, the older buildings perform poorly. As a result, increasing the sustainability of existing buildings must take priority. In order to drastically reduce energy consumption, a large-scale, deep renovation of homes and industrial sites will be needed. Implementing these renovations will require an effective and systematic approach.

In recent years, the range of technical measures to increase energy conservation in the built environment – in the form of sophisticated insulation techniques, for example – has grown significantly. In the future, the integration of PV in buildings, plus a new generation of batteries (both for heat and power) and installations, will even make it possible to transform buildings from energy consumers into energy producers. Increasing built environment sustainability must also be embedded into society. Residents and businesses must get involved, and financial arrangements must be in place to facilitate this large-scale improvement. For energy conservation measures to be fully effective, a continuous focus on the role of users is needed. For example, price incentives and feedback can be used to influence energy use.

## INDUSTRY

The Netherlands has an energy-intensive industrial sector that is heavily reliant on fossil resources. The challenge for energy-intensive companies is to reduce their $CO_2$ emissions through radical energy conservation, the electrification of production, and the replacement of fossil fuels with renewable resources ('renewable feedstock'). This is a massive challenge, and true alternatives are still under development.

We will have to provide $CO_2$-neutral alternatives for products that are currently made from fossil resources. The use of biomass contributes to a reduction in the carbon footprint. For economic reasons, using biomass for products with a high added value will be the focus in the short term.

## MOBILITY AND TRANSPORT

Mobility and transport account for a significant portion of Dutch energy use and $CO_2$ emissions. Increased sustainability can primarily be achieved through energy conservation. The electrification of transportation is also a solution, provided that the electricity used is produced from renewables. A third option is the utilisation of renewable fuels, such as biofuels and hydrogen. Finally, fuels with lower $CO_2$ emissions are a solution for transport. For example, in the maritime industry, LNG could be a viable replacement for oil or diesel. In the passenger transport sector, these options are very close to widespread application. Here, price incentives can affect the choice of transport and fuel type.

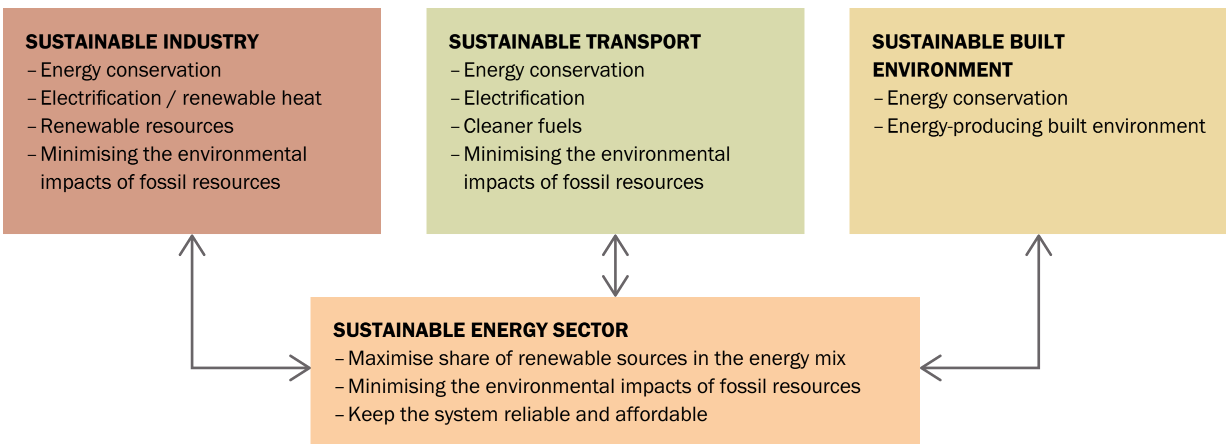



*Figure 5. The challenges of the energy transition.*

With regard to biofuels, it is important to guard against potential trade-off of negative effects. For example, at local level, biofuels can lead to higher $CO_2$ emissions or to loss of biodiversity as a result of land use.

## ENERGY SECTOR

The core challenge for the energy sector is to increase the share of renewable energy sources in the energy mix.

As previously indicated, in a local or central hybrid energy system, renewable and – where necessary – non-renewable sources are flexibly deployed to provide heat and power, supported therein by either storage or conversion. As long as fossil fuels are still in use, it will be necessary to limit their environmental impact as much as possible. This applies not only to the energy production phase, using CCUS for example, but also to other parts of the value chain, from exploration, extraction and transportation to refining.

The hybrid energy system leads to system integration. The distinction between individual energy supplies (gas, electricity, heat, renewable and fossil) will blend together, creating an integrated and distributed system that consists of a combination of small-scale, local energy systems and large-scale, transnational systems. In this context, individual energy carriers must operate as a singular, centralised system. Keeping this complex hybrid system reliable, safe and affordable will be a major challenge. To this end, we must intelligently exploit the system's flexibility, and extend it where possible.

The aforementioned sustainability improvements in the four domains are highly interdependent. In this way, part of the hybrid energy system will be integrated into the built environment. For example, the built environment will not only consume energy, but will also produce it. A similar situation is emerging in electric vehicles with temporary storage in car batteries. Another case of interdependence involves the energy system and industry (see box). This means that traditional boundaries between supply and demand, energy systems, and use sectors are gradually disappearing.

### INTEGRATION OF ENERGY AND INDUSTRY

In many cases, the relationship between the energy system and industry is still somewhat one-dimensional. Namely, it is a producer-consumer relationship. The initial, rather cautious, use of residual heat is already causing changes to occur. The interdependence is expected to continue to grow. Delft University of Technology has made this interdependence transparent by means of the 'energy diamond'[5].

The 'diamond' shows that different energy carriers and carbon sources can be converted into one another, in the direction indicated by the arrows. For example, sun- or wind-generated electricity can be used to create liquids and gases, possibly through the addition of a carbon source. Liquid or gaseous fuels are easily transportable via the existing infrastructure, and can be used for a range of applications (industry, transport, households, etc.).

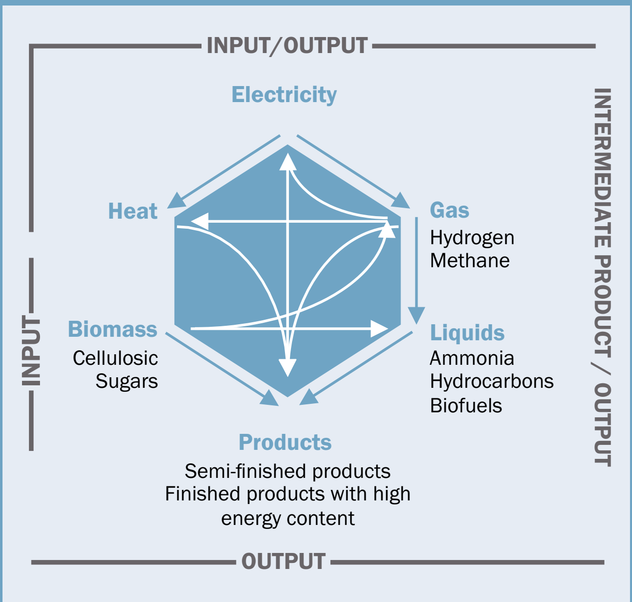



*Figure 6. Energy diamond [5].*

5 The Delft Plan, The Netherlands as an Energy Gateway, Delft University of Technology, March 2015.

# 5. INNOVATION CHALLENGES – OPPORTUNITIES FOR THE NETHERLANDS AND TNO

## OPPORTUNITIES FOR THE NETHERLANDS

Many parties, worldwide, are investing heavily in the research and application of renewable energy technology.

Based on various scenario studies, the *Dutch Energy Report*[6] indicates a bandwidth of 1400 to 2500 PJ for total Dutch energy consumption by 2050. Table 1, taken from this report, lists the potential contributions that various technologies will make to the reduction of $CO_2$ emissions by 2050. It shows that no effort must be spared if we are to meet $CO_2$ reduction targets by 2050. The capture and storage of $CO_2$ from fossil-fuelled power plants has an important role to play in achieving a low-$CO_2$ energy system. Accordingly, the *Energy Report*'s assessment is that the energy system will still be hybrid in 2050.

In the Netherlands, the renewable energy technology industry is very small indeed. Many major technological developments and breakthroughs in the energy field originate in other countries, so the Netherlands will have to monitor these developments closely. Structural cooperation with foreign knowledge institutes is clearly required.

The Netherlands' strengths in a number of specific areas make the country an attractive proposition. The Netherlands is:

- Strategically situated on the North Sea, with state-of-the-art ports and infrastructure.
- An important hub for trade and transport of energy and resources.
- Strong in the maritime, offshore and chemical industries.
- A natural gas country with a great deal of experience and knowledge in this area, coupled with the presence of advanced infrastructure and facilities.
- A modern, high-quality, dense energy system with excellent connectivity, for example with Germany.
- A densely populated country with relatively short distances between the users and producers of energy.
- A country with a long tradition of cooperation spanning various domains, societies and interest groups.
- A nation with a high-quality and well-organised knowledge infrastructure.

If the Netherlands makes the most of these strengths, it may have an important future role in the transport, conversion and marketing of renewable gaseous and liquid resources (from biomass). This opportunity will present itself once we are selling and refining these renewable resources in sufficiently large quantities. Projections show it will be several decades before we achieve this. Making use of its strong maritime sector, the Netherlands can also function as an operating base and development hub for the construction, management and maintenance of large-scale energy infrastructure in the North Sea. The Netherlands can exploit its strong position in the field of fossil resources to accelerate the energy transition, as the technology and infrastructure for fossil fuels and resources can also often be used for renewable applications. The country's strong service sector offers many opportunities for the development of new energy services. These opportunities, combined with the Netherlands' high-quality and dense infrastructure, short distances and collaborative culture, mean that the country is ideally suited as a testing ground for the many technical and non-technical systems-integration solutions and processes that will be needed in the years ahead. The energy transition is, by definition, a challenge that affects many parts of society. Cooperation is crucial. So new, flexible, national and international cooperation models will have to be developed.

*Table 1. Potential low-$CO_2$ options in the Netherlands*[7].

| Options | Potential in 2050 (petajoules) |
|---|---|
| Biomass | 200 (domestic), 120-780 (import) |
| Electricity from renewable sources (solar, wind and water) | 500-750 |
| Heat from renewable sources (solar, soil, air, geothermal and residual heat) | 200-550 |
| Nuclear energy | 30-200 |
| $CO_2$ capture and storage (CCS) | 320-600 |

6 Energy Report, Transition to sustainable energy, Ministry of Economic Affairs, The Hague, January 2016.
7 Energy Report, p. 119.

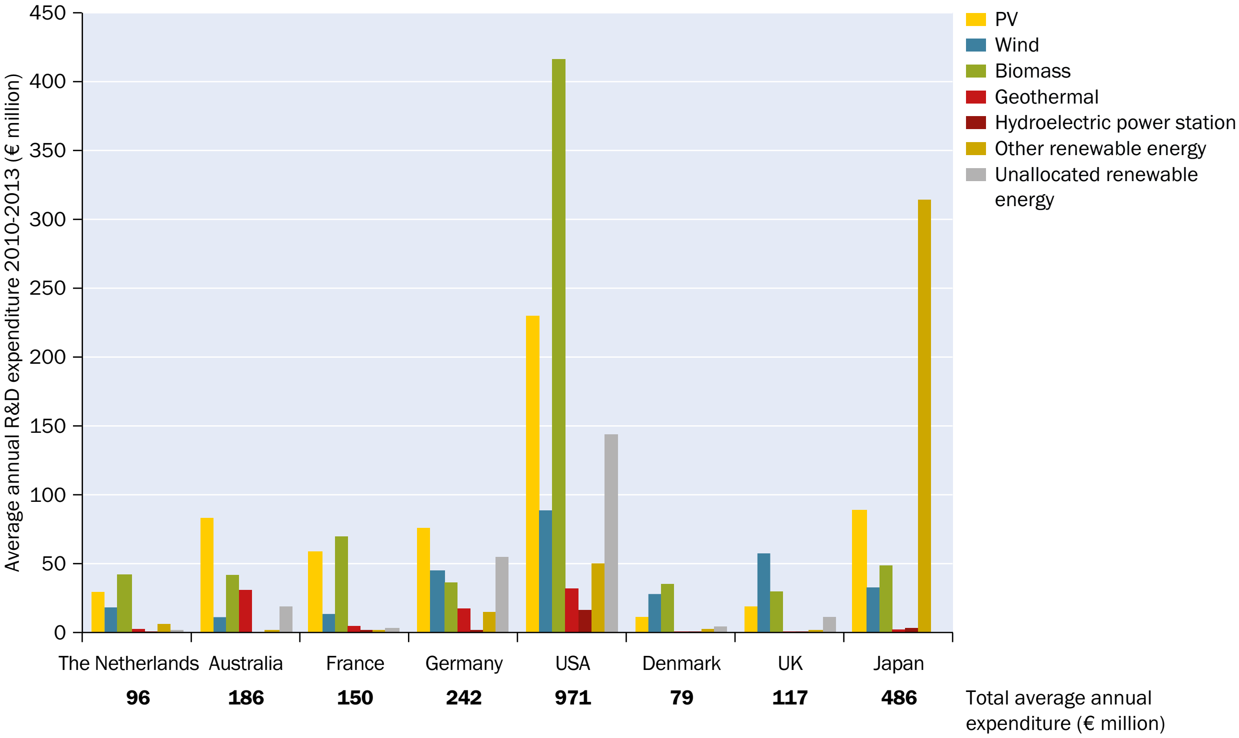



*Figure 7. Public investment in R&D[8].*

## OPPORTUNITIES FOR TNO

In addition to the particular strengths of the Netherlands, TNO adds its own specific strengths. TNO is strongly linked to the domains in which the energy transition must take place: the energy-intensive industries (especially the chemical industry), the transport and mobility sector, the built environment and the energy sector. TNO also has an excellent position in the maritime sector. TNO is an independent and multidisciplinary knowledge institute. Its unique range of technical and non-technical knowledge and skills can be flexibly and efficiently combined into integrated solutions ('smart integrator'). TNO's expertise spans both renewable and fossil energy. It also has extensive experience in the areas of natural gas, energy conservation in the built environment, fuel for engines, PV thin film technologies, $CO_2$ treatment, IT development, and energy management systems.

Finally, TNO has a specially delegated, in-house public authority: the Netherlands Geological Survey[9], which has unique knowledge of the potential uses of the Dutch subsurface. This makes TNO is eminently capable of contributing to the prudent development of the opportunities that the Dutch subsurface offers to accelerate the energy transition.

Various national and international organisations possess essential supplementary knowledge in a range of fields. Cooperation with these parties is therefore a matter of priority ('smart follower'). The following chart indicates TNO's strengths, and their relation to the energy transition.

8 Based on the IEA database of R&D spending by country: www.iea.org/statistics/RDDonlinedataservice.
9 Key Register of the Subsurface Act, September 2015.

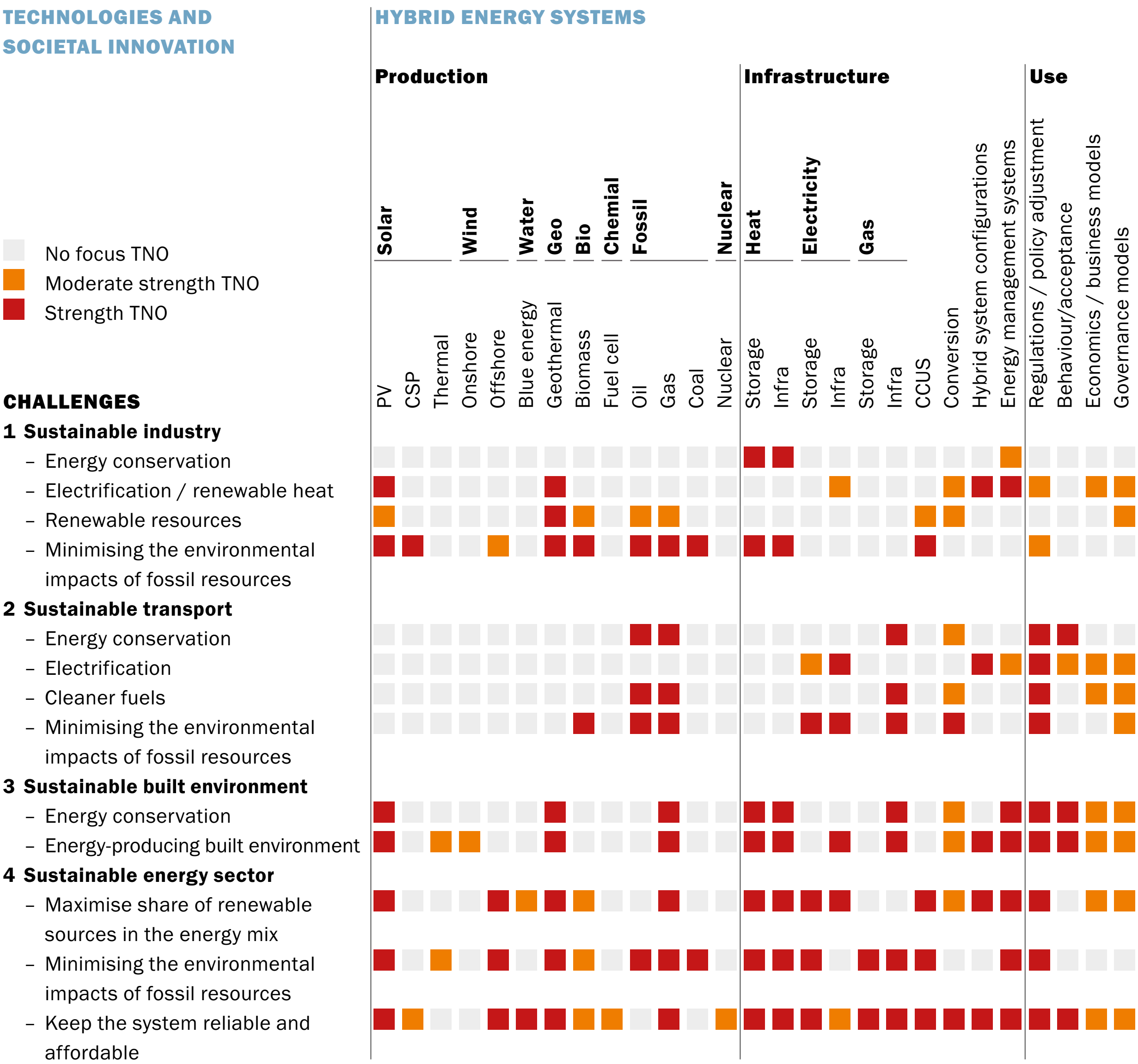



*Figure 8. List of domains in which TNO can make a difference in addressing the challenges posed by the energy transition.*

# 6. TNO'S KEY FOCUS AREAS FOR INNOVATION

Based on its strengths and on the sustainability challenges that the Netherlands is facing, TNO has opted for the following eight key focus areas for innovation. These key focus areas are in line with the four sectors most in need of sustainability measures, as mentioned in Chapter 4. The focus areas also utilise TNO's specific knowledge domains: subsurface knowledge, reliable maritime structures and installations, gas (including CCUS) and societal innovations. Further details of the eight key focus areas are provided below.

1. **An energy-producing built environment**: large-scale realisation of energy conservation, combined on a local level with renewable energy generation and integration into the system. This will make the built environment a local energy supplier. In this connection, TNO combines and integrates innovations in the field of energy conservation, renewable energy equipment, heating systems, PV and energy system knowledge.

2. **A renewable energy-intensive industry**: electrification of the processing industry, involving the use of renewable fuels and resources, thereby reducing $CO_2$ emissions. In this way, TNO makes the maximum use of its extensive knowledge of process technology, combined with its knowledge of energy systems.

3. **Sustainable transport**: innovations in heavy transport by road and water, that lead to fuel savings and significant reduction of $CO_2$ and other emissions. Here, TNO combines its knowledge of the automotive sector, the maritime domain and fuels, such as LNG.

4. **The North Sea as a breeding ground for sustainable offshore energy**: the Netherlands as a hub for the design, construction, management and maintenance of offshore energy systems. With this, TNO contributes to a flexible, robust offshore energy infrastructure, consistent with a strong component of the Dutch economy. TNO makes full use of its maritime knowledge and its expertise in materials, energy systems, sensors, robotics and human behaviour.

5. **Hybrid energy systems**: integrating various components and systems into a reliable, safe and affordable entity. In addition, TNO employs a wide range of knowledge, from gas systems to renewable energy technology, and from process technology to energy systems and IT management systems.

6. **The subsurface as the source and buffer for sustainable energy**: innovations for making optimal and safe use of the subsurface, with minimal environmental impact. For example, to accelerate the energy transition through the production, storage and buffering of energy. In this key focus area, we make use of our knowledge and infrastructure for exploration and for the production of hydrocarbons, together with the extensive knowledge of the Geological Survey of the Netherlands.

7. **Customised gas**: how the use of gas can support the energy transition. In this key focus area, we use our knowledge and infrastructure for exploration, production and transportation of hydrocarbons. We also utilise our specific knowledge of gas and CCUS.

8. **Societal innovation**: support for the energy transition from economic, legal, societal and governance perspectives. In this area, people are the priority. Here, TNO exploits its knowledge of laws and regulations, participation and policy innovation, new forms of partnership, new market models and business models, as well as of human behaviour and performance.

TNO will realise these eight key focus areas in close cooperation with other knowledge institutes and stakeholders. TNO is actively working on new national and international partnerships, as exemplified by the Joint Innovation Centres (JICs). TNO's mission is to harness knowledge for practical application. Activities in support of the energy transition will mainly take place where the innovations will actually be implemented. We do this with the assistance of research laboratories, field labs and living labs.

## AN ENERGY-PRODUCING BUILT ENVIRONMENT: SOLAROAD

The Netherlands and many other countries have extensive paved surfaces, such as roads and sidewalks. In the Netherlands, this amounts to twice the area of all the roofs in the country. If these paved surfaces were to be used for PV, this would potentially create an enormous area of 'solar panels' over which traffic could pass. TNO has developed this idea into a practical, tangible concept called SolaRoad. The first prototype, a bicycle path, has been installed in the village of Krommenie. The next challenge is to scale up the concept into large-scale applications, and to integrate these into the energy system.

The ultimate challenge will be to incorporate induction modules into the road that would automatically recharge the batteries in electric cars that drive upon them.

*Figure 9. SolaRoad.*

## USE OF (ATMOSPHERIC) $CO_2$ IN ENERGY-INTENSIVE INDUSTRIES

Making good use of $CO_2$ emissions is a sustainable way to reduce them. Emissions can be used, for example, as a raw material ('feedstock') for the chemical industry. TNO is working on methods that convert $CO_2$ into resources like methanol. The ultimate challenge would be to find a way to use atmospheric $CO_2$ in this process. This would lead to a reduction of the $CO_2$ concentration in the atmosphere.

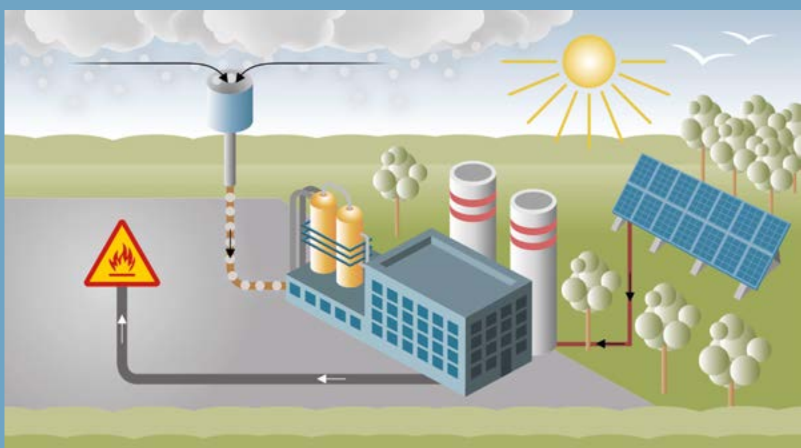


*Figure 10. Schematic representation of conversion of atmospheric $CO_2$.*

## EXPLOITATION OF THE SUBSURFACE FOR ENERGY STORAGE: COMPRESSED AIR ENERGY STORAGE (CAES)

CAES is a system for storing energy in the subsurface, such as in mines or caverns. Electricity is converted into compressed air, which is then stored in a subsurface reservoir. This is a way of storing surplus electricity. When energy is needed, the compressed air passes through a recuperator to drive a generator that converts its energy back into electricity. This technique would help the fluctuating supply of electricity from renewables to better align with energy demand.

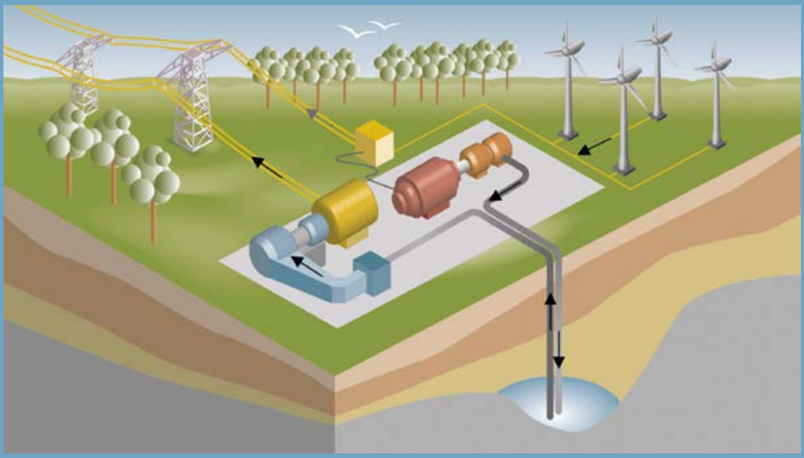


*Figure 11. CAES in the subsurface.*

## HYBRID ENERGY SYSTEM: GAS AND WIND ON THE NORTH SEA

In the North Sea gas fields, gas production is gradually declining. Moreover, the companies operating these fields know they need to reduce emissions from their production platforms. At the same time, wind farms are also being developed in the North Sea. As a result, the production of electrical wind energy will grow significantly in the coming years. Considerable investment in the North Sea electricity grid will be required to handle the additional energy produced.
The companies operating the gas fields, and those operating the wind farms, recognise that combining these two developments would be mutually beneficial. The production platforms could use electrical power generated by the wind farms. This would enable the production platforms to significantly reduce emissions. For the wind farms, it means grid expansion does not need to be so extensive, since specifications for peak loads would now be lower. Furthermore, any excess electricity generated by wind energy can be converted into hydrogen. This can then be stored or mixed into the gas lines.
This would be an explicit example of a hybrid energy system in the North Sea. One that cuts emissions while delivering benefits for oil and gas companies, wind energy operators and other stakeholders.

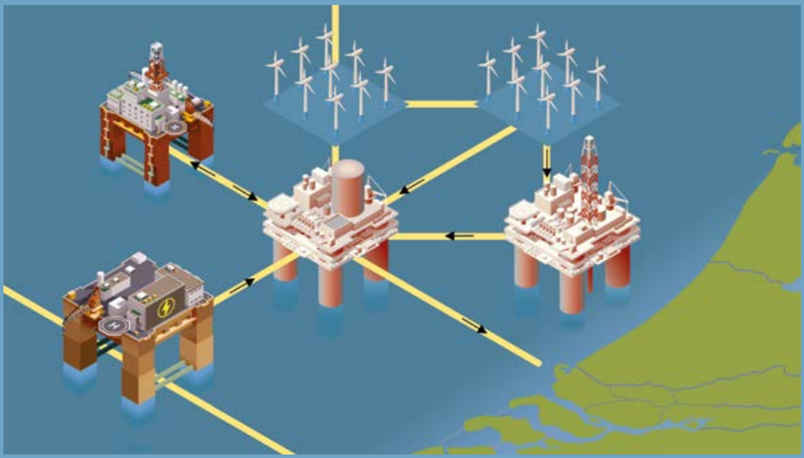


*Figure 12. North Sea hybrid energy system.*

TNO BRINGS PEOPLE AND KNOWLEDGE TOGETHER TO DEVELOP INNOVATIONS THAT ENHANCE THE COMPETITIVENESS OF COMPANIES AND THE WELFARE OF SOCIETY IN A WAY THAT IS SUSTAINABLE OVER THE LONG TERM.

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