The Sustainable Industry Lab

DRAFT for SIL discussion 27 September 2022

Contours of an aspired industry portfolio for the Netherlands

The Sustainable Industry Lab aims to synthesize knowledge related to the transformation of (Dutch) industry that follow from the ambition to reach net-zero emissions and work towards a circular economy. In this paper we synthesize knowledge on renewable technologies and resources to sketch the contours of an *aspired portfolio* of industrial activity in the Netherlands, circa mid-century.

An aspired portfolio requires us to think about our (national) aspirations: What society do we want to become? What level of consumption and material comfort or affluence do we aspire to? And: What contribution to global sustainable production do we want to make?

Answers to these questions can lead into very different directions, reflecting different choices that we will make in the decades ahead. In this paper we explore specifically what contribution the Netherlands can make to sustainable production. We consider the availability of renewable energy (mostly solar and wind) and the availability of circular carbon (i.e. carbon in biomass and waste) as key enablers of a sustainable industry portfolio.

We find that the resource position of the Netherlands, in combination with its geographic location, allows for a future portfolio with a significant share of basic industry, as today, should we choose to develop it. The main preconditions for this are massive deployment of offshore wind as the major energy resource, and the development of an international supply chain for the import of circular carbon, i.e. sustainable biomass and waste.

A portfolio-level assessment is useful as it can act as a touchstone for the plans of individual companies. Both renewable energy and circular carbon are effectively scare resources. Hence, while individual companies work to fulfill their own corporate ambitions, the portfolio approach allows us to check whether individual plans but *add up* to a portfolio of industrial activity that – at the national level – is plausible.

How to think about an Aspired Portfolio of Industrial Activity?

This work is inspired by the idea that the energy transition and the move towards a circular economy put constraints on industrial activity in a fundamental new ways. Even though the fossil fuels on which industry relies were a finite resource, it allowed for a century of effectively unconstrained growth. Ironically, in spite of their abundance and natural renewal, renewable resources are in practice a finite resource that puts real constraints on industrial activity. Hence, more than ever before, there is a need to consider limits on activity and hence to consider industrial activity at the portfolio level.

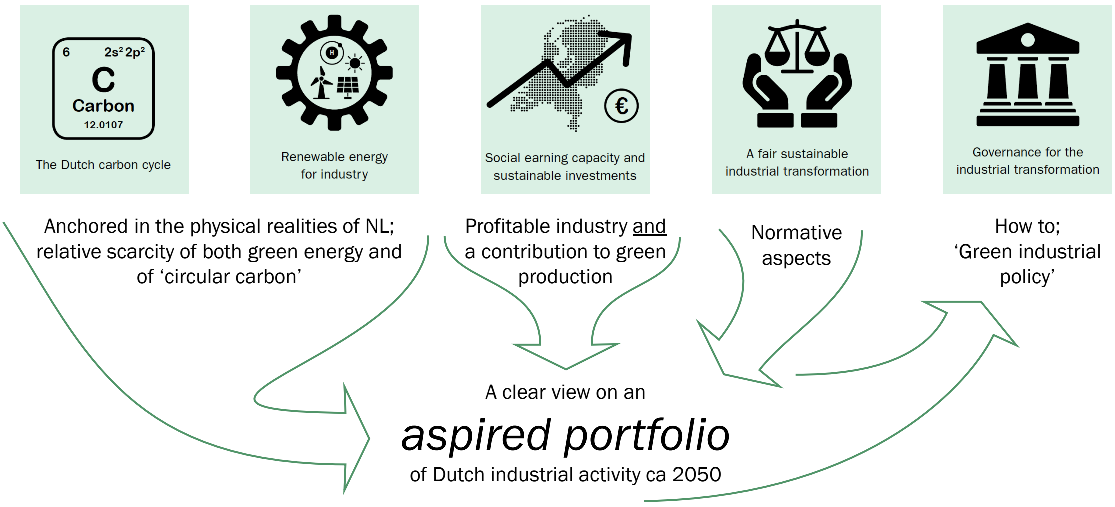

Figure 1: the five themes of the Sustainable Industry Lab, how they inform an aspired portfolio of industrial activity, and how this intern might inform governance under a green industry policy.

The Sustainable Industry Lab (SIL) intends the help articulate choices in the transition and their consequences. A portfolio of industry activity is not prescribed; it presents a choice (or choices). The choice must be informed by what is technically feasible and plausible, as well as what is socially and economically desirable. This is reflected in four of the five themes of SIL: 'energy' and 'carbon' frame the technical boundaries and are the focus of this paper. 'Economics' and 'fairness' are shorthand for the broader societal aspects that weigh in on a portfolio choice. The technical boundaries discussed in this paper are thus meant as a starter for a broader discussion on the future of industry in the Netherlands.

The analysis in this paper is in first instance a *technical* analysis of the amounts of renewable energy and circular (non-fossil) carbon that are needed to convert the *current* levels of consumption and production to meet the dual goals of climate neutrality and circularity. This is effectively portfolio development *absent* major changes in the structure of the economy or in consumption patterns, lifestyle and societal change. It thereby serves as an articulate, quantified starting point and reference for a discussion of precisely those questions. This fits with the mission of SIL to help a discussion on choices and consequences regarding the industry transformation.

Once we converge on a working consensus of the main elements of an aspired portfolio, it will provide guidance to what is presently discussed under the label of 'green industry policy' – a concept that itself needs further definition.

Climate Goals and Circularity

A key insight that has emerged only recently is that for industry transformation we must consider the impact of the energy transition side by side with that of circularity. In particular – and that is the focus here – the circularity of carbon across all industry products, both fuels and chemicals and materials. This is especially relevant for the chemical and petrochemical sectors, which are dominant in the current Dutch industry portfolio. In technical terms it means that we must consider not only scope 1 and 2 emissions, but also scope 3 emissions, i.e. the emissions of the products, whether in their use in the case of fuels, or at the end of life, as for materials. This effectively requires the full replacement of fossil carbon by carbon from biomass, waste (recyclate) or CO_2. This is illustrated in the figure below.

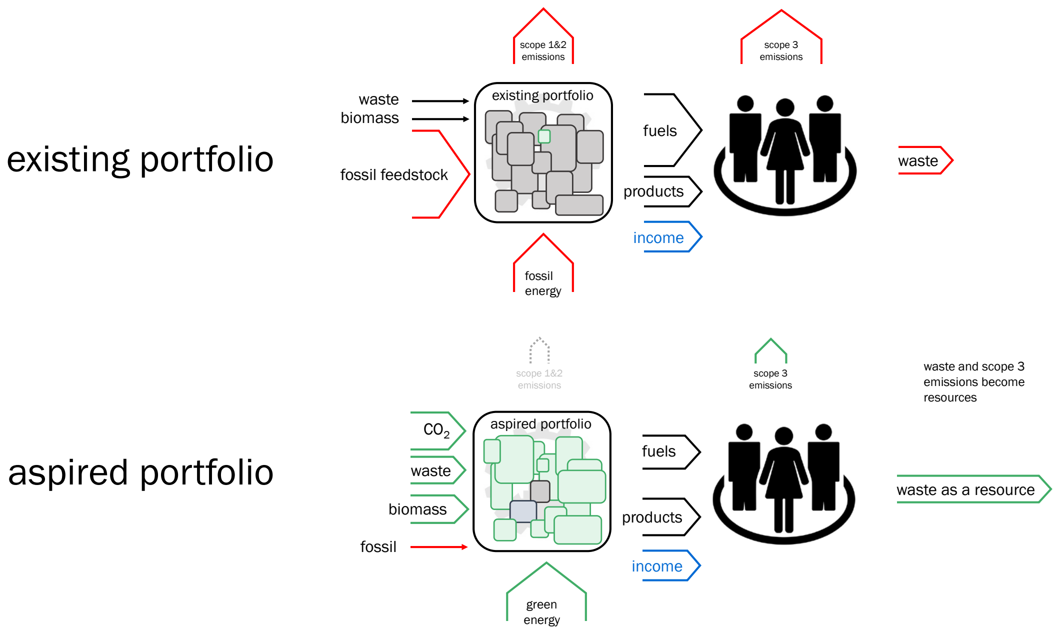

Figure 2: A schematic depiction of the change from the existing portfolio to an aspired portfolio, showing how the challenge to eliminate all emissions (scope 1, 2 and 3) implies a change to renewable (green) energy alongside circularity of carbon in all industry products.

Thus, industrial transformation presents a dual resource challenge: renewable energy to supply the energy needs for heat and power in industry and circular carbon as the new resource base for all future carbon-containing products of industry.

Industry Transformation – three constraints

Based on this high-level analysis we can identify three factors that are critical to the transformation. They provide the analytic framework for the analysis later in this paper. They are renewable energy, circular carbon and time. All three also act as constraints on a future industry portfolio, and the journey towards it.

Renewable energy – electricity and hydrogen

Based on the consensus view of the energy transition, renewable electricity, specifically wind and solar, will be the main sources of primary energy in the future, replacing fossil fuels. This implies that electricity becomes the prime energy carrier, driving an agenda of electrification across the whole energy system. The intermittency of wind and solar brings about the need for storage, while simultaneously the need for power-to-fuels conversion develops. For this electrolysis is the key technology, producing (green) hydrogen as primary fuel of choice in a solar and wind-dominated energy system.

While wind and solar are abundant and as such virtually unlimited, the reality is that the practical resource is limited. One reason is that renewable energy is much more dilute than the fossil fuels they replace. This makes space allocation and spatial planning a constraining factor. Comparatively speaking, the Netherlands is blessed with the proximity of the North Sea which has a unique potential for offshore wind development. This is the main source, especially for the upward expansion of the Dutch local (regional) energy resource.

Whether or not the future will see long-distance (intercontinental) transport of renewable power and green hydrogen is an open question that will be addressed later. We note here that its transport over intercontinental distances is costly and inefficient, making it a point of logic to *first* consider regional supply.

Circular carbon

Circular carbon comes in three (and only three) forms: biomass, waste and CO_2. There is arguable overlap between biomass and waste as waste contains a significant biogenic fraction. Therefore one may think recyclate a better term. But in terms of our analysis, they can be lumped together: both are mixtures of energy-rich hydrocarbon molecules that can be processed into new fuels, chemicals and materials. Processes range from mechanical and chemical recycling to pyrolysis and gasification. In order to maximize the carbon in products (and minimize loss as CO_2), energy, often in the form of (green) hydrogen, has to be added as reactants. The emerging industry vision is one where refining and base chemical industry are transformed from oil processing to biomass and waste processing.

Even more than renewable electricity, circular carbon is a scarce resource whose availability is constrained. In an idealized system, chemical products would be fully recycled, but the carbon of fuels is lost to the atmosphere, from which it is recycled through biogenic processes to biomass. This forces us to limit the use of hydrocarbon fuels to those sectors where no viable alternative exists (aviation being the most prominent example). It also forces us to maximize recycling rates of carbon-based chemicals and materials.

The technical and physical need for local resourcing of carbon is much less than for renewable electricity and hydrogen. The reason is that the long-distance logistics of industrial base materials including biomass and waste is much easier than electricity and hydrogen. Therefore, base materials and feedstocks will be transported to where the energy for conversion is available; it will not be the other way around.

The third carbon resource, CO_2, is not limited, but it is diluted and it requires very significant energy inputs in the form of green hydrogen to be converted into hydrocarbon fuels or chemicals. This means that CO_2 utilization (CCU) is de facto limited by energy availability.

Since our end state represents an energy-industrial system where fuels hydrocarbons fuels are solely used in heavy transport and not in industry – where hydrogen is the fuel of choice – no more point source CO_2 emissions from combustion. CO_2 will be present in the process gases of waste and biomass conversion plants, from which it may or may not be utilized.

The fallback alternative is direct air capture of CO_2. This is costly (both energy- and otherwise) and should be seen as an option of last resort and relevant to those locations that have an excess of renewable energy and green hydrogen that cannot otherwise be utilized.

Time

A third, very different type of constraint is time. We notionally put the timeline for the aspired portfolio in the year 2050, the year for which the Netherlands and the EU have pledged carbon neutrality. It is universally recognized that the timeline is very ambitious. While an energy system based on 100% renewable energy and full circularity is the aspiration, and therefore the basis of our aspired portfolio, meeting the target of climate neutrality can also be achieved by interim solutions. The most prominent one is carbon capture and storage (CCS) which opens up budget for the use of fossil fuels. This allows us to balance energy and carbon differently across energy and industry.

To the extent that such interim solutions are called on, it must be justified by showing that in this manner emission reductions are reached more effectively and resource and environmental pressures are relieved. None of this makes the notion of an aspired portfolio premised on 100% renewables and full circularity less relevant. It still acts as an reference point for the long term.

Corollary – technical efficiency as a guide

When both the key physical resources and time are constraint, efficiency is a paramount consideration. For our analysis of the aspired portfolio, it implies that across and the energy sector and across industry we seek to minimize conversions and conversion losses. This puts emphasis on (in this order) energy efficiency, electrification, hydrogen use and conversion of new carbon-based feedstocks to hydrocarbon fuels and products. It also informs the idea that a long-distance import of carbon feedstock is preferred over a long-distance import of electricity and hydrogen.

Industrial activity in the context of the Dutch energy system

In this section we illustrate what is perhaps *the* key insight into the energy transition in the Netherlands, namely that much of the uncertainty about the shape of the future energy system translates into uncertainty about the future of the national (heavy) industry portfolio.

The first observation is that the energy that goes around in industry, agriculture and logistics (essentially the movement of industrial raw materials and manufactured goods) is three times larger than the combined energy use by private citizens (residential energy use and personal transport) and the service sector. The former adds up to 2800 PJ/year; the latter is 900 PJ/year.

We represent this graphically by representing private energy use and service sector energy consumption as a circle at the center. They represent the core energy needs of the Netherlands, that sustains our personal energy needs, and – through the service sector – provides some 80% of national income at relatively low energy intensity.

The larger outer circle represents all the energy associated with industry, agriculture and logistics. We leave a wedge out of the circle to remind us of the open character of our economy and our industry and agriculture. There are both massive import and export flows of manufactured goods, which represent embodied energy.

Figure 3: a cartoon image of industry and the energy system: the inner circle is the energy for private end use and the service sector (900 PJ/year); the outer shell is energy in industry, agriculture and logistics (2800 PJ/year). The wedge illustrates the open character of our economy: Dutch industry produces for the world market and for our consumption we import industrial products from abroad. This represents a flow of 'embedded energy'.

The Dutch industrial portfolio is shaped by history and geography. The most significant factors were these: Firstly, our location on the delta of the main NW European rivers. Four of the five industry clusters are on the shore, with Rotterdam being a uniquely large harbor-industrial complex. Secondly the availability of cheap natural gas from the Groningen field. Both factors were favorable to the emergence of a profitable heavy industry, notably refining and chemicals.

How this portfolio gets reshaped over the course of the coming decades as the energy transition unfolds is for the moment an open question. If local energy availability (Groningen gas) and international logistics of raw materials (our delta location) shaped industry in the past as it continues to do in the present, we may use this as a guide to the future as well.

A closer look at energy

Having distinguished an inner core of energy use (personal and service) and an outer shell (industry and logistics) it is useful to subdivide these into the main uses and relate the numbers to the general rules of energy statistics. Once we have that, we are ready to explore the transition journey.

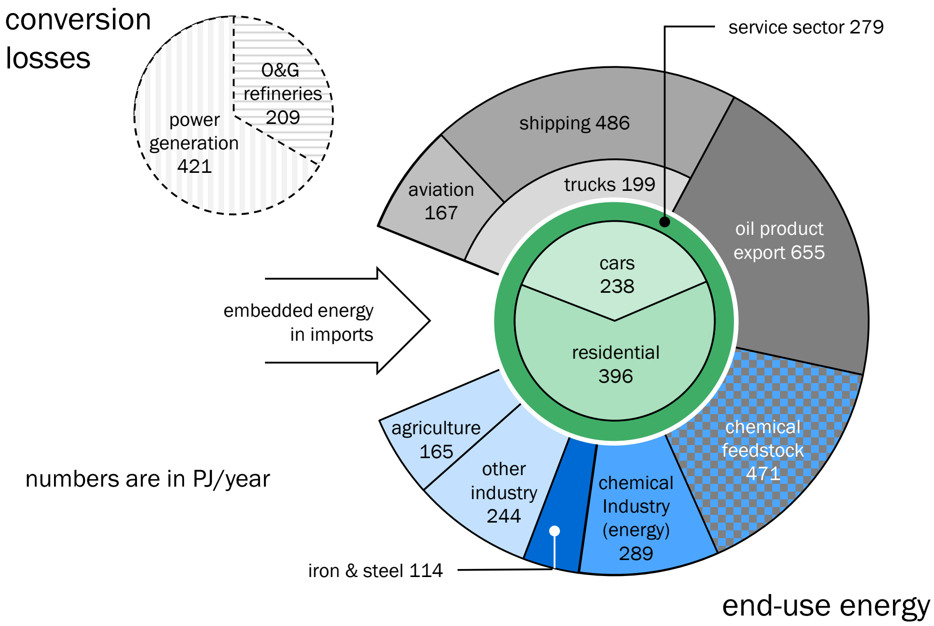

Figure 4: The numbers the energy diagram of figure 3. The inner core in greens is split between the personal energy end-use in the built environment (residential) and for personal mobility (cars) plus the energy used in the service sector. In the outer ring we identify in blues the energy used in industry, and in greys the oil products used in logistics, that are exported and – in blue/grey – the energy (oil fractions) that are used as chemical feedstock. The smaller circle on the left is the losses incurred in energy conversions in power generation and in refineries.

Figure 4 represents an unusual representation of the Dutch energy system and its statistics, that is designed specifically to bring out the challenges of industry in the energy transition. The large, colored circle captures all *end uses* of energy. This is the natural focus of our analysis, namely how we can make end use sustainable. Losses incurred in delivering end-use energy are secondary and are depicted by the shaded grey circle. They are the losses in thermal power generation (gas, coal, nuclear) and the losses in refineries and oil and gas production.

Three challenges

Different end-uses have been assigned different colors. Each of the colors represents both different sectors, as well a different type of transition challenge.

Energy for personal use and the service sector (913 PJ, in green)

Two thirds of the ca. 900 PJ is individual (private) end use for personal mobility (cars) and domestic energy consumption, mostly natural gas for heating and electricity for appliances. The final third is used in the service sector, in office buildings, hospitals, etc. The energy use in this sector is very much alike to residential, namely for heating and appliances. Together end in terms of the energy sector labeling, the green segment encompasses the build environment and personal mobility. As the energy transition unfolds we will see that electrification drives change. Both electrification of cars (electric vehicles, EVs) and electrification of heating (heat pumps) are the dominant technologies. As we will see, electrification will very significantly reduce energy consumption.

Energy use in industry and agriculture (812 PJ, in blue)

Energy use in industry is 650 PJ. When agriculture[1] is added, energy consumption in this combined production sector is roughly 800 PJ, not too different from the 900 PJ used in the built environment and personal mobility combined. Energy in industry is primarily used for heating (ca 500-550 PJ[2]); the remainder is used for motive power for compressors, pumps etc. Also here, electrification is an important part of the solution. Industrial heat pumps are expected to become significant for future provision of low-temperature heat and bring alone significant reduction in energy demand. High-temperature demand (ca 330 PJ), however, provides a different challenge. Heat pumps offer no viable alternative, which leaves direct (Ohmic) electric heating and hydrogen as the two viable non-hydrocarbon alternatives.

Oil product and chemical feedstock (1507 and 471 PJ, in grey)

This largest wedge contains the main outlets of oil products from Dutch refineries to various end use sectors, including feedstock for the chemical industry. (We have colored the latter a checkered blue grey to indicate its hybrid nature.) Much of what is in this wedge is outside of national energy statistics, which treats fuels for aviation and shipping as a form of export; oil products export is also outside the national scope. We deliberately

[1] Our treatment of agriculture is relatively light since our focus is on industry, more specifically on basic industry. Energy supply to greenhouses is a significant part of this and represents a specific challenge. For the remainder we treat it like “other industry”.

[2] Bron: Routekaart Elektrificatie.

include them in our diagram, because they are the products of our (current) industry, notably the refining industry. As we explore the transformation of the national industry portfolio, we need it in order to be able to assess production portfolio change in relation to changing patterns of demand. The left-most three wedges represent the hard-to-abate part of the transport sector: heavy duty (freight) transport, aviation and shipping. The net oil products export from the Netherlands is mostly gasoline and diesel. Finally chemical feedstock is by definition impossible to 'decarbonize' as its utility in the chemical industry is not to provide energy, but the carbon for chemical products. Because energy use in this wedge (with the exception of transport fuel export) is hard to decarbonize, we propose that in this domain the challenge is not primarily an energy challenge, but rather a carbon challenge. We do expect that this wedge will see reduced volumes due to electrification of road transport. But for what remains, the main challenge is a switch to alternative carbon feedstocks.

Our analysis is by design high-level and approximate. There is value in simplifying the complexity of the challenge as much as possible, without compromising the validity of the resulting analysis and conclusions. We believe that by separating the full complexity of the energy-industry transition into three different challenge domains, two of which represent energy challenges and one a carbon challenge, we get a clear view on the defining questions for the future industry portfolio.

Addressing the challenges (1): renewable energy

In the Supplementary Information[3] we provide details about the assumptions that underlie our analysis. Here we just relate the narrative of change. We cover the sectors in the same order as above.

We have noted at the outset that renewable electricity (wind and solar) will be the main sources of primary renewable energy. Therefore electrification takes precedence over hydrogen. This is ultimately an argument that rests on the demand of efficiency, which is of overarching importance.

Personal energy use and the service sector

For personal mobility, the advances in electric vehicles in the past decade makes it plausible that electrification of the car fleet will be driven to completion. Besides making cars emission free, it also reduces energy consumption by a factor three because of the superior energy efficiency of electric motors compared to combustion engines. Keeping other factors constant (a generic assumption in this analysis), energy demand for personal mobility would drop to ca. 80 PJ.

In the built environment, electrification of heating through heat pumps is the key technology. Given the diversity of the housing and building stock, and its longevity, heat pumps will not be as universal a solution as electric vehicles. Heat networks might well play a role. These could be fed by large-scale heat pumps (which would render them

[3] Not yet available.

equivalent for our analysis), but also by waste heat from industry. (Note that power stations, now a common source for waste heat, will be rare.) Our analysis is insufficiently granular to take this into account, and the uncertainties are too large anyway, so we assume that future energy (electricity) demand for heating is set by universal application of this technology. A prerequisite for this is that the insulation of the housing and building stock is improved. The dual approach of insulation and electrification with heat pumps leads to a significant reduction of energy demand which leads us to project a heat-related energy demand for houses and buildings would switch from 400 PJ of natural gas today to less than 100 PJ electricity by 2050.

In line with our generic ‘static’ assumptions for all that is not our prime focus, we assume that electricity demand will remain flat. We note that this may be an underestimation, especially in relation to electricity demand growth in the service sector, notably that for data centers.

Industrial energy use

As in the service sector and personal energy use, electrification comes first when considering industrial energy provision. In the short term hybrid electric/gas boilers offer a means to simultaneously decarbonize energy and provide demand flexibility, easing the strain on the power system from the intermittency of increasing wind and solar production. In the longer run natural gas can be replaced with hydrogen, both in boilers and in high-temperature furnaces. Full electrification of all types of energy demand is unlikely, so we anticipate a combination of electricity and hydrogen. Since (green) hydrogen production will take off anyhow when power production becomes dominated by wind and solar to utilize the green power in periods of renewable power oversupply. Once hydrogen is produced, the option to directly use it as a fuel rather than convert it back to power is attractive from a system perspective. Here industry is at an advantage because high-temperature heat provision meets that criterion. Also industry use makes the infrastructure challenge of hydrogen distribution manageable, especially in the case of the large industry clusters.

Whereas the transition leads to a very significant energy demand reduction in personal energy use and the service sector, this is less so for industry. The reasons for this are that i) energy in industry is already very efficient, ii) even low-temperature industrial heat is at a level where heat pumps are less efficient than in the built environment. Where hydrogen is used, it has no end-use efficiency gain over natural gas. In terms of primary energy, it actually requires more, as ca. 30% of electric energy is lost in the conversion of renewable power to green hydrogen.

With these high-level considerations which represent a technical consensus view of likely development, and as detailed in the Supplementary Information, we arrive at an estimate of 350 PJ final energy (power and hydrogen) and from 420 PJ primary green power. This is admittedly a crude approximation: neither change the use in other (light) industry or in agriculture is considered in detail. Nor does it take into account possibilities for other renewables, notably geothermal to play a (significant) in low-temperature heat supply. But is should be borne in mind that such assessments would be tentative. And since our focus in this work is naturally on the energy-intensive basic industries, our simple analysis still produces a useful estimate of the renewable energy from solar and wind that would supply the main of industry and agriculture. (We note that our numbers are in line with those of the both the II3050 outlook and the current TNO scenarios.)

Taking stock: green energy demand and domestic green power production

Before we move the third sector (oil products and chemical feedstock) it is useful to take stock of the future energy demand for power and hydrogen that we have identified so far and compare it to the projected local (i.e. Dutch) production. This is shown in Figure 5, where the future call on primary green power is plotted against the CO_2 abatement it affects as a sector switches from current to future energy provision. This number in kton of CO_2 abatement for every PJ of green power is useful as it points to the sequential order in which one would ideally proceed with the transition – working from highest to lowest.[4]

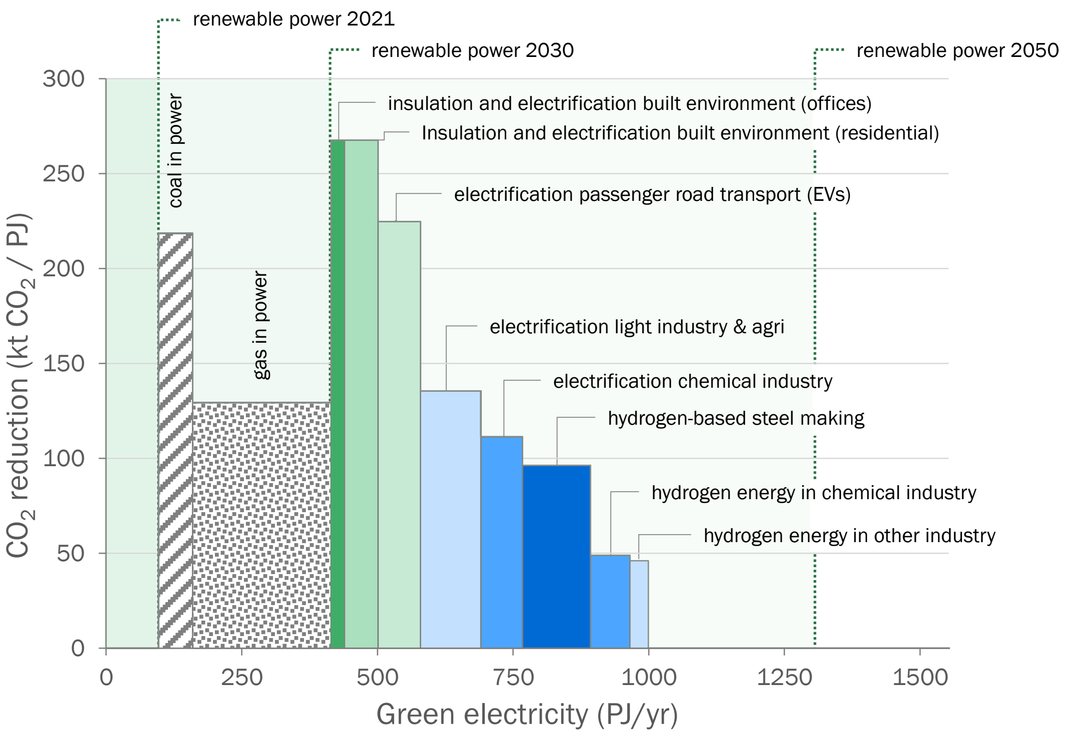

Figure 5: Primary green electricity requirement to decarbonize the power sector (in grey), personal energy use and the service sector (in green) and industrial energy use (in blue). The vertical scale gives for each type of use the CO_2 abatement resulting from today's energy usage to green electricity or green hydrogen. The backdrop shows the amounts of green power in the Netherlands in 2021 (the left-most line – because renewable power has increased so rapidly we have chosen here to use 2021 rather than 2019 which is otherwise our base year) and approximate figures for 2030 (according to the Klimaatakkoord). For 2050 we have used a high production scenario, dominated by 75 GW offshore wind.

[4] This is the concept of *emissionality*, a quantitative measurement that compares the impact of renewable energy projects on driving down emissions.

Two observations stand out:

Firstly that there are considerable differences in the abatement effectiveness for green power to displace current (fossil) energy use. The abatement is highest for electrification (in combination with insulation!) in the built environment, in electrification of road transport, and in phasing out coal-fired power generation. All these are priorities in this decade. Next in line are the phase-out of gas-fired power generation and electrification in industry. Green hydrogen has the lowest abatement effectiveness, due to both conversion losses in its production and the absence of efficiency gains in end use. The highest abatement value is for hydrogen in the iron and steel industry because it replaces coal rather than mostly gas, which is replaced in other industries. As we manage our way through the transition it is important to try and deviate not too much from this logical order, in order to achieve emissions reduction fastest and most effectively.

Secondly, the total primary energy demand for the sectors considered so far adds up to ca. 1000 PJ/yr. This is 280 TWh (the conventional unit in which electric energy is measured), which is almost two and a half times the current power production in the Netherlands of 115 TWh (2019).

Of the 1000 PJ primary electric energy, 770 PJ (215 TWh) is used as electricity, close to double the current use. The remaining 230 PJ is converted to 160 PJ of green hydrogen for use in industry. This would require some 15 GW of electrolyser capacity at 50% utilization. This is roughly one and a half times the current Dutch hydrogen consumption. But whereas the latter is used as a chemical reactant in chemical conversions in refineries and chemical plants, this green hydrogen would be for energy production. It is thus all *new* hydrogen demand as today hydrogen is not used for energy purposes. (We come to conversions later.)

1000 PJ of green power demand is well within scope of what the Netherlands envisages it can produce if offshore wind build-out on the North Sea is vigorously pursued. Proposals go up to 75 GW or higher. This number has been used in the figure. (There is considerable onshore wind and solar as well, but the main source of renewable expansion of the Dutch generation potential is in offshore wind.)

But we have not yet considered the energy required for third challenge, oil products and chemical feedstock.

Oil products and chemical feedstock

The third challenge is to find sustainable, circular alternatives for the use of oil products in hard-to-abate energy sectors (freight transport, shipping and aviation) and chemical feedstock. We have also included here the export of oil products form the (large) Dutch refining sector. This is not normally included in national energy statistics. We have chosen to include it, because the refining sector is a large part the of Dutch industry portfolio.

Our first approach should be to consider how much of this is likely to be replaced, and what is the remaining demand for fuels and chemical products.

If we look at the three subsectors of transport (freight transport, shipping and aviation), we know that for each of them alternative (non-hydrocarbon) options are being considered.

The main carbon-free alternatives are hydrogen and ammonia. It is impossible to say how much inroads these will have made by 2050, but it is fair to assume – as most scenarios do – that hydrogen and ammonia replacement across these transport modes will be partial. To cut through the complexity and intractability we will assume that freight transport will switch to hydrogen, and that aviation and shipping will continue to rely on hydrocarbon fuels. (The reality might show a more mixed picture, but what matters is that this, in terms of decarbonization, is still quite an aggressive assumption on the penetration of alternative fuels.)

The fuel switch for domestic freight transport from diesel (199 PJ in 2019) to hydrogen would require ca 130 PJ hydrogen for which 190 PJ of green power is needed. This should the added to the 1000 PJ. The abatement is 77 kton CO_2/PJ, which puts the abatement effectiveness of hydrogen in transport in between hydrogen use in different industry sectors.

With road transport switching to electric (cars) and hydrogen (trucks), the market for gasoline and diesel would be very significantly reduced and along with that the fuel export. Directionally, this is understood by the refining sector, even if remaining market share is unsure. Based on our assumptions, the total of hydrocarbon fuels produced in the Netherlands would go down from 1745 PJ in 2019 to 650 PJ, that is a two-third reduction in fuel production and delivery.

Chemical feedstock is used specifically for its carbon to produce the rich variety of carbon-based products that society uses. Also, globally the chemical industry will see its total product volume grow. As a consequence, there is no a priori reason to assume that Dutch production will shrink. So in line with our logic to explore the development of the Dutch portfolio without change other than implied by the direct impact of the energy transition, we assume that the demand for carbon as feedstock will remain constant.

Adding the feedstock demand to the remaining hydrocarbon fuel demand gives ca 1300 PJ of remaining hydrocarbon demand, down from 2200 PJ in 2021. 1300 PJ is more than the sum total of the estimated future primary demand for power and hydrogen to service the other sectors combined (see earlier). The carbon content of these streams is ca. 23 Mton of pure carbon, down from 47 Mton in 2019.

We argue that seeking alternatives for this carbon demand for Dutch industry is first and foremost a carbon resourcing issue. The reason for this is that the only abundant source of circular carbon is CO_2. Conversion of CO_2 to products is often called CCU (carbon capture and utilization). One would need to convert 85 Mton of CO_2 to produce the 1300 PJ of hydrocarbons. This would require ca 3500 PJ of primary green power for (air) capture of CO_2 and for the production of green hydrogen to convert the CO_2 to useful products. This is completely out of range in relation to energy availability. We note that importing energy (in the form of hydrogen) to drive CCU is rather farfetched since one would rather do CCU in a place where energy is abundant.

This shows that CO_2 and CCU can only play a minor role in making carbon circular. This might be in the conversion of CO and CO_2 containing waste gases from future conversions. The Dutch renewable energy resource position is insufficient to allow for carbon conversion staring from air-captured CO_2. Thus, the sources of a future Dutch circular fuels and chemicals industry must be biomass and waste.

This brings us to the second constraint after energy, namely that of circular carbon.

Addressing the challenges (2): circular carbon

This demand and supply outlook is shown in Figure 6, below. As discussed above we expect that the natural demand reduction following from the unfolding of the energy transition will approximately halve the product volume from 47 to 23 MtonC, with the fuels/chemicals split going from roughly 75:25 to 50:50.

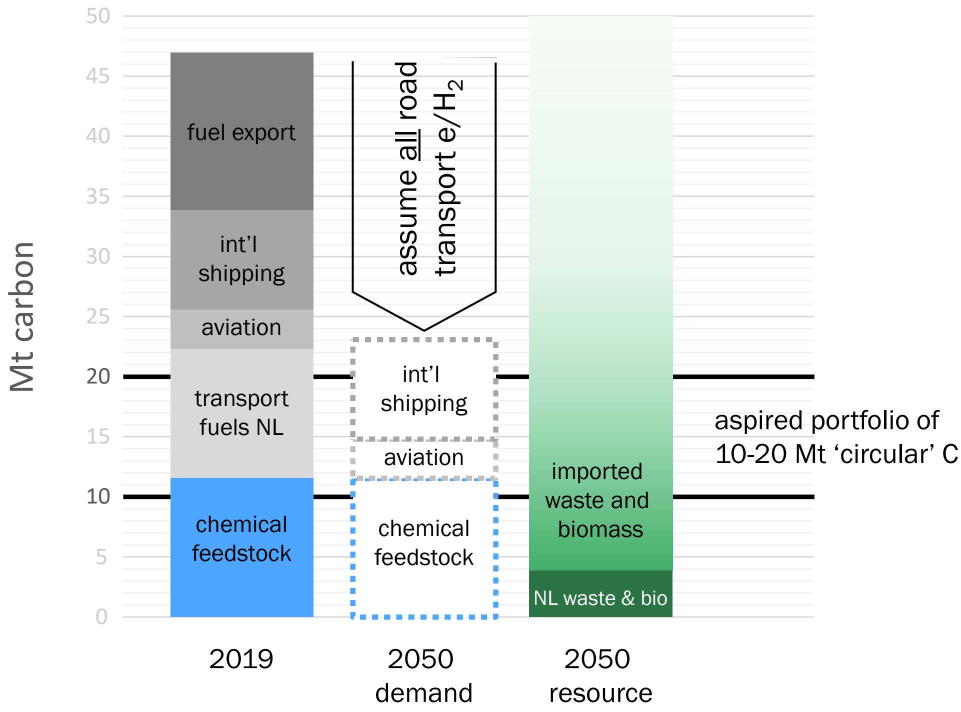

Figure 6: The current situation and the outlook for the challenge area of oil products and chemical feedstock. The 2019 product slate is almost entirely oil-based and corresponds to ca. 1 million barrels per day of oil. The 2050 demand outlook is based on assumptions discussed in the text. The 2050 resource outlook illustrates that domestic resources of circular carbon (biomass and waste) fall very much short of resourcing what could be the level for an aspired portfolio: 10-20 MtonC.

We saw earlier that for those energy challenges where electricity and hydrogen is a solution, the Netherlands could be largely self-supporting. This is not the case for the challenge of carbon-based fuels and chemical feedstock. For an export-oriented industry (90% of the Dutch chemical production is exported), circularity implies a return import at end of life. For chemicals (and necessarily for fuels), the carbon losses have to ultimately made up from atmospheric CO_2. As argued above, the artificial synthetic route of air capture and CCU is not scalable in the Netherlands. Hence biogenic carbon (biomass) is necessarily the other major source of a carbon for industry. A rough estimate of the local

Dutch resource of biomass and waste that would be available for industrial conversion would be 3 MtonC. This falls far short of the requirement to sustain the level of basic industrial activity in the fuels and chemicals sector at a level that is commensurate with the today's even taking into account the expected and very significant reduction in hydrocarbon fuel demand.

Carbon is more constraint than energy

The corollary of the analysis so far is that Dutch resource position for circular carbon (bio and waste) is more limiting than energy. This is at odds with the current focus of discussions, which is very much on import of green hydrogen and derivatives.

Finally, to complete the picture of carbon *and* energy, we must look at the energy requirements for conversion of circular carbon feedstock to products.

Green energy for future carbon conversions

As said, in a circular system, biomass and waste are resources that are valued primarily for their carbon, and second only for their energy. To reiterate, this is so because carbon is scarcer that renewable energy in the form of power from wind and solar and green hydrogen. The challenge for the future portfolio of chemical conversion plants is thus to maximize the fraction of resource carbon that ends up in products (fuels and chemicals). This requires energy, mostly in the form of (green) hydrogen.

Biomass and waste and waste have a lower energy density than the product chemicals and fuels. Biomass and waste have an energy content of circa 34 PJ/MtC; the product circa 50 PJ/MtC. (As throughout this paper, we use rough numbers to make our argument.)

Waste that is not recycled is incinerated for power and heat. This will have to change in order to achieve carbon circularity. For waste recycling, the hierarchy is as follows: mechanical recycling comes first, then chemical recycling, followed by pyrolysis and gasification. The backstop is combustion followed by CCU. For the first processes (up to pyrolysis), there are (significant) limitations to the feedstock. Mechanical and chemical recycling requires specific plastic waste streams, and – to a lesser extent – does pyrolysis. The upside is that the energy inputs for these processes is relatively minor. This changes when we proceed to gasification. Gasification is a more omnivorous process wherein a carbon-containing feedstock is converted to synthesis gas (a mixture of CO and hydrogen), from which the full range of hydrocarbon products can be synthesized. But it comes at the cost of a significant energy input in the form of hydrogen that is required to steer a large fraction of carbon to the products and avoid CO_2. Combustion and CCU is really a backstop route as the net energy input for CCU is very high.

Current practice in biomass conversion (e.g. to biofuel) is to burn part of the carbon to provide the energy for the conversion of the remainder. This typically lead to 50% carbon efficiency in biomass-to-biofuel conversion, with the other half ending up as CO_2. If a higher fraction of the feedstock carbon is to be retained in the products, then gasification is one of the key pathways, with similar characteristics as for waste conversion.

Based on this general understanding it is possible to construct a conceptual graph of the net energy requirement for the conversion of an aspired 20MtC from waste and biomass into products. This is shown in Figure 7. Plotted on the horizontal axis is the mass of carbon contained in products. When no carbon is converted to products, its use is combustion for power and. Of the 680 PJ of energy contained in the 20 MtC, typically 70% would be useful energy (power and heat), so in this case some 480 PJ would be delivered to society – hence a negative net energy *requirement*. If the full 20 MtC of biomass and waste carbon were converted into products, the energy content would by 320 PJ higher than of the source materials (680 PJ feedstock, 1000 PJ product). Therefore, full conversion of 20 MtC carbon to products will require a net energy input of more than 320 PJ.

Going from left to right and adhering to the hierarchy of conversion/recycling processes outlined above, first have the processes that are selective with respect to feedstock but low on energy demand. In our baseline assumption (thick line) we assume that 20% of all carbon is converted via these routes. Next is gasification which we see as the main omnivorous route to products. But it comes at a higher energy cost, shown by the steeper slope of the line. In the base case we have assumed that 70% of all biomass and waste would be gasified. All processes (with the exception of mechanical recycling) produce some CO_2 even when the lineup is such as to minimize it. This means that in order to reach 100% carbon conversion, some CCU will always be needs. In our baseline scenario this would be 10% from waste (2 MtC) that is combusted, plus the process CO_2 from the all other conversions, some 3 MtC. CCU is very energy demanding, so the line rises steeply.

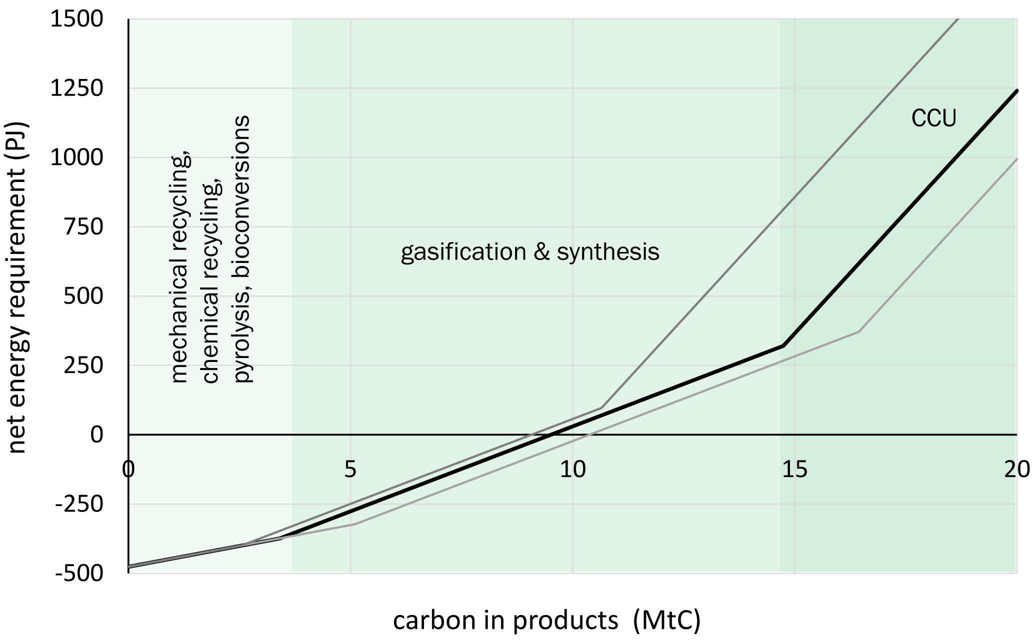

Figure 7: Net energy requirement for the conversion of 20 MtC to products. When carbon is not converted to products it is assumed to be incinerated for power and heat. Hence at zero carbon-to-products, the net energy requirement is negative, i.e. energy is delivered to society. With increasing conversion to products the net energy balance changes sign and additional energy is required for the conversions. The thick line is the base case discussed in the text. The thin lines are alternative cases.

Variations on the base case are plotted as thin lines: a low-conversion case with 15% mild conversions and 50% gasification, and a high-conversion case with 30% and 70%.

Putting the energy requirement in context, we see that up to 75% conversion of carbon to products (15 MtC) is an approximate limit of what is feasible based on our technology choices and their approximate characteristics (specifically CO_2 from process gases) for process options other than CCU. At this level of conversion of 20 MtC the green energy (primary electricity – wind and solar) requirement is ca. 300 PJ. This would fit in a realistic but aggressive scope of development of renewables in the Netherlands as discussed above and illustrated in Figure 5.

Beyond that and resorting to CCU pushes the energy requirements beyond the current 'ceiling' (which is never hard, of course) and gives a poor return on energy - as inherent in CCU. This is not a hard argument against CCU, but it shows that it logically the option of last resort.

Since the ambition we set out to fulfil is carbon neutrality, it does follow that if the remaining CO_2 is not utilized, it should be stored. This brings us to the topic of CCS which we have so far avoided. But we have now come to the end of our exploration of the fully renewables based Dutch energy system hosting a carbon-circular industry. In this narrative, CCS is the technical fallback that is needed to close the carbon balance, as when CCU is not viable, but also when technology performance and or technology penetration and falls short of the aspirations and assumptions, or when transition time constraints force it in.

Addressing the challenges (3): the journey through time

In the above analysis we have been very optimistic about the scope and penetration of electrification and hydrogen, about the possibilities of carbon circularity, and about the pace of change. We have also assumed that the transition journey would be completed by 2050. If we fall short in any of this, we fall short on the emissions target. In order to still meet the net-zero emission target by 2050, the only technical option is carbon capture and storage (CCS). Capture be applied to fossil or biogenic CO_2 emissions from point sources, specifically in industry. When biogenic CO_2 is sequestered this creates negative emissions, which can be used to offset fossil emissions elsewhere.

It is generally acknowledged that CCS buys time. It should not in any way diminish the pace of renewables roll-out. But it may be necessary when the feasible pace falls short of the required pace to meet net-zero by 2050. It is noted that what is feasible is highly contentious, which points to the fact that the scale and duration of CCS as a mitigation option is a societal choice that lies before us.

But can CCS in any way change the view of the portfolio that we developed. The answer to that is: Not in the very long term, but definitely in the medium term. In the very long term, there is an inevitable drift towards the all-renewables, fully-circular scenario. So our analysis does provide guidance in that respect. The boundary conditions of the aspired portfolio (energy and carbon) to assess whether certain types of industry are plausible in the Netherlands in long term.

The journey through time is directly related to the choices we make in relation to the aspired portfolio. To this we now turn.

This concludes our technical analysis of an aspired portfolio of industrial activity with a strong focus on basic industry, because that is where the impact of the energy transition is most profound. Based on a natural evolution of the *existing* portfolio and the availability of green energy and circular carbon, we have sketched the rough outlines of what a future basic industrial portfolio *could* be. This serves are the starting point for a debate, which is ultimately a societal debate, about the choices that are needed to build such a portfolio. Below we highlight a number of them.

Choices for an Aspired Portfolio

The text below is specifically meant to be a discussion starter on 27 September

How large a basic industry portfolio does the Netherlands aspire to? This is a profound, normative. In discussing the findings of the analysis in this paper, this question always comes up. From the perspective of global technical effectiveness, industry should be located where future resources and logistics are most favorable. The Netherland has a strong renewable energy resource base from offshore wind, a prime location in the delta of NW Europe and a strong legacy portfolio. Do we aspire to maximize the use of this resource and to make as large a contribution as is resource-wise feasible to the global demand for sustainable basic industry products? Or do we start from a more restrained perspective by not taking present global production and consumption as a starting point and anticipating lower volumes, different products and more local production in a future world? These are but two lines of argumentation that bookend a complex discussion.

What is the role of energy and carbon imports? Related to the previous question, but different in scope is the role of energy and carbon imports. It plays out mostly for ambitious portfolio choices. We saw that the technical assessment for the Netherlands points to a high share of local energy production, while domestic carbon is more limited. But one can argue that import requirements are better considered at the scale of NW Europe. Carbon sourcing, notably of biocarbon, is a controversial topic, but one that we have to come to grips with in the light of the continued need for carbon as an industrial feedstock. Green energy is less contentious but import raises the question who the plausible exporters are. This is not so much a commercial issue (even though the price tag of import may be high), but just as much an issue of global transition efficiency. Should not exporters have made their own energy supply renewable first? If so, this clearly has an impact on the timeline. Finally, should energy imports be seen as a source of energy to fuel industry? Or will it rather be import of end-use fuel (for marine and aviation) or industrial feedstock? And if it is to fuel *basic* industry, isn't relocating that industry economically more attractive – since basic industry tends to locate in places of cheap energy.

Are climate change and circularity targets of equal importance? In this paper we have treated the two as equally important. Arguably, climate change mitigation has a greater priority. At the same time, the two objectives come together in the need to close the carbon loop. Are carbon-based fuels to be treated differently in policy that carbon-based, long-lived products? Or is it better to consider the carbon pool in total and direct policy towards conversion routes of optimal carbon- and energy efficiency, irrespective of the nature of the products? Specific policy choices that play out at the interface between emissions reduction and circularity are: How to incentivize CCU in relation to other carbon conversions; Whether to treat recycled carbon from waste different from biogenic carbon; and Whether to value circular carbon differently for fuels or for chemical products.

What is the timescale on which portfolio questions play out? A third choice is to decide when this type of questions need to be answered. They are of a type that defy quick answers and might take the form of a consensus that slowly develops over time. If so, choices are made not as future portfolio choices, but rather on the momentary merit of individual projects. This seems to be at odds with the notion that more central guidance is called for. Notably for the sizing and time of energy infrastructure, a long term perspective is helpful even now. The same goes for decisions on transition technologies, notably CCS.

Fourthly, we want to highlight a key uncertainty hanging over the choices:

What are the timelines of new technology development and deployment? The key technologies on which the technical story of this paper critically depends are electrolysis for production hydrogen and the suit of circular carbon conversion technologies. All of these exists in some form, but as a whole the set of carbon conversion technologies is not yet matured; electrolysis is at a late development stage, but the electrolyser industry has yet to be established. The EU and Dutch 2030 targets on green hydrogen are enormously challenging. At the same time, green hydrogen availability is a pacesetter for the transition, which could adversely impact the timeline of the transition in industry. By using CCS for blue hydrogen production one could decouple the deployment timelines of electrolysis and novel carbon conversion technologies that depend on hydrogen.

In summary, we set out to sketch the contours of a future industry portfolio in the most general terms: energy and carbon requirement and find that they lead to a set of difficult, societal choices to be made under significant uncertainty. We hope that the analysis in this paper is helpful to that discussion.

About this paper and the Sustainable Industry Lab

The Sustainable Industry Lab (SIL) distils important choices and their consequences of the industrial sustainable transformation between 2020 and 2050. By means of synthesizing academic and expert knowledge, SIL aims to improve the quality of the societal and political debate to reach a carbon-neutral Dutch industry by 2050. Over the next five years, SIL will work on academic and policy papers, informing society and policy makers on the consequences of certain choices. This perspective is the second in a series.

The paper was written by **Gert Jan Kramer** based on discussions with the following team:

- **Bert Bosman*** (SABIC)
- **Martijn Broekhof** (VNCI)
- **Wouter Jongepier*** (Westlake Chemical)
- **Sascha Kersten*** (U Twente),
- **Sikke Klein** (Nobian)
- **Coby van der Linde*** (CIEP)
- **Wouter Meiring*** (Shell)
- **Paco Rutten** (ISPT)
- **Geoffrey Schouten** (ISPT)
- **Diana Visser*** (Corbion)
- **Ester van der Voet*** (U Leiden),
- **Ernst Worrell*** (U Utrecht)
- **Kira West** (TNO)

* SIL members.