Brightsite Transition Outlook 2023

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Transforming industry

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With only 27 years to go until our climate-neutral target, there is a scarcity of raw materials, land area, CO_2-free energy, time and labour. What's more, the raw materials transition for the chemical industry forms part of a much wider societal system transition, with societal acceptance constituting the most important driver underlying the transition.

Summary

Collectively – companies, research institutes and authorities – achieving climate goals at Chemelot and shaping a future sustainable circular economy

Brightsite Transition Outlook (BTO) 2023 has been formulated for companies, research institutes, policymakers and support organisations that are collectively shaping the raw materials transition for the chemical industry. A fictional chemical complex, CHEM-NL, encompassing the entirety of the Netherlands' ethylene and ammonia production, is shedding light on the requisite renewable raw materials and energy.

Ethylene and ammonia are indispensable basic chemicals for plastics, food supply and related industries. Hence making these environmentally friendly is important for society. The carbon (C) and hydrogen (H) atoms currently obtained from petroleum and natural gas will in future be obtained from four possible renewable sources: waste, biomass, atmospheric CO_2 and water. With this complex raw materials transition in mind, the Chemelot Integral Model System (CIMS) is modelling a fictional chemical complex, CHEM-NL, to design optimal transition pathways towards net zero emissions by 2050 based on assumptions vis-à-vis costs, technologies and availability of raw materials. Production volumes of plastic and fertiliser by 2050 have been presumed to be at current levels.

Significant findings

- The raw materials transition will result in scarcity of available renewable raw materials, thereby necessitating maximally efficient management of usage. Plastic waste is optimal for the chemical industry, meaning that the highest priority will be to continue developing recycling and circularity.
- The lower energy content of renewable raw materials will push up the need for CO_2-free energy significantly, on top of the requirement for the energy transition.
- This additional energy requirement can be contained by means of a rational approach that entails selecting and developing available raw materials (plastic waste, various bio-based raw materials, mixed waste) based on minimum energy requirements for reprocessing. Subject to availability, atmospheric CO_2 will then have to be harnessed, which will require a great deal more energy.
- Optimal integration of the processing of renewable raw materials for plastics could generate hydrogen as a co-product, e.g. for ammonia preparation.
- The transition will introduce new technologies, such as electrification in existing processes. Gasification and plasma will open up new routes to chemicals and circularity, and the same goes for biomass to new, efficient biopolymers and bio applications.
- The raw materials transition is inextricable from a sustainable approach to industrial water usage.
- Industrial transition will have major consequences for society and will require a proactive approach entailing the participation of citizens.

Significant recommendations

A systemic approach is required if we are to achieve efficient circularity entailing maximally efficient management of energy and raw materials. Developments will need to proceed accordingly and in parallel:

- Creating large-scale, efficient cycles for current and new (bio)materials, with growth in volume and topping up losses from renewable sources: raw material extraction and production of chemical building blocks from waste, sustainable biomass and in the long run from atmospheric carbon dioxide. Plus robust technology for production of chemical building blocks and hydrogen.
- Electrification of high-temperature processes, disruptive technologies such as plasma activation
- Development of accompanying infrastructure
- Development of responsible industrial water usage
- Organising societal support through participation

In view of the demand for renewable energy and raw materials that are in short supply, scarcity is likely to become more acute.

- Regulation of the demand from various sectors will be a prerequisite for an efficient societal transition towards a sustainable circular society.

René Slaghek
Technology Manager Brightsite

Scarcity of sustainable raw materials is a challenge for the transition of the chemical industry towards 2050

The temperature on Venus is approximately 500°C at a pressure of about 90 atmospheres: the greenhouse effect is responsible for this. The atmosphere contains 96% carbon dioxide (CO_2) and a cloud cover with sulphuric acid and dust that traps solar heat. When the planets formed billions of years ago, Venus and the Earth had similar atmospheres, with an estimated 25-50% CO_2.

Volcanic activity probably released large amounts of CO_2 into the atmosphere on Venus, which amplified the greenhouse effect. The rising temperature eventually pushed water out of the atmosphere. In the meantime, life developed on Earth, first as small crustaceans and later as plants. These life forms caused sequestration of CO_2 from the atmosphere, causing the CO_2 concentration to drop (to about 280 ppm parts per million around 1750, before industrialisation) and the oxygen concentration to increase to about 21% now. Over billions of years, all that CO_2 from the atmosphere ended up in the crust in the form of rocks – the marl in South Limburg and the White Cliffs of Dover – and huge supplies of oil, gas and coal.

Over the last one hundred and fifty years, humans have discovered how these riches contribute to increasing our prosperity and comfort. We turn marl into cement to build houses, buildings, bridges and roads. We use oil, gas and coal for energy supply and the production of all kinds of products. However, using these fossil raw materials puts CO_2 back into the atmosphere, returning it faster than the earth can absorb it. As a result, CO_2 concentration has now risen (to over 400 ppm) and that is causing climate change. In order to curb climate change, we aim to reduce CO_2 emissions from fossil raw materials (limestone, oil, gas and coal). The ultimate aim is to discontinue our use of fossil raw materials. All this sounds logical, but with a growing world population, will we be able to maintain or even improve our prosperity and well-being if we stop using fossil raw materials?

Where do the non-fossil raw materials for our energy and material needs come from?

We are only at the beginning of the transition to renewable energy and green raw materials. Replacing 'fossil' is a huge challenge. Fossil carbon is woven into our society; only 14% currently comes from renewable sources. Renewable carbon and energy are scarce.

Arnold Stokking
Managing Director Brightsite

The quantities of non-fossil carbon available from such sources as recycling plastic and biomass are still far from sufficient, and the same applies to renewable energy. There will be competition for green raw materials and renewable energy.

Accelerating the process of becoming sustainable will only be possible if we are able to eliminate the scarcity of green carbon and energy and prevent inefficient use.

This requires direction across sectors. At Brightsite, we come up with solutions, substantiated by quantitative analysis. We find the best transition paths for using renewable resources as efficiently as possible. In each of our six programme lines, we are examining which (technological) choices need to be made, in conjunction with society, in order to make the chemical industry in the Netherlands more sustainable. To this end, a systemic approach has been developed that will help us get a grip on the many possibilities and actions. An approach that shows the economic and climate effects of choices and policies. In this regard, we are looking beyond the system level of Chemelot. The focus is on the Dutch chemical industry and on consequences at national level, taking safety and societal impact into consideration. The transition is complex and choices have a major impact. For example, an electric car is up to three times as energy-efficient as a hydrogen car: by choosing hydrogen, you 'cannibalise' scarce, clean energy that can no longer be used by other sectors or applications.

The transition to climate neutral requires a vision and many choices towards the ultimate target by 2050, as well as identify interim solutions to get there.

For example, the priority around alternative raw materials is now focused on plastic waste, as this is the most similar to fossil raw material and can be efficiently reprocessed for existing plants. Biogenic sources, if sustainable, are the next best route and they will need to be given greater attention later on, because there is simply far too little waste available for the production of new plastics. There is also scope for CO_2 capture from the air in future, assuming there is sufficient CO_2-free energy for this energy-intensive process.

Transitioning chemistry: energy and raw materials

Today's chemical industry is part of a linear economy that extracts fossil fuels (oil, natural gas and coal) from the earth and, to a large extent, burns them to meet our energy needs. In order to meet national and European climate targets, the burning of fossil material must be stopped. The chemical industry will thus be forced to switch to alternative energy sources, such as CO_2-free electricity or energy carriers.

This **energy transition** will eliminate CO_2 emissions at the chemical site, the so-called Scope 1 emissions[1]. The chemical industry also uses petroleum and natural gas as raw materials and turns them into materials. This way, fresh fossil carbon also ends up in plastics. CO_2 and methane are released upstream of the chemical industry during oil and natural gas extraction and downstream when plastic waste is incinerated or decomposes in landfills or in the environment: the so-called Scope 3 emissions. These emissions must also be avoided: for a chemical site, these Scope 3 emissions even far exceed the Scope 1 emissions.

However, abolishing carbon per se is not possible: there is no alternative, but there are carbon sources other than fossil oil or natural gas. The conversion of the chemical industry to these alternatives is the so-called raw material or carbon transition.

Alternative raw materials very scarce
Alternative raw materials include biomass and CO_2 from the atmosphere. These preserve the possibility of fostering a linear economy, in which there is no recycling. '*No more fossil energy, carbon only from biomass and atmospheric CO_2; making all plastics biodegradable or burning them as waste for energy recovery*': would such a vision not be the easiest one? The **circular economy** is a term in common usage, often seen as something self-evident. In a circular economy, plastic waste is (re)used as a raw material and is not incinerated, and biomass and atmospheric CO_2 are added to make up for losses. Is circular better than linear? Yes. Is circular *always* better? No, definitely not. So when is it and when is it not, and why? And how can the chemical industry's raw material transition to a circular economy be encouraged? What policy is required for this? These are very relevant questions.

Only an integrated approach will generate answers and, more importantly, transparency around issues and options, rational levers for encouraging the raw materials transition within the chemical industry and other sectors of society. In order to scrutinise these complex challenges in greater detail, a fictitious chemical site called **CHEM-NL** has been created. CHEM-NL produces the Netherlands production of ammonia (3 Megatonnes per year, Mt) and ethylene (4 Mt), in both 2021 and 2050.

This Brightsite Transition Outlook showcases why scarcity and sustainable circularity are important and what is needed to achieve climate neutrality.

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[1] See Brightsite Transition Outlook 2022 for an explanation on Scope 1, 2 and 3 emissions.

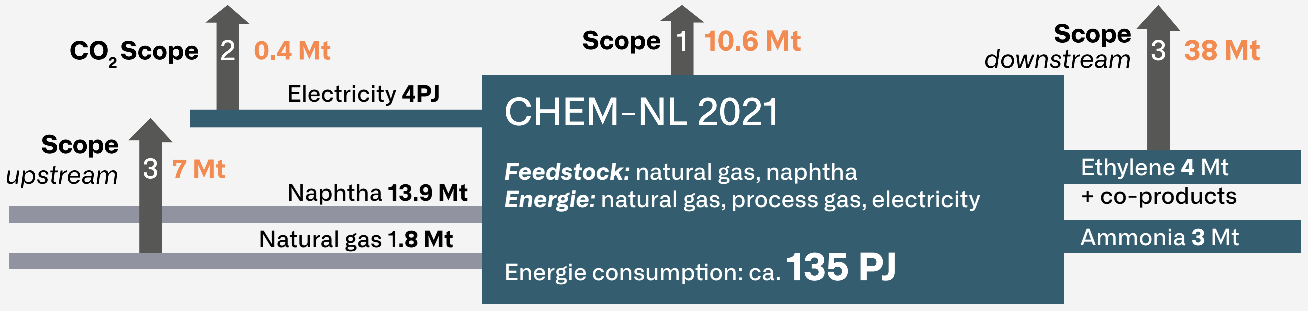

Figure 1: Schematic representation of CHEM-NL 2021

‘CHEM-NL 2021’ uses natural gas and naphtha as raw materials and grey electricity to produce 4 Mt of fossil ethylene (excluding other monomers) and 3 Mt of ammonia. Figure 1 shows estimates (2021) of the energy consumption (Petajoules, PJ) and CO_2 emissions of CHEM-NL (Scope 1), the electricity used (Scope 2), emissions related to the extraction and transport of raw materials to CHEM-NL (Scope 3 Upstream) and emissions caused by (co)products of CHEM-NL in materials (Scope 3 downstream).

Raw material transition cannot be viewed separately from the national energy transition
In practice, what does it imply for CHEM-NL’s supply of raw materials to be solely based on recyclate, biomaterial or CO_2 supplemented with hydrogen and electricity by 2050? The combinations of raw materials that will exist then are as yet unknown. How ethylene and ammonia will be produced at that time is also not known: the technology landscape could change considerably.

For example, a steam cracker produces multiple plastic monomers (propene, etc.). In 2021, roughly 2/3 of the carbon from naphtha ends up in plastics (9 Mt out of 13.9 Mt). In 2050 this will be more complex. Electrification and non-fossil naphtha, for example, increase the efficiency of steam cracking. Direct routes to ethylene avoid coproduction, but produce other carbon losses.

The aim of the infographic is to provide insight into this. The current fossil production of 9 Mt of plastics is notionally (2050) realised from the three types of non-fossil raw materials separately: recyclate, biomass, or CO_2 from air. The comparison pertains to fundamental consequences, such as the quantities required and the dependence of raw material options on the availability of CO_2-free energy. Beyond steam cracking other processes to plastics are also possible. These shortcut-routes also compete with the others in terms of integrated energy and carbon efficiency between source and material (mentioned laterally in the infographic). System models such as CIMS (Chemelot Integrated Model System) have been developed in order to deal with this complexity.

Towards 2050
In the transition to 2050, the linear fossil economy and an, as yet very modest, sustainable economy will initially coexist. Too little municipal waste and biomass is currently available as a raw material. Resources and conversion technologies are underdeveloped and comprehensive policies surrounding the role of biomass and CO_2-free energy in the transition are lacking. The danger here is that for the time being choices can still be made that will not lead to the desired circularity and sustainability of the economy. Moreover, there is still no prospect of CO_2-free electricity and circular infrastructure being available in time. Nevertheless, the new economy will have to take over from the old one in due course. Many technologies are being developed for this purpose, each with their own use of raw materials and energy consumption, the question being to what extent they fit in to a transition to climate neutrality that has been designed as efficiently as possible.

Technical developments offer a multitude of possibilities and opportunities, but will also lead to just as many barriers in terms of complexity, diverging interests and lack of incentives from the linear economy to be phased out, which together will still inhibit the dynamic development of circularity in the chemical industry.

Calculate optimal transition path with CIMS

Systematic modelling approach
Brightsite has designed modelling approaches to shape the raw materials transition in terms of main and ancillary issues from now to 2050. This BTO shows **CIMS**: a **modelling approach for transition path optimisation.** It starts from the current fossil commodities from oil and natural gas. CIMS has (scenario-based) integrated **technology maps**[2] and **information packages**[3] as input and calculates optimal transition paths from the fossil present to a final situation in 2050 with net zero Scope 1 emissions. CIMS calculates the most economical way to reach that final situation and takes into account the costs entailed each year en route to 2050, rather than just the optimal end point. The optimal transition path and end point will depend on the information package used: preformed assumptions regarding prices, availability of renewable resources, existing and new technologies to be included, and prevailing government policies. Results of CIMS modelling serve primarily to illustrate the consequences of assumptions made and to learn from them. The availability over time of resources, technologies and policy incentives plays an important role in this, given the choices that are made over time on that basis. If societal developments should slow down or fail to materialise, the consequences for CHEM-NL’s transition can be visible.

The infographic on the next page provides insight into future dependence on raw materials and CO_2-free energy as a result of an assumed, successful transition. Figures for CHEM-NL 2050 depend on choices to be made. If CCS is a thing of the past by 2050, CHEM-NL in 2050 will use a combination of recyclate (plastic waste), biomaterial (fields, forestry and their waste) or CO_2 from the air, supplemented with CO_2-free electricity and green hydrogen for the production of green ammonia, ethylene and coproducts. The infographic illustrates the energy and raw materials requirements for three alternative ways to produce ethylene and ammonia: from 100% recyclate, 100% biomass or 100% CO_2 as a carbon source, respectively.

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[2] A set of sustainable technologies, matching and integrated with the CHEM-NL complex.
[3] Such as assumptions about prices and taxes, emission limits, availability of raw materials and technologies over time.

The raw material transition for chemistry, made transparent for ethylene and ammonia

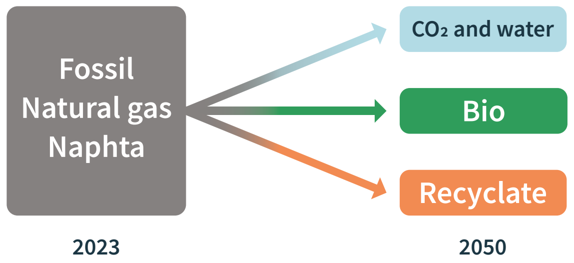
Ethylene and ammonia constitute an indispensable basis for plastics applications, global food supply and associated sectors. The transition from oil and gas to renewable raw materials in 2050 is leading to a scarcity of available renewable materials. This is illustrated by future projections for the current Dutch output, if 100% replacement is based on the three possible solution pathways separately. Differences between pathways are important indicators for decision-making and management, including factors such as new technology and human behaviour.

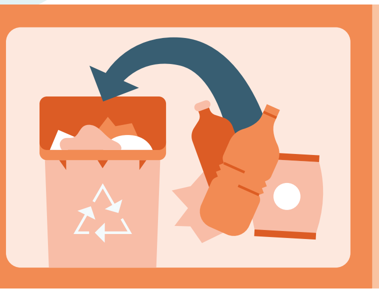
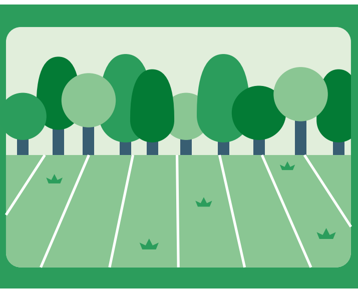
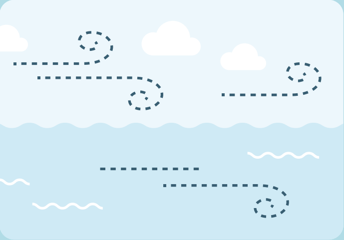
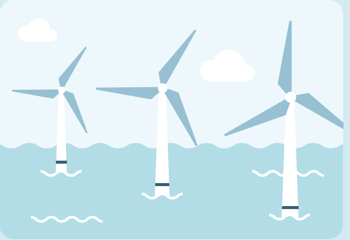
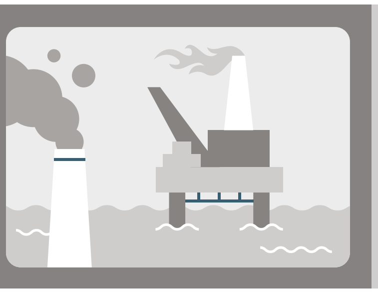
Proportions:

1 PJ (petajoule) of energy can bring 1200 Olympic swimming pools to boil

1 Mt (megaton) is equivalant to one billion kilograms

Dynamic raw materials portfolio



What is the feasible period?	What is the raw material demand?	What is the demand on resources?	What is the total energy demand?	What are the major challenges?
Raw material: Recyclate Achievable in the short-term		Plastic waste: **11.5 Mt** Household waste: **9 Mt** (for hydrogen) • Consumers • Logistics • Storage space	**Source of energy** From raw materials: **650 PJ** From electricity: **100-250 PJ**	• Completing the cycle • Commoditisation • Technology upscaling • Wastewater • End-of-waste status 
Raw material: Biomaterial Achievable in the medium/long-term		Biomass: **45 Mt** • Woodland: 90,000 km^2 (natural growth) or • Fields: approx. 25,000 km^2	**Source of energy** From raw materials: **800 PJ** From electricity: **150 PJ**	• Sustainable production • Land use • Application development • Raw material vs fuel 
Raw material: CO_2 and water Achievable in the long-term		Carbon dioxide from air: **32 Mt** Hydrogen from water: **4.8 Mt** • Air: 44,000 km^3 • Water: 43,000,000 m^3 • Electricity: 10 MW mills: 5000 • Sea surface: 5000 km^2	**Source of energy** From raw materials: **0 PJ** From electricity: **1050 PJ**	• Huge electricity consumption • CO_2-capture technologies • Efficient production technologies 
Raw material: Petroleum and gas The current situation		Petroleum naphtha: **13.9 Mt** Natural gas: **1.8 M** • CO_2 storage: by the global ecosystem	**Source of energy** From raw materials: **750 PJ** From electricity: **30 PJ**	• From linear to circular chains • Phasing out fossil fuel • Effective transition regulation 

What are the technologies?

Recycling
- Mechanical
- Solvolysis
- Pyrolysis

Electric cracking

Hydrogen pathways
- Gasification
- Water elektrolysis

Disruptive pathways
- Biopolymer-based
- Plasma technologies

CHEM-NL 2050

C1 chemistry - Syngas
- Methanol to Olefins
- Fischer-Tropsch
- Direct Air Capturing

What are the game changers?

7R model

Rethink
Reduce
Repair
Reuse
Refurbish
Recycle
Recover

New chemistry

New entrepreneurs

CO_2-free energy

Availability

- Steam cracking
- SMR
- Haber-Bosch
- CCS

CHEM-NL 2023

3 Mt ammonia
4 Mt ethylene etc. for fertilisers and
9 Mt plastics

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Figures are indicative. Data is aggregated, based on public information and/or own calculations and does not reflect the precise circumstances. The current state of technology is often less favourable.

CHEM-NL in CIMS

CIMS' first version was developed for Chemelot's products and processes. The **fictitious CHEM-NL site** was subsequently modelled in CIMS, making use of publicly-available information on technologies at Chemelot for producing ethylene (steam cracking of naphtha) and ammonia (steam methane reformer [SMR] and Haber-Bosch). This was scaled up to national annual production capacities of 3 Mt ammonia (5 identical plants) and 4 Mt ethylene (6 identical plants). Each plant can be greened separately. This does not correspond exactly to the Netherlands' ammonia and ethylene production, but it does not affect the results.

Visualising synergy
CIMS is characterised by the fact that current and/or future integration and synergy opportunities between processes are taken into account during the transition (with the exception of detailed heat integration). This was inspired by process integrations at Chemelot and was purposely retained for CHEM-NL to quantify possible future synergy opportunities between the ethylene and ammonia production paths. This integration is not present at national level and renders CHEM-NL a virtual model that is independent of a specific industrial site in the Netherlands and is ideally suited to help shape transition paths.

Technology map shows routes to climate neutral
CIMS contains a '**technology map**' of CHEM-NL, a technical modelling network of:

1. CHEM-NL in 2021, with ethylene and ammonia production, the associated mass and energy integrated consumption of energy and raw materials and scope 1 and 2 CO_2 emissions
2. Selected (based on currently known) realistic technologies with integrated alternative raw material supplies (with associated technologies and CO_2-free energy supply e.g. for electrification of processes) that can contribute to fostering a climate neutral CHEM-NL:
   - Recyclate (plastic waste, municipal solid waste [MSW]) for ethylene and hydrogen production
   - Biomass, in the form of bionaphtha to be used directly in crackers (import) or as a source for hydrogen (via gasification)
   - CO_2 from MSW or from air; conversion to Fischer-Tropsch naphtha or MtO (Methanol to Olefins) for ethylene production
   - A selection of greening options: replacement of fossil feedstock from existing technologies or (very limited) via new chemistry such as ethylene from methane via plasma technology
   - Electrification of high temperature processes (steam crackers, SMR), CO_2 storage via CCS

The infographic illustrates the energy and raw materials requirements for three alternative ways to produce ethylene and ammonia from 100% recyclate, 100% biomaterial or 100% CO_2 as a carbon source respectively. CIMS' technology map includes existing and future routes under development, which can also make use of blends, and also includes non-naphtha based ethylene production options (not exhaustive in this BTO).

The role of the information package (scenarios)
Besides technology options, assumptions are needed on the availability of (alternative) raw materials volumes, (CO_2-free) electricity, new logistics and specific technologies over time. Economic evaluations require assumptions about raw material and energy price developments, about legislation related to CO_2 emissions and taxes. **Future scenarios** are a way of dealing with this: logical, consistent stories that pave the way for change. The choice of scenario largely determines the content of the '**information package**' (parameter values) fed into CIMS. Various information packages are possible with one technology map (multiple perspectives).

This BTO employs an 'ideal future scenario'. Europe and society are pushing for fulfilment of the Climate Agreements, with tough supporting legislation geared towards renewable resources being developed into raw materials and shared worldwide and fossil resources being phased out.

This scenario may not be realistic, but it has its advantages: the potential for the chemical industry is rendered visible, the consequences for the required resources are clarified and lessons can be learned, such as '**what must be ready in time for this scenario to materialise**' (backcasting). **Deviations from the ideal** can also be assumed and examined, such as barriers and restrictions, delays in the materialisation of alternative energy and raw materials. This will show what the consequences are for the chemical industry and how the industry can respond to this.

The technology map and information package of CIMS are similar to road maps and traffic information, but say nothing about the route to be travelled.

Determining expected CO_2 emissions Scope 1 from CHEM-NL
Based on the assumptions in the information package, CIMS performs an accounting exercise for future Scope 1 CO_2 emissions associated with each route to 2050 (Figure 2).

CIMS records these emissions by adding up the different types of CO_2 formed . Combustion or gasification of fossil carbon gives positive emissions, bio-based carbon has zero emissions. Incineration of plastic waste, now virtually fossil, also counts as positive emissions: a deliberately conservative approach. After all, the biogenic content of recycled plastic will increase over time, which will reduce the fossil Scope 1 emissions from incineration. Captured and stored CO_2 (CCS) counts as neutral, except for biogenic CO_2 which counts as negative.

Recording of CO_2 emissions in CIMS in a future technology landscape is comparable to CO_2 emissions from car traffic. Fuel consumption will be less and emissions and costs will be lower if steep, winding mountain roads or tolls can be avoided through shortcuts, tunnels and diversions. That is what CIMS 'navigates' and records on the technology network en route to 2050.

CIMS navigates optimal routes towards 2050
In this BTO, CIMS optimises transition routes on an **economic base** (Net Present Value) to net zero emissions in 2050: a prerequisite. All associated price assumptions form part of the information package. Until 2030, these are derived from the mid-price scenario of the Climate and Energy Outlook (KEV) 2022 of the Netherlands Environmental Assessment Agency (PBL) or from other public sources if not in the KEV. From 2030 to 2050, a national tax on the use of pristine fossil raw materials has been implemented: a simulation of a gradual increase in the price of fossil feedstock. Free emissions rights were also phased out linearly to zero in 2050, in parallel with a rising CO_2 price.

Interim interactions with CIMS
Additional technical or economic input is possible or desirable. Interventions often take place on the basis of initial CIMS results: adjustment of CIMS input in the information package. In this way, scenarios and results can be optimised interactively: **'build the bridge while you drive'**

	Fossil	**Biogenic incl. biogenic wastes**	**Plastic wastes**
Combustion/ gasification	positive	zero	positive
CCS	zero	negative	zero

Figure 2: Classification of CO_2 emissions from CHEM-NL depending on the origin of the carbon and use.

CHEM-NL's transition in view

In order to illustrate CIMS's interactive use, three case studies are presented on the next pages. All case studies use the same technology map and information package. Case study 1 starts simply: the availability of alternative resources (infographic) is unlimited. The availability of plastic waste is subsequently limited in case study 2, as well as that of MSW; (municipal solid waste, household waste; assumption: constant 60% biogenic carbon until 2050) in case study 3. CIMS calculations do not reflect an expected reality, but form the basis for analyses and refinements, as will be illustrated.

Case study 1: No restrictions on resources

The evolution over time of the demand on raw materials for the calculated optimal transition path is shown in Figure 3. Fossil naphtha and natural gas are being completely phased out. Ethylene is mainly being produced from plastic waste (pyrolysis oil), which leads to huge demand for plastic waste by 2050: 13 Mt. And to a lesser extent from MSW (gasification, followed by Fischer-Tropsch reaction). The crackers are partly electrified. The situation is more complex in the case of ammonia. A proportion of the ammonia production is replaced by green ammonia imports (39%). The required hydrogen is still partly being produced by steam methane reforming, but natural gas is replaced by by-product methane from steam crackers and Fischer-Tropsch. The reformers are electrified. The demand for hydrogen more than doubles, due to additional demand for pyrolysis (hydrotreatment) and Fischer-Tropsch. Additional hydrogen is produced by gasification of biomass and MSW, which also creates huge demand for MSW by 2050: 14 Mt for carbon and hydrogen production.

Figure 4 shows the corresponding Scope 1 CO$_2$ emissions. Net zero emissions are achieved by 2050 through a combination of a reduction in positive-counting (see Fig. 2) fossil CO$_2$ emissions, neutral-counting CCS from fossil CO$_2$, neutral-counting biogenic emissions, as well as negative-counting biogenic CCS that offsets residual positive-counting fossil emissions. Comprehensive CCS is the most financially appealing option in this case. This is due to the autothermal pyrolysis of plastic waste, which causes an increase in Scope 1 emissions: flue gas counts (conservatively) as 100% fossil. Pure CO$_2$ from SMR process gas was chosen for CCS as CCS is less favourable for flue gas due to the low CO$_2$ concentration (6%) requiring more investment and energy.

Case study 2: Limited availability of plastic waste

Even all plastic waste from the Netherlands (currently a large net [poly]ethylene exporter) would be insufficient to supply CHEM-NL's crackers with sufficient pyrolysis oil: imports would be required. There is, however, uncertainty as to the quantity that will become available and the associated price. Therefore, a follow-up simulation was carried out in which the amount of plastic waste was reduced to 40% of the 2050 ethylene production (TNO[4]) with linearly increasing availability 2021-2050. The question is what will be the consequences of this limitations and how will this affect the resources required.

The optimal transition path shifts

The extra carbon required for ethylene production will then come from: gasification of MSW (via Fischer-Tropsch) and via plasma technology (available after 2040). The resulting MSW demand is huge: as much as 23 Mt in 2050. Plasma technology uses methane by-product from steam crackers and Fischer-Tropsch as a raw material for ethylene. The consequences for the ammonia production is that less methane is available for the electrified SMR than in case 1, and that less hydrogen is available for Haber-Bosch due to the increases hydrogen demand for Fischer-Tropsch reaction. This means that less ammonia can be economically produced and that a switchover is made to ammonia imports (50%).

The demand for hydrogen is even higher than in case study 1 and is also now partly being imported. Another striking difference with case study 1 is the decreased CCS (7 instead of 14 Mt in 2050): see Figure 6. This is because pyrolysis in case study 1 generates a lot of fossil CO$_2$ emissions that are compensated with CCS. This is partly making way for more biogenic emissions from MSW and emission-free ethylene production plasma technology.

Case study 3: Limited availability of plastic waste and MSW

While society is pursuing waste reduction, the demand for MSW in case study 2 rises to 23 Mt by 2050. Such an availability is unlikely. MSW was therefore also limited in a third model run to what was available in the Netherlands in 2021: 199 kg/inhabitant or 3.5 Mt (Statistics Netherlands CBS).

Place for bionaphtha, more ammonia imports

When both plastic waste and MSW availabilities are limited, bionaphtha (steam cracking) and by-product methane (via plasma technology) provide additional routes to ethylene. Bionaphtha (next to the limited amount of plastic waste and MSW routes) will completely replace naphtha as of 2034, a few years after the introduction of the tax on fossil resources (Figure 7). Bionaphtha itself will be partially replaced by ethylene production with plasma technology (as of 2040). Even in 2050, some fossil natural gas will be imported for this purpose.

The consequences for ammonia are huge. In the optimal transition path, process gas methane and locally produced hydrogen are being used for ethylene production instead of ammonia. In 2050, CHEM-NL no longer has SMRs, 85% of ammonia will be imported and 15% will be self-produced.
This case study relies even less on CCS than case study 2 (3.8 Mt in 2050, see Figure 8). This is mainly due to the almost complete elimination of ammonia production.

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[4] https://www.tno.nl/en/newsroom/2020/11/roadmap-circular-plastics-2050/

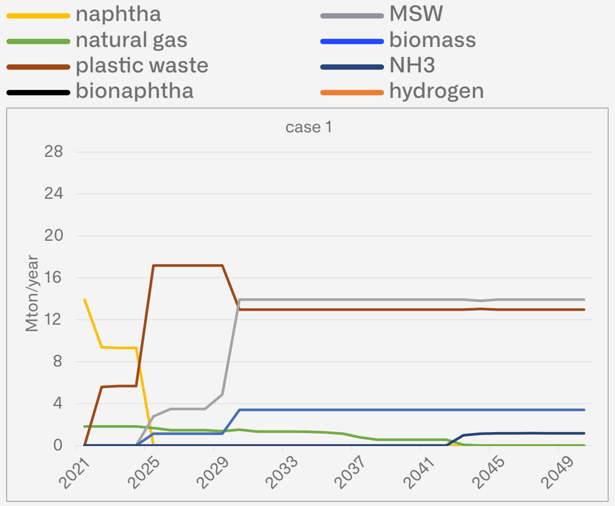


Figure 3: Import of raw materials in case study 1: no restrictions in terms of availability

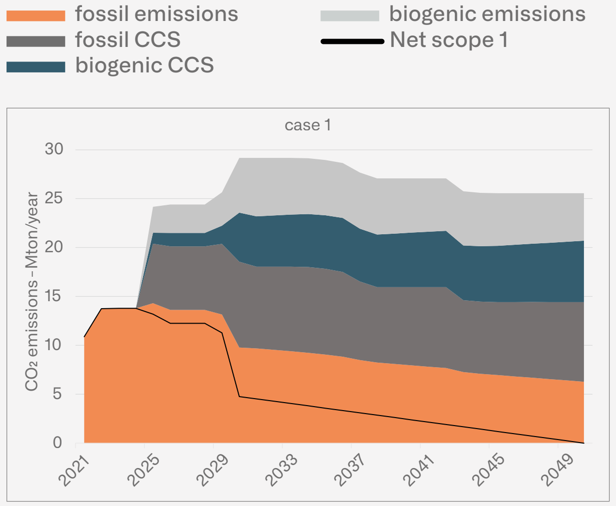


Figure 4: Reduction of net Scope 1 CO$_2$ emissions from CHEM-NL to zero between 2021 and 2050, with no restrictions on raw materials in case study 1

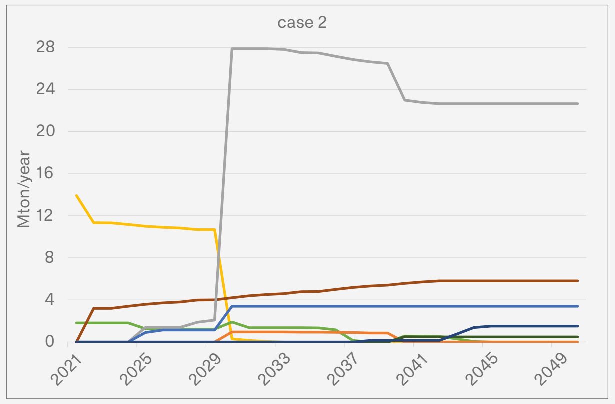


Figure 5: Import of raw materials in case study 2, with limited availability of plastic waste

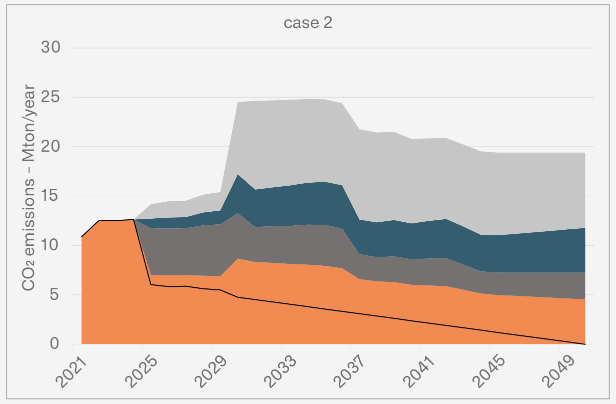


Figure 6: Reduction of net Scope 1 CO$_2$ emissions from CHEM-NL to zero between 2021 and 2050, with limited availability of plastic waste in case study 2

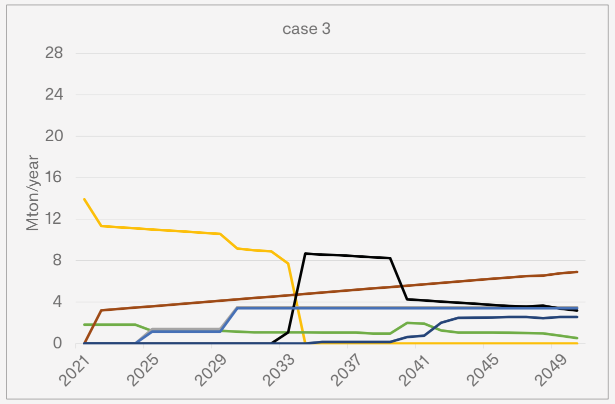


Figure 7: Import of raw materials in case study 3: limited availability of plastic waste and MSW

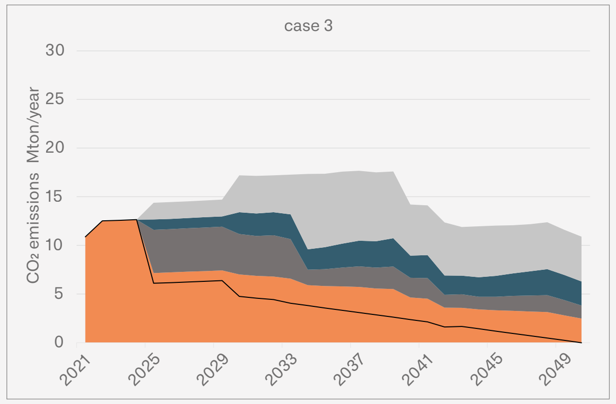


Figure 8: Reduction of Scope 1 CO$_2$ emissions from CHEM-NL to zero between 2021 and 2050, with limited availability of plastic waste and MSW in case study 3

Consideration and conclusions CHEM-NL

1. Origin of raw materials

Figure 9 shows the origin of the carbon for ethylene and of the hydrogen/ammonia for ammonia in cases 1, 2 and 3 by 2050.

Carbon from ethylene is mainly coming from recyclate: plastic waste and MSW. Biomass is only used as a carbon source if the availability of recyclate is limited (case study 3). This is so cost-intensive that some fossil natural gas use remains despite the notional tax on fossil resources. The assumption that plasma chemistry will unlock a new route to ethylene (with hydrogen as by-product) after 2040 makes this possible. **This underlines the importance of continuing to develop new chemistry and technology.**

Bio-based raw material was assumed to be available in unlimited quantities for the purpose of the modelling. Large volumes, such as for CHEM-NL, still require major steps in the field of integral sustainability and the unlocking of raw material. The price of bionaphtha was assumed to be 25% higher than fossil naphtha (excluding tax on fossil resources) and held constant after 2030: a conservative approach. Much higher prices can arise from such factors as other competing applications, such as biofuels. Low prices were assumed for waste: MSW 0 €/t, plastic waste 325 €/t with no increase over time. Rising prices can influence technological choices. CO_2 capture from the air, an available option, never became cost-competitive enough to be selected. If both the recyclate and the bio-based raw materials would be limited, CO_2 would eventually be 'selected by necessity': there is no other alternative.

Ammonia is also ideally produced from recyclate (if available), but hydrogen production from biomass and ammonia imports are competitive alternatives. In such a scenario, imported ammonia will need to be sustainable as well, of course. The more the availability of recyclate is limited, the more ammonia is imported. Case study 3 entailed the use of biomass being limited indirectly via the number of available gasification systems in the model: a model-based way of dealing with potentially limited future availability of sustainable biomass. There is still a long way to go in the field of sustainable bio-based raw material.

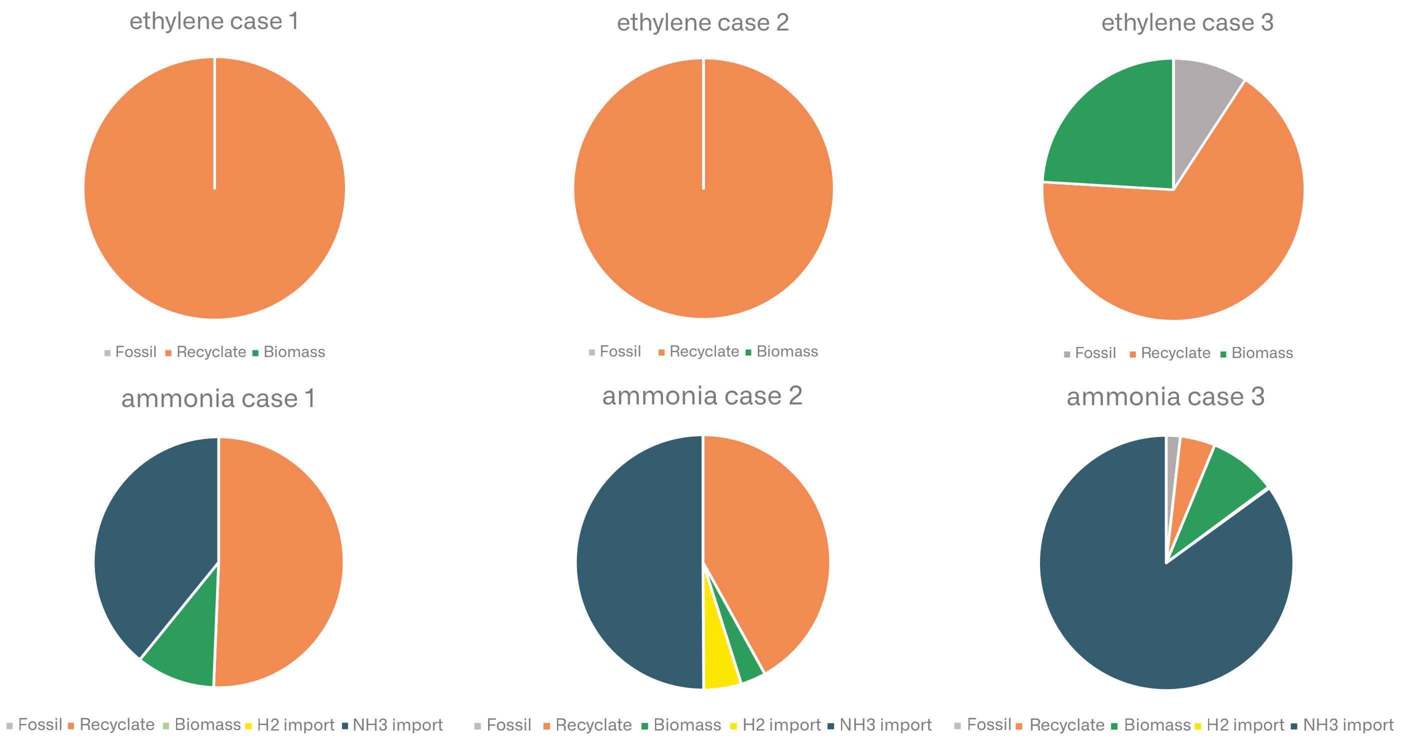


Figure 9: Origin of the raw materials in 2050 for the three case studies. Ethylene production: carbon origin fossil, from recyclate (plastic waste, MSW) or biomass (bionaphtha). Ammonia: from hydrogen produced from fossil fuel, biomass or recyclate (plastic waste, MSW), imported hydrogen, or from imports.

2. Rise in production costs

CIMS calculates variable costs, including capex depreciation and CO_2 tax (combination of ETS and CO_2 tax). There are of course uncertainties associated with this: prices and price developments (mainly relative and with no adjustment for inflation), commercial availability in terms of time and capacity of technology and CO_2-free electricity; raw material and energy efficiency. Only trends can therefore be derived from these three case studies. The transition is accompanied by a cost increase of 25% in 2050, compared to 2021 (Figure 10). During the transition, production costs are initially higher, up to 70% more, because not all technological options have become available yet in the first decade. When both plastic waste and MSW are limited, prices rise further.

3. Interconnected production processes

The model results clearly show **synergy benefits** of interconnecting ethylene and ammonia production. The ammonia process uses by-product methane from the steam cracker and the Fischer-Tropsch process to completely phase out fossil natural gas use for SMRs. The ethylene processes benefit from CCS of pure CO_2 streams from the ammonia route, which are much cheaper to capture than diluted flue gas streams from the ethylene route. Both routes benefit from biomass and MSW gasification for hydrogen production. Ammonia and ethylene production compete with one another for fuel gas and hydrogen, as shown in case studies 2 and 3. Ammonia production is being phased out because there is an import option for it, which is not the case for ethylene. Independent optimisations of the transitions of both production processes would lead to different results, but that was not verified in this study (out of scope).

> **The energy sector competes for the same scarce renewable carbon sources for energy generation through the combustion of biomass, biofuels and waste. Thus the greening of CHEM-NL appears to be both dependent on and in competition with energy transition. This inextricably links the raw material transition with the energy transition.**

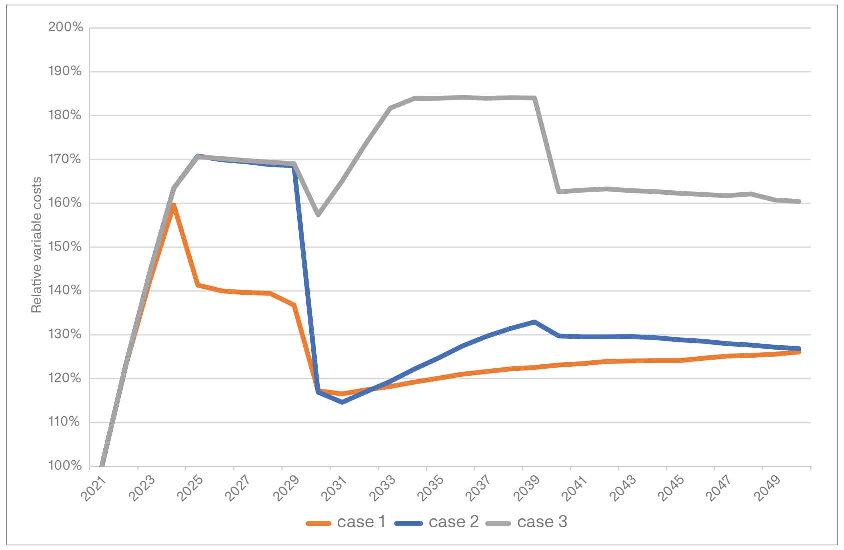


Figure 10: Variable costs (including CO_2 tax and capex depreciation) relative to 2021 production costs. Case study 1: unlimited resources; case study 2: limited availability of plastic waste; case study 3: limited availability of plastic waste and MSW

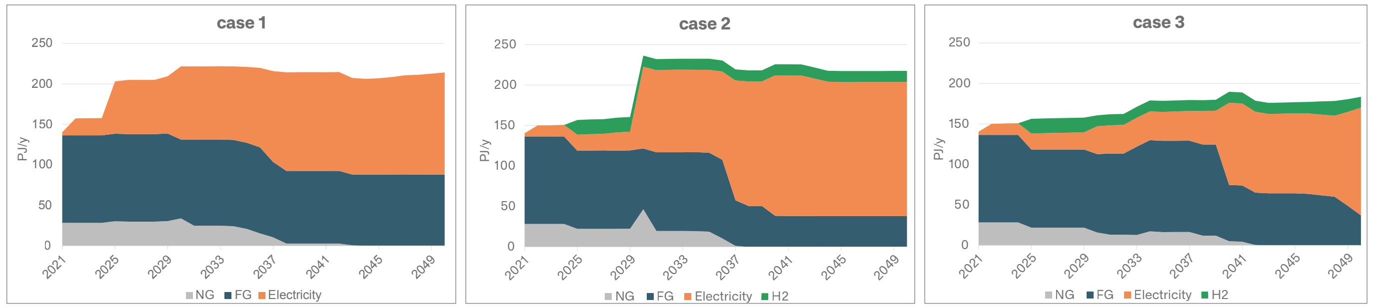


Figure 11: Evolution of CHEM-NL's energy demand in case studies 1, 2 and 3. NG: imported fossil natural gas as fuel, FG: process gas methane produced within CHEM-NL, used as a fuel, H2: hydrogen used as a fuel in hydrogen furnaces, and electricity

4. Interconnected raw materials and energy transition
CHEM-NL's transition is accompanied by an increase in energy consumption of approximately 50% in case studies 1 and 2 (Figure 11). The increase is more limited in the third case study, due to ammonia production almost entirely outside CHEM-NL.

CHEM-NL's increased energy consumption is mainly caused by the usually much lower **energy content of renewable raw materials** than that of fossil naphtha and natural gas. Switching to renewable raw materials is therefore accompanied by an increased demand for energy. **No less important, however, are the consequences of the raw materials transition beyond CHEM-NL** such as the extra electricity required and the burden on the use of waste and land. The infographic underlines the considerable demand on resources that is intrinsically linked to the raw material transition and the dependence of integrated energy consumption on the carbon source. This means that shortcuts must continue to be sought, such as plasma chemistry and biopolymers. Thermodynamics sets limits as to what is feasible.

Figure 12 shows the calculated electricity consumption for the three case studies up to 2050. The sizeable increase in electricity demand is mainly caused by the electrification of the SMR, the partial electrification of the crackers (30-70% of the crackers, depending on the case study) and plasma technology. In case studies 2 and 3, some of the crackers' furnaces use hydrogen produced at CHEM-NL as fuel (20% of the furnaces). The electricity used must be CO_2-free. If this is not the case, only exchange between Scope 1 and 2 emissions takes place and a cure may be worse than the disease. However, CHEM-NL is not the only contender for renewable raw materials.

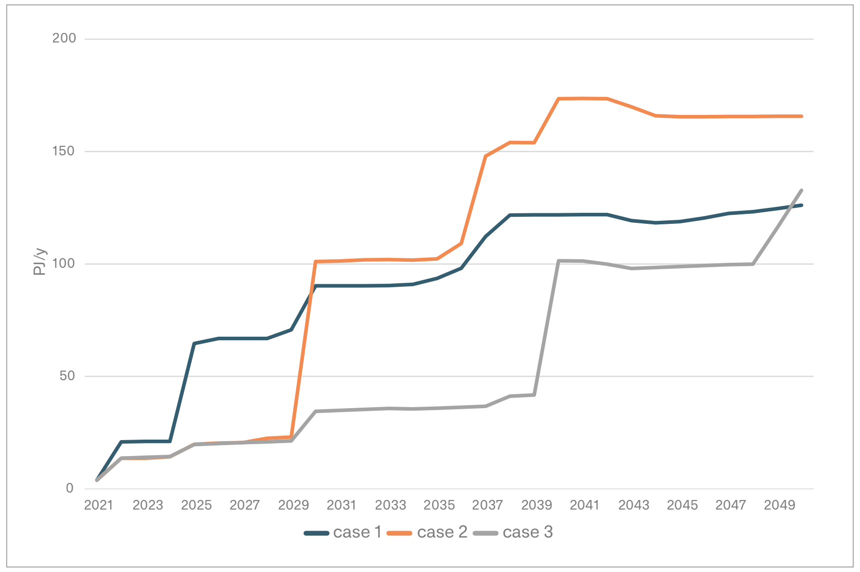


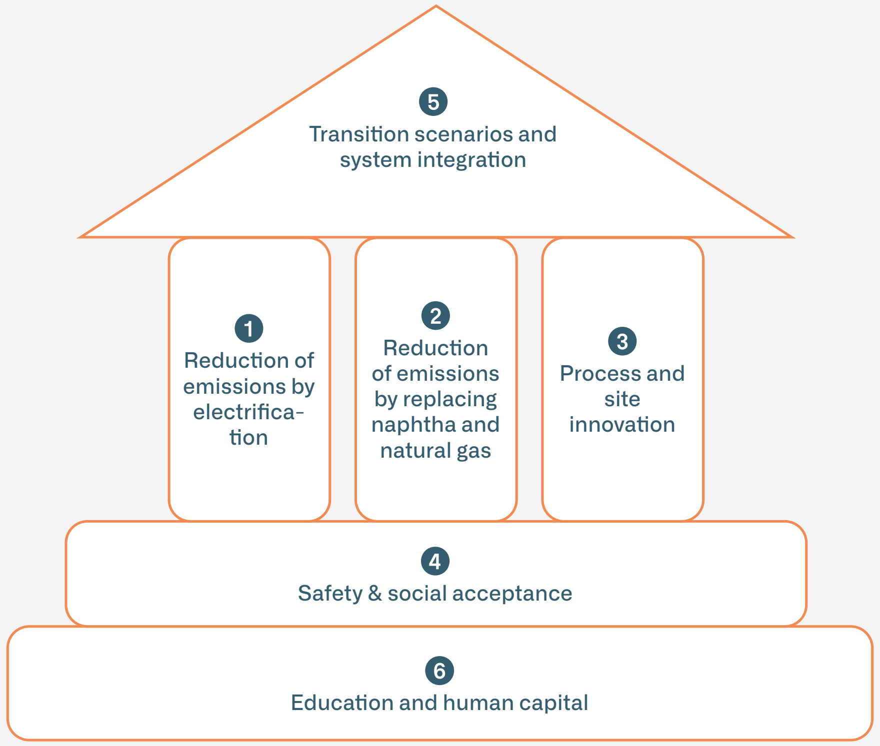
Figure 12: Evolution in the demand for (green) electricity for case studies 1, 2 and 3. NB More than 150 PJ per year corresponds to 1,000 x 10 MW wind turbines (production factor 50%)

Brightsite and the six mutually reinforcing programme lines

As an open innovation platform for sustainable process technology and circularity, Brightsite is engaged in the assembly of knowledge from a wide array of parties and in cooperation with Brightlands Chemelot Campus the provision of facilities for scaling up and commercial demonstration. It also provides support when it comes to selecting and developing the right technologies to make the chemical industry greener.

In order to contribute efficiently to achieving national climate objectives, Brightsite was set up by Sitech services (on behalf of the companies on the Chemelot site), TNO, Maastricht University and Brightlands Chemelot Campus in 2019. Brightlands Chemelot Campus, which is encircled by major chemical industry, provides an ideal base for this. Brightsite's mission is to demonstrate that climate targets at Chemelot are genuinely feasible, functioning as a think tank, facts and science based, tackling transition issues in an integrated fashion (multi-stakeholder perspective) and promoting education for the new generation of researchers and staff to accomplish this.

The climate targets leave the chemical industry faced with huge challenges, though they also present opportunities. Solid transition management will foster economic growth and attract talent and business. As the development and utilisation of new technology encompasses far more than just the technical aspects, the work will also include safety aspects, societal acceptance, legal and economic viability, job opportunities and training. In short, contributing to creating a broad foundation for future prosperity in conjunction with industrial partners.



Brightsite is approaching the transition in an integrated fashion with three development programme lines, pertaining to 1) electrification, 2) renewable raw materials and 3) process and site innovation, as well as three ancillary programme lines pertaining to 4) safety and societal acceptance, 5) transition scenarios and system integration, 6) education and human capital. The transition will only be achieved through collective, concerted cooperation between these six areas of activity, as Figure 13 shows diagrammatically.

Program line 1
Reduction of emissions by electrification

Electrification: developing and scaling up plasma technology
Switching over to electric heating, with sustainably generated electrical energy, can make a significant contribution to reducing CO_2 emissions at Chemelot over the 2030-2050 period. Brightsite sees **plasma technology as a potential 'game-changing' technology**, as it can reduce CO_2 emissions while keeping carbon in the cycle of a circular economy. For the short term, up to 2030, electrification options have been identified that can reduce Scope 1 greenhouse gas emissions by approximately 40% compared to 2015.

Brightsite focus: new value chains & Plasmalab
A feasibility study by Brightsite showed that methane can be converted into hydrogen and carbon products using plasma technology, with no CO_2 emissions and up to 85% less energy consumption compared to water electrolysis. The current CO_2 emissions from the chemical industry can therefore be reduced with a simultaneous increase in energy efficiency. This makes it possible to produce both hydrogen and ethylene from natural gas or methane released during electrified cracking processes. In the process, SABIC is working on electric steam cracking.

Brightsite has initiated a **unique 3-generation approach** in the Brightsite Plasmalab. In doing so, maximum carbon and energy efficiency is developed and scaled up through:

1. Fully understanding existing technology and plasmas and their limitations
2. Improving existing plasma technology for the short term
3. For the longer term: designing the best possible technology from the perspective of the manageability and control of plasmas and desired plasma chemistry to new building blocks for the chemical industry

Methane research has led to the first small-scale conversion of methane into ethylene, acetylene and hydrogen with enhanced ethylene selectivity. The practicality of plasma as a platform technology has also been further explored: various **other molecules**, for example nitrogen and CO_2, **can also be used effectively for the production of new-generation raw materials** for the chemical industry and/or as building blocks for the new value chains at Chemelot. Deepening and broadening the research into scaling up plasma processes will thus lead to new options for the raw materials transition and circularity in 2050.

A site-wide and region-wide approach is necessary
The expectation is that the current CO_2 Scope 1 emissions at Chemelot can be reduced by 95% by 2050 compared to 1990 through the electrification of heating processes and the production and use of non-fossil hydrogen[5]. Plasma technology can make an important contribution in this regard because it can keep carbon energy-efficiently in a cycle, thus preventing emissions of scarce non-fossil carbon. Conversion to CO_2 is avoided, so no CCS, no other carbon sources and no energy-intensive routes, such as CCU, are required. However, production, transport and use of the sustainable electricity will require large-scale investments in power generation, transport links and related infrastructure in and beyond Chemelot. This will require a site-wide and region-wide approach.

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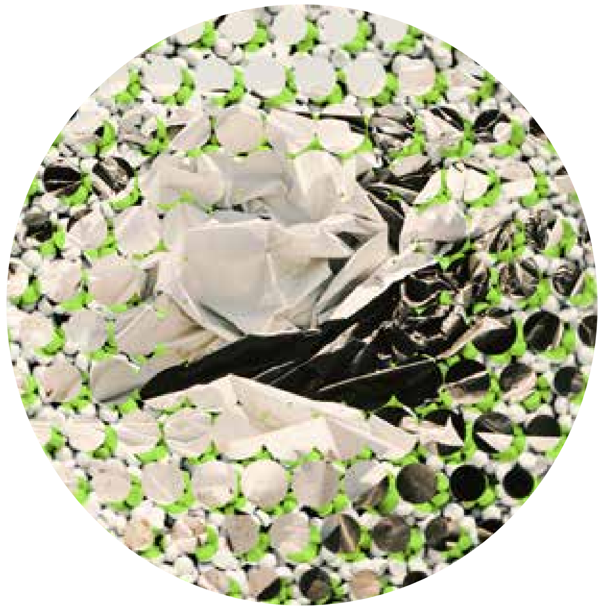
[5] Reference to BTO 2022

Program line 2
Reduction of emissions by replacing naphtha and natural gas



Replacing fossil raw materials
Companies at Chemelot have **three options** when it comes to reducing the use of fossil raw materials and the associated fossil CO_2 emissions, and thus becoming greener: 1) **recycling materials** from 'end-of-life' products to produce new, circular raw materials, 2) preparing **raw materials from bio-based sources** or 3) **using CO_2 from the atmosphere.** To enable a significant phase-out of fossil raw materials effectively, development of **large-scale use is implied**, for example for blending non-fossil raw materials from new production processes with fossil feedstock, or by means of new non-fossil products. However, there is still a long way to go. This is partly due to the underdevelopment of carbon sources, processes and new value chains of which they are part, combined with the need for risk management through controlled deployment, and trust in established value chains.

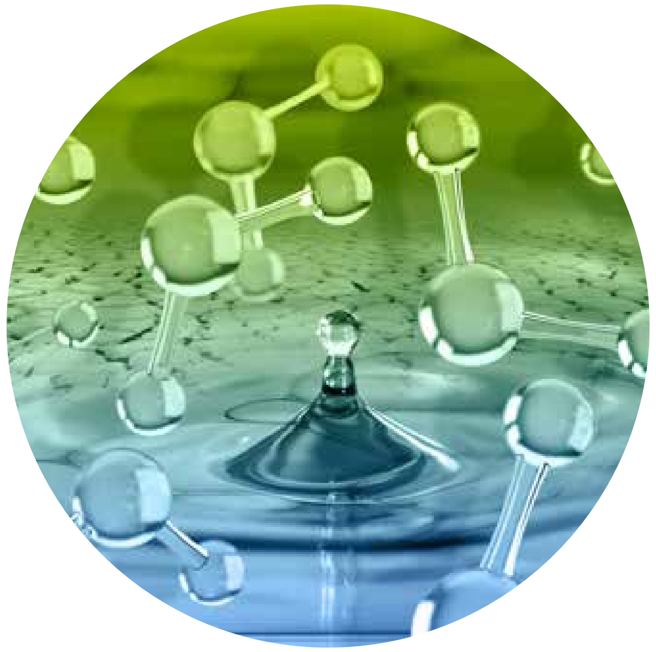
Developments at Chemelot
Companies at Chemelot **evaluate and realise new technology options**. For example, circular raw materials are used at the **SPEAR** pyrolysis unit that will produce raw materials from plastic waste for the **SABIC** naphtha crackers. **Fibrant** is studying opportunities for depolymerising nylon waste into nylon monomers and **Black Bear Carbon** plans to build a plant for recycling car tyres to produce new raw materials. Furthermore, **RWE** is considering building a large-scale unit for gasification of feedstock from waste to produce hydrogen. The challenge with biomass is that it contains large amounts of oxygen and water. Nevertheless, some interesting options are being developed to use waste streams as cracker feed or to further develop ethylene production from sugars. New possibilities with bio-raw materials at Chemelot are also being considered.

Brightsite focus: upgrading waste
The Brightsite renewable raw materials programme focuses on plastic waste, the quality and availability of which do not yet meet the thermochemical recycling requirements. The research aims to **increase the amount of usable plastic waste by separating and cleaning plastic from waste-sorting fractions that have so far been rejected.** This increases usable plastic waste for circular raw materials with a factor of 2 or 3 and at the same time reduces incineration and related CO_2 emissions.

Other examples are the development of new technologies, such as the catalytic decomposition of plastics to high-quality chemicals in collaboration with **Utrecht University** and research into plasma technology for the pyrolysis of plastics. Brightsite supports applications for the **National Growth Fund**, in which the connection is made for bio-based raw materials for both the greening of established and development of new disruptive technologies, products and value chains ('value cycles') from carbohydraterich bio-based raw materials from agriculture or forestry.

New situation, new approach
The new 'green value chains' will have to deal with scarcity and new aspects of significance for the future economy that differ markedly from those of the current 'fossil' value chains. The limited availability of non-fossil raw materials and other aspects, such as the sustainable use of bio-mass and environmental planning priorities, are important.

Program line 3
Process and site innovation



Chemelot needs process and site innovations to meet climate objectives as well as remaining attractive to investors. **The focus is on reducing greenhouse gases, more efficient use of energy and residual heat, digitisation and water.**

Futureproof water system
In order to develop a future proof water system for Chemelot, Brightsite has, in collaboration with **USG, Sitech, RoyalHaskoning DHV** and site users, drawn up a **Water Road Map** entitled 'Towards Zero Emissions and Zero Water Intake'. This road map aims to eliminate emissions into surface water and to significantly reduce water usage. Read more on the development of a future-proof water system in 'WATER-NL', on page 23.

Digitisation: importance of digital twins
Brightsite also uses digitisation to reduce the footprint of factories. This is described in more detail in '**Digital factory of the future**': a vision for the process industry drawn up by Brightsite. Brightsite is developing so-called **digital twins** and **smart information systems** for predictive maintenance, training, safety studies and the testing of new control techniques. The use of Machine Learning (ML) and Artificial Intelligence (AI) increases process insights and plant knowledge (continuous improvement). This is in line with developments within the EU. For example, an EU report of the **Joint Research Center** (2022) describes how **the green and digital transition can reinforce each other**. And the EU report '**Transition Pathways for the Chemical Industry**' (2023) reaffirms the strategic role of the chemical industry for the EU and the importance of this twin transition for the chemical industry.

Potential of CCU and heat battery
CCU can be used to prevent CO_2 from entering the atmosphere and to provide a renewable carbon source. A comprehensive study into the potential for Chemelot shows that CO_2 could provide approximately 20% of the carbon required for the future. However, this requires more than 60 Petajoules (PJ) of CO_2-free energy annually, while the electrification of Chemelot itself requires an increase in renewable energy of 20 to 60 PJ. **Utilisation of CCU at Chemelot is** therefore **not an option for the time being.** Brightsite will continue to monitor whether this changes due to developments, such as shortages of alternative circular carbon sources, price developments in renewable energy and technical breakthroughs. A significant proportion of Chemelot's **residual heat can be used for heating of buildings in the surrounding area.** The heat battery is an interesting innovation to accelerate development of heat networks. Brightsite is endeavouring to run a pilot in conjunction with TNO-TU/e spin-off **Cellcius** for the storage, transport and release of residual heat from industrial sources in a salt hydration-based heat battery.

WATER-NL

Water crucial for plant operation
Water is necessary for basic processes such as cooling, heating, transport and safety. For example, water – in the form of steam – is necessary for heating processes and provides cooling by dissipating heat. Water is also used as a solvent and serves as a means of conveyance.

Circular water use
Water is becoming more and more of a societal issue as a result of increasing drought, torrential rain and concerns about water quality. Adequate water purification and reduction in water consumption are therefore the focus of increasing attention. Brightsite is developing a vision and testing technologies to **return used water as cleanly as possible and to use as little water as possible**. This means developing **Circular Water Use** in addition to circular carbon use.

Looking ahead: scarcity leading to development of circularity
Chemelot takes water from the Juliana Canal and after treatment discharges it into the Ur, a brook that flows into the River Meuse. And the Meuse is a source for drinking water production. Chemelot is very aware of the importance of proper water treatment. Various Chemelot-wide options for improved water treatment and reuse are being identified: taking into consideration both increasingly strict rules regarding water permits and drastic process changes that will occur in terms of sustainability steps. After all, **the transition to a climate-neutral Chemelot by 2050 includes water use and production of waste water by future factories**. Here too, scarcity leads to the development of circularity.

Complex European legislation
All bodies of water will have to comply with the European Water Framework Directive (Kaderrichtlijn Water, KRW) and thus with **targets and specified chemical and ecology standards** by 2027. It is expected that only 35-65% of regional Dutch waters will be fully compliant with the requirements, with possible EU sanctions as a result. European regulations are implemented locally: requirements for the quality of the discharged water are determined by the upstream and downstream situation. The permitted concentration of a substance in water to be discharged (the standard) is therefore determined on a situation-specific basis. **Future water use will therefore be location dependent**, unlike CO_2, for example.

Chemelot as forerunner
The new European requirements require **further improvement of water quality and the development of methods to measure and analyse substances**. Chemelot was the first major chemical site to go through the new Dutch licensing process. More than 600 substances emanating from factories *may* end up in the wastewater treatment plant at Chemelot have been assessed. Previously, standards were issued for substance categories; now component levels are looked at. As a result, the number of substances to be measured increased by a factor of twenty, of which no standard was yet known for about two thirds. Surface water is being put under strain from various sources, including microplastics. It is a wide-ranging societal issue that will require everyone to play their part. For example, Chemelot has taken action to prevent plastic granules ending up in the water and a monitoring method is being developed regarding how many and which microplastics are present in wastewater and how this can be prevented. So, Chemelot is helping to develop environmental care further in this new area and nationwide as well.

Viewing the entire picture
The '**Circular Water for Chemelot**' programme describes which steps can be taken to optimise water usage and purification. Purified water can be reused after reprocessing. However, this creates a concentrated stream of waste products, called brine, which is preferably not discharged. As far-reaching wastewater treatment often involves considerable costs and an increase in energy consumption, **a systemic approach is required to assess measures and their impact**.

Emission-free 'by design'
Waste substances entering the system must also be disposed. The focus at present is on removal, but the best option is 'emission-free by design'. Take cooling towers, for instance. Cooling water conditioning agents are currently used to prevent scale build-up, microbiological contamination and corrosion in the cooling system. Many plants have recently switched over to a more environmentally-friendly conditioning agent. Non-chemical alternatives to conditioning are also being developed, such as ways to remove calcium in advance. Cooling systems will ideally be designed in such a way that no or far fewer conditioning agents will be necessary. This shows how better **design criteria contribute to limiting discharges and why it is important to include the entire system in the considerations**.

Program line 4
Safety & societal acceptance

Chemelot wants not only to be the most sustainable and efficient chemical site in Europe, but also the safest and healthiest, in order to guarantee a good living and working environment for employees and local residents. Changes resulting from the energy and raw materials transition can affect safety and the (living) environment. Brightsite is working on processes and methods for **guaranteeing integrated process safety and societal acceptance**.

Transparency on impact transition choices

Much remains to be done if we are to achieve a climate-neutral, fossil-free, circular society with widespread prosperity and a high quality of life. It will require choices that are not stand-alone, but have an impact on other transition paths, including those of other sectors. Brightsite is helping by **making choices and their effects specific and by identifying both advantages and disadvantages.**

Power of participation

A Brightsite exploration of different elements of transition and societal acceptance shows that stakeholder participation is crucial for Chemelot's transition. Community participation has been examined, based on the conviction that involving the local community will serve to bolster acceptance of the chemical industry's transition processes. Choices made during the transition will impact on society as a whole and on individuals. Drawing on literature, interviews on historical and current case studies and in consultation with scientists, a **manual for Chemelot's participation approach** has been drawn up. This manual provides users with participation tools. Consider in this regard such topics as: what is necessary and what is permissible, analysis of stakeholders as a necessary first step, possible forms of participation and the degree and timing of participation per stakeholder. Read more on the impact of transition choices and the meaning of participation in 'SOCIETAL-NL', on page 25.

Safety: Learning from data

The technologies and products required for transitioning to climate-neutral and circularity must first of all be safe; only then will they be accepted by employees and society. Society has changed over the years. The learning curve for achieving safe processes and factories will also be much shorter than the chemical industry is used to from past experience. Brightsite is actively committed to using 'big data' to improve safety in combination with AI and ML techniques, the so-called Early Warning System (EWS), based on the conviction that this will make incidents more predictable and preventable over time.

SOCIETAL-NL

Making specific choices

The chemical industry will go through a period of scarcity during the transition. Scarcity of sustainable energy and raw materials, though also of space and professional skill. This will require **choices that impact on society as a whole** as well as on individuals; general versus personal interest, current versus future interest. Take the local nuisance caused by the construction of wind turbines for energy supply or the construction of improved logistics for industrial transport. How can the benefits and burdens be shared fairly? Here, there is a role not only for science, business and politics, but also for the general population. **It is important that the whole of society contributes ideas before irreversible choices are made.**

Participation in a broad sense is important

Participation is needed and must come from several sides. The perception around chemistry can be greatly improved by a more proactive attitude aimed at participation. Chemistry and society need each other. After all, countless consumer products and direct or indirect prosperity stem from chemistry. Awareness of chemistry's interconnectedness with society and current prosperity can be raised by getting society more involved, through citizens' interest groups for example. In short: a major societal catch-up is needed.

You go faster alone, but you go further together

What does a bridge between science, politics and groups within society look like? Listening, trusting, the desire to understand one another and transparent decision-making are important. **Early stakeholder involvement can lead to better solutions, decisions and more support.** 'You may well go faster alone, but you go further together'. With a well-run process, acceptance of the result is more significant. To achieve this, it is necessary to know which groups society consists of and what is important to them, in order to convey messages about choices in a way that is readily comprehensible: in language that is clear, tangible and specific. **The correct use of language is crucial for mutual understanding**.

Who will make the choices en route to 2050?

A representative cross-section of the population will help to make better choices. One important consideration is who will make the choices en route to 2050. The current over-50s or those who will have to do it further down the line: today's twentysomethings? Is there sufficient realisation among young adults that they ought to be making their voices heard right now? Are they sufficiently involved? What forms of participation will be necessary to set the decision-making process in motion?

Encouraging behavioural change

There is no escaping the fact that society will have to change its behaviour, by flying less, repairing rather than buying new, and electric driving. Such behavioural change will not happen by itself, instead requiring a combination of incentivisation and obligation. The government will have to play a role in this, for example by providing information, regulating, subsidising and charging.

Being transparent...

The (chemical) industry can play a pioneering role by being proactive and transparent in using and saving energy and raw materials, in choosing sustainable solutions. **Showing in specific terms what works and what does not**. The technologies and processes required for transition to climate-neutral and circular must be safe. Only then will they be accepted by society. Safety requires thinking beyond what is regulated by law. Integrated safety is a mix of issues and topics from the local community, the environment, occupational health and safety, road safety, quality of life and employment.

... and knowing what matters to people

For local residents, day-to-day nuisances are often the most significant issues, such as hearing a continuous droning sound, feeling sporadic vibrations or seeing a brown dust cloud coming their way. These create a sense of unease, even though they are permissible by law. **Proactively devoting attention to participation at all stages of development makes sense**. The question to be addressed in all developments is: What is the effect of proposed developments within the chemical industry on **integrated safety and well-being**? Only then will society's perception of the chemical industry be liable to change for the better. And this is necessary.

Program line 5
Transition scenarios and system integration

Integral climate transition
Given the complexity of a chemical site like Chemelot and the countless sustainability options, an efficient climate transition cannot take place without an integrated, systematic approach. Based on accumulated systems knowledge, **Brightsite is developing models capable of dealing with complexity in order to develop optional transition routes**, options in terms of fostering transition, clarifying choices and the impact of choices on current and future society for (political) decision-making.

Further developments of models.
The **Chemelot Integrated Model System** (CIMS) has been developed in order to optimise routes on the path towards Chemelot's climate neutrality. This model is also being used to generate Chemelot's supporting data for national bodies. The many factors influencing Chemelot's transition will require the functionality of the modelling tools to be extended. For instance, more robust ways have been identified to include different (future) scenarios parameterisation and Scope 3 emissions (upstream and end-of-life) in the optimisation. All kinds of alternative technologies can also be modelled.

Brightsite scenarios crystallise transition paths and their impact
Brightsite scenarios for the European chemical industry have been used to determine which external factors specifically affect Chemelot. Modelling tools are used to formulate responses, such as **effects on optional paths for Chemelot and its accompanying infrastructure**. 'No regret' options and early investment decisions are therefore made more transparent. It also shows policymakers what a site like Chemelot needs in order to achieve climate-neutral status. A next step is to generalise the system modelling approach and make it suitable for other chemical clusters.

System dynamics charted with SCIARS
The **SCIARS** (**Source, Commodity, Intermediates, Application, Re-Source**) model puts Chemelot in perspective with competing technologies, applications and sectors that all depend on the same scarce renewable resources. SCIARS includes Chemelot in current linear and future circular value chains and charts current and future required and available (inter)national energy and raw material flows for the production of chemical products for various applications, including the associated system dynamics. SCIARS can be used to visualise resources and raw materials, identify dilemmas vis-à-vis optimal use of scarce renewable resources and energy, and clarify trade-offs between possible routes. Based on the development of these visualisations in a mathematical model (2023-2024), integrated modelling of growing circularity through (future) carbon cycles and options for growing them becomes possible.

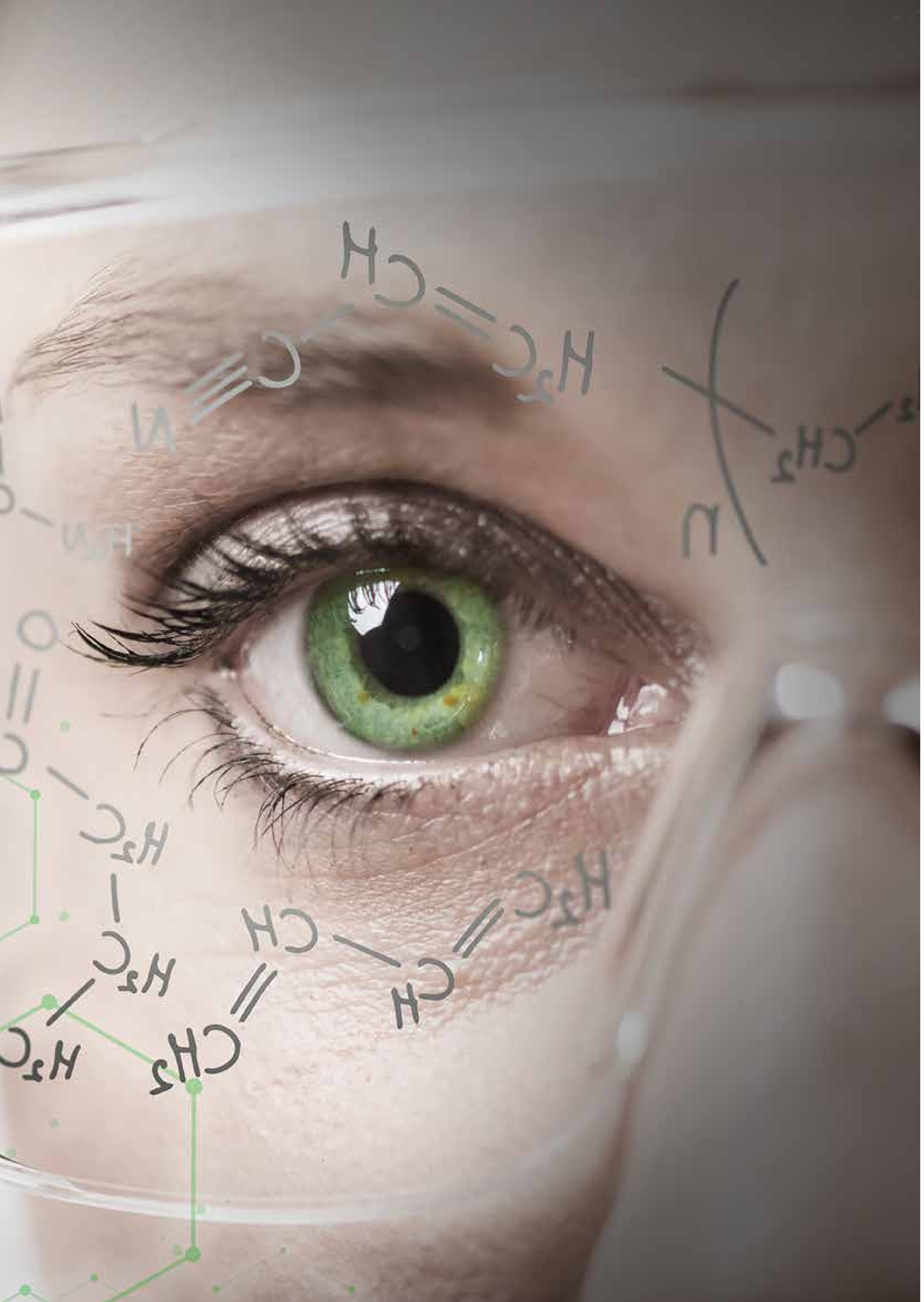
'Zero waste' chemical site
Given the increasing pressure to ease environmental impact, work has started on developing a **'zero waste' chemical site-concept: a chemical site with no or minimal environmental impact**. This concerns not only the elimination of emissions into air and water, but also the elimination of future waste streams. How can the formation of current or future waste products be prevented or lead to useful products? Circularity, the responsible use of scarce renewable resources and the attractivity of the site are key here.

Program line 6
Education and human capital

Training the engineer of the future for Chemelot's transition
The human dimension of the chemical industry transition is at least as important as the technological one. With the tight labour market and the limited supply of engineers, the development of educational programmes focusing on the technical and social climate transition in the chemical sector is crucial. Brightsite is contributing by **training the engineer of the future and strengthening the region's pool of technical workers.**

Focusing on relevant education
The regional industrial base and the research teams at the Brightlands Chemelot Campus, linked to the wider educational landscape in Limburg, are focusing on delivering highly qualified technical graduates in relevant fields. Brightsite is advancing the development of education with the **Bachelor's programme in Circular Engineering** and the development of **study programmes at higher levels**, including preparation for a Master's degree. Students in the bachelor programme obtain a solid foundation in general engineering subjects and a wide range of elective subjects. This allows them to focus on one of three areas during their studies: **sustainable bio-technology, circular chemical engineering** and **engineering physics for sustainable production.**

Students contributing to Chemelot's transition
We are keen to see students, trained within the Brightsite programmes and the wider Brightsite partner network, stay in the region and contribute to the transition with their valuable knowledge and skills. That is why Brightsite focuses on s**trong ties with industrial partners** through **project periods and guest lectures**. Project work is a very important part of engineering courses and students from **Maastricht University** have worked closely with regional industry over the past year. For example, student teams have worked on solutions to challenges in the energy and technology transition and on issues such as improving circularity and developing solutions for waste-to-raw materials. Education is continuously being strengthened and benefits from courses developed by **Maastricht University** research teams, including 'Remake, Reuse, Repair, Recycle' taught by the Circular Plastics team, and 'Circular Business Development' provided by the **Maastricht Sustainability Institute.** The wide range of technical and topical elective subjects offers graduates a broad perspective on the transition, creating a **new generation of flexible problem solvers well versed in systems theory**. The coming year will see the development of more educational opportunities in manufacturing and mechanical engineering and the strengthening of ties within the Brightsite partner network.



Review and concluding remarks

With only 27 years to intended climate neutrality, there is a scarcity of raw materials, land area, CO_2-free energy, time and even labour[6]. Without these means of production, there will be no transition.

Ideally, the transition to climate neutrality will be completed quickly and efficiently by switching from fossil raw materials and energy to alternative raw materials and energy. Earlier in this BTO, some questions about circularity were asked:

In a circular economy, plastic waste is (re)used as a raw material and is not incinerated.
Is circular better than linear? Yes. Is circular always better? No, definitely not. But not for obvious reasons. So when is it and when is it not, and why? And how can the chemical industry's raw material transition to a circular economy be encouraged? What policy is required for this?

Can the above questions be answered? By no means comprehensively, but scenarios and calculations with models will help in this regard. We are sure that if the chemical industry achieves climate neutrality by 2050, it will have switched to combinations of recyclate, bio-material and CO_2 from the air, as well as CO_2-free electricity and hydrogen. Which combinations will be difficult to predict, but models like CIMS help to estimate this, as the present BTO illustrates. The transition paths identified with CIMS do not predict the future, but do make it possible to examine effects such as the effect of legislation, the availability of renewable resources, prices, etc.

Scarcity: shortage of plastic waste

If renewable resources were available in unlimited supply, then the chemical industry could run almost entirely on plastic waste and MSW. Recycling keeps carbon in a cycle, reducing the need for fresh fossil carbon: the principle of a circular economy. However, the supply of waste is totally inadequate and, moreover, circularity comes with inevitable losses.

Biomass 'next best', if sustainable

The case studies show that biomass can play a key role as a preferred source for replenishing losses in circularity. In addition to being efficient, the exploitation of biomass as a carbon source must also be sustainable. This is underdeveloped, certainly in relation to the quantities needed and, partly in view of alternative applications (such as food, energy, wood construction), will still require a great deal of public debate and development. All the more reason to keep carbon in circulation as much as possible, so that volume claims on new biomass can be limited to replenishment and growth of circularity. Using biomass for (new) biopolymers, developed for targeted, efficient bio-applications can also play an important role in this. On the other hand, competition for biomass for other applications might drive up prices. Prices that can be afforded in aviation, for example, but not by the chemical industry: a major risk for the chemical industry in Europe. In the most extreme scenario, this would thwart efforts to make the chemical industry in Europe sustainable.

Transition requires sizeable volumes of CO_2-free energy

The case studies also illustrate that transition leads to intrinsically higher energy consumption. That energy must be CO_2-free. CIMS cannot provide exact figures due to too many uncertainties in the assumptions. But the trends are clear: converting MSW or biomaterial into ethylene or water and nitrogen into ammonia, for example, will take more energy than converting petroleum into ethylene or natural gas and nitrogen into ammonia respectively. Hence developing and fostering new, low-energy, resource-efficient routes and technologies (plasma technology; bio-routes) are extremely important.

CO_2 as a carbon source in the (distant) future?

If there is insufficient availability of both waste and biomaterial, routes based on CO_2 and water are the only alternative besides fossil carbon. Atmospheric CO_2 as a carbon source for the chemical industry, would be a very elegant solution, as there is no shortage of that! But the inherent thermodynamic nature of CO_2 and water (they are 'energyless' molecules), the dilution factor in air and the energy needed for water electrolysis make this route permanently far more energy-intensive than any other. Therefore, this route did not emerge in any of the case studies.

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[6] Pag. 27, program line 6

Energy versus a source of raw materials

The favourable starting position for using recyclate and biomaterial in chemistry is largely due to its own energy content and the often present reusable molecular structures. In general, the higher the energy content of the raw material, the less additional energy required to convert it into intermediate products. The key question is: which is more desirable? Use of bio-based raw materials and waste for energy purposes or as raw material for the chemical industry? If used for energy purposes, the chemical industry will be forced to switch to CO_2 and water. In that case, the extra energy consumption by the chemical industry will far outweigh the usable energy that can be generated by these raw materials. Hence the answer is for the use of biomass and waste for the chemical industry to take precedence over its use for energy purposes.

Proper management can avoid inefficiencies and wasting

The case studies also illustrate the potential synergy of ethylene and ammonia production to jointly achieve net zero CO_2 emissions. However, once resource scarcity comes into play, competition for joint production steps between the two products also begins. The case studies indicate that increasing resource constraints lead to increasing imports of ammonia from abroad. However, it is quite possible that, with different assumptions, ethylene production would be phased out and ammonia retained in CHEM-NL. The scenarios arising all point towards the Netherlands being unable to be selfsupporting. The point is that, due to scarcity, proper management and development of renewable resources are paramount in order to avoid inefficiencies and wasting.

Systemic approach for ensuring success of circularity transition

Many constraints in the CIMS information package relate to restricted availability: future scarcity of plastic waste, MSW, current scarcity such as underdeveloped technologies, alternative raw materials, and even scarce incentives towards circularity. The raw materials transition will place a significant additional burden on already scarce green energy and other resources. A circular economy, where reuse and sustainability have priority in addition to costs (in contrast to the current linear economy) thus seems the way forward, but it comes with many questions. Alternative sources of energy and raw materials still have to be opened up and developed and unproven technologies have to be scaled up. The new economy is therefore more expensive than the current fossil economy. Yet, en route to circularity, fossil and sustainable systems will have to coexist in hybrid form. However, current interests in the linear fossil economy that cause climate change and its associated costs are competing with our future. This too emphasises the need for a systemic approach to the best use of renewable resources and to avoiding inefficiencies in their use.

There is a need for a central, integrated Dutch-European approach to allocating scarce resources where better alternatives are lacking, and encouraging the efficient use of scarce resources.

Approaching transition comprehensively

The raw materials transition for the chemical industry is part of a much wider transition affecting society as a whole. Circularity of materials is not new: plastic bottles, glass, metal and paper are well-known, advanced forms of circularity. Other substances, such as strategic metals and now even carbon will follow. Circularity is also becoming increasingly necessary for fresh water use. The Chemical industry's transition to sustainability will not be possible without a sustainable approach to industrial water usage. The forces driving the emergence and growth of circularity were and are, for instance, the scarcity of raw materials, energy consumption, environmental considerations and government interventions: these too play a role in the circularity of carbon and water. Brightsite is taking a holistic approach to this problem with transition scenarios, demonstrating new technologies, promoting good education for the future and the social aspects of the transition for the chemical industry. The aggregate of the programme lines is more than the sum of its constituent parts. With such a sweeping social transition as the lying ahead of us, **Societal Readiness** is key to every step, and a proactive approach to citizen participation is a prerequisite. In fact, social acceptance is the main driver behind the transition.

This Brightsite Transition Outlook 2023 has been developed under the direction of Céline Fellay, Program Manager Transition scenarios & system integration and Paul Brandts, Intelligence Officer Brightsite, in collaboration with the Program Managers.

Are you keen to contribute to the chemical industry's transition?

Brightsite is committed to achieving a sustainable and competitive chemical industry. To this end, we make a significant contribution to transitioning the chemical industry towards renewable energy and raw materials, with the objective being to make the sector climate-neutral without job losses.

Can you relate to Brightsite's way of working? Are you interested in finding out more about our perspective on the chemical industry's transition or are you eager to work with us?

Then we'd like to talk with you.

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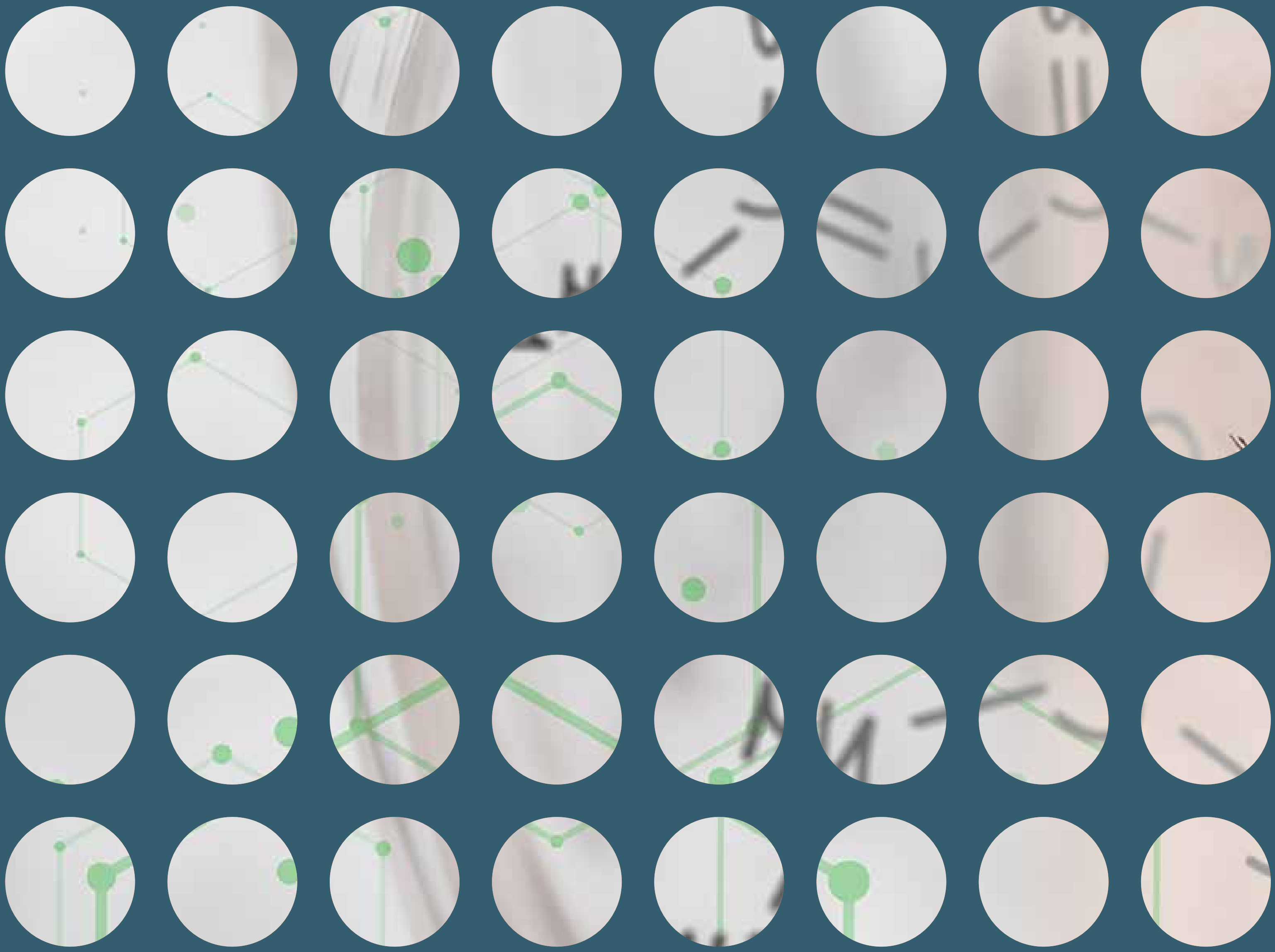
DISCLAIMER

Scenarios and modelling in this BTO are examples of multiple variants and are intended solely to provide insight into how the circularity of plastics, the energy results transition and greenhouse gas reduction can be optimally integrated. Results are sensitive to assumptions and are not predictions, but provide insight into key factors that characterise the transition from a linear to a circular system and can facilitate decision-making on projects, synergies to be pursued and incentives. The approaches and results discussed in this report do not necessarily correspond to approaches taken by individual companies.



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