strategy&
Part of the PwC network

Study on the future chemical raw material value chain and the role of alternative waste processing technologies

Final report

20 December 2024

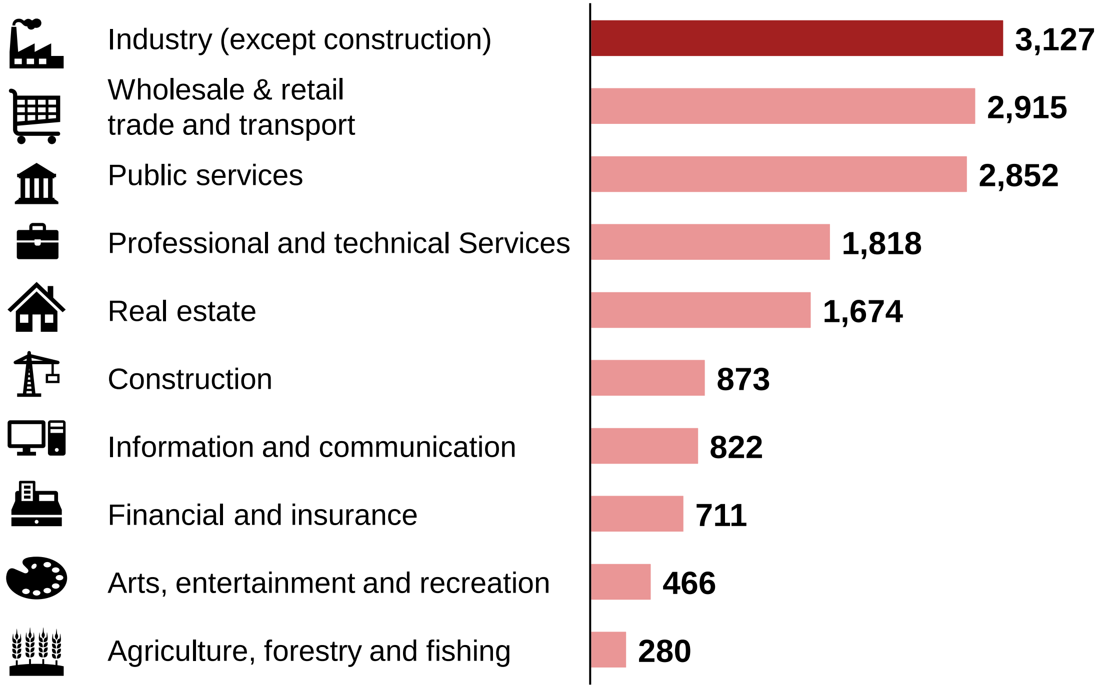
Content

The industrial sector adds the most value to the EU's economy with a leading role for the chemical industry

Value added of EU's chemical industry

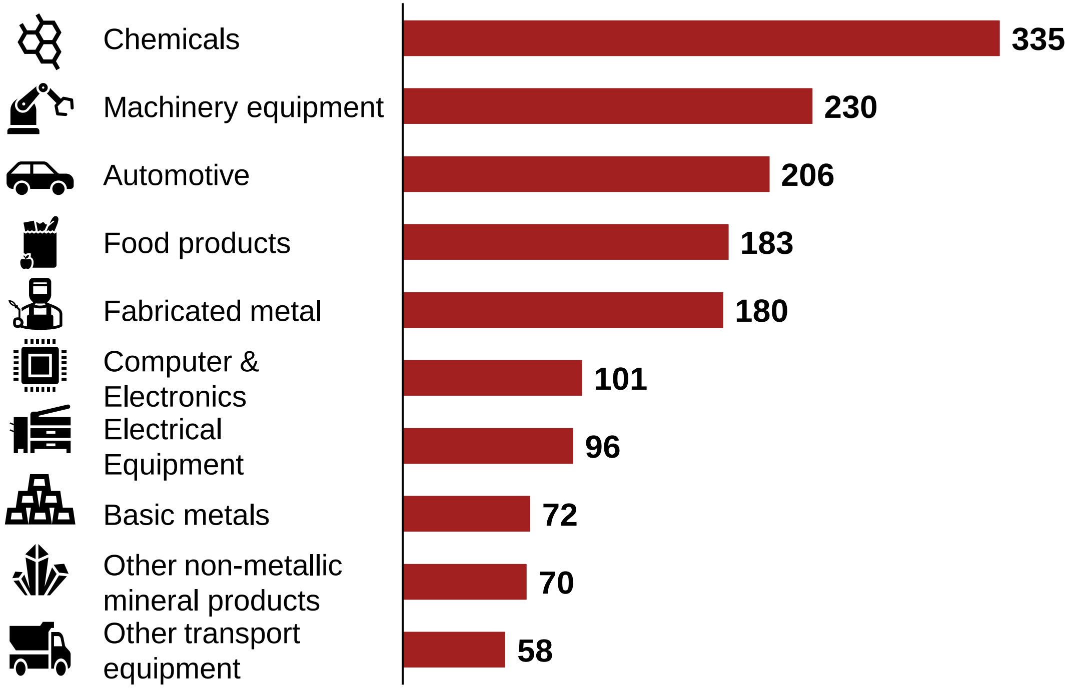
Industry adds the most value in the EU…

(Gross value added in billion €, 2023)



…With a leading role for the chemical industry

(Gross value added in billion €, 2018)



- **The EU has the 2nd largest chemical industry in the world, contributing approximately 5% to the EU GDP**
- **The chemical industry generates €760 billion in revenues end employs over 1.2 million people**

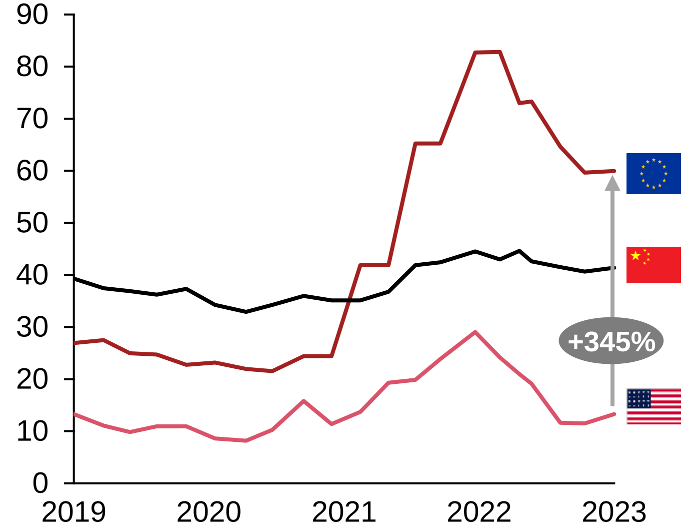
Sources: Eurostat, CEFIC, S& analysis

However, the EU chemical industry is under pressure due to high feedstock prices, low GDP growth and high decarbonization costs

Challenges EU chemical industry

Higher feedstock prices in the EU

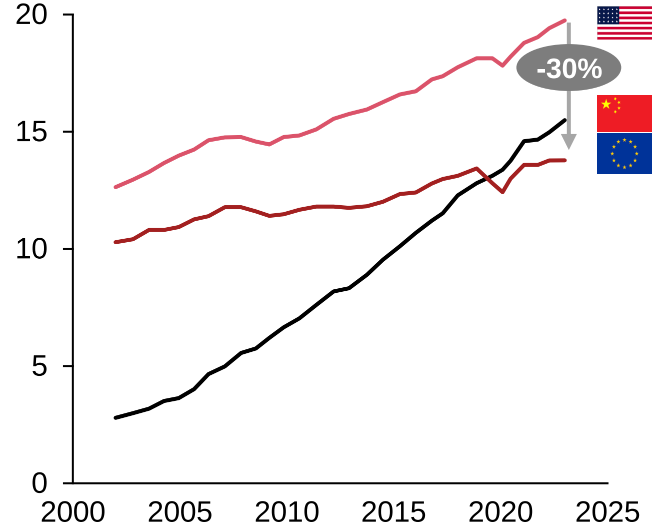
Industrial gas prices
(2019 – 2023, in €/MWh)



The price differential is amongst others driven by 1) the EU's **lack of natural resources**; 2) the EU's **limited bargaining power** despite being the world's largest buyer of natural gas; 3) the EU's **slow infrastructure investments**; 4) the EU's **higher energy taxation**; and 5) the EU's **stricter regulation**

Lower GDP growth in the EU

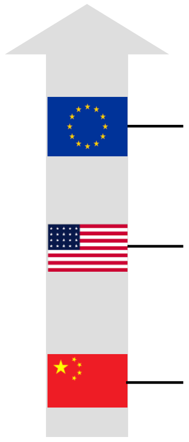
GDP evolution at constant prices
(2002 – 2023 , in trillion €)



The GDP differential is amongst others driven by 1) the EU's relatively **low labor productivity growth** (80% below US level); and 2) the EU's **lagging position in the breakthrough of digital technologies** (e.g., artificial intelligence)

Higher decarbonization costs in the EU

High ambitions



Binding legislation to reduce GHG[1]-emissions by at least 55% by 2030 compared to 1990 levels

Non-binding target to reduce GHG-emissions by 50-52% by 2030 compared to 2005 levels

Non-binding target to peak carbon emissions by the end of the decade

Low ambitions

High decarbonization ambitions lead to **high near-term investments needs for the EU industry** that their competitors do not face. The **non-metallic minerals, basic metals, chemicals and paper** sector face **€500 billion decarbonization costs** over the next 15 years

---

[1] Greenhouse gas

Source: CEFIC; Mario Draghi - 'EU competitiveness: Looking Ahead' (2024); Strategy& analysis

The EU’s transition to a circular climate-neutral economy with raw material security is needed to ensure a competitive chemical industry

Ambitions EU

100% circular, climate-neutral economy

- Current raw material production and consumption is one of the main causes of **climate change, biodiversity loss and pollution** as primary materials are (largely) fossil-based and difficult to recycle
- Therefore, the EU aims to replace finite raw materials with **renewable and secondary alternatives** and stimulate high quality **recycling** and **negative emissions**

European Commission

> “The transition to a **circular economy** is necessary to reduce pressure on natural resources and to achieve the **2050 climate neutrality target**.”

Raw material security

- Global population growth and economic development are **driving the demand for raw materials** putting pressure on countries to ensure a **stable supply of resources**
- Therefore, the EU strives to **more efficiently use available raw materials, shorten the supply chain** and **reduce import dependency**

PBL Netherlands Environmental Assessment Agency

> “The **global raw material use is expected to double between now and 2060** if policies are unchanged.”

Competitive position (chemical) industry

- The **competitive positioning of the (chemical) industry in the EU is under pressure** (see previous page)
- Therefore, the EU aims to safeguard the economic strategic importance of the (chemical) industry by **stimulating the transition towards a “green industry**” and the **replacement of fossil-based feedstock with circular alternatives**

The future of European competitiveness

Mario Draghi

> “The only way out is to **grow and become more productive**; the only way to become more productive is to **radically change**.”

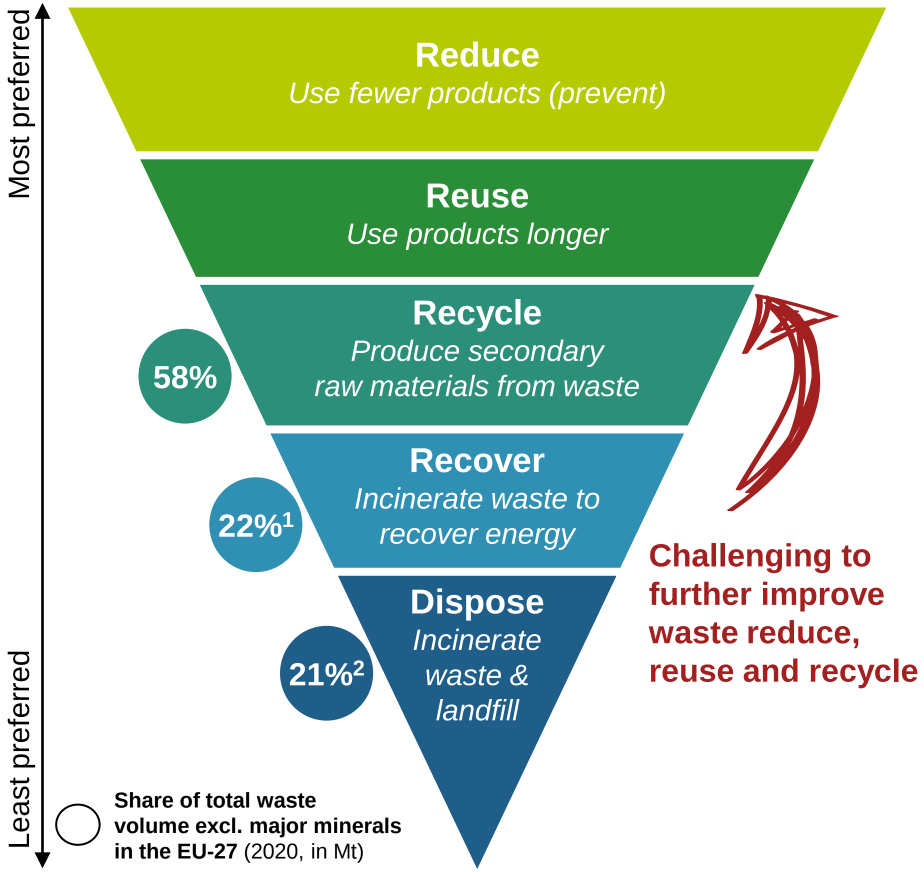
The transition in the EU is enabled by innovative solutions to boost productivity and counterbalance impact of ageing population

Source: European Commission; PBL; Mario Draghi – ‘EU competitiveness: Looking Ahead’ (2024); Strategy& analysis

The EU faces challenges to further 'climb' the waste hierarchy – large waste volumes are still landfilled or incinerated

Transition up waste hierarchy

Waste Framework Directive: 'EU waste hierarchy'



Challenging to further improve waste reduce, reuse and recycle

○ **Share of total waste volume excl. major minerals in the EU-27** (2020, in Mt)

Enabler	Challenges to further 'climb' the waste hierarchy	Example
Product design	× Materials have a finite lifetime (e.g., paper can be recycled 5-7 times) × Complexity of products has increased × Products are designed to meet customer requirements, not for optimal recyclability	
Human behaviour	× Material use is expected to increase × Households and companies often do not comply with rules for source separating waste	
Infrastructure & technology	× Waste processing technologies have typical yields of 50-90% × High quality materials are often downcycled	
Regulation & incentives	× Market for recycled materials and products is nascent × Strict quality standards × Recycled weight is prioritized over output quality	

---

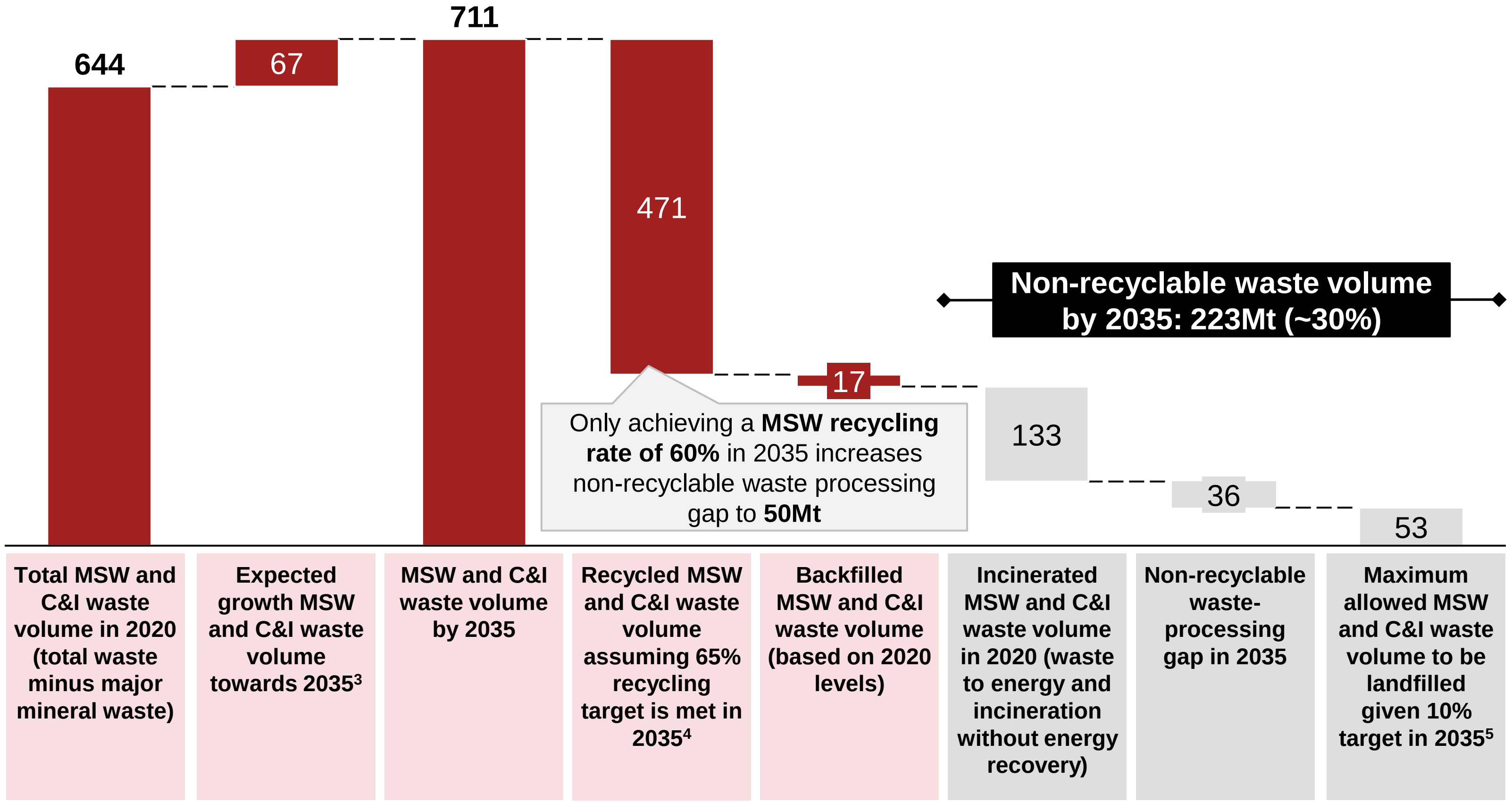
1) Includes 'backfilled waste volume (3%-pt.): backfilling is a recovery operation where suitable waste is used for refilling an excavated area with suitable materials, typically after a foundation, trench, or other structure has been built.; 2) Includes waste incinerated without energy recovery (1%-pt.); Note: numbers may not add up due to rounding.
Source: European Commission; EU Waste Framework Directive; Eurostat; Strategy& analysis

Outlook indicates >30% of EU waste to be non-recyclable by '35 – potential for affordable and low carbon alternative waste processing technologies

High-level waste processing outlook in the EU (towards 2035)

Processed MSW and C&I waste volumes in the EU

(in Mt per year)



Non-recyclable waste volume by 2035: 223Mt (~30%)

Only achieving a **MSW recycling rate of 60%** in 2035 increases non-recyclable waste processing gap to **50Mt**

Key insights

- The **total waste volume in the EU amounted to 1,942Mt in 2020** including 1,298Mt major mineral waste volume from mining and construction & demolition
- The remaining waste is combination of **MSW[1] and C&I[2] waste: 644Mt in 2020**
- High-level outlook indicates waste volumes to grow towards **711Mt by 2035**
- **471Mt of waste will be recycled in 2035, if the 65% recycling targets are achieved** (improving recycling rates is challenging due to e.g., product design, finite material lifetime)
- The remaining **waste volume** (excl. backfilled waste) **is 223Mt (~30%) by 2035**, which is considered **non-recyclable**
- This includes an expected **non-recyclable waste processing gap of 36Mt,** requiring more processing capacity

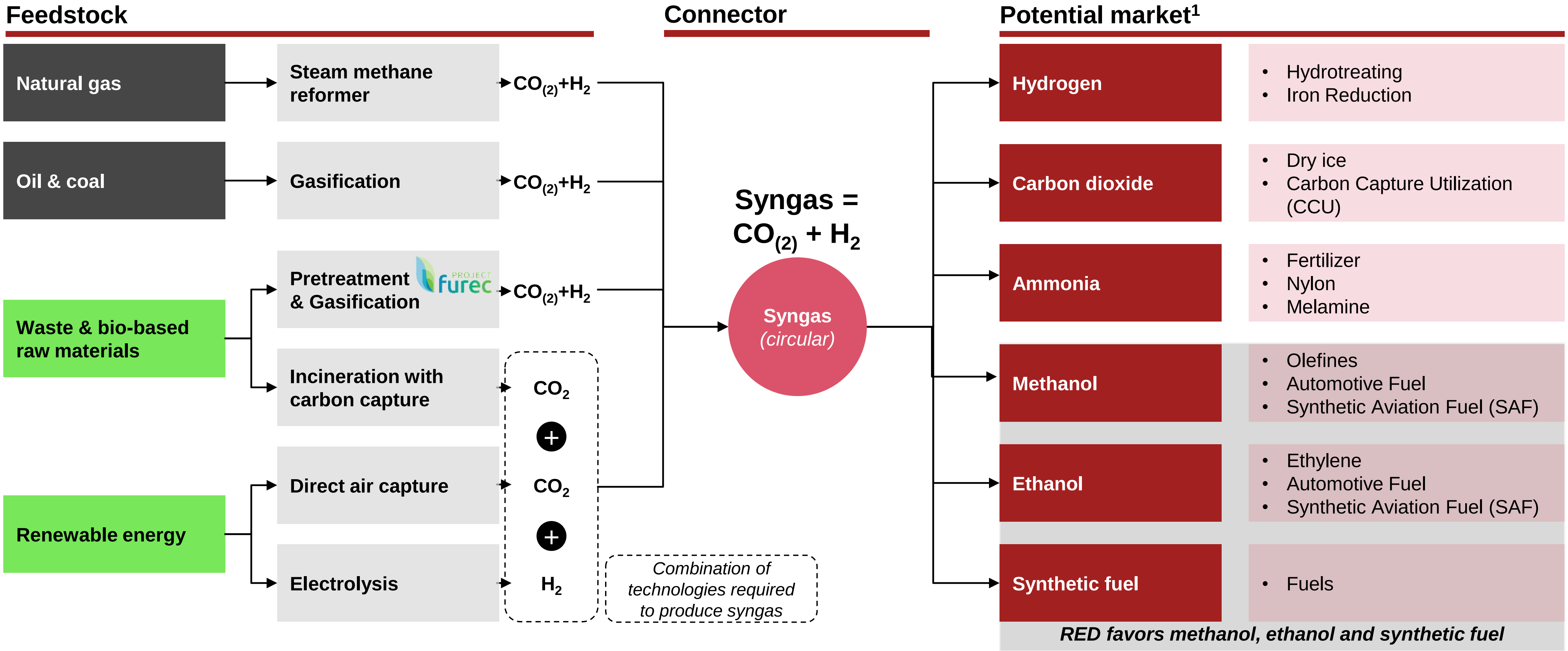
---

1) Municipal Solid Waste; 2) Commercial & Industrial; 3) Growth rate of 1.0% YoY for MSW and 0.5% for C&I based historical growth rates for MSW and C&I ('10-'18) – in line with growth projections for material use; 4) Includes digestion & composting and assumed that recycled volumes of C&I improve with 1% YoY; recycled C&I waste reaches 67% compared to total C&I waste in 2035; 5) Assumed 10% target also applies for C&I

Source: Eurostat; OECD; Strategy& analysis

The production of circular syngas from non-recyclable waste enables the production of a wide range of circular products

Role of syngas



Feedstock

Natural gas → **Steam methane reformer** → $CO_{(2)}+H_2$

Oil & coal → **Gasification** → $CO_{(2)}+H_2$

Waste & bio-based raw materials → **Pretreatment & Gasification** (PROJECT furec) → $CO_{(2)}+H_2$

Waste & bio-based raw materials → **Incineration with carbon capture** → CO_2

Renewable energy → **Direct air capture** → CO_2

Renewable energy → **Electrolysis** → H_2

CO_2 + CO_2 + H_2

Combination of technologies required to produce syngas

Connector

Syngas = $CO_{(2)} + H_2$

Syngas *(circular)*

Potential market[1]

Hydrogen	- Hydrotreating - Iron Reduction
Carbon dioxide	- Dry ice - Carbon Capture Utilization (CCU)
Ammonia	- Fertilizer - Nylon - Melamine
Methanol	- Olefines - Automotive Fuel - Synthetic Aviation Fuel (SAF)
Ethanol	- Ethylene - Automotive Fuel - Synthetic Aviation Fuel (SAF)
Synthetic fuel	- Fuels

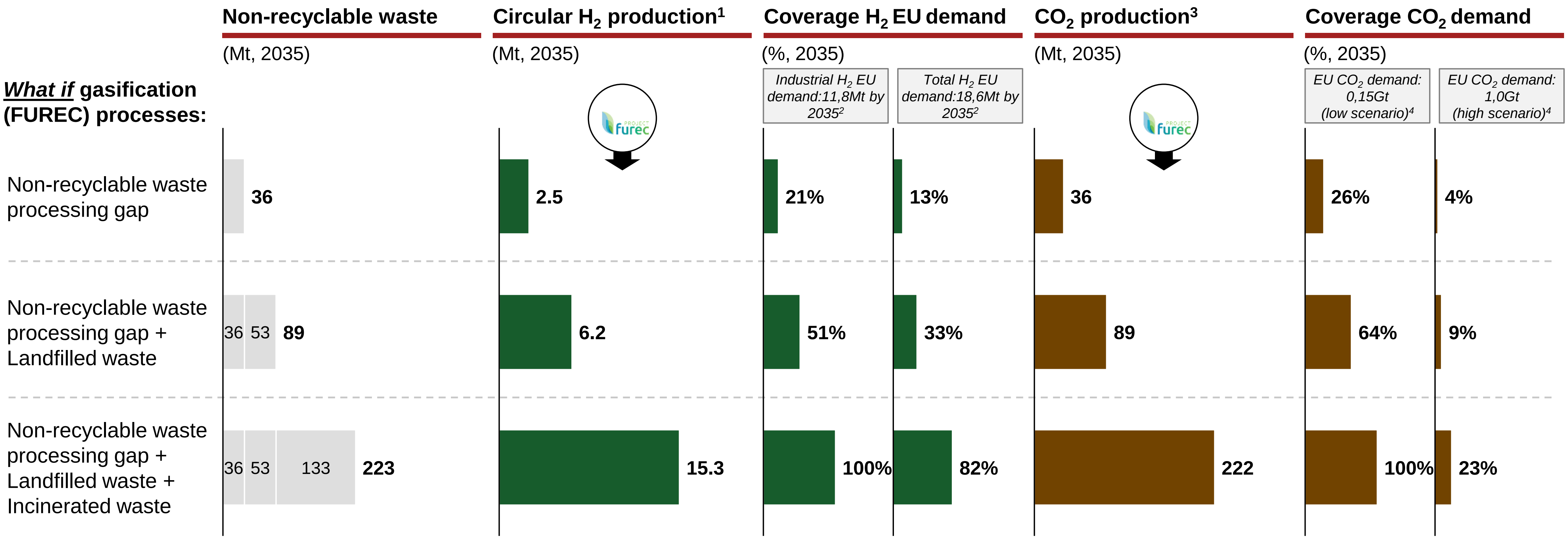
RED favors methanol, ethanol and synthetic fuel

[1] Methanol, Ethanol and Synthetic fuel are prioritized in current policies

Source: Chemistry Europe – 'Towards the Use of Renewable Syngas for the Decarbonization of the Industry' (2024); Expert input

Processing large non-recyclable waste volumes via gasification can cover a large share of future EU hydrogen and CO_2 demand

Potential of gasification via FUREC in covering EU hydrogen (H_2) and CO_2

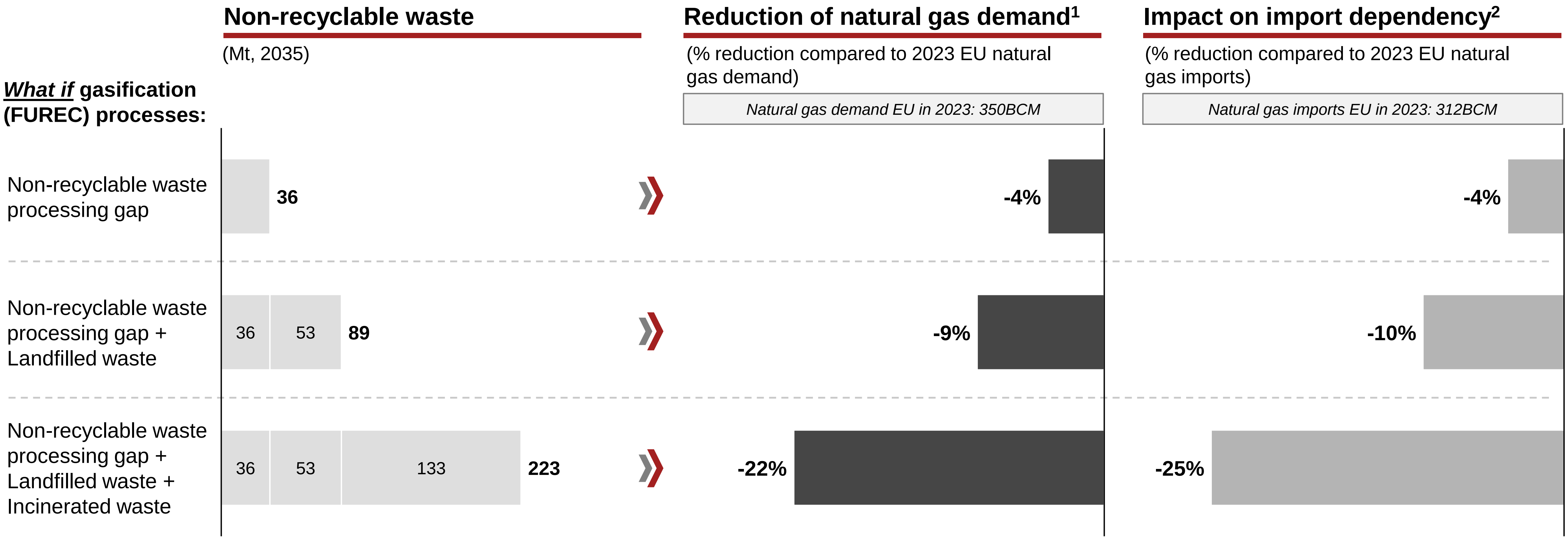


The FUREC platform is scalable. Example: Closing the non-recyclable waste processing gap with the FUREC platform requires the construction of ~45 platforms (800kt/yr. capacity per platform). This build-up (incl. supporting infrastructure) requires large Capex investments and time

1) Conversion of FUREC applied: gasification of 800kt of waste yields 55kt of H_2; 2) Demand in 2035 interpolated from projections for 2030 and 2040; 3) Conversion of FUREC applied: FUREC produces 800kt of CO_2 out of 800kt of waste; 4) Future scale of CO_2 use is highly uncertain. Global estimates for CO_2 derived products range from less than 1Gt CO_2 use to 7Gt of CO_2 use for 2030. The higher estimates are considered very optimistic. It is assumed these estimates also provide indication for the future scale in 2035. Estimates scaled to EU based on EU size of chemical industry compared to global size of chemical industry (~15%)
Source: The European Hydrogen Market Landscape (November 2023); IEA, Putting CO2 to use; CEFIC, World Bank, Strategy& analysis

Gasification of non-recyclable waste can also reduce EU natural gas demand, consequently lowering import dependency

Potential of gasification via FUREC on reducing EU natural gas demand



---

1) Gasification (FUREC) reduces natural gas demand by 280 million m³ for processing 800kt of non-recyclable waste (as gasification (FUREC) replaces steam methane reformer capacity); 2) EU natural gas production equals 38bcm in 2023, hence 312 BCM import dependency (e.g. Norway, US, Russia, Algeria, etc.)

Source: Eurostat, IEA; FUREC website, Bruegel (Future European Union gas imports: balancing different objectives), Strategy& analysis

Gasification via FUREC is designed to convert non-recyclable waste into circular syngas and complement other waste processing technologies

Overview of waste processing technologies

Feedstock conversion

Method	Description	Typical input		Typical output	Players (examples)
		Non-recyclable waste	*Specific waste stream*		
Mechanical recycling	Waste is **recovered** (e.g., through sorting, washing, drying, grinding and regranulating) **without changing the material's chemical structure**		✓ e.g., plastic, metals, paper	Materials (e.g., plastic flakes)	VEOLIA pre zero REMONDIS WORKING FOR THE FUTURE renewi
Digestion/ composting	Biowaste (e.g., food waste) is **broken down by bacteria** in a controlled environment		✓ e.g., biowaste	Biogas + digestate	Biogas-
Chemical recycling	Waste is **broken down into molecules via controlled chemical processes** (multiple methods exist such as pyrolysis and gasification)		*Most technologies focus on plastic waste*	Molecules	
Pyrolysis	Waste is decomposed by **heating waste to high temperatures without oxygen**		✓ Mostly plastic (or bio)	Pyrolysis oil (naphtha)	سابك sabic LYB LyondellBasell Exxon
Gasification via FUREC	Waste is **pre-treated and converted to pellets** which are **heated under high temperatures**	✓		Circular syngas	RWE
Incineration (Waste-to-Energy)	Waste is **incinerated in a controlled environment**	✓		Heat + electricity	Twence fortum
Landfill	Waste is **disposed into or onto land**	✓		No product	INDAVER REMONDIS WORKING FOR THE FUTURE

Source: Company websites; Strategy& analysis

The FUREC platform contributes to a circular and climate-neutral economy, raw material security and a competitive industry in the EU

Contribution FUREC platform to society

	Ambitions EU		
The FUREC platform…	**100% circular, climate-neutral economy**	**Raw material security**	**Competitive position (chemical) industry**
…produces circular and affordable molecules for the (chemical) industry, bolstering its competitive and circular positioning	✓	✓	✓
…offers flexibility as FUREC's core output product (syngas) enables the production of a wide range of circular products, e.g., fertilizers and olefines (plastics)	✓	✓	✓
…offers a waste processing technology at scale (first planned plant has capacity of 800Kt per year), which can be built across the EU	✓	✓	✓
…offers an alternative for processing non-recyclable waste, which is currently incinerated or landfilled	✓	✓	
…has a positive environmental impact, substantially reducing emission of greenhouse gas (CO2), nitrogen and toxic fly and bottom ashes (compared to alternatives)	✓		

Gasification (FUREC) is a first-of-its-kind platform that combines individually mature technologies;
its potential in the future waste market is endorsed by the European Innovation Fund with a subsidy of €108M

Note: Potential contributions of FUREC platform to society based on insights from this reports (incl. like-for-like comparison with alternative non-recyclable waste processing technologies)

Details on policy recommendation on p. 56

Chemical recycling technologies can be further stimulated via policies on output demand, availability of feedstock and financial incentives

Proposed policy recommendations

- **Chemical recycling technologies have the potential to contribute to the EU's transition** to a circular climate-neutral economy with raw material security and a competitive (chemical) industry
- These technologies require **demand for their output, availability of feedstock and sufficient financial resources**
- These requirements can be established via targeted **transition policies that are harmonized across EU member states and value chains**

Requirement	Proposed policy recommendations	Level
Demand for output	**Stimulate the use of circular feedstock in new products incl. redefinition of recycling** (to stimulate high-quality recycling and prevent downcycling)	🇪🇺 & 🇳🇱
	Harmonize RED II & III targets for the transport and industry sector	🇪🇺
	Exclude circular syngas (hydrogen) from the RED III target	🇪🇺 & 🇳🇱
Availability of feedstock	**Embrace cross-border transport of waste across EU member states**	🇪🇺
	Extend waste tender criteria with environmental impact and preferred processing method	🇪🇺 & 🇳🇱
Financial incentives	**Financially support circularity innovations and business models**	🇪🇺 & 🇳🇱
	Include hydrogen from waste projects in the SDE++ subsidy scheme	🇳🇱

🟥 *Prioritized policy recommendations*

Source: Strategy& analysis

So, the FUREC platform holds the potential to enable the EU chemical industry by addressing the non-recyclable waste challenge

Key statements

The industrial sector adds the most value to the EU's economy with a **leading role for the chemical industry**

However, the **EU chemical industry is under pressure** due to high feedstock prices, low GDP growth and high decarbonization costs

Hence, the EU's **transition to a circular climate-neutral economy** with raw material security is needed to ensure a **competitive chemical industry**

Simultaneously, the EU faces **challenges to further 'climb' the waste hierarchy** – large waste volumes are still landfilled or incinerated

Outlook **indicates >30% of EU waste to be non-recyclable by '35 – potential** for affordable and low carbon **alternative waste processing technologies**

The **production of circular syngas** from **non-recyclable waste** enables the production of a wide range of **circular products**

Processing large **non-recyclable waste volumes via gasification** can cover a large share of **future EU hydrogen and CO_2 demand,** while **reducing natural gas demand**

Gasification via FUREC is designed to convert non-recyclable waste into circular syngas and complement other waste processing technologies

The FUREC platform **contributes to a circular and climate-neutral economy, raw material security and a competitive industry in the EU**

Chemical recycling technologies should be **stimulated** via policies on **output demand, availability of feedstock and financial incentives**

Content

The EU’s ambition is to transition to a circular climate-neutral economy with raw material security and a competitive industry

Ambitions EU

100% circular, climate-neutral economy

- Current raw material production and consumption is one of the main causes of **climate change, biodiversity loss and pollution** as primary materials are (largely) fossil-based and difficult to recycle
- Therefore, the EU aims to replace finite raw materials with **renewable and secondary alternatives** and stimulate high quality **recycling** and **negative emissions**

European Commission

> “The transition to a **circular economy** is necessary to reduce pressure on natural resources and to achieve the **2050 climate neutrality target**.”

Raw material security

- Global population growth and economic development are **driving the demand for raw materials** putting pressure on countries to ensure a **stable supply of resources**
- Therefore, the EU strives to **more efficiently use available raw materials, shorten the supply chain** and **reduce import dependency**

PBL Netherlands Environmental Assessment Agency

> “The **global raw material use is expected to double between now and 2060** if policies are unchanged.”

Competitive position (chemical) industry

- The **competitive positioning of the (chemical) industry in the EU is under pressure** due to high feedstock prices, low GDP growth and high decarbonization ambitions and costs
- Therefore, the EU aims to safeguard the **economic strategic importance of the (chemical) industry** and to stimulate the transition towards a “green industry”

Mario Draghi

> “The only way out is to **grow and become more productive**; the only way to become more productive is to **radically change**.”

Details in appendix p.58-59

The transition in the EU is enabled by innovative solutions to boost productivity and counterbalance impact of ageing population

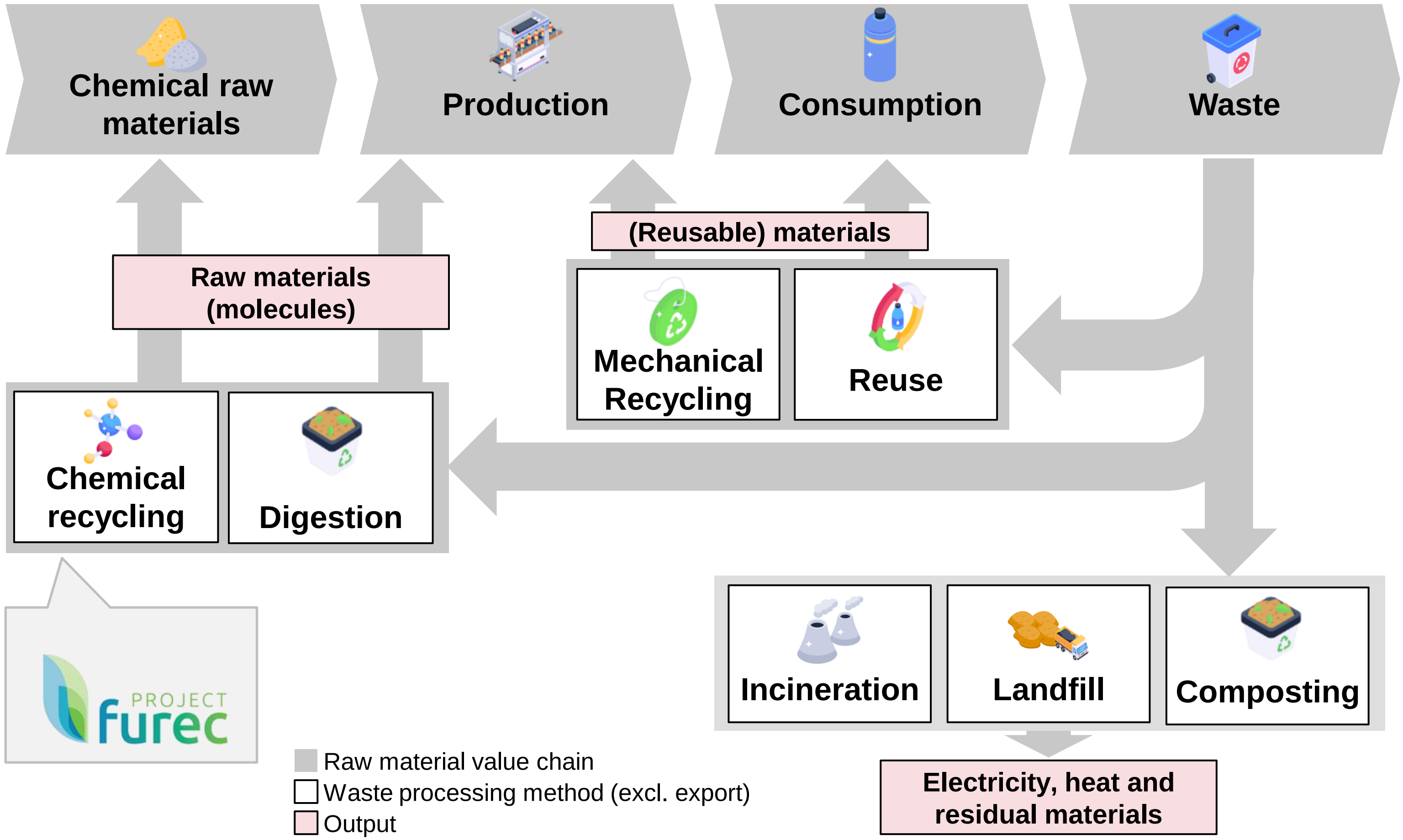
Source: European Commission; PBL; Mario Draghi – ‘EU competitiveness: Looking Ahead’ (2024); Strategy& analysis

DETAILS ON FUREC IN APPENDIX P.60-61

FUREC can play a role in the raw material value chain transformation by converting non-recyclable waste into valuable molecules via gasification

Introduction FUREC platform

Illustration role FUREC in chemical raw material value chain



Chemical raw materials

Production

Consumption

Waste

Raw materials (molecules)

(Reusable) materials

Mechanical Recycling

Reuse

Chemical recycling

Digestion

PROJECT furec

Incineration

Landfill

Composting

Electricity, heat and residual materials

▨ Raw material value chain

☐ Waste processing method (excl. export)

🟥 Output

Introduction FUREC platform

- The **raw material value chain needs to become more circular** with more focus on reduce, reuse and recycling
- FUREC consists of **two processes**: i) **pre-treatment of waste** (converting heterogenous waste into homogenous waste pellets); and ii) **gasification** of waste pellets at extremely high temperatures (~3.000 °C) to break down these pellets into molecules
- **FUREC offers an alternative waste method** in the raw material value chain for **processing non-recyclable waste**, which is currently incinerated or landfilled
- The **potential role of chemical recycling technologies** such as FUREC in the raw material value chain is also **highlighted** in the study **"Trajectverkenning klimaatneutraal 2050"** by PBL

Source: FUREC website; PBL – 'Trajectverkenning klimaatneutraal 2050' (2024); Strategy& analysis

The FUREC platform contributes to a circular and climate-neutral economy, raw material security and a competitive industry in the EU

Contribution FUREC platform to society

	Ambitions EU		
The FUREC platform…	**100% circular, climate-neutral economy**	**Raw material security**	**Competitive position (chemical) industry**
…produces circular and affordable molecules for the (chemical) industry, bolstering its competitive and circular positioning	✓	✓	✓
…offers flexibility as FUREC's core output product (syngas) enables the production of a wide range of circular products, e.g., fertilizers and olefines (plastics)	✓	✓	✓
…offers a waste processing technology at scale (first planned plant has capacity of 800Kt per year), which can be built across the EU	✓	✓	✓
…offers an alternative for processing non-recyclable waste, which is currently incinerated or landfilled	✓	✓	
…has a positive environmental impact, substantially reducing emission of greenhouse gas (CO2), nitrogen and toxic fly and bottom ashes (compared to alternatives)	✓		

Note: Potential contributions of FUREC platform to society based on insights from this reports (incl. like-for-like comparison with alternative non-recyclable waste processing technologies)

This study explores the chemical raw material value chain, the role of alternative waste processing technologies and proposes recommendations

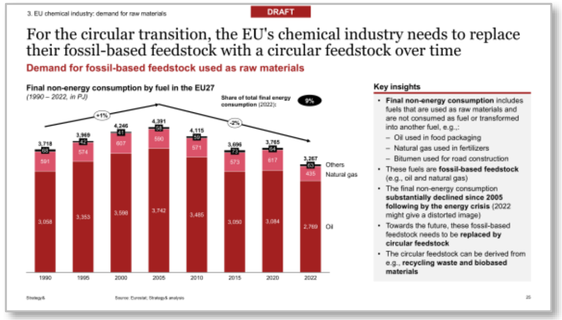
Scope of study and research questions

EU chemical industry: demand for raw materials

☐ What is the outlook of the **chemical raw materials demand** (e.g., natural gas for fertilizer) **by the EU chemical industry**?

Section 2

P.21-27



3. EU chemical industry: demand for raw materials

DRAFT

For the circular transition, the EU's chemical industry needs to replace their fossil-based feedstock with a circular feedstock over time

Demand for fossil-based feedstock used as raw materials

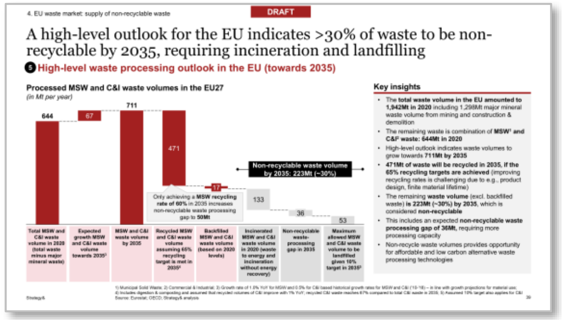
EU waste market: supply of non-recyclable waste

☐ What is the **outlook for the EU waste market**?

☐ Which **part of EU waste volumes** is not recycled and has potential to be **used as raw material by the chemical industry**?

Section 3

P.28-44



4. EU waste market: supply of non-recyclable waste

DRAFT

A high-level outlook for the EU indicates >30% of waste to be non-recyclable by 2035, requiring incineration and landfilling

❺ High-level waste processing outlook in the EU (towards 2035)

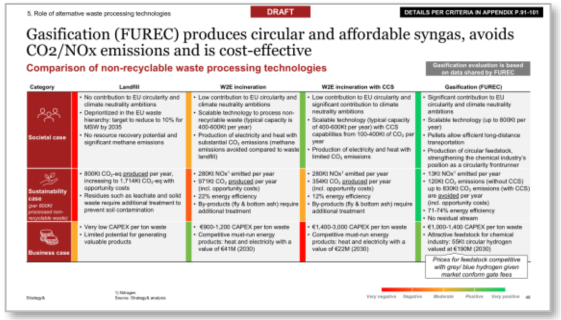
Role of alternative waste processing technologies to convert non-recyclable waste

☐ Which **alternative waste processing technologies** exist to convert non-recyclable waste into raw materials for the chemical industry?

Appendix provides overview emerging alternative waste processing technologies (see p.82-92)

Section 4

P.45-51



5. Role of alternative waste processing technologies

DRAFT

DETAILS PER CRITERIA IN APPENDIX P.91-101

Gasification (FUREC) produces circular and affordable syngas, avoids CO2/NOx emissions and is cost-effective

Comparison of non-recyclable waste processing technologies

Recommendations to stimulate alternative waste processing technologies

☐ What are **recommendations** to stimulate alternative waste processing technologies?

Section 5

P.52-56

6. Recommendations to stimulate alternative waste processing technologies

DRAFT

Chemical recycling should be further stimulated by adopting additional policies, e.g. embracing cross-border transport of waste within the EU

Proposed policy recommendations to further stimulate chemical recycling

Content

DETAILS ON NL CHEMICAL INDUSTRY IN APPENDIX P.62-64

The EU has the 2nd largest chemical industry in the world, contributing approximately 5% to the EU GDP

Overview EU chemical industry

Key figures EU chemical industry (2022)

2nd largest chemical industry in the world in terms of revenue

€760 billion revenue contributing **approximately 5% to the EU27 GDP**

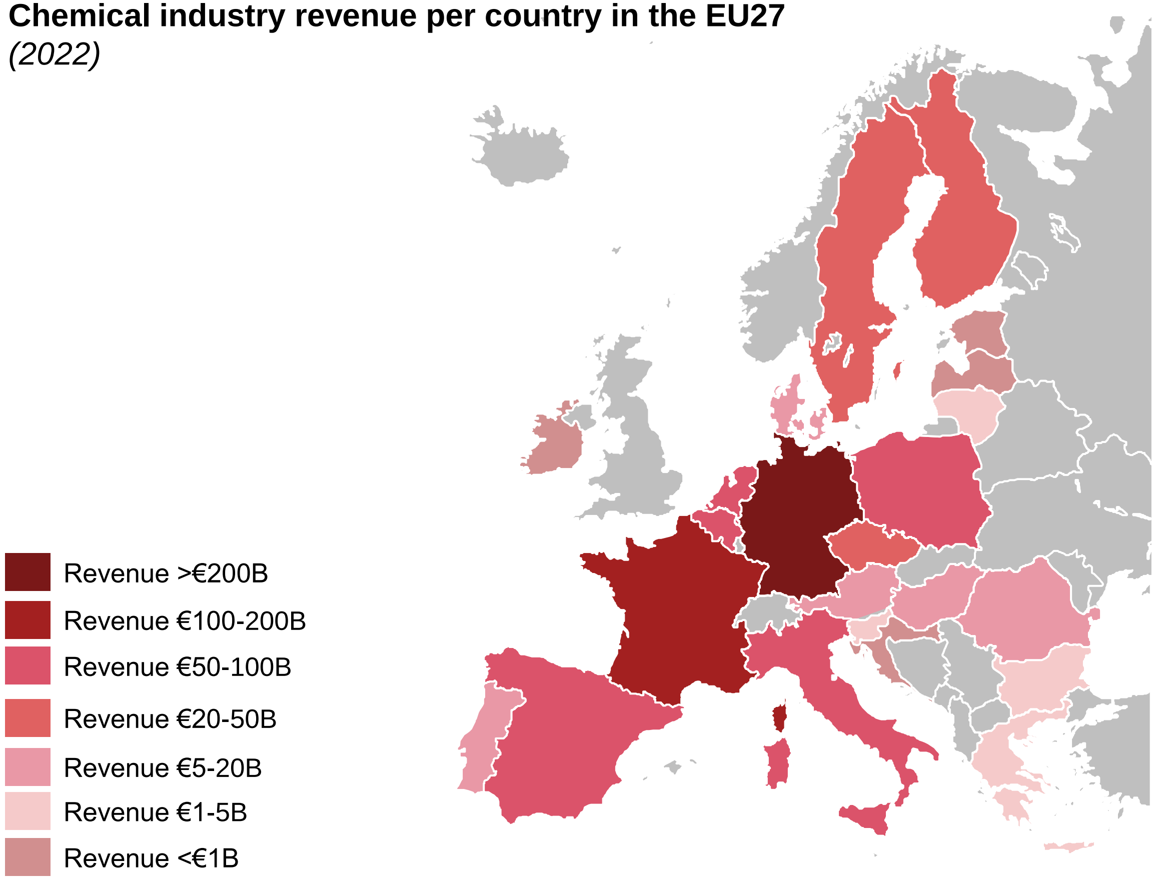
Over **1.2 million employees** active in **29,000 chemical companies**

Key players (examples)

BASF We create chemistry · LYB LyondellBasell · Air Liquide · SOLVAY · ARKEMA · AkzoNobel

Chemical industry revenue per EU country

Chemical industry revenue per country in the EU27 *(2022)*



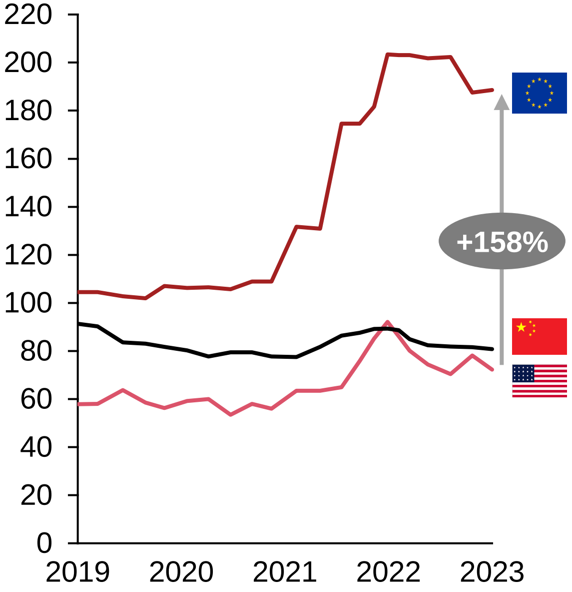
Source: CBS; CEFIC; Strategy& analysis

The EU chemical industry's competitive positioning is under pressure due to relatively high feedstock prices and low regional GDP growth

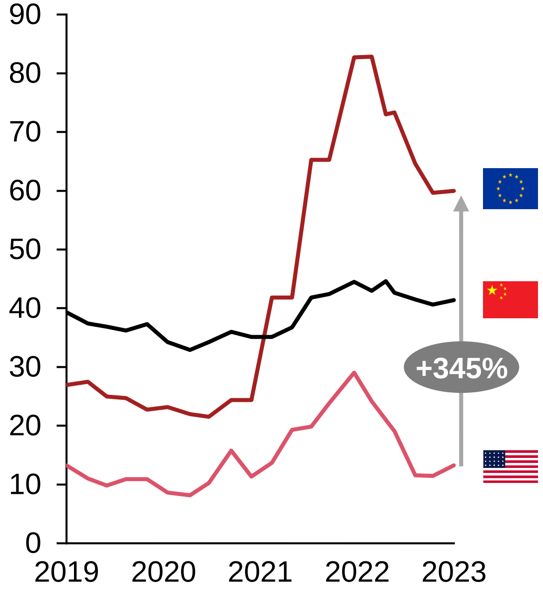
Challenges EU chemical industry (1/2)

Relatively high feedstock prices in the EU vs. USA & China

Industrial retail power prices
(2019 – 2023, in €/MWh)



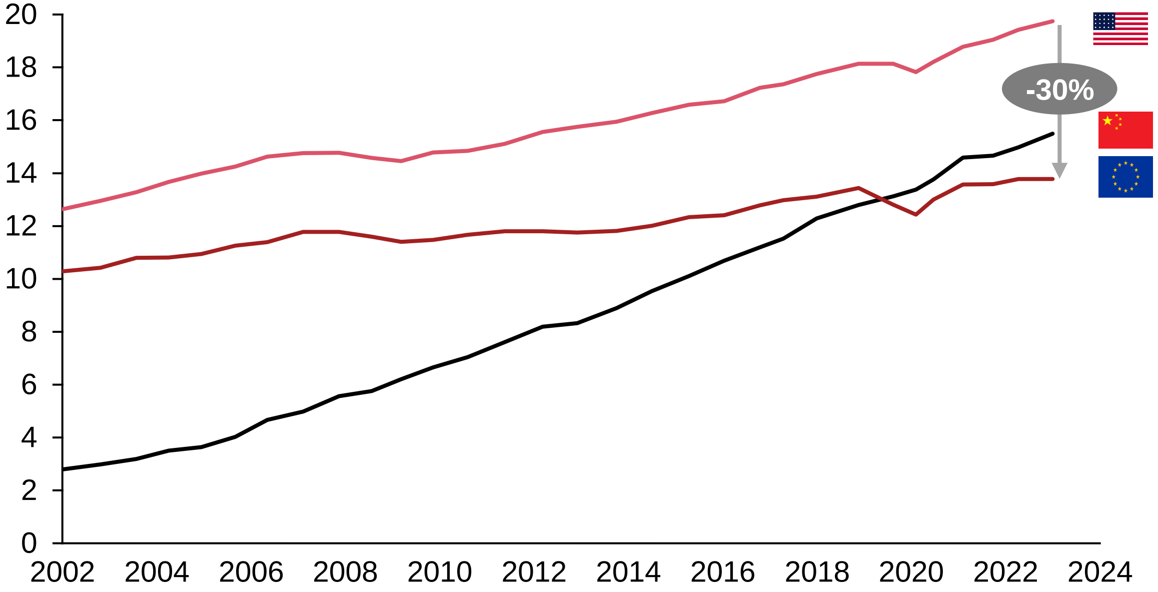
Industrial gas prices
(2019 – 2023, in €/MWh)



The price differential is amongst others driven by 1) the EU's **lack of natural resources**; 2) the EU's **limited bargaining power** despite being the world's largest buyer of natural gas; 3) the EU's **slow infrastructure investments**; 4) the EU's **higher energy taxation**; and 5) the EU's **stricter regulation**

Relatively low GDP growth in the EU vs. USA & China

GDP evolution at constant prices
(2002 – 2023 , in trillion €)



The GDP differential is amongst others driven by 1) the EU's relatively **low labor productivity growth** (80% below US level); and 2) the EU's **lagging position in the breakthrough of digital technologies** (e.g., artificial intelligence)

Source: Mario Draghi - 'EU competitiveness: Looking Ahead' (2024); Strategy& analysis

In addition, the EU’s decarbonization goals are more ambitious, creating pressure to reduce CO2-emissions and high investment needs

Challenges EU chemical industry (2/2)

More ambitious EU decarbonization goals

High ambitions

Binding legislation to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels

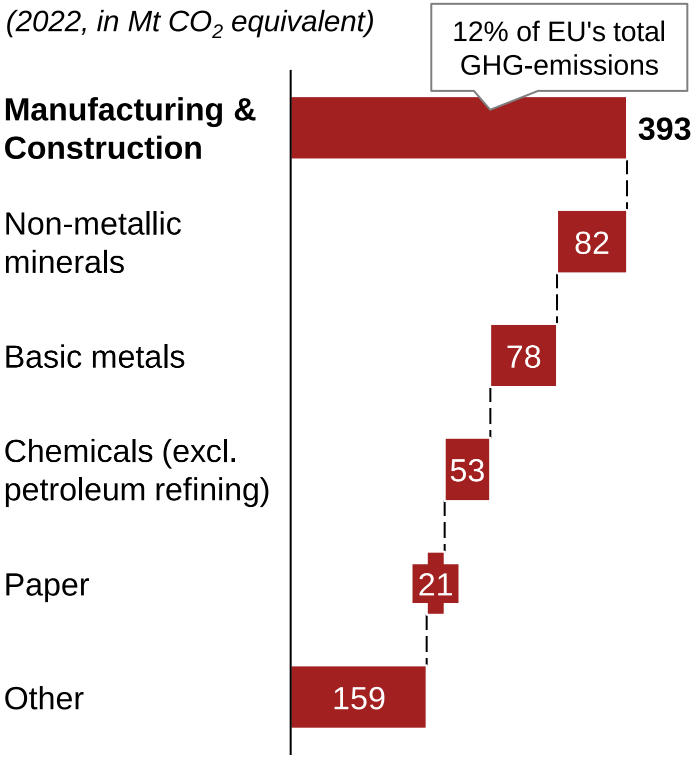
Non-binding target to reduce greenhouse gas emissions by 50-52% by 2030 compared to 2005 levels

Non-binding target to peak carbon emissions by the end of the decade

Low ambitions

High GHG-emissions chemical industry

GHG-emissions EU27
(2022, in Mt CO_2 equivalent)



High investments for decarbonization

- According to the report ‘The future of European Competitiveness’ by Mario Draghi:
  - The EU’s four largest Energy Intensive Industries – **non-metallic minerals, basic metals, chemicals and paper – face €500 billion decarbonization costs over the next 15 years**
  - The ‘hardest-to-abate’ parts of the EU transportation sector **– maritime and aviation – face €100 billion decarbonization costs each year from 2031 to 2050**
- In addition, **the EU introduced the most substantial carbon pricing compared to the US and China:** heavy industrial production has been largely covered by free allowances under the ETS[1], but this will be progressively phased out with the introduction of the CBAM[2]

---

1) Emissions Trading Scheme; 2) Carbon Border Adjustment Mechanism
Source: Mario Draghi - ‘EU competitiveness: Looking Ahead’ (2024); Eurostat; European Environment Agency; Strategy& analysis

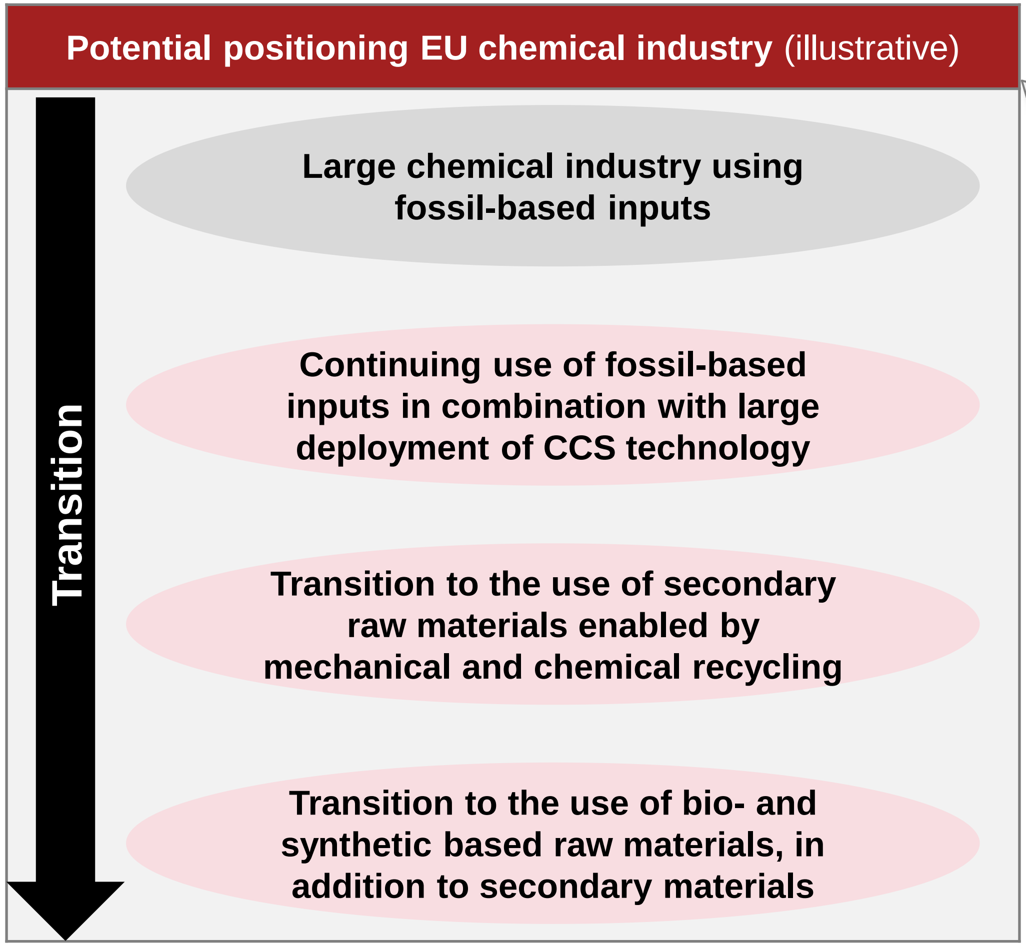
Hence, the EU chemical industry is at a crossroad: *"how will the chemical industry evolve given their challenges?"*

Future positioning EU chemical industry

Fossil-based raw materials

Secondary raw materials

Bio-and synthetic based raw materials



Potential positioning EU chemical industry (illustrative)

Large chemical industry using fossil-based inputs

Continuing use of fossil-based inputs in combination with large deployment of CCS technology

Transition to the use of secondary raw materials enabled by mechanical and chemical recycling

Transition to the use of bio- and synthetic based raw materials, in addition to secondary materials

The competitive position of the EU chemical industry mainly depends on 1) access to **affordable feedstock**; and/or 2) close **proximity to end-consumer** market(s)

Current positioning

Potential future positioning

c&en

"Can Europe's chemical industry survive net zero?"

bruegel

"Draghi's industrial masterplan has decarbonization at its core"

S&P

"Europe's chemicals sector braces for new policy impact"

Source: Chemical & Engineering News; Bruegel; S&P Global; Strategy& analysis

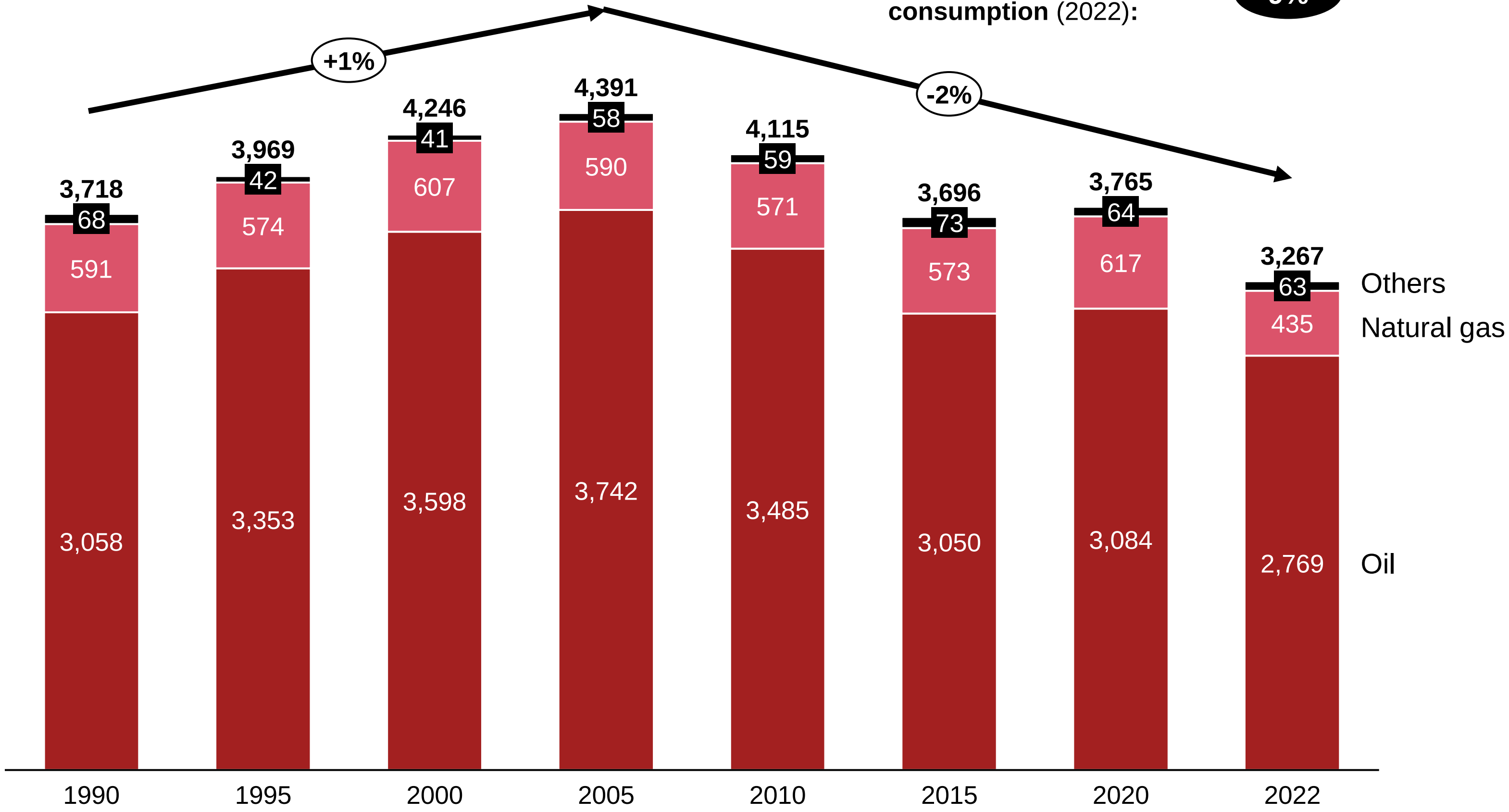
For the circular transition, the EU's chemical industry needs to replace their fossil-based feedstock with a circular feedstock over time

Demand for fossil-based feedstock used as raw materials

Final non-energy consumption by fuel in the EU27

(1990 – 2022, in PJ)

Share of total final energy consumption (2022): **9%**



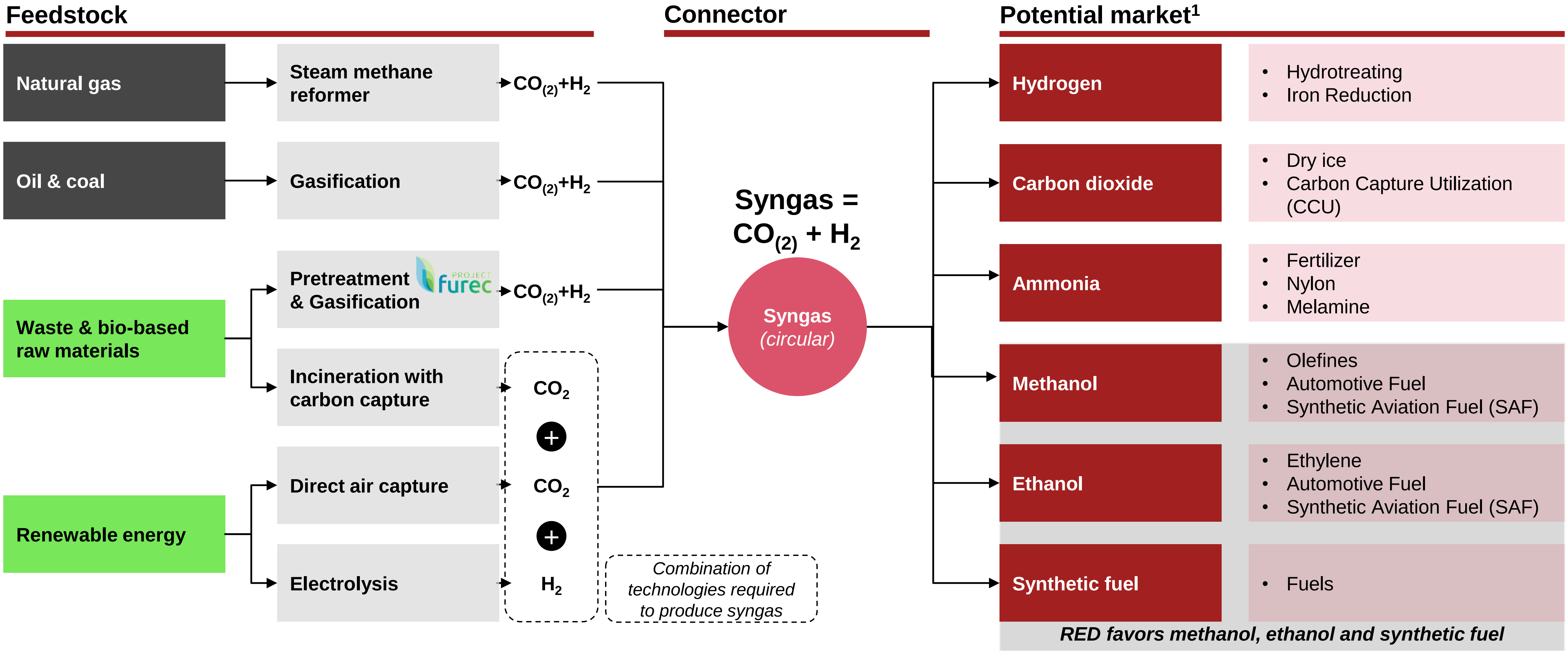
Key insights

- **Final non-energy consumption** includes fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel, e.g.,:
  - Oil used in food packaging
  - Natural gas used in fertilizers
  - Bitumen used for road construction
- These fuels are **fossil-based feedstock** (e.g., oil and natural gas)
- The final non-energy consumption **substantially declined since 2005 following by the energy crisis** (2022 might give a distorted image)
- Towards the future, these fossil-based feedstock needs to be **replaced by circular feedstock**
- The circular feedstock can be derived from e.g., **recycling waste and biobased materials**

Source: Eurostat; Strategy& analysis

Part of the demand for circular feedstock can be fulfilled by the conversion of non-recyclable waste into circular syngas

Role of syngas



Feedstock

- **Natural gas** → **Steam methane reformer** → $CO_{(2)}+H_2$
- **Oil & coal** → **Gasification** → $CO_{(2)}+H_2$
- **Waste & bio-based raw materials**
  - → **Pretreatment & Gasification** → $CO_{(2)}+H_2$
  - → **Incineration with carbon capture** → CO_2
- **Renewable energy**
  - → **Direct air capture** → CO_2
  - → **Electrolysis** → H_2

CO_2 + CO_2 + H_2

Combination of technologies required to produce syngas

Connector

Syngas = $CO_{(2)}$ + H_2

Syngas *(circular)*

Potential market[1]

Hydrogen
- Hydrotreating
- Iron Reduction

Carbon dioxide
- Dry ice
- Carbon Capture Utilization (CCU)

Ammonia
- Fertilizer
- Nylon
- Melamine

Methanol
- Olefines
- Automotive Fuel
- Synthetic Aviation Fuel (SAF)

Ethanol
- Ethylene
- Automotive Fuel
- Synthetic Aviation Fuel (SAF)

Synthetic fuel
- Fuels

RED favors methanol, ethanol and synthetic fuel

1) Methanol, Ethanol and Synthetic fuel are prioritized in current policies

Source: Chemistry Europe – 'Towards the Use of Renewable Syngas for the Decarbonization of the Industry' (2024); Expert input

Content

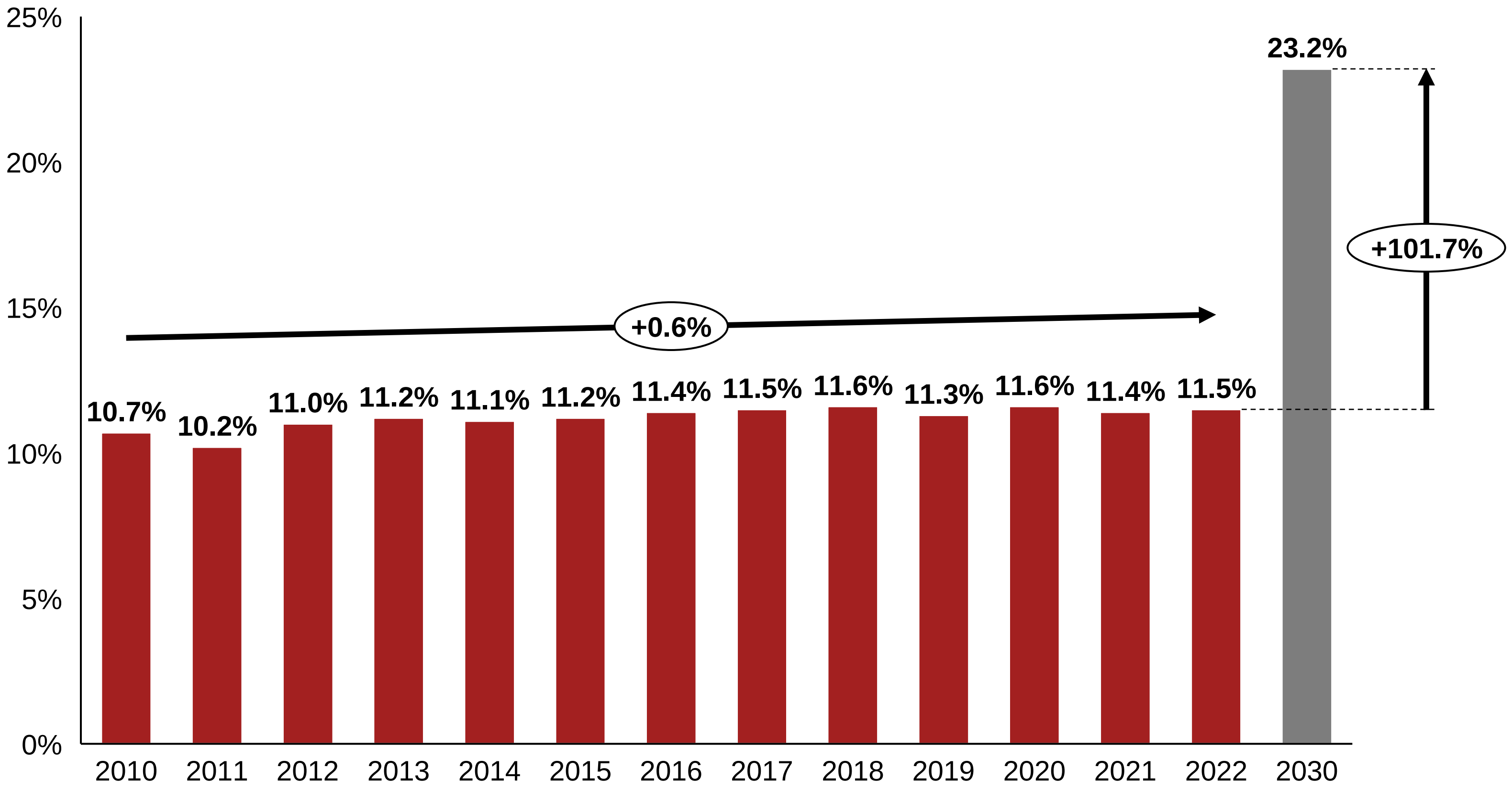
DETAILS ON EU WASTE LANDSCAPE IN APPENDIX ON P.65-71

The circularity rate in the EU has ranged between 10-12% in the past decade – doubling is required to reach the EU target by 2030

Circularity rate in the EU

CMUR in the EU27: actuals and target

(2010 – 2022 and target 2030, %)



Key insights

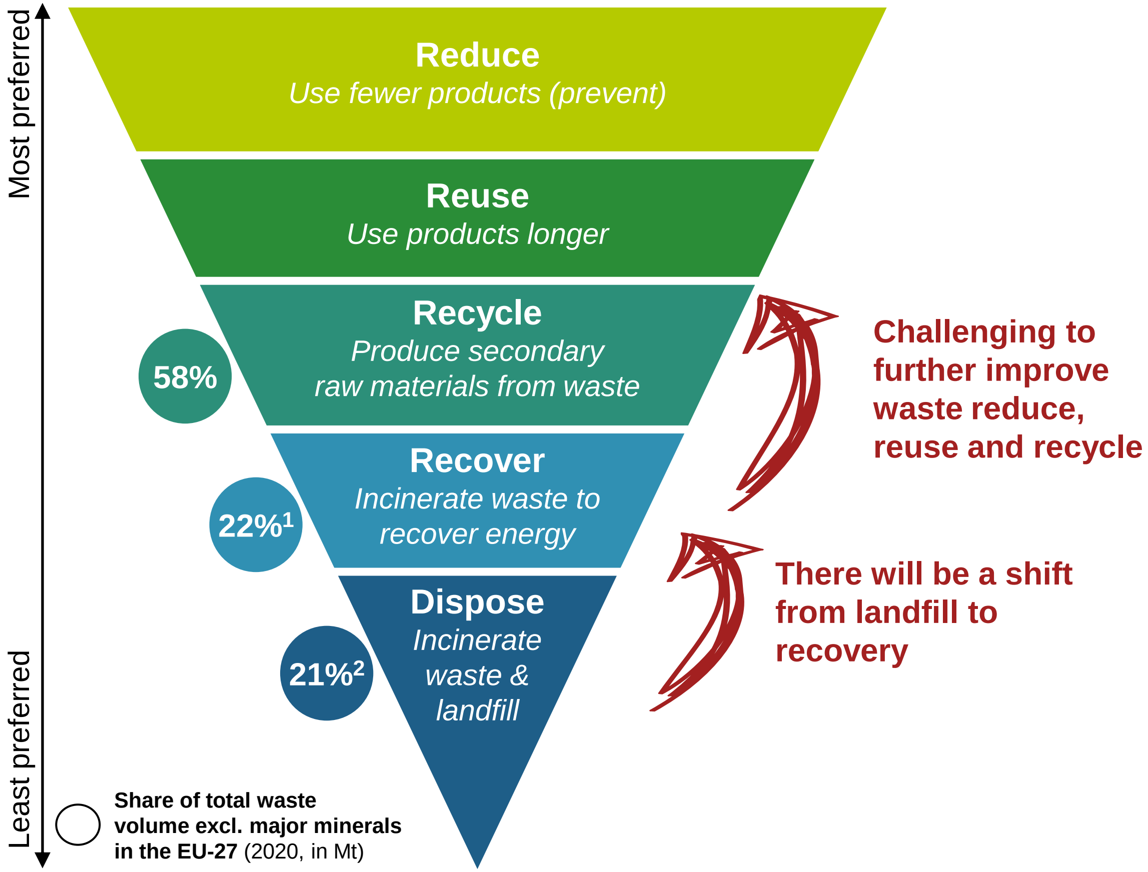
- The **Circular Material Use Rate (CMUR)** indicates the **circularity of materials in the economy** and refers to the share of the total amount of **material used in the economy that is accounted for by recycled waste**
- Between 2010 and 2022, the **CMUR in the EU hovered between 10 and 12%**
- The **EU's circular economy action plan** aims to reduce pressure on natural resources and states that the **EU aims to double its CMUR between 2020 and 2030**
- The CMUR can be improved by **increasing the amount of recycled waste** and/or **decreasing the use of materials**
- This would **reduce the amount of primary material extracted for production** and the associated **negative impacts on the environment and climate**

Source: European Environment Agency; Strategy& analysis

The EU faces challenges to further ‘climb’ the waste hierarchy – large volumes of waste are still landfilled or incinerated

Transition up EU waste hierarchy

Waste Framework Directive: ‘EU waste hierarchy’



○ **Share of total waste volume excl. major minerals in the EU-27** (2020, in Mt)

Key insights

1. The **material use is expected to increase with 1.1% CAGR towards 2060** driven by amongst others economic and population growth, technological advancements and ongoing urbanization, increasing waste streams
2. Many **EU member states are at risk of not reaching the 2025 recycling targets** as it is challenging to recycle more waste due to e.g., **increasing product complexity and finite material lifetime**
3. The **maximum 10% MSW landfill rate by 2035** in the EU will cause a **shift from landfill to recycling and W2E** since many EU member states are currently above this threshold
4. Therefore, **waste incineration plays a dominant role in the EU waste landscape accounting for 21%[3]** of the processed MSW and C&I waste in 2020
5. A high-level outlook for the EU indicates a **non-recyclable waste volume up to 223Mt** (~30% of total MS and C&I waste) **including a processing gap of 36Mt by 2035**

See details point 1-5 on next pages

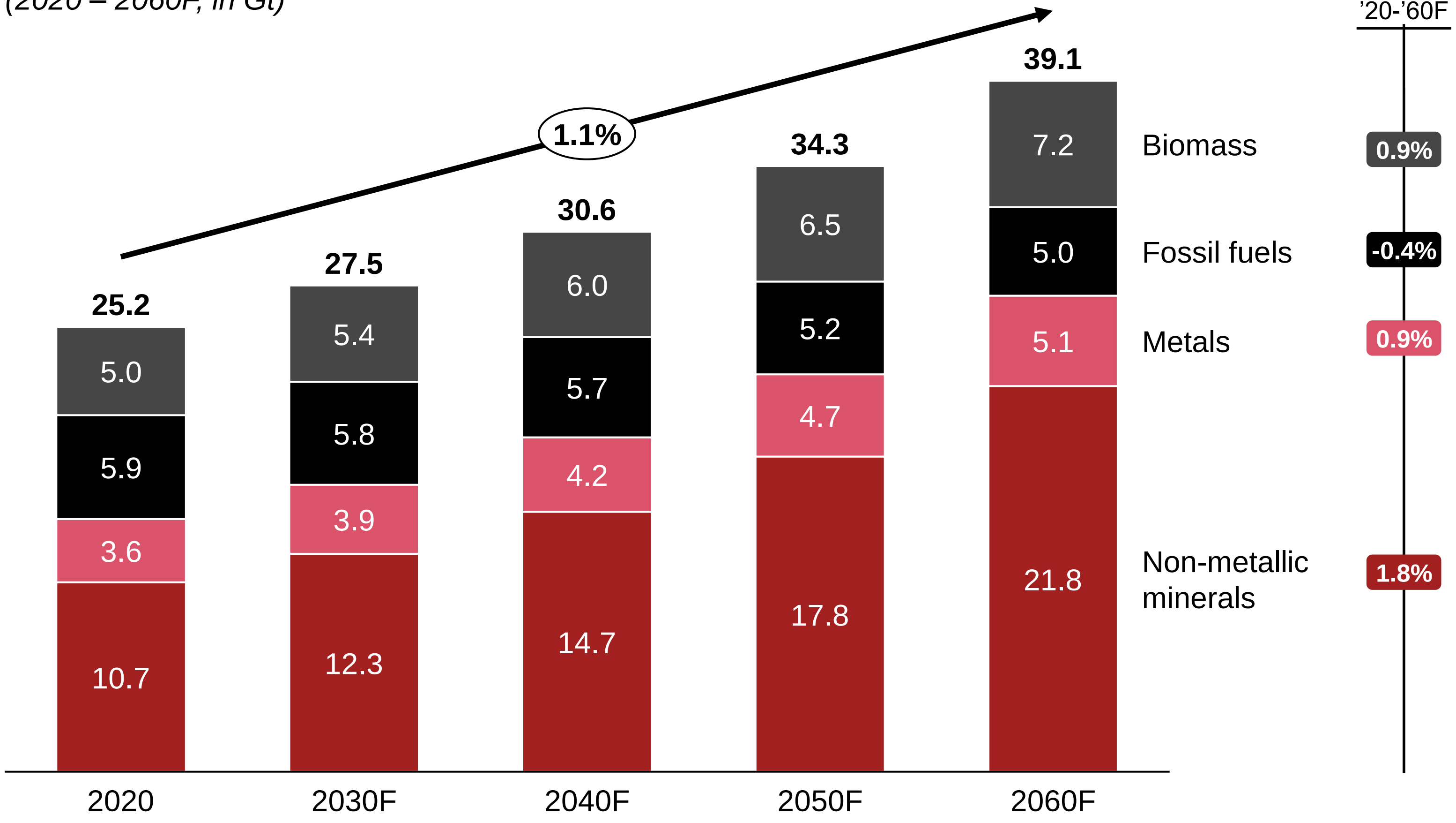
---

1) Includes ‘backfilled waste volume (3%-pt.): backfilling is a recovery operation where suitable waste is used for refilling an excavated area with suitable materials, typically after a foundation, trench, or other structure has been built.; 2) Includes waste incinerated without energy recovery (1%-pt.); 3) Waste incineration consists of waste to energy 19%-pt. (part of recover) and waste incineration without recovery 1%-pt. (part of dispose); Note: numbers may not add up due to rounding.
Source: European Commission; EU Waste Framework Directive; Eurostat; Strategy& analysis

The material use of OECD countries is expected to grow with 1.1% CAGR towards 2060, increasing waste streams

1 Outlook for material use in OECD countries

Material use in OECD countries (OECD includes EU27)
(2020 – 2060F, in Gt)



	2020	2030F	2040F	2050F	2060F	CAGR '20-'60F
Biomass	5.0	5.4	6.0	6.5	7.2	0.9%
Fossil fuels	5.9	5.8	5.7	5.2	5.0	-0.4%
Metals	3.6	3.9	4.2	4.7	5.1	0.9%
Non-metallic minerals	10.7	12.3	14.7	17.8	21.8	1.8%
	25.2	27.5	30.6	34.3	39.1	

Key drivers

- **Economic and population growth** increase the demand for goods and services, leading to increased material use
- **New technological advancements** often require new materials, driving up material use
- **Ongoing urbanization and the need for infrastructure development** (e.g., buildings, roads) contribute significantly to material use
- Changes in **consumer behavior and lifestyles**, such as increased consumption of electronic goods and vehicles and increasing living standards, drive material use
- While **environmental policies and regulations** aim to reduce material use and improve recycling, they can also lead to increased material use in the short term as industries adapt to new standards and technologies

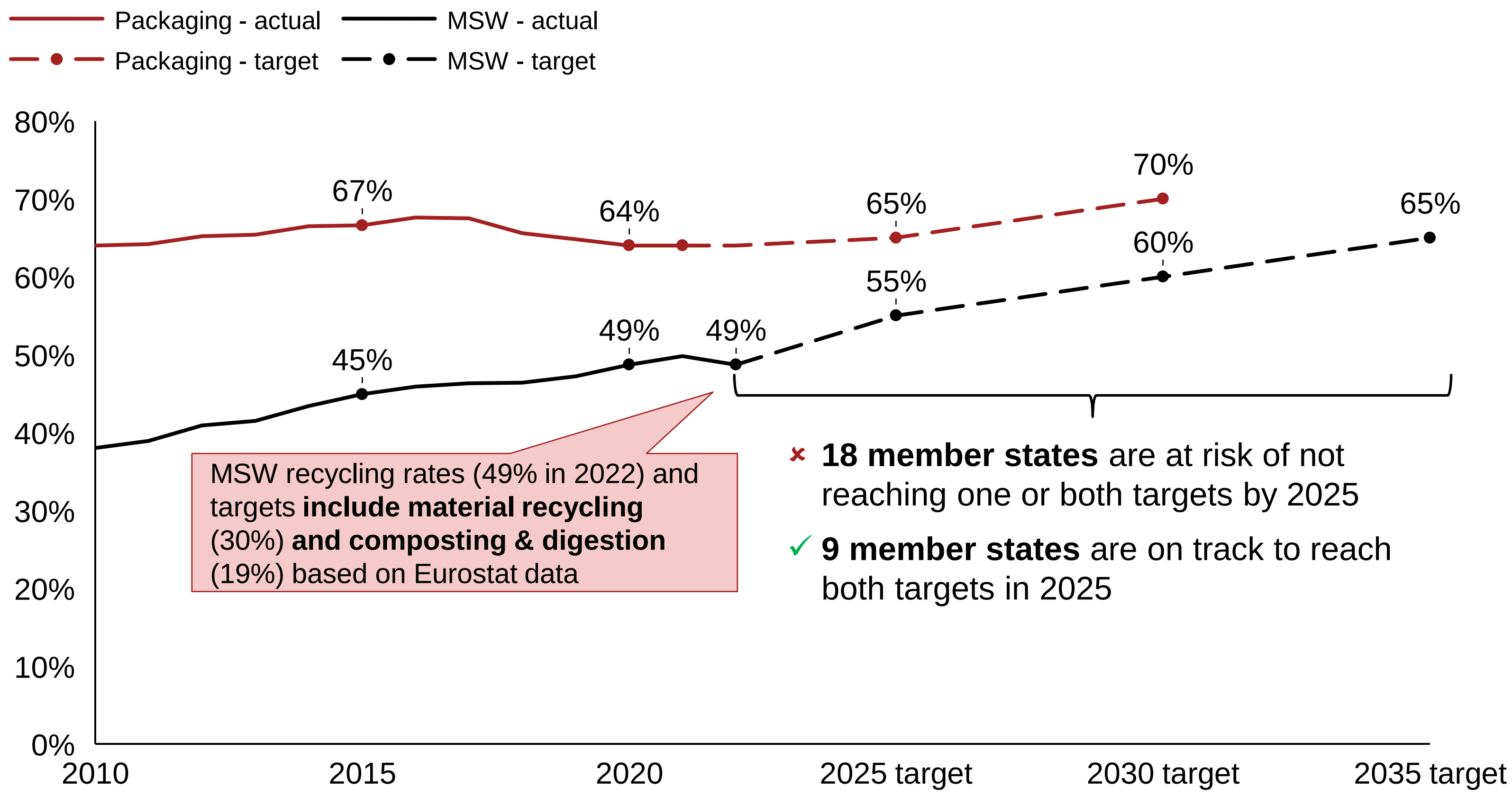
Source: OECD – 'Global Material Resources Outlook to 2060' (2019); Strategy& analysis

Although recycling rates in the EU have improved in the past decade, many countries are at risk of not reaching the 2025 recycling targets

❷ Recycling: actuals and targets

Packaging and MSW recycling rates and targets in the EU27[1]

(2014 – 2024 and targets 2025, 2030 and 2035, in %)



MSW recycling rates (49% in 2022) and targets **include material recycling** (30%) **and composting & digestion** (19%) based on Eurostat data

- ✗ **18 member states** are at risk of not reaching one or both targets by 2025
- ✓ **9 member states** are on track to reach both targets in 2025

Key insights

- Since 2010, **EU member states have successfully increased the MSW recycling rate to 49% in 2022**
- In contrary, the **packaging recycling rate remained stable** around 64% in the past decade
- Going forward, the EU has set **ambitious MSW and packaging recycling targets** to stimulate the transition up the EU waste hierarchy
- Yet, **many EU member states are currently at risk of not reaching these targets:**
  - ○ **10 member states are at risk of not reaching both targets** by 2025 (e.g., Poland, Romania, Hungary)
  - ○ **8 member states are at risk of not reaching the MSW target** by 2025, but are on track to meet the packaging target (e.g., Spain, France)
  - ○ **9 member states are likely to meet both reach recycling targets** by 2025 (e.g., Denmark, Belgium, Italy) – only 4 are likely to meet all material-specific packaging recycling targets (incl. the NL)

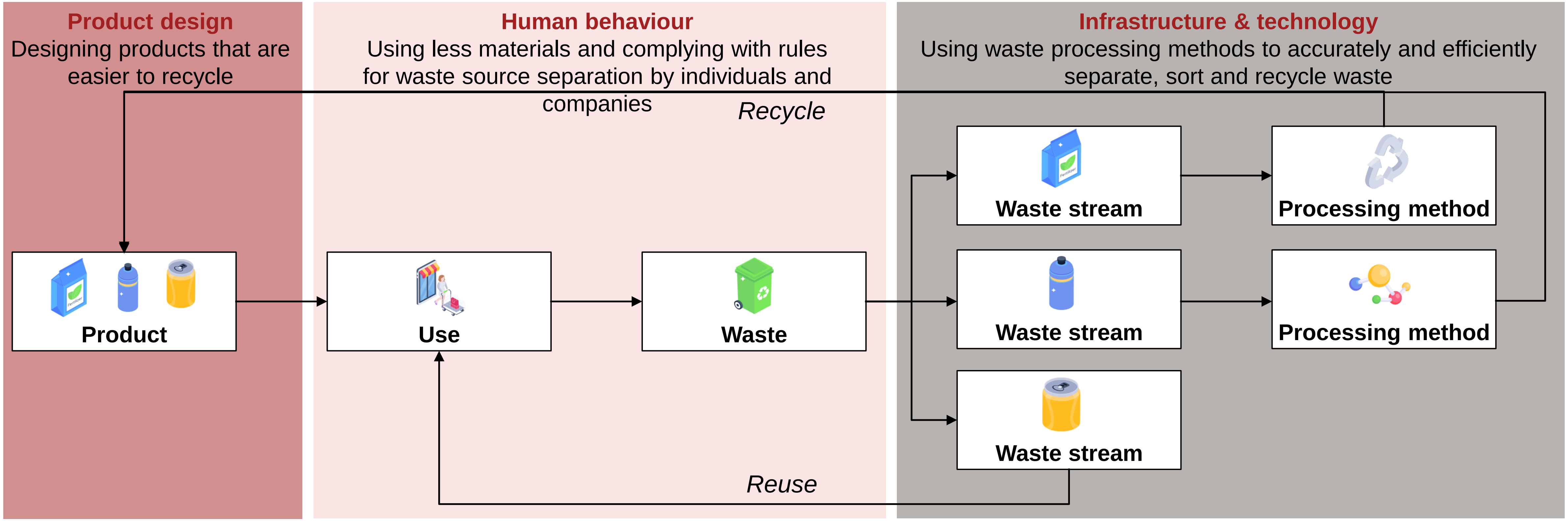
---

1) Packaging recycling rates have been monitored up to 2021, MSW recycling rates up to 2022

Source: Eurostat; European Environmental Agency; Strategy& analysis

Recycling is enabled by product design, human behaviour, infrastructure & technology and regulation & incentives

❷ Recycling: enablers



Product design
Designing products that are easier to recycle

Human behaviour
Using less materials and complying with rules for waste source separation by individuals and companies

Infrastructure & technology
Using waste processing methods to accurately and efficiently separate, sort and recycle waste

Regulation & incentives
Stimulating individuals and companies to conduct better waste management practices through a push effect (regulation) and a pull effect (financial incentives)

Source: Strategy& analysis

Yet, the recycling potential is limited by amongst others finite material lifetime, product complexity and improper waste sorting

2 Recycling: improvements and challenges

Enabler	Improvements	Challenges
Product design	✓ Increased production **easier to recycle products** (e.g., bio-based or biodegradable packaging, 100% paper packaging instead of plastic composite)	× **Materials have a finite lifetime** due to loss of original material properties, degradation and contamination from the recycling process: e.g., paper can be recycled 5-7 times × **The complexity of products has increased** over time (e.g., use of multilayer material), negatively affecting recyclability × Products are **designed to meet customer requirements, not for optimal recyclability**
Human behaviour	✓ Increased **awareness and efforts** by individuals and companies to **apply proper waste sorting techniques** (e.g., more separated-at-source plastic waste and biowaste) and **consume more recyclable materials** (e.g., biobased plastics)	× **Households and companies often do not comply with rules for source separating waste** (driven by e.g., unawareness and/or ease), leading to contaminated waste streams
Infrastructure & technology	✓ Emerging **alternative waste processing technologies** improve sorting and recycling quality and yield (e.g., advanced sorting technology, plastic chemical recycling technology, biowaste processing technology – see overview emerging technologies in appendix p.81-91)	× **Waste processing technologies** (separating, sorting and recycling) **have typical yields of 50-90%** (e.g., for plastics, roughly one third of the collected waste is recycled and the rest is incinerated in the NL) × **High quality materials are often downcycled into lower quality products** due e.g., contamination in the waste system
Regulation & incentives	✓ Introduced **regulation and (financial) incentives to promote waste recycling** (e.g., maximum 10% MSW landfill rate, MSW and packaging waste recycling targets – see planned EU regulation overview in appendix p.65)	× **The market for recycled materials and products is nascent** – no to limited incentives to pay a premium (compared to virgin) × **Strict quality compliance standards** for reusing recycled waste in new products (e.g., requirements from European Food Safety Authority) × **Recycled weight is prioritized over output quality** due to lack of quality requirements

Selected deep dives on next pages

Source: European Commission; O.Berk; Strategy& - 'Plastic Pathways' (2022); Nationaal Testcentrum Circulaire Plastics; Company websites; Strategy& analysis

Materials have a finite lifetime as recycling leads to loss of original material properties, degradation and contamination

❷ Recycling challenges: finite material lifetime

Waste type	Recycling multiple	Loss rate	Comments
Wood waste	5-10 (mostly A and A/B wood)	10-20%	Depending on the type, wood can be recycled up to 10 times, resulting in a 10-20% loss rate
Paper waste	5-7	15-20%	Paper can be recycled up to 7 times and the quality of the output declines every cycle, resulting in a 15-20% loss rate
Plastic waste	2-3 (depends on type)	33-50%	Depending on type and regulation, plastics can be recycled up to 3 times, resulting in a 20-40% loss rate
Biowaste	1	0%	Biowaste is recycled once, as 1) it mostly becomes animal feed and 2) its material properties result in quick decomposition of the waste
Sludge waste	1	0%	Solid materials in sludge are extracted during treatment process and used as primary or secondary raw material input
Glass waste	∞	10%	Glass (both flat and packaging) can be recycled indefinitely (is melted and transformed into new products), some loss incurs when mixed with other materials
Mineral waste	∞	0%	When mineral waste is not recycled or reused, it is stored to be used at a later stage
Metal waste	∞	0%	Metal can be recycled indefinitely (is melted and transformed into new products) and is never lost as the waste has a positive economic value

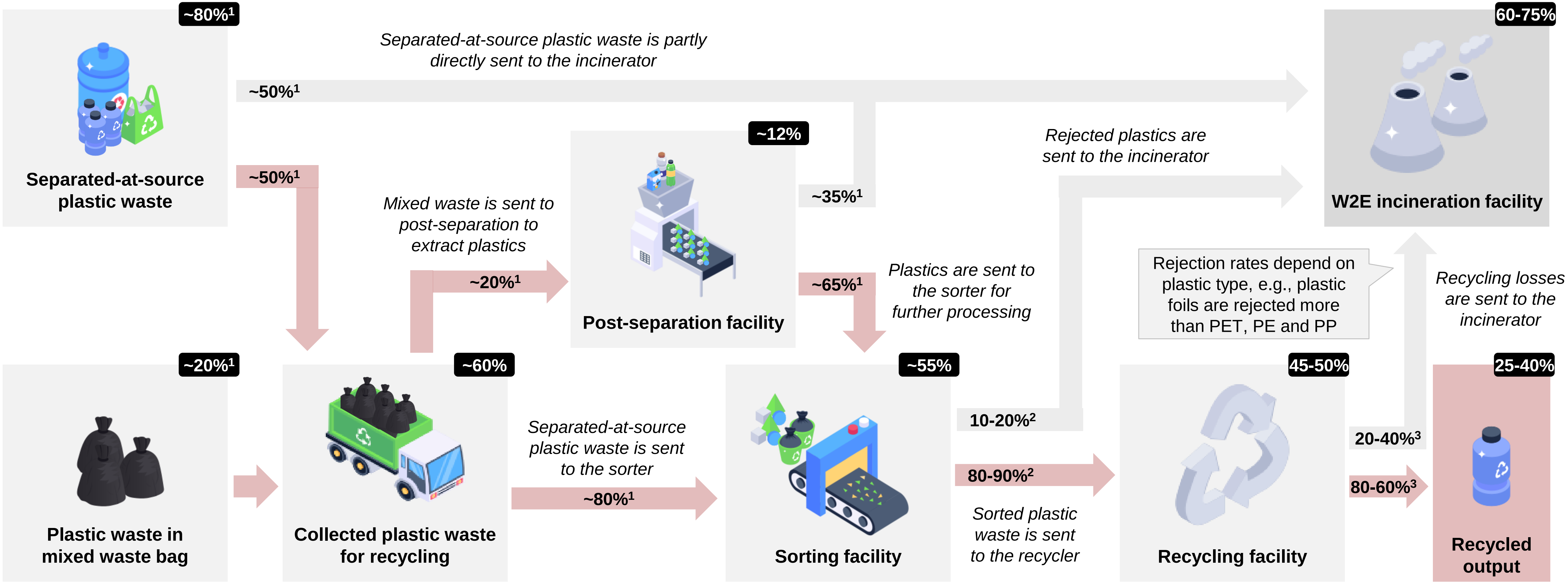
Key insights

- **Most materials have a finite lifetime,** since each recycling cycle:
    - The material **loses some of its original properties** (e.g., paper fibres become shorter and weaker)
    - The material undergoes some level of **degradation** making it less suitable for further recycling
    - The material undergoes some level of **contamination**, making it more difficult or even impossible to recycle again
- The table indicates the number of times a material can be recycled (‘**recycling multiple**’) and the corresponding loss from the recycling process (‘**loss rate**’)
- Evidently, some materials such as wood, paper and plastic can be **recycled a finite number of times**
- Other materials such as **metal and glass have an infinite recycling multiple**, and can therefore be recycled infinitely

Source: Vlakglas Recycling Nederland; Recycling Nederland; CE Delft; Strategy& – ‘Plastic Pathways’ (2022); European Environmental Agency; BVOR; WUR; Verpact; Strategy& analysis

There are substantial losses in the system: roughly one third of the collected plastic waste is recycled and the rest is incinerated in the NL

❷ Recycling challenges: losses in the system *(illustration plastic chain NL)*



~80%[1]

Separated-at-source plastic waste

Separated-at-source plastic waste is partly directly sent to the incinerator

~50%[1]

~50%[1]

Mixed waste is sent to post-separation to extract plastics

~20%[1]

~12%

Post-separation facility

~35%[1]

~65%[1]

Plastics are sent to the sorter for further processing

Rejected plastics are sent to the incinerator

60-75%

W2E incineration facility

Rejection rates depend on plastic type, e.g., plastic foils are rejected more than PET, PE and PP

Recycling losses are sent to the incinerator

~20%[1]

Plastic waste in mixed waste bag

~60%

Collected plastic waste for recycling

Separated-at-source plastic waste is sent to the sorter

~80%[1]

~55%

Sorting facility

10-20%[2]

80-90%[2]

Sorted plastic waste is sent to the recycler

45-50%

Recycling facility

20-40%[3]

80-60%[3]

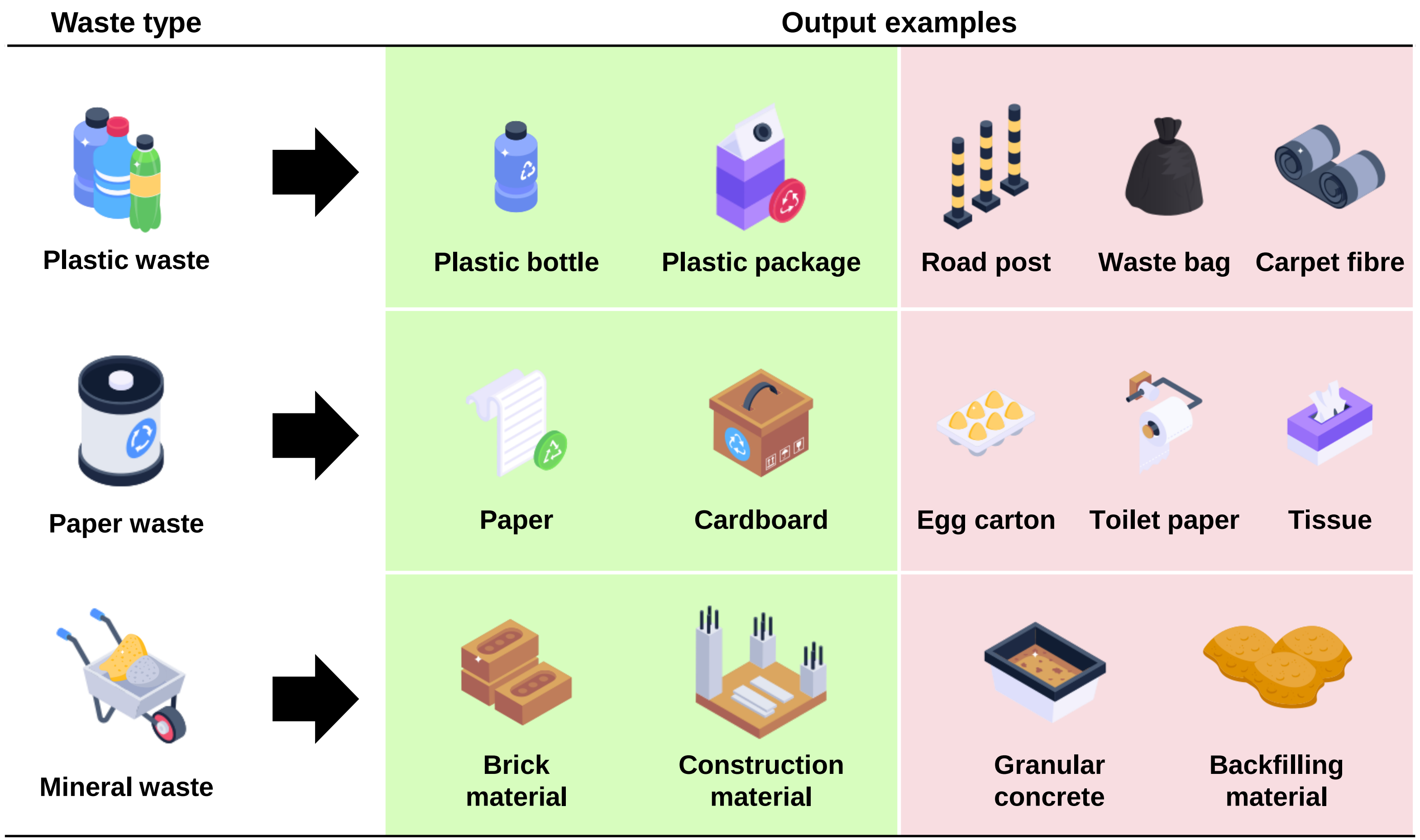
25-40%

Recycled output

Note: Three sources have been combined to define losses in the system, footnotes specify how numbers and ranges have been defined; recycling and incineration output fall within the range of all three analyses; 1) In line w/KPMG report; 2) In line w/S& analyses for different collection types; 3) Upper range in line w/S& analysis and Plastics Europe; lower range w/KPMG; Source: KPMG – 'Plastic feedstock for recycling in the Netherlands' (2023); Strategy& – 'Plastic Pathways' (2022); Plastics Europe; Strategy& analysis

High quality materials are regularly downcycled into lower quality products due to bottlenecks in the system such as contamination

② Recycling bottlenecks: downcycling



Waste type	Output examples				
Plastic waste	Plastic bottle	Plastic package	Road post	Waste bag	Carpet fibre
Paper waste	Paper	Cardboard	Egg carton	Toilet paper	Tissue
Mineral waste	Brick material	Construction material	Granular concrete	Backfilling material	

🟩 High quality recycling output 🟥 Low quality recycling output (downcycling)

Key insights

- Recycling output can be classified as **high quality or low quality** (‘downcycling’)
- **High quality materials are regularly downcycled into lower quality products**: research at the municipal level in the NL indicates that **one third to half of the recycled material volume, is downcycled** into lower quality alternatives
- This is amongst others caused by challenges in the system such as **contamination from the recycling process or from improper waste source separation** by individuals and companies
- **Downcycling can also be a side-effect from regulation**: strict food-grade packaging regulation (European Food Safety Authority) results in materials being downcycled as it cannot be reused for food applications
- Although downcycling technically **counts as recycling**, it is **not (always) desirable as virgin material must be acquired** to produce the original product again, putting pressure on natural resources

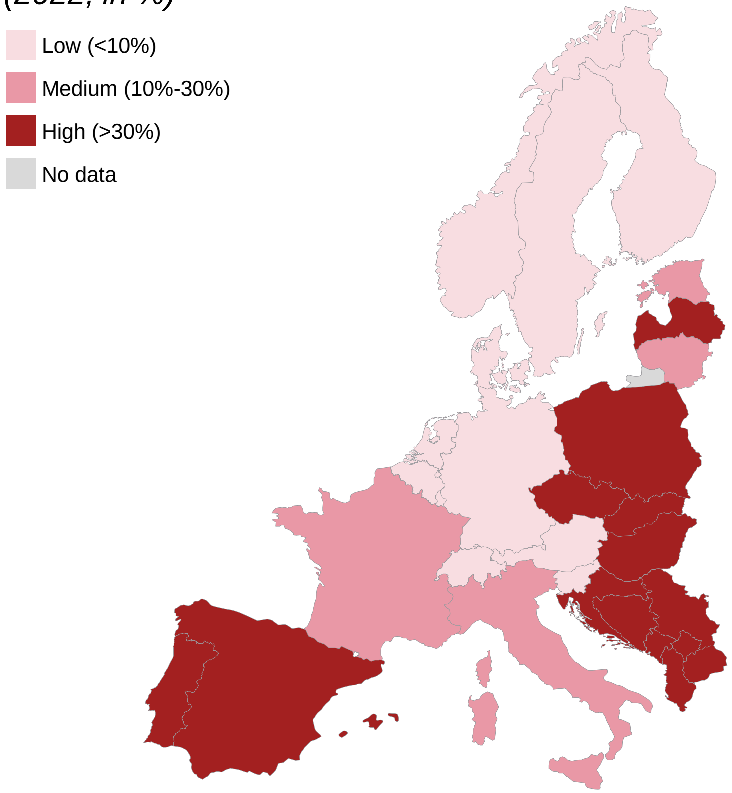
Source: PBL – ‘Integrale Circulaire Economie Rapportage’ (2023); Strategy& analysis

The maximum MSW landfill rate of 10% for all EU member states by 2035 will cause a shift from landfill waste to more recycling and W2E

❸ Shift from waste landfill to recycle and W2E

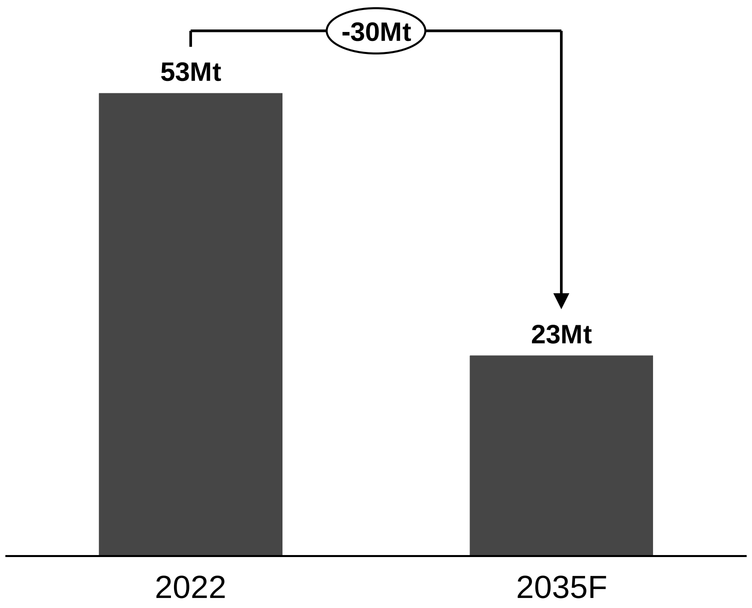
Most EU countries landfill >10% of MSW

MSW landfill rate per EU27 country[1]
(2022, in %)



Impact max. 10% MSW landfill rate in EU

Landfilled MSW volume in the EU27[3]
(2022 vs. 2035F, in Mt)



Key insights

- **EU member states demonstrate much variation** in terms of their MSW landfill rate
- In 2022, **Spain** (11Mt), **France** (8Mt), **Italy** (5Mt) and **Poland** (4Mt) account for the largest landfilled MSW volume
- In recent years, **landfill has become more challenging in the EU** following strict regulations on what waste can (not) be landfilled
- To stimulate the transition up the EU waste hierarchy further, all **EU member states cannot landfill more than 10% of their MSW volume by 2035**
- Since many EU member states are currently above this threshold, there will be **a shift from waste landfill to other waste processing methods**
- Between 2022 and 2035, approximately **30Mt of MSW waste can no longer be landfilled** by EU member states and therefore **must be processed by other processing methods leading to more recycling and W2E incineration**

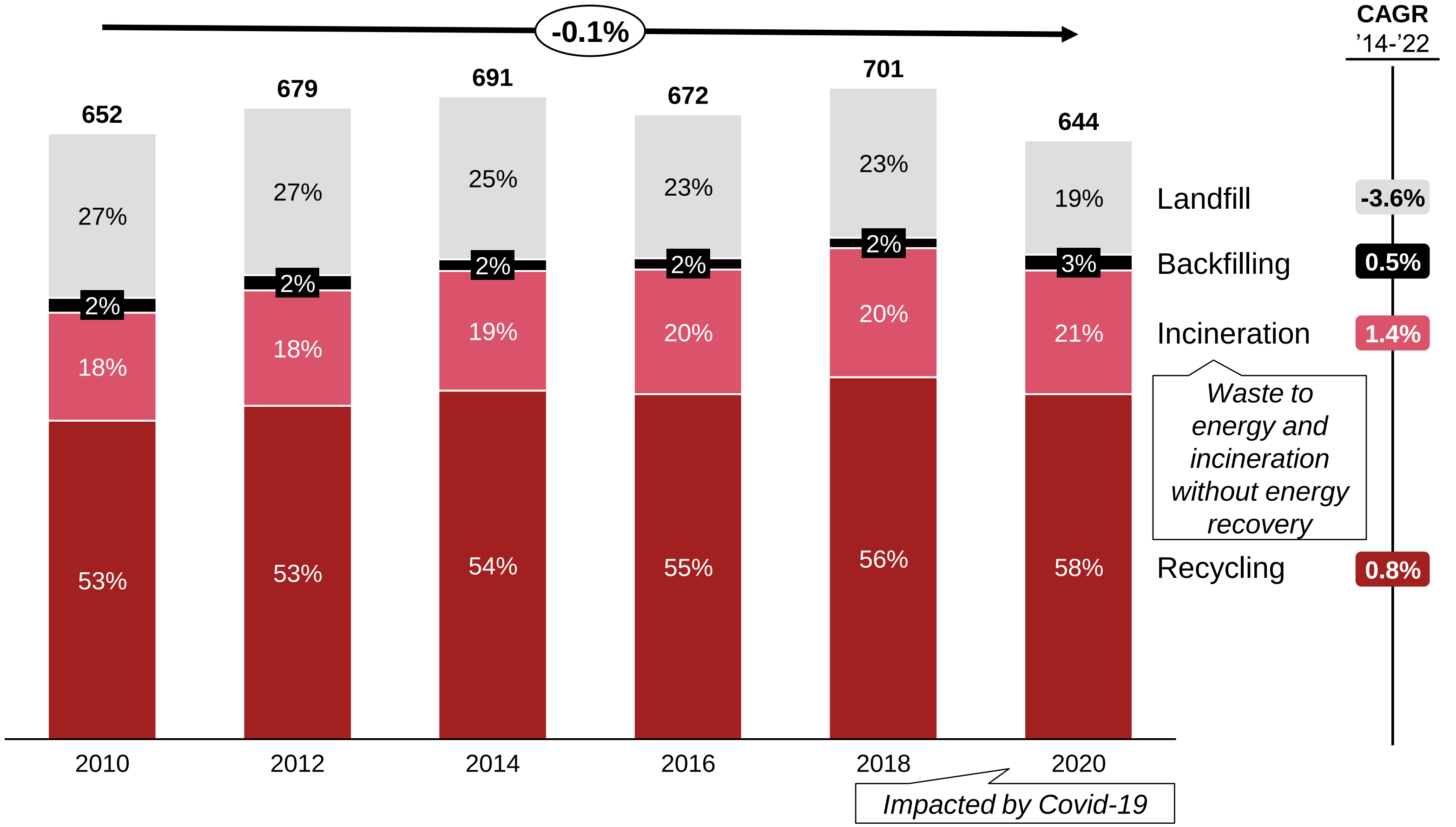
1) For Czechia 2022 data is missing, hence 2021 data has been used to assess the landfill rate; 2) Not all waste types that are currently landfilled can be processed in W2E-plants such as hazardous waste; 3) Impact of landfill target when total MSW volume remains at 2022 levels
Source: Eurostat; European Environmental Agency; CEWEP; University of Edinburgh; Strategy& analysis

Waste incineration plays a dominant role in the EU waste market, processing 21% of the total MSW and C&I waste in 2020

④ Incinerated waste volume

MSW and C&I waste volume excl. major minerals in the EU27 per processing method

(2010 – 2020, in Mt)



Key insights

- The **total processed MSW and C&I waste volume in the EU (excl. major minerals) decreased from 652Mt in 2014 to 644Mt in 2020** (-0.1% CAGR)
- Waste processing in the EU is largely **governed by directives and regulation** such as the EU waste hierarchy
- As a result, **relatively more MSW is currently processed by more favourable waste processing methods** compared to 2010:
  - ○ ***The landfill rate*** decreased from 27% to 19% in the past decade, mostly driven by the Landfill Directive that sets landfill requirements and restrictions
  - ○ ***The recycling rate (incl. composting & digestion)*** increased from 53% to 58% in the past decade, driven by successful efforts to stimulate recycling (e.g., CEAP[1])
- Despite efforts to 'climb' the EU waste hierarchy, a **substantial amount of MSW and C&I waste in the EU is incinerated (21%) or landfilled (19%)**

[1] Circular economy action plan

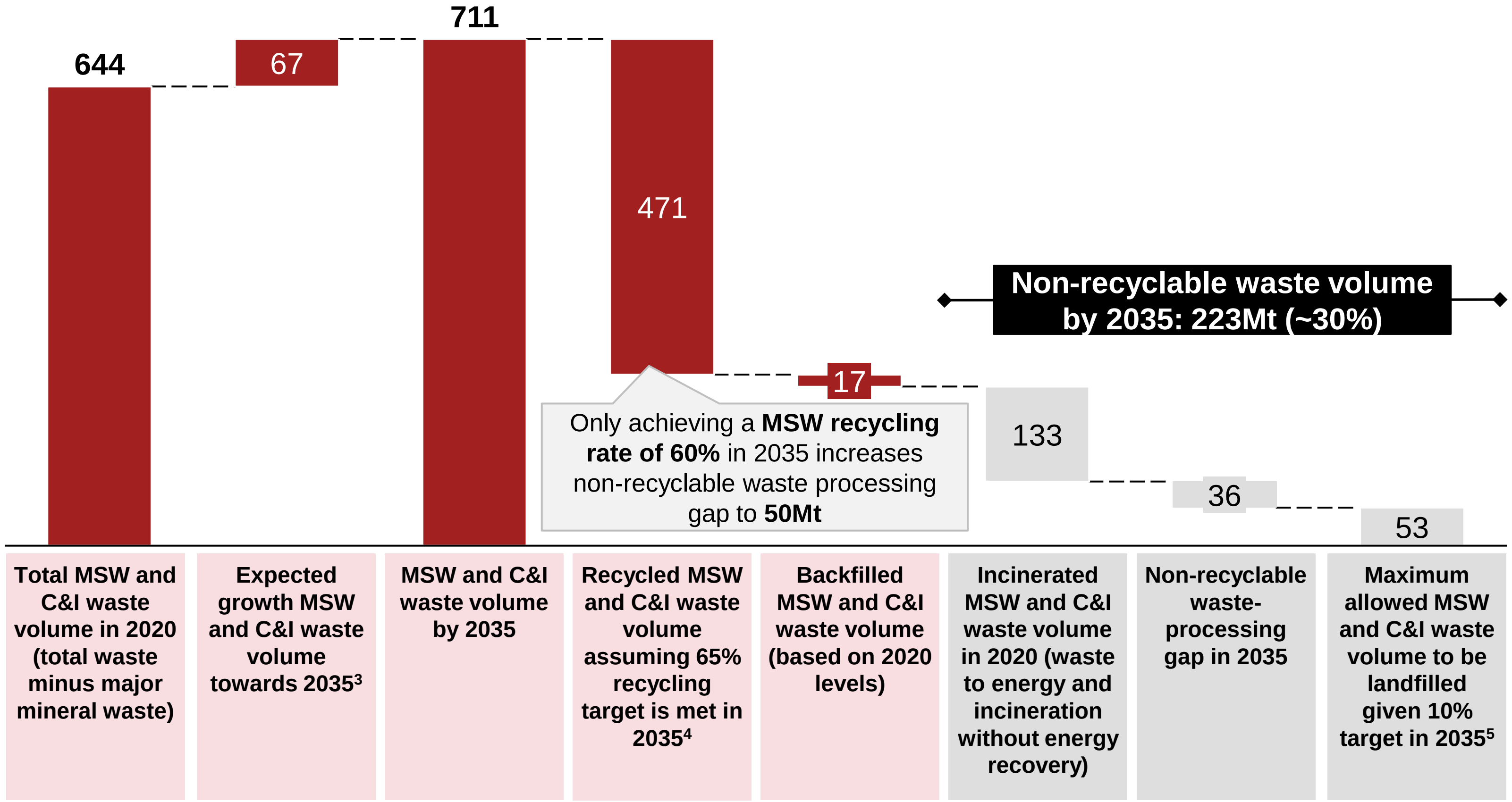
Source: Eurostat; EU Directive 2008/98/EC; Directive 1999/31/EC; Strategy& analysis

A high-level outlook for the EU indicates >30% of waste to be non-recyclable by 2035, requiring incineration and landfilling

5 High-level waste processing outlook in the EU (towards 2035)

Processed MSW and C&I waste volumes in the EU27

(in Mt per year)



Key insights

- The **total waste volume in the EU amounted to 1,942Mt in 2020** including 1,298Mt major mineral waste volume from mining and construction & demolition
- The remaining waste is combination of **MSW[1] and C&I[2] waste: 644Mt in 2020**
- High-level outlook indicates waste volumes to grow towards **711Mt by 2035**
- **471Mt of waste will be recycled in 2035, if the 65% recycling targets are achieved** (improving recycling rates is challenging due to e.g., product design, finite material lifetime)
- The remaining **waste volume** (excl. backfilled waste) **is 223Mt (~30%) by 2035**, which is considered **non-recyclable**
- This includes an expected **non-recyclable waste processing gap of 36Mt,** requiring more processing capacity
- Non-recycle waste volumes provides opportunity for affordable and low carbon alternative waste processing technologies

1) Municipal Solid Waste; 2) Commercial & Industrial; 3) Growth rate of 1.0% YoY for MSW and 0.5% for C&I based historical growth rates for MSW and C&I ('10-'18) – in line with growth projections for material use; 4) Includes digestion & composting and assumed that recycled volumes of C&I improve with 1% YoY; recycled C&I waste reaches 67% compared to total C&I waste in 2035; 5) Assumed 10% target also applies for C&I

Source: Eurostat; OECD; Strategy& analysis

Content

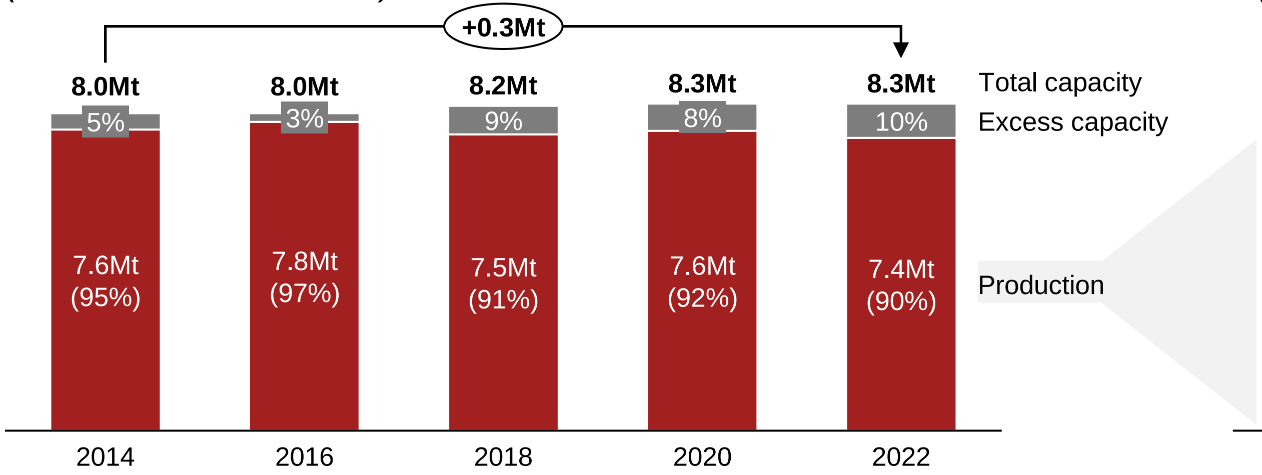
DETAILS ON NL WASTE LANDSCAPE IN APPENDIX ON P.72-81

The NL faces W2E overcapacity, hence W2E-plants rely on waste imports to maintain a ~90% utilisation rate

Overcapacity and import dependency W2E-plants in the NL

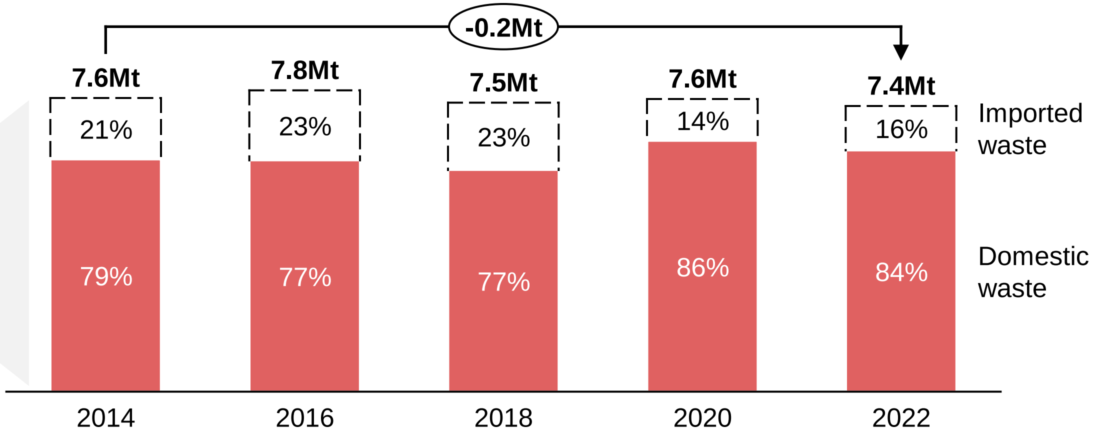
Total capacity vs. production W2E-plants NL

(2014 – 2022, in Mt and %)



Imported vs. domestic incinerated waste by W2E-plants NL

(2014 – 2022, in Mt and %)



- The **total incineration capacity of W2E-plants** in the NL has **grown by 0.3Mt in the past decade to 8.3Mt in 2022**
- This increase is caused by an **increase of the permitted waste volume** at EEW Energy From Waste Delfzijl (+192Kt), SUEZ ReEnergy (50Kt) and Zavin (+2Kt)
- In contrast, the **production of the W2E-plants declined over time** from 7.6Mt in 2014 to 7.4Mt in 2022
- As a result, the **excess capacity in the Dutch W2E market increased in the past decade, growing from 5% to 10%** between 2014 and 2022

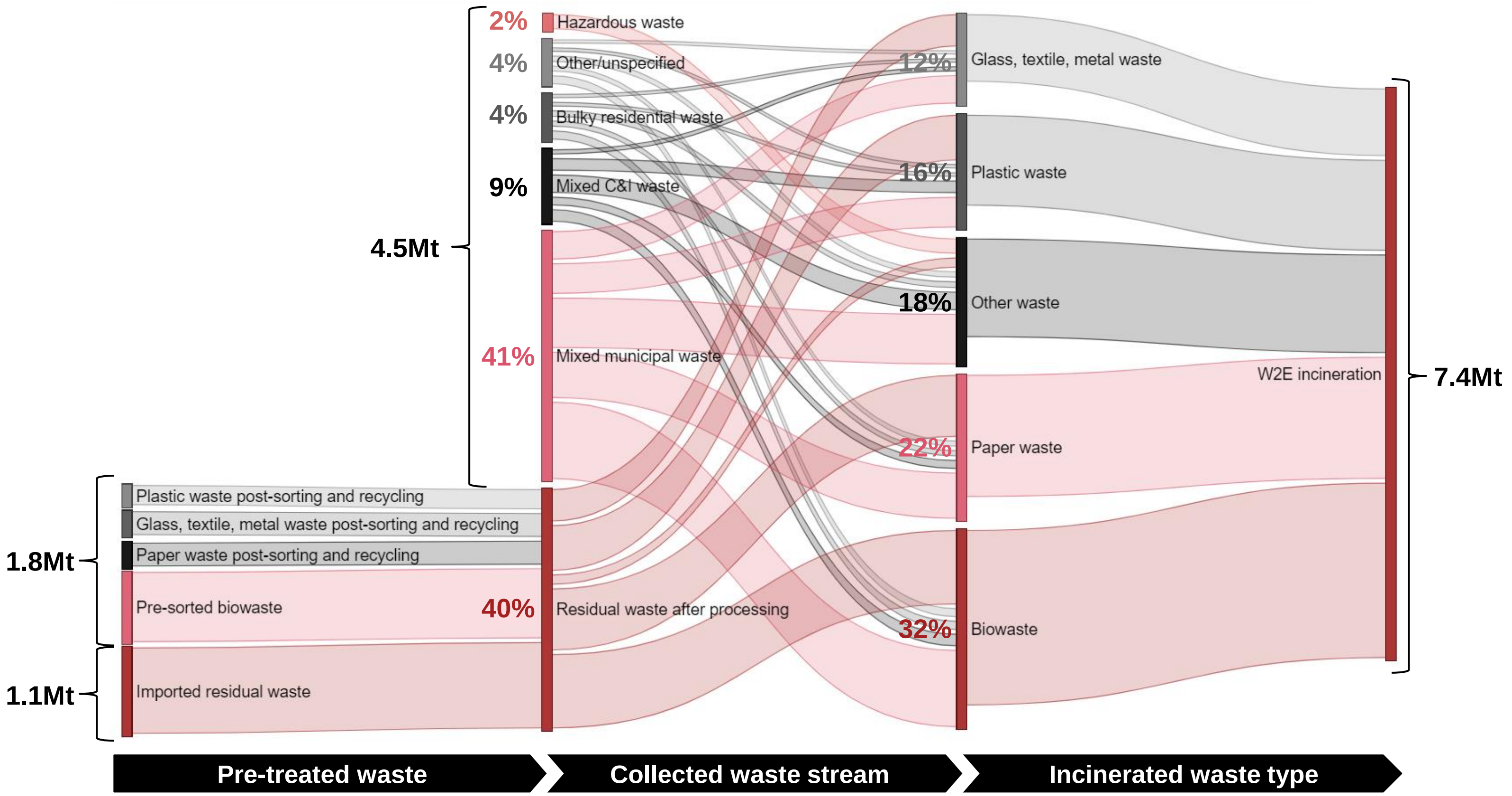
- **Most incinerated waste in W2E-plants is domestic (84%)** and the share of domestic incinerated waste has grown from 79% in 2014 to 84% in 2022
- The **remaining incinerated waste volume (16%) is imported from abroad** (e.g., Belgium, Germany and the UK)
- Even though less incinerated waste in W2E-plants is imported than in 2014, **W2E-plants still rely on waste imports to partly fill the excess capacity** and to maintain a utilisation rate of ~90%

Source: CBS; Afvalverwerking in Nederland reports; Strategy& analysis

Roughly 70% of the incinerated waste volume by W2E-plants in the NL consists of bio-, paper and plastic waste

Incinerated waste volume by W2E-plants per waste type

Sankey diagram incinerated waste volume by W2E-plants in the NL incl. import
(2022, in Mt and %)



Incinerated waste often consists of a composition of different material types

Incinerated waste volume by W2E-plants in NL (%)

Waste type	*PwC*	*PBL*
Biowaste	~32% (2.4Mt)	28%-35%
Paper waste	~22% (1.6Mt)	20%-30%
Plastic waste	~16% (1.2Mt)	~12%
Glass, textile, metal waste	~12% (0.9Mt)	~12%
Other waste[1]	~18% (1.3Mt)	8-22%
Total	**100%** (7.4Mt)	**100%**

~70%

---

[1] Including all remaining waste types in the Dutch waste landscape amongst others wood waste, rubber waste and hazardous waste

Source: Rijkswaterstaat – 'Afvalverwerking in Nederland' (2022); CBS; KPMG – 'Plastic feedstock for recycling in the Netherlands' (2023); PBL & TNO – 'Decarbonisation options for the Dutch waste incineration industry' (2022); Strategy& analysis

Specific plastic waste volumes can be processed alternatively, but >95% of the remaining waste is gasified or incinerated

Applicable processing technologies for incinerated waste

		Incinerated waste volume by W2E-plants in the NL (2022, in Mt)		Applicable technologies to process incinerated waste				
				Pyrolysis	**Depolymerization**	**Solvolysis**	**Gasification**	**W2E (+CCS/U)**
Biowaste		**2.4Mt**					2.4Mt	2.4Mt
Paper waste		**1.6Mt**					1.6Mt	1.6Mt
Plastic waste	**PE/PP[1]**	**0.1Mt**	**1.2Mt**	0.1Mt				
	PET[1]	**0.05Mt**			0.05Mt			
	EPS[1]	**0.01Mt**				0.01Mt		
	Others[2]	**1.0Mt**					1.0Mt	1.0Mt
Glass, textile, metal waste		**0.9Mt**					0.9Mt	0.9Mt
Other waste		**1.3Mt**					1.3Mt	1.3Mt
Total		**7.4Mt**		**0.1Mt**	**0.05Mt**	**0.01Mt**	**7.2Mt**	**7.2Mt**

Incinerated waste often consists of a composition of different material types

- PE/PP, PET and EPS can alternatively be processed via chemical recycling: <5% of total incinerated waste volumes
- The output products have a higher value than when these plastic waste volumes are incinerated or gasified
- Effective chemical recycling of these plastics requires increase in source and post-separation

- >95% waste remains, when specific plastics are processed via chemical recycling
- Gasification or W2E (+CCS/U) technologies are required for processing the remaining waste
- Gasification and W2E + (CCS/U) technologies can also process PE/PP, PET and EPS

---

1) Packaging waste; 2) Other plastic packaging waste holds potential for chemical recycling

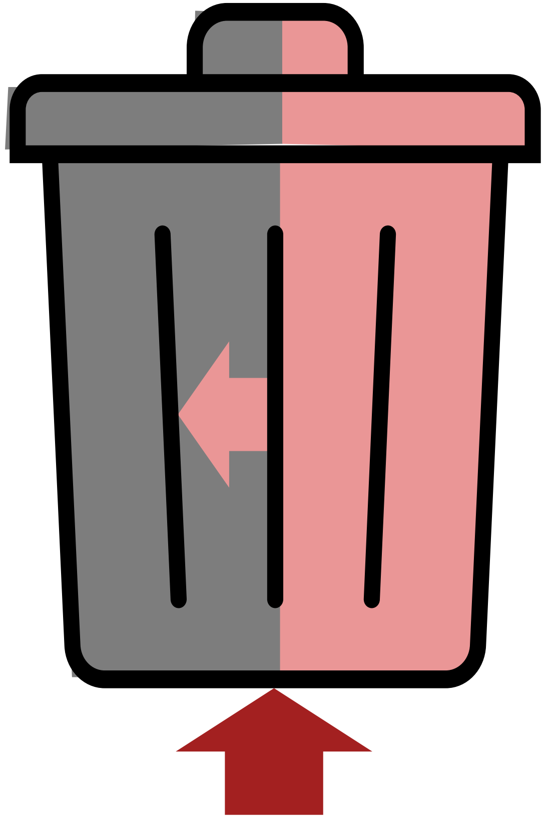
Source: PBL & TNO – 'Decarbonisation options for the Dutch waste incineration industry' (2022); Strategy& analysis

Content

DETAILS ON EMERGING TECHNOLOGIES IN APPENDIX P.82-92

Alternative waste processing technologies can play a future role in processing non-recyclable waste in addition to W2E (with CCS)

Overview non-recyclable waste processing technologies



Non-recyclable waste processing technologies

In scope like-for-like comparison?

Landfill

- Landfill is the oldest waste processing method in the EU
- Decomposition of landfilled organic waste results in large methane emissions
- Landfilled waste volume will be reduced in the future driven by the 10% maximum MSW landfill rate by 2035 for all EU member states

☑ **Landfilling**

W2E incineration (with CCS)

- W2E incineration converts waste into heat, steam and residual materials
- Waste incineration emits greenhouse gasses (e.g., CO2), hence deployment of carbon capture storage is emerging
- The EU Waste Framework Directive creates a policy environment where incineration is a less favorite option compared to recycling and reus

☑ **W2E**

☑ **W2E + CCS**

Alternative waste processing tech.

- Emerging alternative waste processing methods (e.g., gasification (FUREC)) can play a role in processing non-recyclable waste in the EU in addition to W2E incineration (with CCS technology)
- Gasification use chemical processes to convert waste into molecules, while reducing the emissions of greenhouse gas emissions

☑ **Gasification (FUREC) designed for processing non-recyclable waste**

Source: EU's Waste Framework Directive, Strategy& analysis

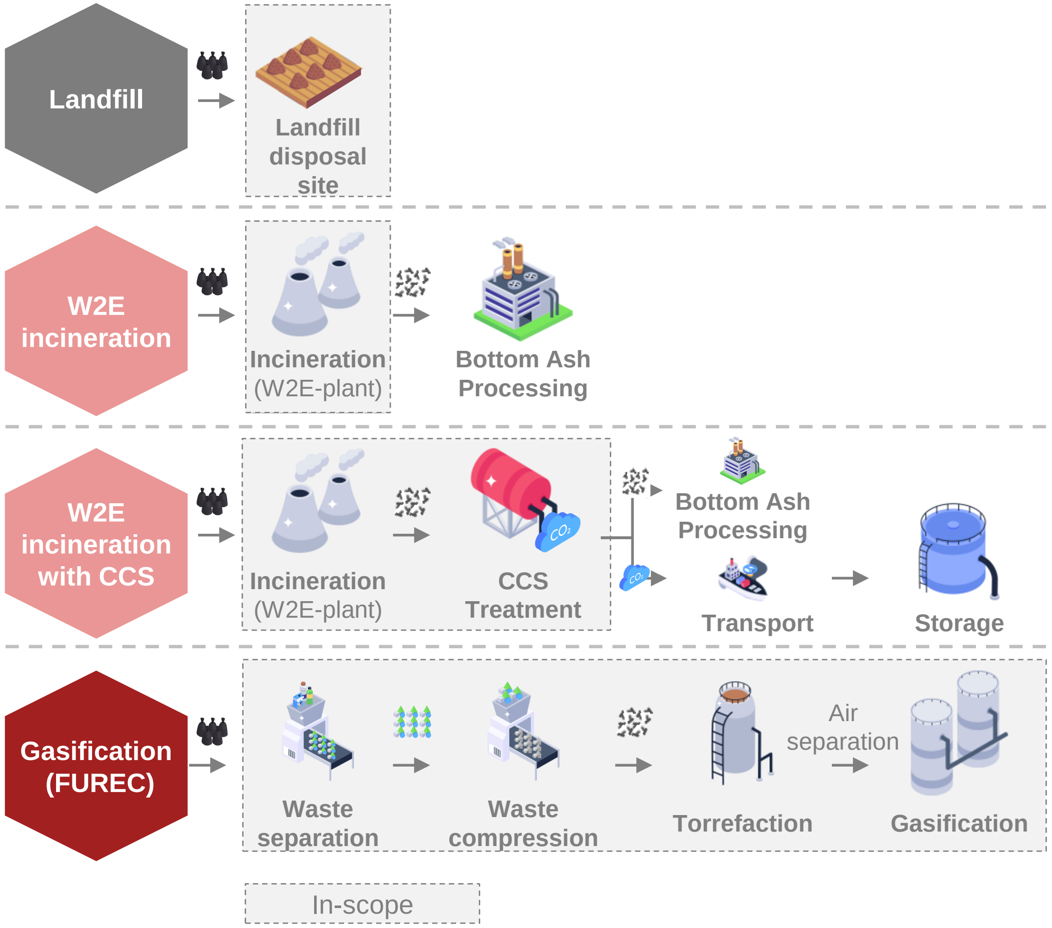
The scope of these non-recyclable waste processing technologies is clearly outlined and defined

Scope non-recyclable waste processing technologies

Scope like-for-like comparison

- The like-for-like comparison prioritizes the applicable methods for processing non-recyclable waste:
  - **Landfill –** focused on waste disposal site
  - **W2E incineration –** focused on W2E-plant only (given other steps in the value chain, such as waste sorting and separation, are not mandatory)
  - **W2E incineration with CCS –** identical to incineration with additional CCS capabilities
  - **Gasification –** FUREC is used for reference (with and without CCS capabilities)
- To ensure a **like-for-like comparison**, we assess these technologies at a standardized waste processing capacity of **800Kt of non-recyclable waste,** considering **only greenfield operations**

Scope included non-recyclable waste processing technologies



Landfill requires waste disposal site with some infrastructure (e.g., impermeable liners, gas recovery mechanisms, and capping layer) to ensure efficient operation and prevent environmental contamination

W2E incineration plants have **standard infrastructure** including standard combustion incinerator, heat recovery systems, and handling of by-products (such as fly/bottom ash)

W2E incineration plants have **standard infrastructure requirements**, but **additional complexity with CCS** as this requires large-scale infrastructure to capture, transport and store

FUREC uses **a vital pre-treatment step** with **entrained flow gasification technology** to ensure homogeneity of input and output quality (CCS capabilities can be embedded in the FUREC process)

Source: RWE input; Strategy& analysis

The non-recyclable waste processing technologies are evaluated based on societal, sustainability, and business case criteria

Evaluation framework

Category	Criteria	Evaluation of non-recyclable waste processing technology's…
Societal case	**Strategic fit with EU and NL ambitions**	…Alignment with EU and NL ambitions such as circularity, climate neutral economy, raw material security, and competitive positioning (chemical) industry …Scalability
Sustainability case	**Environmental impact**	…Environmental impact, including by-products treatment and NOx emissions
	Climate impact	…Climate impact, including CO_2 emissions and CO_2 opportunity cost emissions
	Energy efficiency	…Energy efficiency (%), considering the energy balance of each processing technology
Business case	**Key financials**	…Key financials, including capital expenditures of corresponding facilities (in € per ton of waste capacity)
	Value of outputs	…Overview of generated outputs and the value of the primary generated output, considering the mass balance of each processing technology and the projected 2030 value

Source: Strategy& analysis

DETAILS PER CRITERIA IN APPENDIX P.93-103

Gasification (FUREC) produces circular and affordable syngas, avoids CO2/NOx emissions and is cost-effective

Comparison of non-recyclable waste processing technologies

Gasification evaluation is based on data shared by FUREC

Category	Landfill	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Societal case	🟥 - No contribution to EU circularity and climate neutrality ambitions - Deprioritized in the EU waste hierarchy: target to reduce to 10% for MSW by 2035 - No resource recovery potential and significant methane emissions	🟨 - Low contribution to EU circularity and climate neutrality ambitions - Scalable technology to process non-recyclable waste (typical capacity is 400-600Kt per year) - Production of electricity and heat with substantial CO_2 emissions (methane emissions avoided compared to waste landfill)	🟩 - Low contribution to EU circularity and significant contribution to climate neutrality ambitions - Scalable technology (typical capacity of 400-600Kt per year) with CCS capabilities from 100-400Kt of CO_2 per year - Production of electricity and heat with limited CO_2 emissions	🟢 - Significant contribution to EU circularity and climate neutrality ambitions - Scalable technology (up to 800Kt per year) - Pellets allow efficient long-distance transportation - Production of circular feedstock, strengthening the chemical industry's position as a circularity frontrunner
Sustainability case *(per 800Kt processed non-recyclable waste)*	🟥 - 800Kt CO_2-eq produced per year, increasing to 1,714Kt CO_2-eq with opportunity costs - Residues such as leachate and solid waste require additional treatment to prevent soil contamination	🟧 - 280Kt NOx[1] emitted per year - 971Kt CO_2 produced per year (incl. opportunity costs) - 22% energy efficiency - By-products (fly & bottom ash) require additional treatment	🟨 - 280Kt NOx[1] emitted per year - 354Kt CO_2 produced per year (incl. opportunity costs) - 12% energy efficiency - By-products (fly & bottom ash) require additional treatment	🟢 - 13Kt NOx[1] emitted per year - 120Kt CO_2 emissions (without CCS) up to 830Kt CO_2 emissions (with CCS) are avoided per year (incl. opportunity costs) - 71-74% energy efficiency - No residual stream
Business case	🟨 - Very low CAPEX per ton waste - Limited potential for generating valuable products	🟩 - €900-1,200 CAPEX per ton waste - Competitive must-run energy products: heat and electricity with a value of €41M (2030)	🟥 - €1,400-3,000 CAPEX per ton waste - Competitive must-run energy products: heat and electricity with a value of €22M (2030)	🟩 - €1,000-1,400 CAPEX per ton waste - Attractive feedstock for chemical industry: 55Kt circular hydrogen valued at €190M (2030)

Prices for feedstock competitive with grey/ blue hydrogen given market conform gate fees

🟥 Very negative 🟧 Negative 🟨 Moderate 🟩 Positive 🟢 Very positive

[1]) Nitrogen

Source: Strategy& analysis

Despite its promising potential, gasification (FUREC) remains a first-of-its-kind innovation, combining individually mature technologies

Technological maturity

Gasification evaluation is based on data shared by FUREC

Category	Criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Technological case	**Track record**	**Significant track record: > 2,700 W2E-plants** • W2E incineration is a widely used waste processing technique all over the world: >2700 W2E-plants worldwide	**Significant track record: 4 active W2E-plants** • W2E incineration with is still relatively new with limited deployment:~4 W2E-plants with CCS capabilities, worldwide	**First-of-its-kind technology, significant track record for underlying technologies** • Gasification (FUREC) is a first-of-its-kind technology, combining widely deployed pelletization, torrefaction, and entrained flow gasification plants (e.g., in China)
	Technological readiness levels (TRL)[1] *Deep-dive on FUREC on next page*	**Commercial technology, TRL = 9** • W2E incineration is an established and mature technology with a significant commercial deployment **W2E incineration:** TRL = 9	**Commercial technology, TRL = 9** • W2E incineration with CCS are successfully demonstrated prototype[2] (TRL=7-9) with increasing levels of commercialization **W2E incineration:** TRL = 9 **CCS treatment[2]:** TRL= 7-9 • Additional improvement are required to reduce costs and increase efficiency	**Commercial technology, TRL = 9** **Successful pilot TRL= 8, each with a TRL > 8** • Gasification (FUREC)'s individual technologies are widely used and commercially available – overall technology has a TRL=8 **Pelletization:** TRL = 8-9 **Torrefaction[3]:** TRL = 8 **Entrained Flow Gasification[4]:** TRL = 9
	Conclusion	**Commercial & highly deployed technology** Fully deployed technology around the world, commercial technology TRL=9	**Commercial & moderately deployed technology** Limited track record for W2E plants, commercial technology TRL=9	**First-of-its-kind for waste processing** TRL=8, underlying technologies are individually mature but first-of-its-kind when combined for waste-processing

1) Technology Readiness Levels is a scale from 1 to 9 to assess the maturity of a technology: TRL 1 is earliest stages of research, and TRL 9 is a fully mature and commercially deployable technology; 2) Literature indicates TRL = 7-9 – TRL is assumed as 9 due to successful commercial deployment of CCS/U technology; 3) Torrefaction as a stand-alone process is classified at TRL 8-9, with some mature applications reaching TRL=9. To remain conservative, we have opted for TRL 8; 4) Literature indicates that entrained flow gasification has TRL=8 but wide commercial deployment in China is indicative of a TRL =9; 4); Sources for TRL in appendix

FUREC addresses gasification challenges in the UK with a vital pre-treatment process and proven entrained flow gasification technology

Technological case: deep-dive UK

UK context

- The **UK government** promoted **gasification** as a **cleaner** and **more efficient waste processing method** compared to traditional incineration
- Gasification was seen as part of the **UK's broader strategy** to meet **its CO_2 emission targets** and **move towards a sustainable energy solution**
- The government offered substantial support in the form of subsidies, such as through the **Contracts for Difference with the Green Investment Bank** also co-financing some of these projects
- Despite over **£1B invested** and government support and once being hailed as a central component of the UK's sustainable ambitions, **many gasification projects have failed** leaving a legacy of financial losses and skepticism

Challenges facing gasification in the UK and lessons learned for FUREC

Technical and operational challenges – The used plasma gasification technology proved highly sensitive to waste composition, with many plants unable to effectively process varying waste quality and types

Economic challenges – Technical issues have made gasification plants financially unsustainable, with high repair costs excessive parasitic loads reducing efficiency

Collapse of investor confidence – Repeated failures have eroded trust in gasification technology with numerous companies abandoning large investments in gasification

FUREC addresses these key challenges by using:

1. **A vital pre-treatment process** (incl. sorting, pelletizing and torrefaction) to handle the heterogeneity of the input waste
2. **Proven entrained flow gasification technology** (instead of plasma) since this is the only commercially successful gasification technology in the world

Source: Expert interviews; Strategy& analysis

Content

Chemical recycling can contribute to a circular climate-neutral economy with raw material security and a competitive industry in the EU

Potential contribution of chemical recycling

Potential contribution chemical recycling to EU ambitions

100% circular, climate-neutral economy

- ✓ Chemical recycling technologies (e.g., pyrolysis, solvolysis, depolymerization, gasification) are complementary to mechanical recycling technologies and can convert (non-recyclable) waste into circular feedstock, while lowering GHG-emissions

Raw material security

- ✓ Chemical recycling technologies enable the conversion of (non-recyclable) waste into circular feedstock, reducing the dependency on import of raw materials from outside the EU

Competitive positioning (chemical) industry

- ✓ Chemical recycling technologies can convert waste streams into circular feedstock for the EU's chemical industry, strengthening its circular and competitive position

So, the EU should build and maintain an **effective and efficient waste recycling industry** with a **solid position for chemical recycling**

Source: Expert Input; Strategy& analysis

To be effective on a large scale, chemical recycling requires demand for the output, availability of feedstock and financial incentives

Requirements for chemical recycling

Requirements for (emerging) chemical recycling technologies to be effective on a large scale

Demand for output: chemical recycling technologies can sell their produced output (circular molecules) on the market for a competitive price compared to other alternatives (e.g., RFNBO-sourced molecules[1])

Feedstock availability: chemical recycling technologies can attract the required volumes of waste with the right quality across the borders of EU member states

Financial incentives: (emerging) chemical recycling technologies can attract sufficient financial resources to accelerate the process from financial investment decision, go-live moment and scale up

- **Regulation is key** to establish the requirements for (emerging) chemical recycling technologies
- **Regulation needs to be harmonized across the whole EU member states and the raw material value chain** (incl. waste)

---

[1] Renewable fuels and non-biological origin sourced molecules

Source: Expert input; Strategy& analysis

Today, the EU and the NL already have multiple policies in place to establish these requirements and stimulate chemical recycling

Existing EU and NL policies to stimulate chemical recycling (non-exhaustive)

Requirements	Policy	Level	Description	Associated targets and future measures (if applicable)
Demand for output	**RED II & III**	🇪🇺	• Defines the overall EU target for renewable energy consumption, including hydrogen • Amended to include additional targets for industry and transport	• 42% of hydrogen in industry must come from RFNBO (renewable fuels and non-biological origin) sources by 2030 and 60% by 2035 • 1% of hydrogen in transport must come from RFNBO sources by 2030 and 5.5% by 2035
	EU ETS	🇪🇺	• Requires waste processors to pay for their CO2-emissions (negative externality) to stimulate processing methods that are less polluting; currently, W2E-plants are exempted	• Exemption of W2E-plants is lifted by 2028
	National Circular Plastic Norm (NCPN)	🇳🇱	• Sets requirements for a minimum share of recyclable plastic in new products (€267M budget is available to achieve this by 2030)	• 15% of plastic products must be of recyclable plastic by 2027 and 25-39% by 2030
Feedstock availability	**Waste Framework Directive**	🇪🇺	• Sets requirements for waste management and treatment • Sets the criteria for End-of-Waste status (which determines when waste is defined as secondary raw materials)	• Maximum MSW landfill rate of 10% by 2035 • MSW recycling target of 55% by 2025, 60% by 2030 and 65% by 2035 • Packaging recycling target of 65% by 2025 and 70% by 2030
	Waste Shipments Regulation	🇪🇺	• Sets rules for transporting waste across borders (intra- and extra-EU) to ensure the proper treatment of waste (in line with WFD[1])	• Plastic waste export to non-OECD countries is banned by 2026
Financial incentives	**EU Innovation Fund**	🇪🇺	• Provides subsidies for innovative low-carbon technologies (FUREC received €108M funding)	
	SDE++ subsidy	🇳🇱	• Provides subsidies for companies that generate renewable energy or reduce CO2-emissions on a large scale and are subject to an 'unprofitable top'	

---

[1] Waste Framework Directive

Source: Expert input; Directive 2008/98/EC; Directive 2003/87/EC; Directive 2018/2001/EU; Regulation (EU) 2024/1157; Ministerie van Infrastructuur en Waterstaat; RVO; Strategy& analysis

Chemical recycling can be further stimulated by adopting additional policies, e.g. embracing cross-border transport of waste within the EU

Proposed policy recommendations to further stimulate chemical recycling

Requirements	Recommendation	Level	Description
Demand for output	**Stimulate the use of circular feedstock in new products incl. redefinition of recycling** (to stimulate high-quality recycling/ prevent downcycling)	🇪🇺 & 🇳🇱	• The WFD[1] states that **high quality recycling output is preferred over lower quality output**, but recycling targets are currently focused on weight rather than output quality; in addition, there is currently no specific target for chemical recycling • The EU should stimulate the use of circular feedstock in new products by implementing targets for **minimum recycled content in new products with a higher classification/rank for circular feedstock vs. virgin and bio-based alternatives**
	Harmonize RED II & III targets for the transport and industry sector	🇪🇺	• In RED II & III, **targets have been set for the industry and transport sector regarding the use of hydrogen from RFNBO-sources** (renewable fuels and non-biological origin)**,** but the targets for the transport sector are lower than for the industry • The EU should **Harmonize RED II & III targets for the transport en industry sector** to create a common pathway and equal incentives
	Exclude circular syngas (hydrogen) from the RED III target	🇪🇺 & 🇳🇱	• **RED targets exclusively focus on stimulating the use of RFNBO-sourced hydrogen,** which pushes the industry demand towards RFNBO-sourced hydrogen rather than a circular alternative (e.g., from chemical recycling) • The EU should exclude circular syngas from the RED targets (i.e. the target of RNFBO-sourced hydrogen is determined after correcting for circular hydrogen usage) creating a level playing field for circular and RNFBO-sourced hydrogen
Feedstock availability	**Embrace cross-border transport of waste across EU member states**	🇪🇺	• Waste Shipment Regulation sets criteria **for waste shipments across the EU** limiting the possibility of waste flows to move freely within the EU; in addition, some **countries have set additional criteria** (e.g., the NL has stricter contamination criteria for plastic waste) or **import taxes** • The EU should **embrace cross-border transport of waste** across EU member states, and should harmonize the regulation across EU member states
	Extend waste tender criteria with environmental impact and preferred processing method	🇪🇺 & 🇳🇱	• Municipalities in the NL set out tenders for waste processers based on several criteria (e.g., price, quality)**:** environmental impact is not always a dominant criteria in the evaluation of potential contractors • NL & European municipalities should **extend waste tender criteria with environmental impact** (e.g., CO2-emissions) and **preferred processing method** (R3/4 should be preferred over R1) to favour cleaner and more waste efficient processing methods
Financial incentives	**Financially support circularity innovations and business models**	🇪🇺 & 🇳🇱	• Circularity innovations (like chemical recycling) can **struggle to acquire financial resources from the market**: besides typical innovation risks (e.g., technology risk), these innovations also face e.g., regulatory uncertainty, limited market demand and high CAPEX • The EU should **Financially support circularity innovations with subsidies, favourable loan conditions and/or tax deductions to** accelerate the process from final investment decision, go-live and upscaling to other countries and to further develop markets
	Include hydrogen from waste projects in the SDE++ subsidy scheme	🇳🇱	• The SDE++ is a subsidy for projects generating renewable energy or reducing CO2 emissions, but **generating hydrogen from waste is currently excluded from the subsidy (**whereas the CCU/S technology for W2E-plants is included) • The NL should **include hydrogen from waste projects in the SDE++ subsidy scheme** to create equal opportunity costs for waste processing methods that are potentially relevant in the future waste landscape

Prioritized policy recommendations

[1] Waste Framework Directive

Source: Expert input; Strategy& analysis

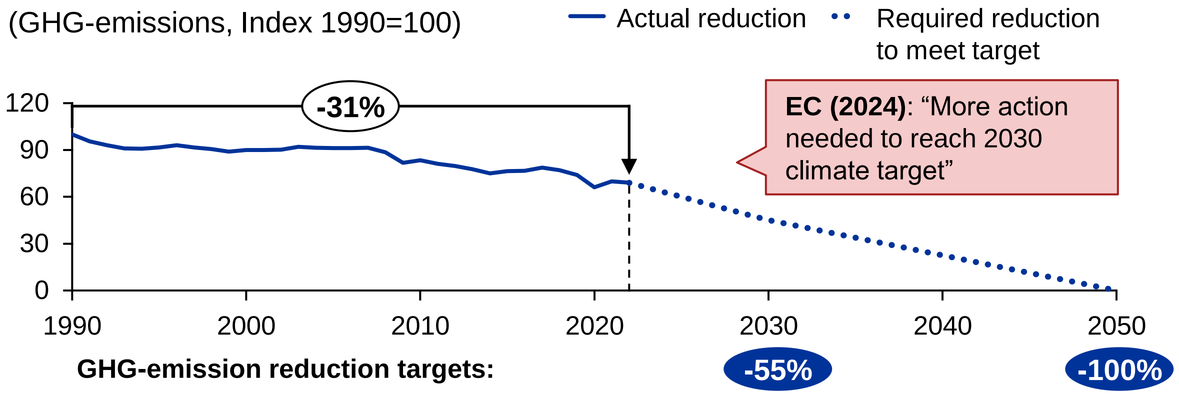
Appendix

1. **Introduction FUREC**
2. EU chemical industry: demand for raw materials (deep-dive NL)
3. EU waste market: supply of non-recyclable waste
4. Role of alternative waste processing technologies to convert non-recyclable waste
5. Details scope of study and availability and quality of information

The EU and NL aim to transition towards a 100% circular, climate-neutral economy by 2050; unlikely that 2030 targets will be met

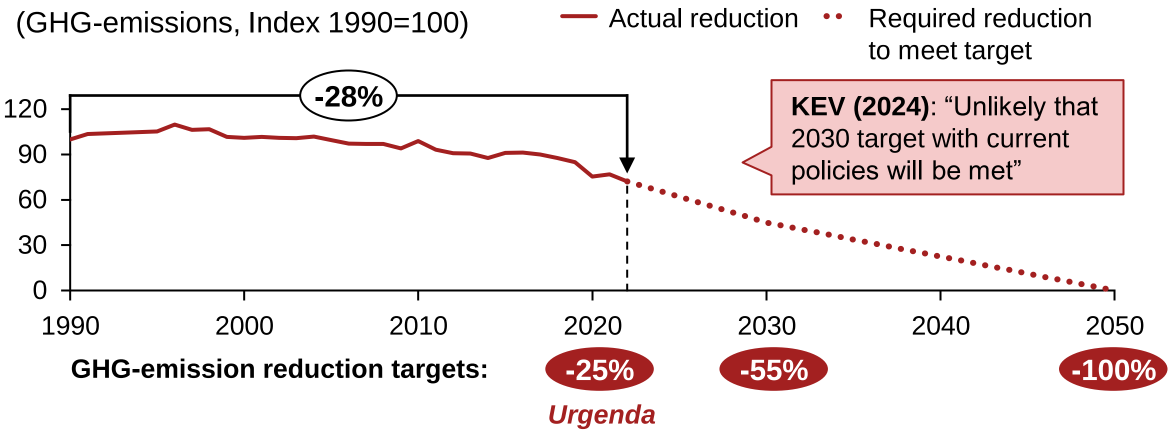
Drive towards sustainability and circularity

Sustainability target EU: climate-neutral by 2050



EC (2024): “More action needed to reach 2030 climate target”

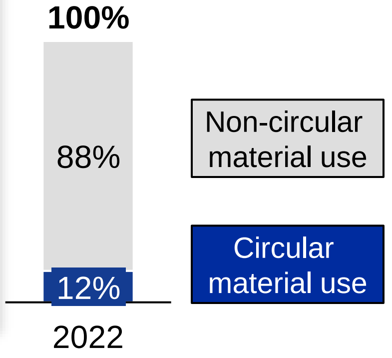
Sustainability target NL: climate-neutral by 2050



KEV (2024): “Unlikely that 2030 target with current policies will be met”

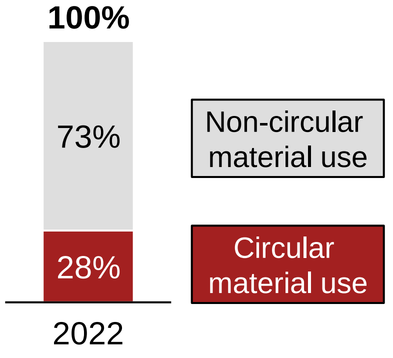
Circularity target EU: transition to a circular economy

“The **transition to a circular economy** is necessary to reduce **pressure on natural raw materials**, is necessary to achieve the **EU’s 2050 climate neutrality target** and ensures a **secure and sustainable supply of raw materials**.”



Circularity target NL: 100% circular by 2050

“NL is committed to reach a **100% circular economy by 2050.** This is an economy that uses **sustainable** and **renewable** raw materials and that **reuses** materials to make us **less dependent on fossil energy and foreign countries.** The **intermediate target** is to **halve abiotic raw material use by 2030.”**

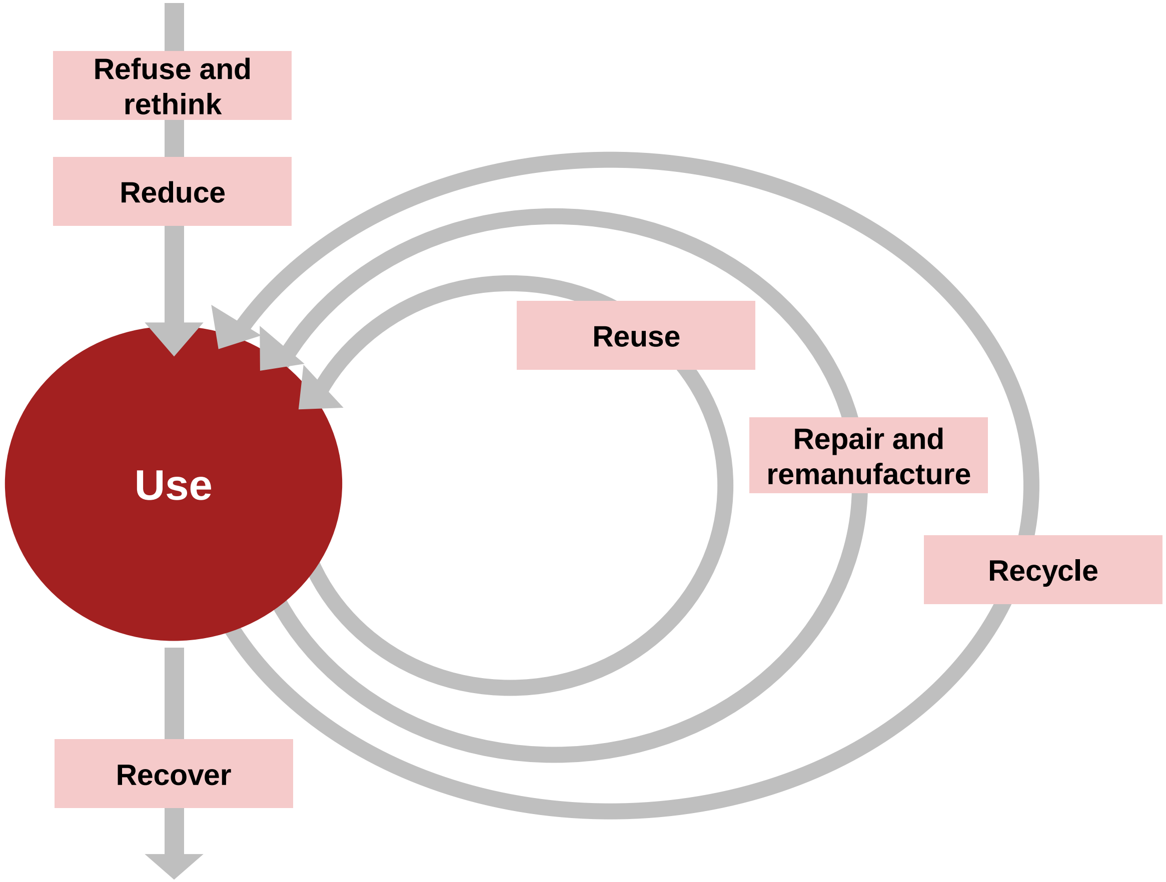


Source: European Commission; Rijkswaterstaat; Eurostat; PBL – ‘Klimaat- en Energieverkenning’ (2024); Circularity Gap Report 2024; Strategy& analysis

To realize these sustainability and circularity ambitions, the raw material value chain must transform

Transformation raw material value chain

Schematic visualisation ‘circular R-strategies’



Key insights

- The transition to a 100% circular climate-neutral economy requires are **transformation of the raw material value chain**
- This can be achieved in four ways:

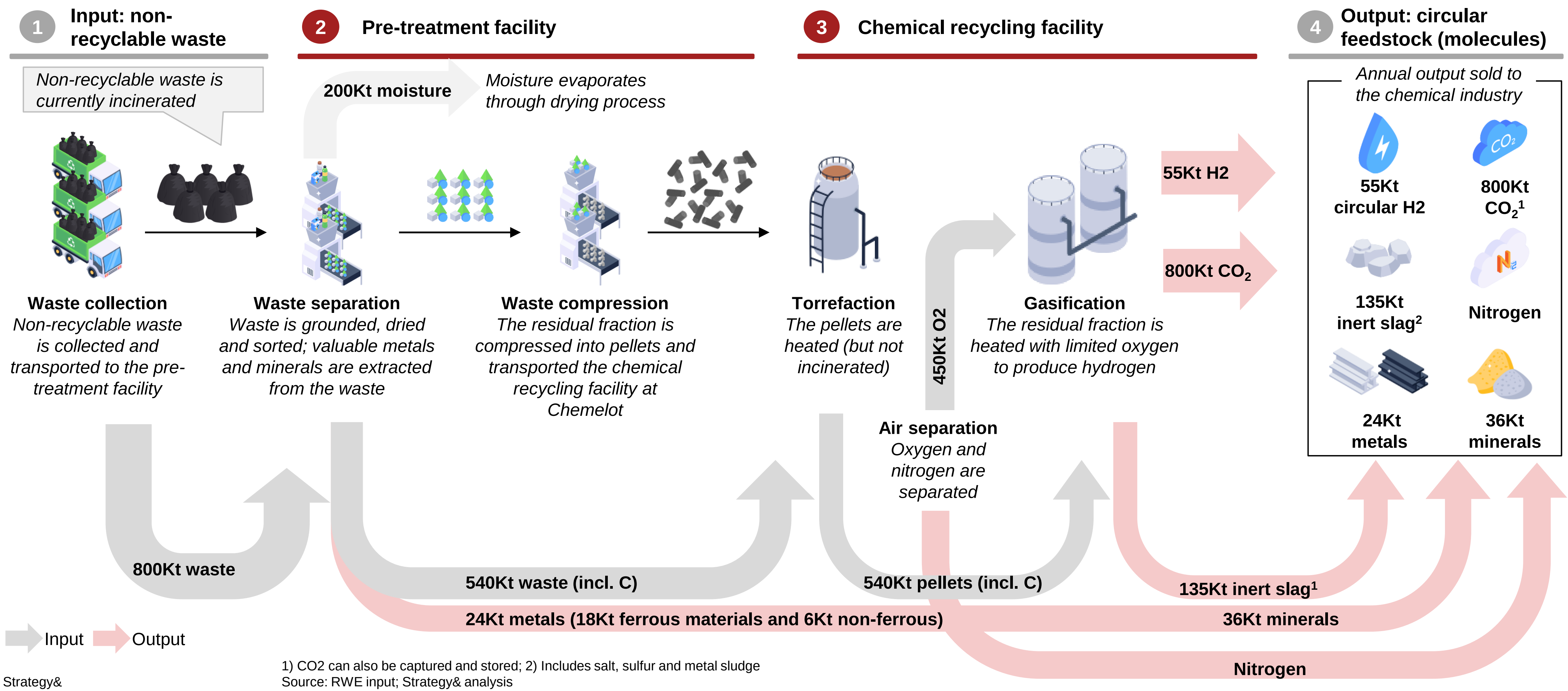
1. **Narrow the loop**: use fewer products (**Refuse**), share products (**Rethink**) or produce products more efficiently (**Reduce**)
2. **Slow the loop**: use products longer (**Reuse)** by extending the product life cycle (**Repair and Remanufacture**)
3. **Close the loop**: replace finite raw materials by secondary alternatives and avoid the loss of valuable raw materials (**Recycle**)
4. **Substitution**: replace finite raw materials by renewable and bio-based alternatives and recover energy from materials (**Recover**)

- Waste processing technologies such as **pyrolysis** and **gasification (FUREC) can play an important role** by offering an alternative way to close the loop

Source: European Commission; PBL – ‘Trajectverkenning klimaatneutraal 2050’ (2024); Strategy& analysis

FUREC contributes to these ambitions by using non-recyclable waste to produce circular feedstock for the (chemical) industry

FUREC value chain



1 Input: non-recyclable waste

Non-recyclable waste is currently incinerated

Waste collection
Non-recyclable waste is collected and transported to the pre-treatment facility

2 Pre-treatment facility

200Kt moisture
Moisture evaporates through drying process

Waste separation
Waste is grounded, dried and sorted; valuable metals and minerals are extracted from the waste

Waste compression
The residual fraction is compressed into pellets and transported the chemical recycling facility at Chemelot

3 Chemical recycling facility

Torrefaction
The pellets are heated (but not incinerated)

450Kt O2

Gasification
The residual fraction is heated with limited oxygen to produce hydrogen

Air separation
Oxygen and nitrogen are separated

55Kt H2

800Kt CO_2

4 Output: circular feedstock (molecules)

Annual output sold to the chemical industry

55Kt circular H2

800Kt CO_2[1]

135Kt inert slag[2]

Nitrogen

24Kt metals

36Kt minerals

800Kt waste

540Kt waste (incl. C)

540Kt pellets (incl. C)

135Kt inert slag[1]

24Kt metals (18Kt ferrous materials and 6Kt non-ferrous)

36Kt minerals

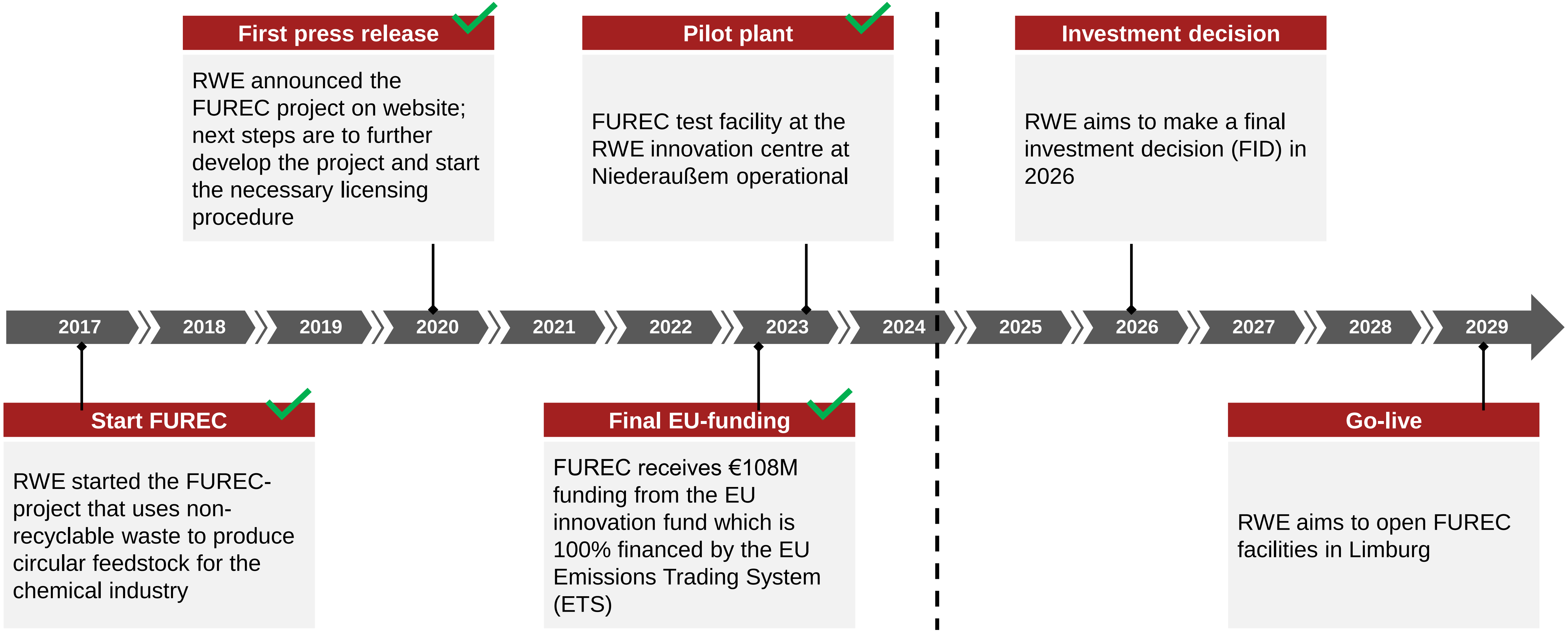
Nitrogen

Input Output

1) CO2 can also be captured and stored; 2) Includes salt, sulfur and metal sludge
Source: RWE input; Strategy& analysis

RWE received €108M EU funding and aims to make a final investment decision regarding FUREC in 2026 and go live in 2029

FUREC high-level timeline



Start FUREC ✓

RWE started the FUREC-project that uses non-recyclable waste to produce circular feedstock for the chemical industry

First press release ✓

RWE announced the FUREC project on website; next steps are to further develop the project and start the necessary licensing procedure

Final EU-funding ✓

FUREC receives €108M funding from the EU innovation fund which is 100% financed by the EU Emissions Trading System (ETS)

Pilot plant ✓

FUREC test facility at the RWE innovation centre at Niederaußem operational

Investment decision

RWE aims to make a final investment decision (FID) in 2026

Go-live

RWE aims to open FUREC facilities in Limburg

- - - Today ✓ Completed

Source: RWE input; Strategy& analysis

Appendix

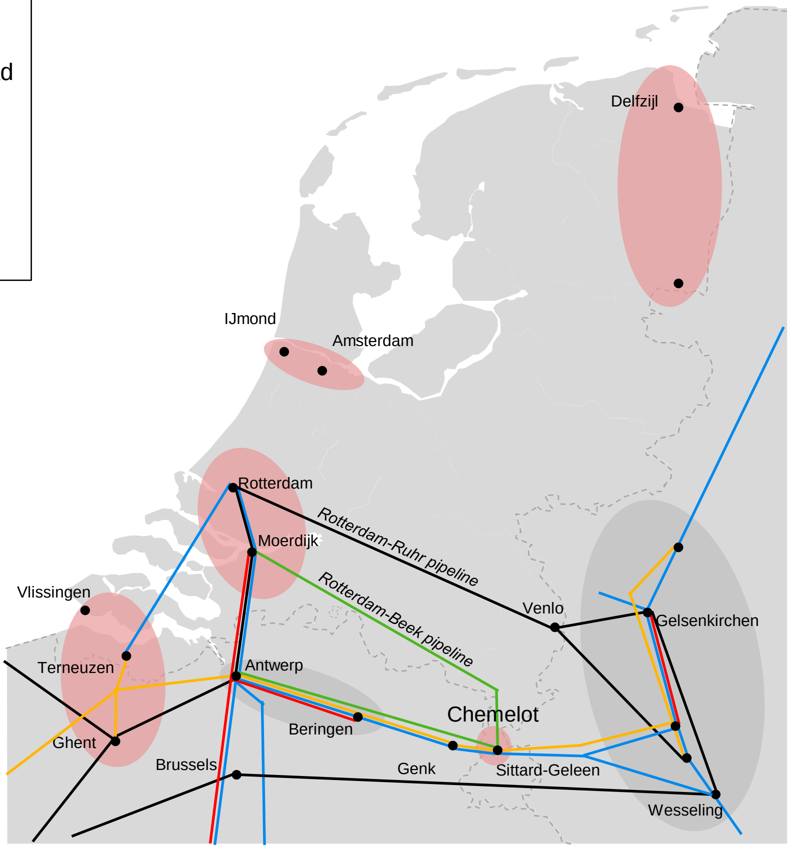
The chemical industry ecosystem in the NL consists of 5 main clusters that are well connected with each other and abroad

Overview Dutch chemical industry

Overview Dutch chemical industry

Existing infrastructure

- ● Main chemical clusters NL
- ● Main chemical clusters abroad
- — Crude oil pipelines
- — Industrial gas pipelines
- — Propylene pipelines
- — Ethylene pipelines
- — Naphtha pipelines



Key figures Dutch chemical industry

10th largest chemical industry in the world in terms of revenue

4th largest chemical industry in the EU in terms of revenue

Approximately **€90 billion revenue** contributing **9% to the Dutch GDP**

Approximately **16% of the total exported value** of the NL

Approximately **45,000 employees** and **395 chemical companies**

Key players (examples):

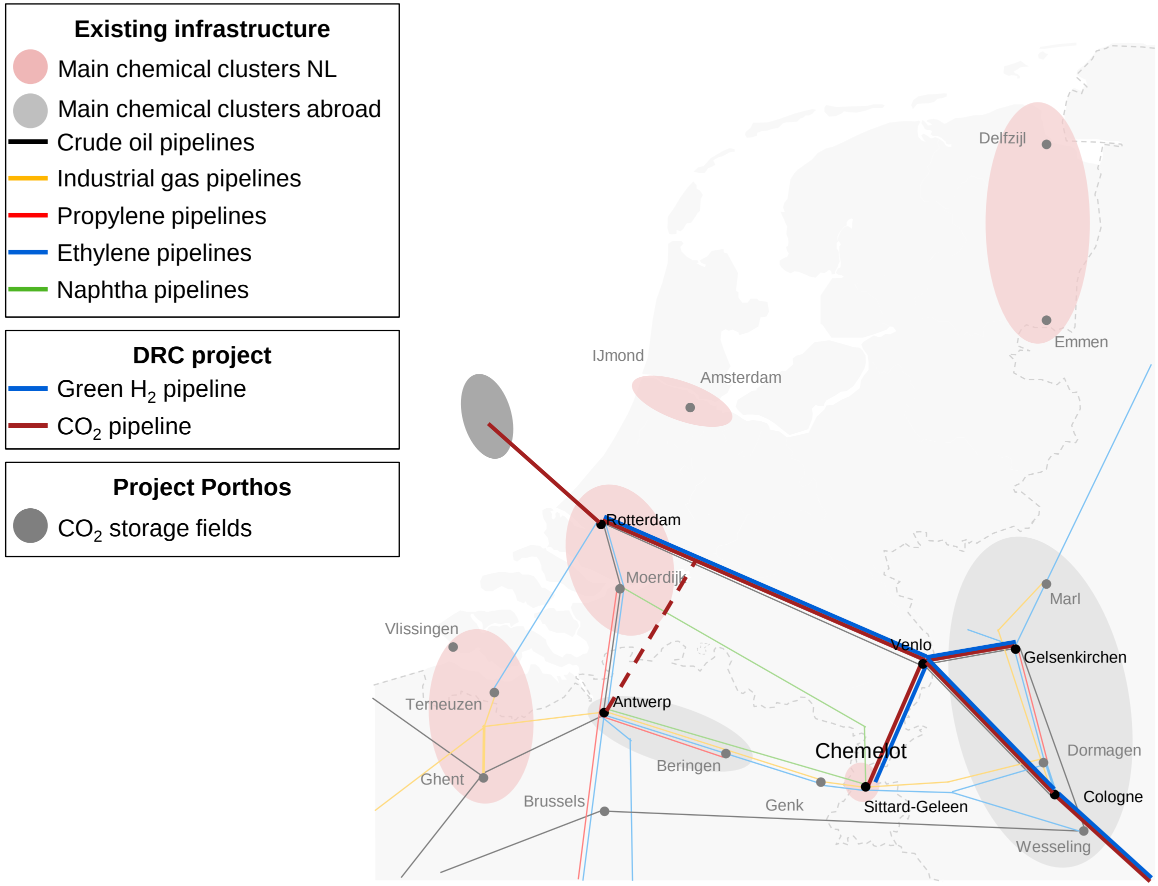
AkzoNobel DOW BASF We create chemistry سابك sabic DSM

Source: VNCI; CBS; Strategy& analysis

The leading position of the chemical industry in NL will be solidified by the “Delta Rhine Corridor” pipeline transporting green H2 and CO2

Upcoming pipeline connection Dutch chemical industry

Project overview



Key insights

- Planned connection of largest chemical clusters in Rotterdam, Antwerp, Chemelot and North Rhine-Westphalia – supplying clean energy (H_2) and CO_2 offtake to decarbonize operations
- Expected completion of construction in 2028
- Backed by:

BASF We create chemistry

OGE

gasunie

Case study: Project Porthos

Porthos CO₂ TRANSPORT & STORAGE

- CO_2 from Delta Rhine Corridor (DRC) to be pressurized on-shore and pumped into empty natural gas fields ~20 km off the Dutch coast
- Total capacity of ~37Mt CO_2, expect to be filled over a duration of 15 years
- Final investment decision taken in October 2023, start of construction in 2024 with expected completion in 2026
- Project set up in open model – allowing various companies/industrial clusters along the DRC pipeline to benefit from the project
- Project jointly developed by Air Liquide, Air Products, Shell and ExxonMobil

Air Liquide

AIR PRODUCTS

ExxonMobil

Source: Company information; Strategy& analysis

Appendix

1. Introduction FUREC
2. EU chemical industry: demand for raw materials (deep-dive NL)
3. **EU waste market: supply of non-recyclable waste**
4. Role of alternative waste processing technologies to convert non-recyclable waste
5. Details scope of study and availability and quality of information

New regulations will drive the transition towards more reduce, reuse and recycle in the EU

Overview EU regulation

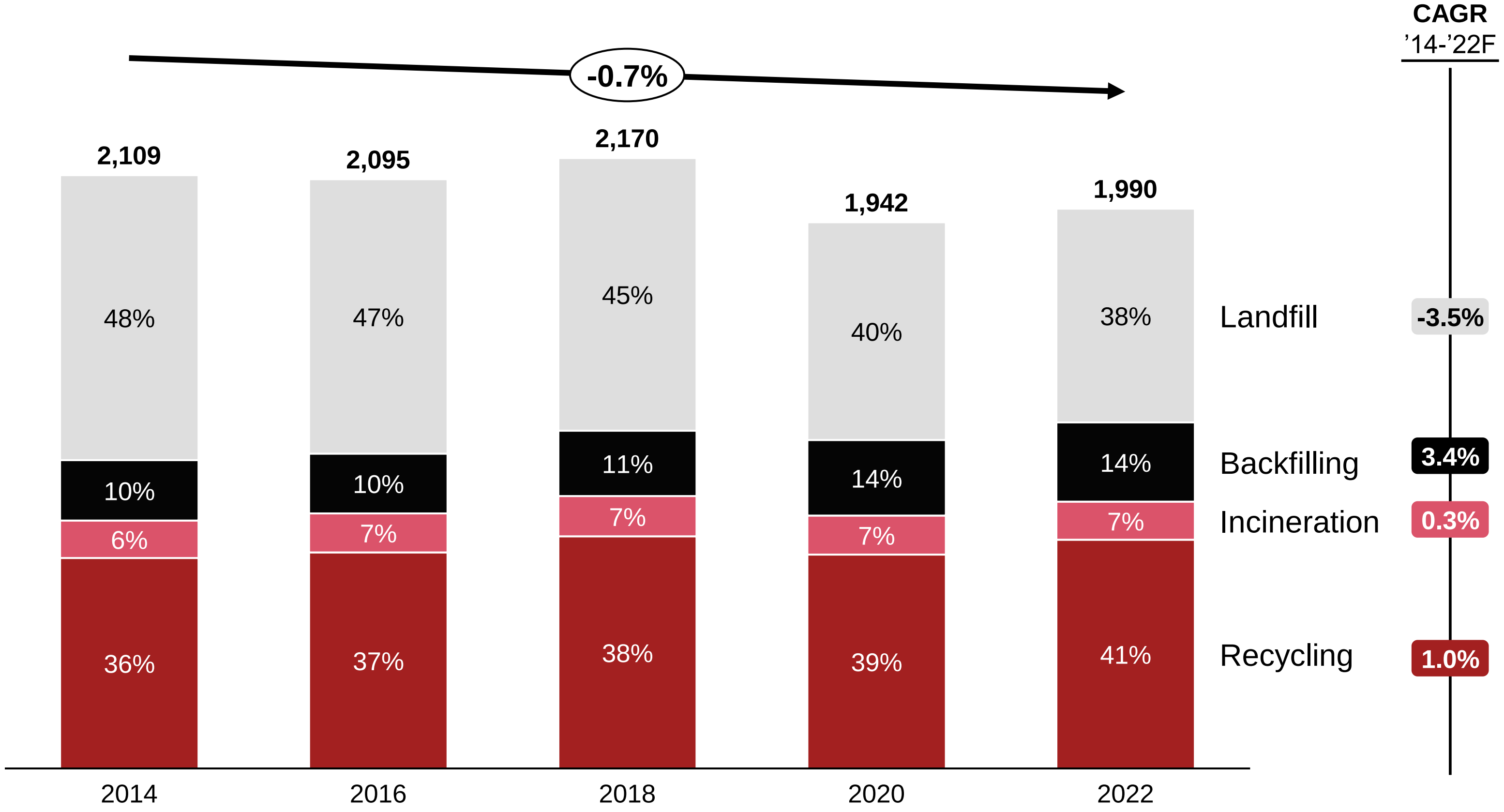
EU regulation	2025	2030	2035
Maximum landfilled MSW volume			10%
MSW recycling target	55%	60%	65%
Packaging recycling target		65%	70%
Paper packaging recycling target	75%	85%	
Glass packaging recycling target	70%	75%	
Ferrous metal packaging recycling target	70%	80%	
Aluminium packaging recycling target	50%	60%	
Plastic packaging recycling target	50%	55%	
Wood packaging recycling target	25%	30%	
Minimum recycled content plastic bottles	25%	30%	

Source: European Environment Agency; Strategy& analysis

The total processed waste volume in the EU was 1,990Mt in 2022, of which 7% is incinerated and 38% is landfilled

Overview waste market in the EU

Total waste volume incl. major minerals in the EU27 per processing method
(2014 – 2022, in Mt)



Key insights

- The total processed waste volume in the EU **slightly declined in the past decade to 1,990Mt in 2022** including major minerals (-0,7% CAGR)
- Waste processing in the EU is largely **governed by directives and regulation** (e.g., the EU waste hierarchy sets the hierarchy of waste processing methods)
- As a result, **more waste is currently processed by more favourable processing methods at the expense of less favourable alternatives**:
  - ***The landfill rate*** decreased from 48% to 38% in the past decade, mostly driven by the Landfill Directive that sets landfill requirements and landfill restrictions
  - ***The recycling rate*** increased from 36% to 41%, driven by the Waste Framework Directive and CEAP[1]
- Nonetheless, a **substantial amount of waste in the EU is still incinerated (7%) or landfilled (38%)**

---

[1] Circular economy action plan

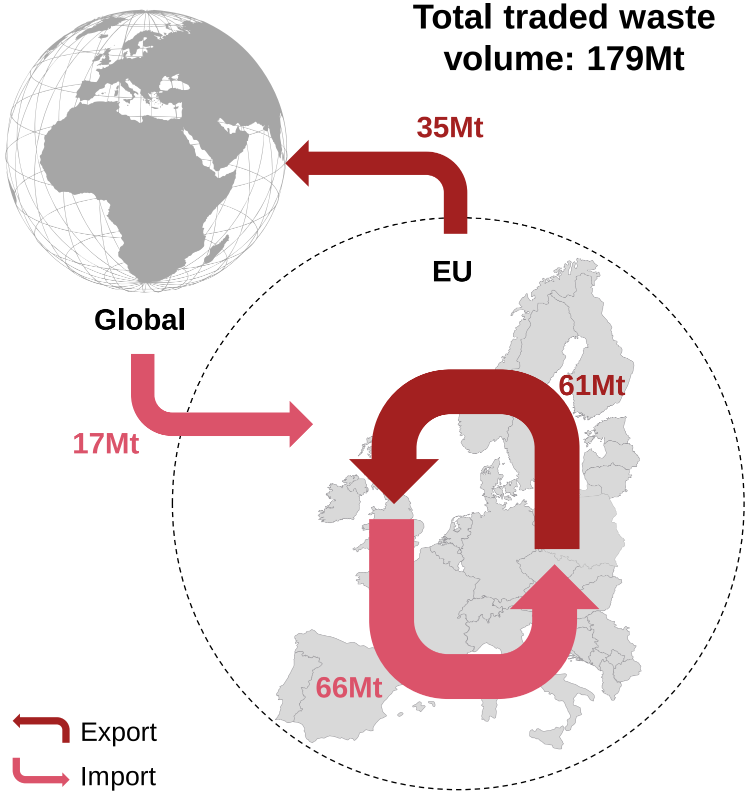
Source: Eurostat; EU Directive 2008/98/EC; Directive 1999/31/EC; Strategy& analysis

A substantial amount of waste is traded within and outside the EU, with waste exports becoming more challenging due to EU regulation

Waste trade within and outside the EU

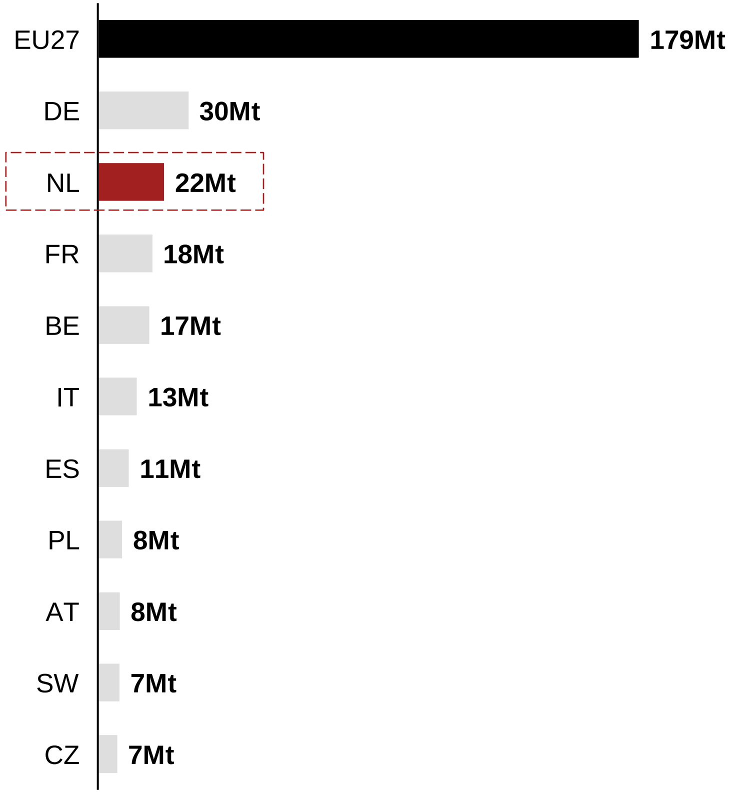
Much waste trade within or outside EU

Traded waste volume within or outside EU27
(2023, in Mt)



NL is the second largest waste trader

Traded waste volume per EU country (top 10)
(2023, in Mt)



Key insights

- The **total traded waste volume by EU member states** (within or outside the UE) was **179Mt** in 2023
- In 2023, the **imported waste volume was 83Mt** with the majority (66Mt) being imported from other EU countries, and the remaining part (17Mt) being imported from outside the EU
- In addition, **96Mt waste was exported:** 61Mt was exported to other EU member states and the remaining 35Mt outside the EU
- Waste trade **varies substantially between EU member states**, with Germany, the NL, France, Belgium and Italy being the top-5 waste trading countries
- In recent year, **waste export outside the EU has become more challenging due to EU regulation** (e.g., plastic waste export ban from EU tot non-OECD countries)
- This regulation forces EU member states to **take ownership over their waste**, process waste locally in accordance with Waste Framework Directive and avoid environmental damage from waste incineration or landfill abroad

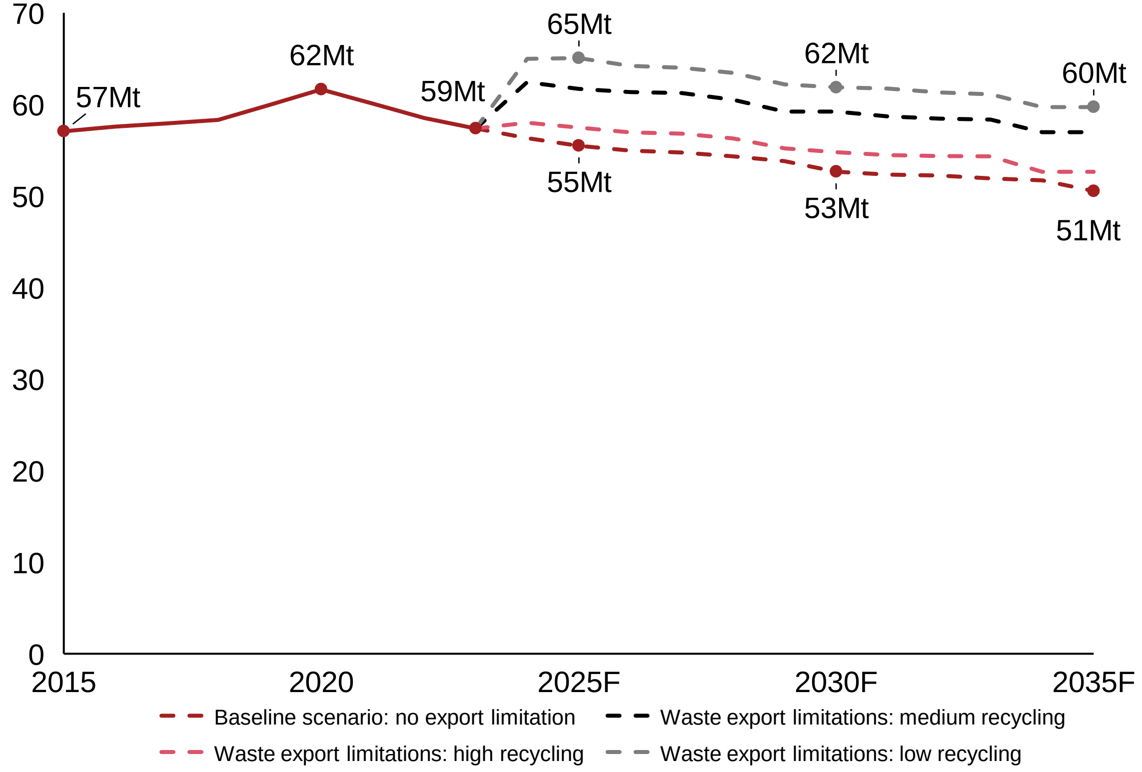
Source: Eurostat; European Environment Agency; Strategy& analysis

The incinerated MSW volume in the EU might increase up to 60Mt by 2035 following potential export limitations

Projected incinerated MSW volume in the EU

Projected incinerated MSW by W2E-plants in the EU27[1]

(2015 – 2035F, in Mt)



Key insights

- In the **baseline scenario**, the **incinerated MSW volume by W2E-plants** in the EU is expected to **decrease from 59Mt in 2022 to 51Mt in 2035**
- This incinerated MSW volume could be higher due to **potential waste export limitations** forcing EU member states to take ownership over their own waste and process waste within the EU
- Since 2023, plastic waste export from the EU to non-OECD countries is prohibited and currently the EU is **investigating a complete waste export ban outside the EU**
- As more waste will be processed within the EU, the **incinerated MSW volume by W2E-plants** in the EU is expected to increase up to 60Mt depending on the scenario (see table below)
- Evidently, there is expected to be a **substantial amount of non-recyclable waste in the future waste landscape in the EU**

Scenario	**Assumed recycling rate of repatriated waste**		
	Low	***Medium***	***High***
Paper waste	50%	72%	95%
Plastic waste	20%	33%	80%
Metal waste	60%	75%	100%
Glass waste	60%	76%	95%
Other waste	50%	75%	95%

1) Note: the graph shows actual incinerated MSW up to 2022, afterwards the scenario trend of the Zero Waste Europe report has been used to project incinerated waste up to 2035

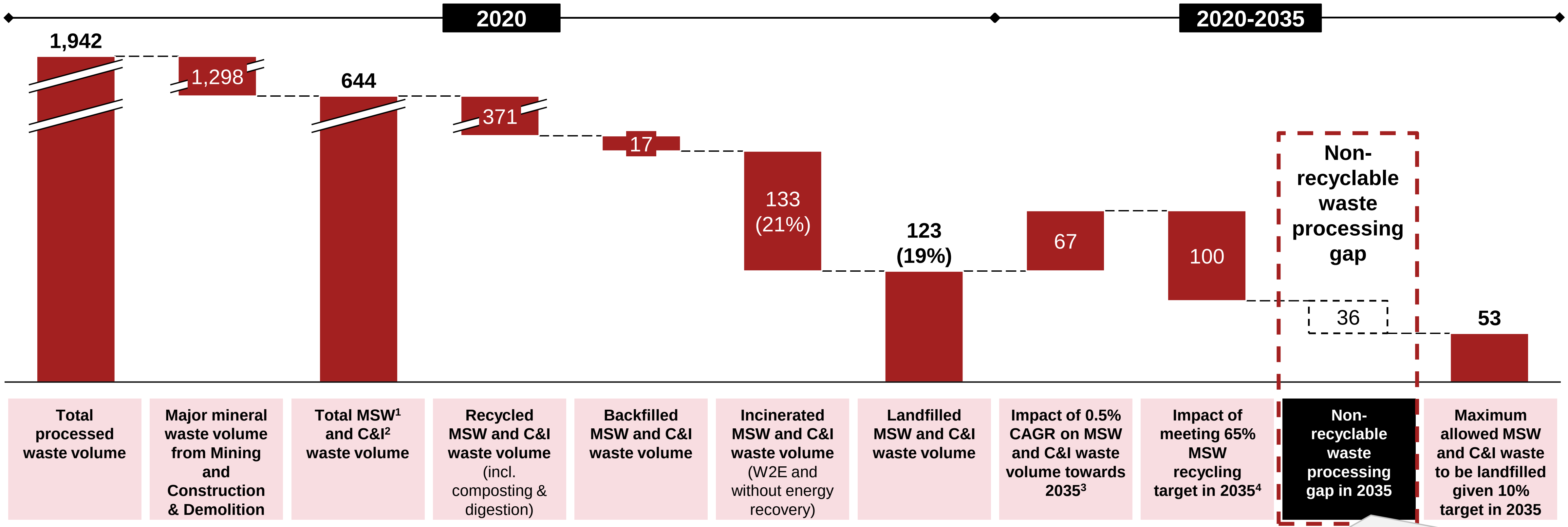
Source: Zero Waste Europe – 'Waste trade and incineration: debunking an unnecessary alliance' (2022); Strategy& analysis

Overall, a high-level waste processing outlook indicates a non-recyclable waste processing gap of 36Mt in the EU by 2035

High-level waste processing outlook in the EU

Processed waste volumes in the EU27

(in Mt per year)



Only achieving a **MSW recycling rate of 60%** in 2035 increases non-recyclable waste processing gap to **50Mt**

1) Municipal Solid Waste; 2) Commercial & Industrial; 3) Growth rate of 1.0% YoY for MSW and 0.5% for C&I based historical growth rates for MSW and C&I ('10-'18) – in line with growth projections for material use; 4) Assumed that recycled volumes of C&I improve with 1% YoY; recycled C&I waste reaches 67% compared to total C&I waste in 2035; 5) Assumed 10% target also applies for C&I

Source: Eurostat; OECD; Strategy& analysis

Recent investments in W2E-plants in the EU indicate that investors expect a consistent supply of non-recyclable waste in the future

Investor appetite in W2E-plants in the EU

Fortum to sell its recycling and waste business to Summa Equity for approximately €800 million (2024)

Ardian to acquire leading European waste management and circular economy platform Attero (2023)

Babcock & Wilcox Enterprises to acquire VODA A/S, a Danish W2E service provider (2021)

Energy Capital Partners to acquire Biffa lpc, an integrated waste management and circular economy business (2023)

SUEZ to reintegrate major waste business after acquiring it back from Veolia (2022)

First Sentier Investors to acquire seven of Wheelabrator's W2E facilities in the UK (2021)

Key insights

- In recent years, there has been much **appetite from investors to acquire W2E-plants** in the EU
- Investors typically have a **long-term financial perspective (10-20 years)** when acquiring a new business
- For W2E-plants to be profitable, they **rely on incinerating (non-recyclable) waste to generate steam and electricity** that are supplied to e.g., industrial sites or heating networks
- In other words: **without sufficient input (waste) there is no output (steam and electricity)** to be sold
- This financial reality demonstrates that investors expect a **consistent supply of non-recyclable waste to be processed** by W2E-plants in the future

Source: MergerMarket; Company websites; Strategy& analysis

Appendix

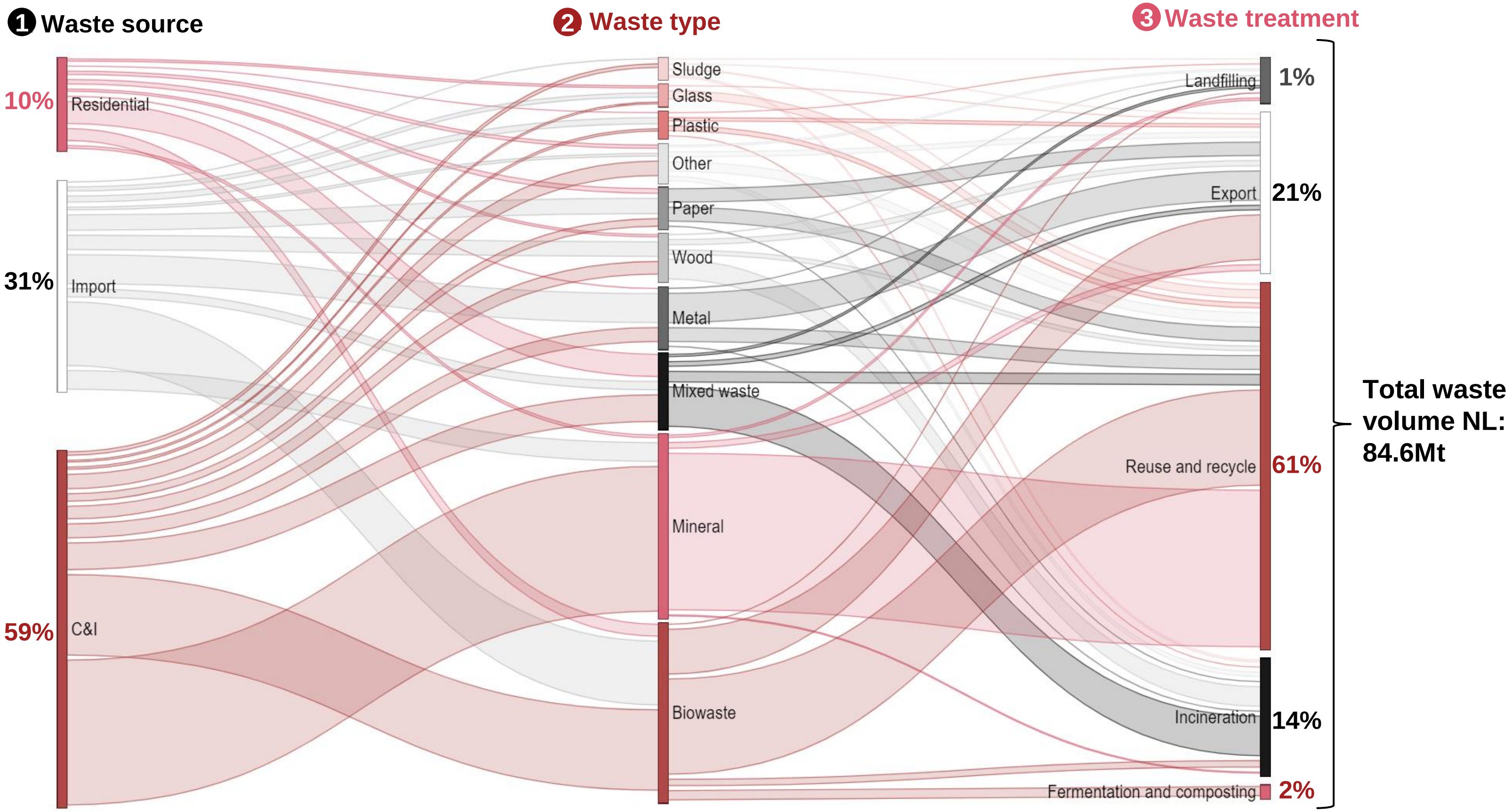
1. Introduction FUREC
2. EU chemical industry: demand for raw materials (deep-dive NL)
3. **EU waste market: supply of non-recyclable waste**
   - **Deep-dive: NL waste market**
4. Role of alternative waste processing technologies to convert non-recyclable waste
5. Details scope of study and availability and quality of information

The NL generates 84.6Mt waste per year, primarily mineral and biowaste from the C&I segment that is mostly reused and recycled

Overview Dutch waste market

Sankey diagram Dutch waste market

(2022, in %)



Key insights

1. The **total waste volume in the NL has hovered around 84-86** Mt in the past decade; the **volume distribution over waste source remained stable**
2. The volume **distribution over waste types also remained stable over time**, with mineral and biowaste accounting for 62%
3. The **volume distribution over processing method remained stable** over time; the NL is frontrunner in the EU with a 61% reuse and recycle rate
4. **Reuse and recycle is driven by mineral and biowaste**: the reuse and recycle rate in the NL is 13% when these waste types are excluded

- See details point 1-4 on next pages

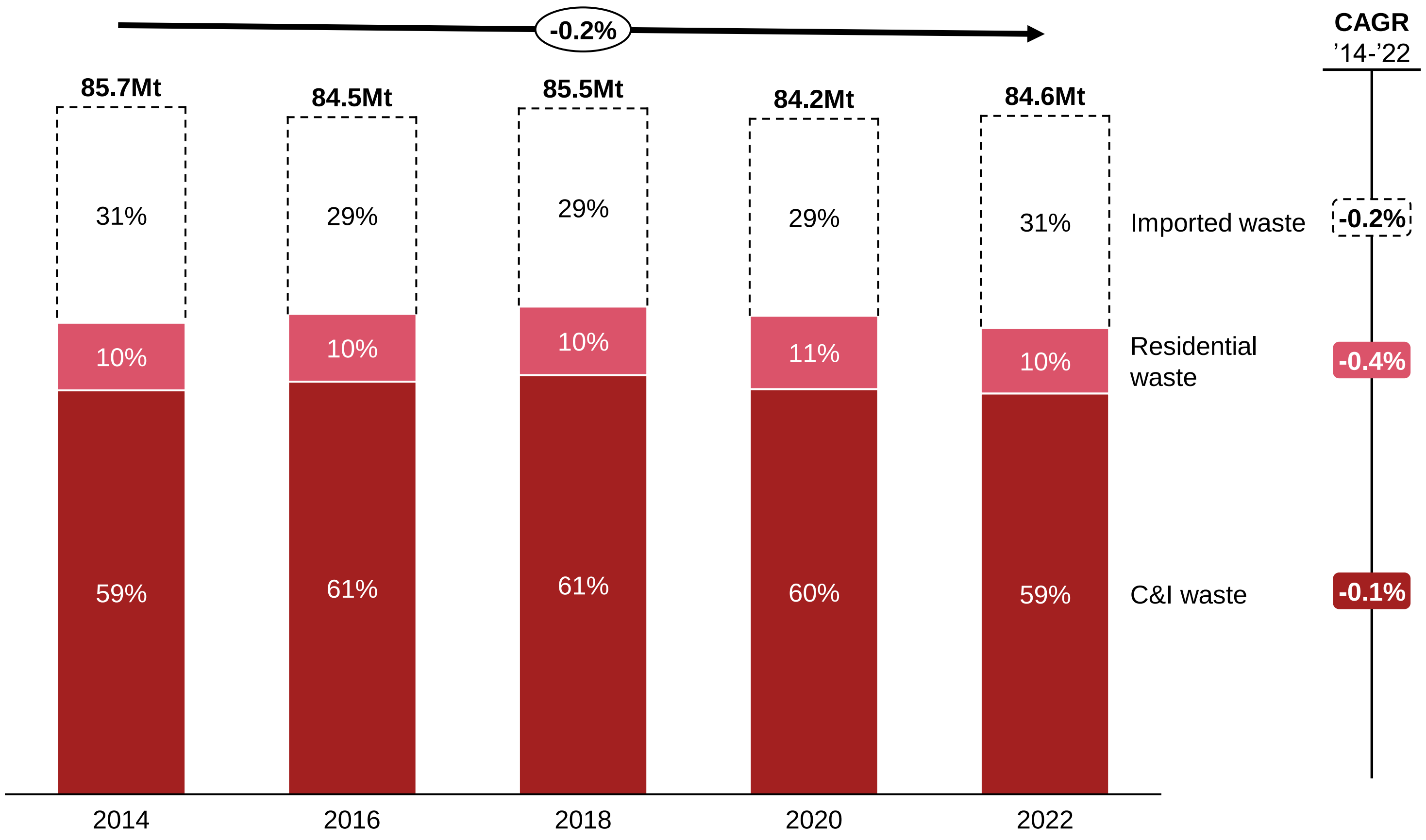
Note: numbers may not add up due to rounding.
Source: CBS; Eurostat; Strategy& analysis

The total waste volume in the NL has hovered around 84-86 Mt in the past decade; the volume distribution over waste source remained stable

1 Dutch waste market: waste volume per waste source

Generated waste volume in the NL per waste source

(2014 – 2022, in Mt and %)



Key insights

- The **total waste volume generated in the NL declined from 85.7Mt in 2014 to 84.6Mt in 2022**
- Between 2014 and 2022, the total waste volume has experienced a **slight decrease** with a compound annual growth rate (CAGR) of -0.2%
- The **C&I segment accounts for the majority** (59%) of the waste volume; 31% of the waste is imported, and the remaining 10% is generated by residents
- Over time, the **distribution of waste volumes among the waste sources** – C&I, residential and import - has **remained stable**
- The NL is one of the **leading waste importers in the EU:**
  - NL was **ranked top-1 importer** in the EU in 2016, 2017, 2021 and 2022
  - In other years since 2014, the NL has always been in the **top-4 largest importing countries in the EU**

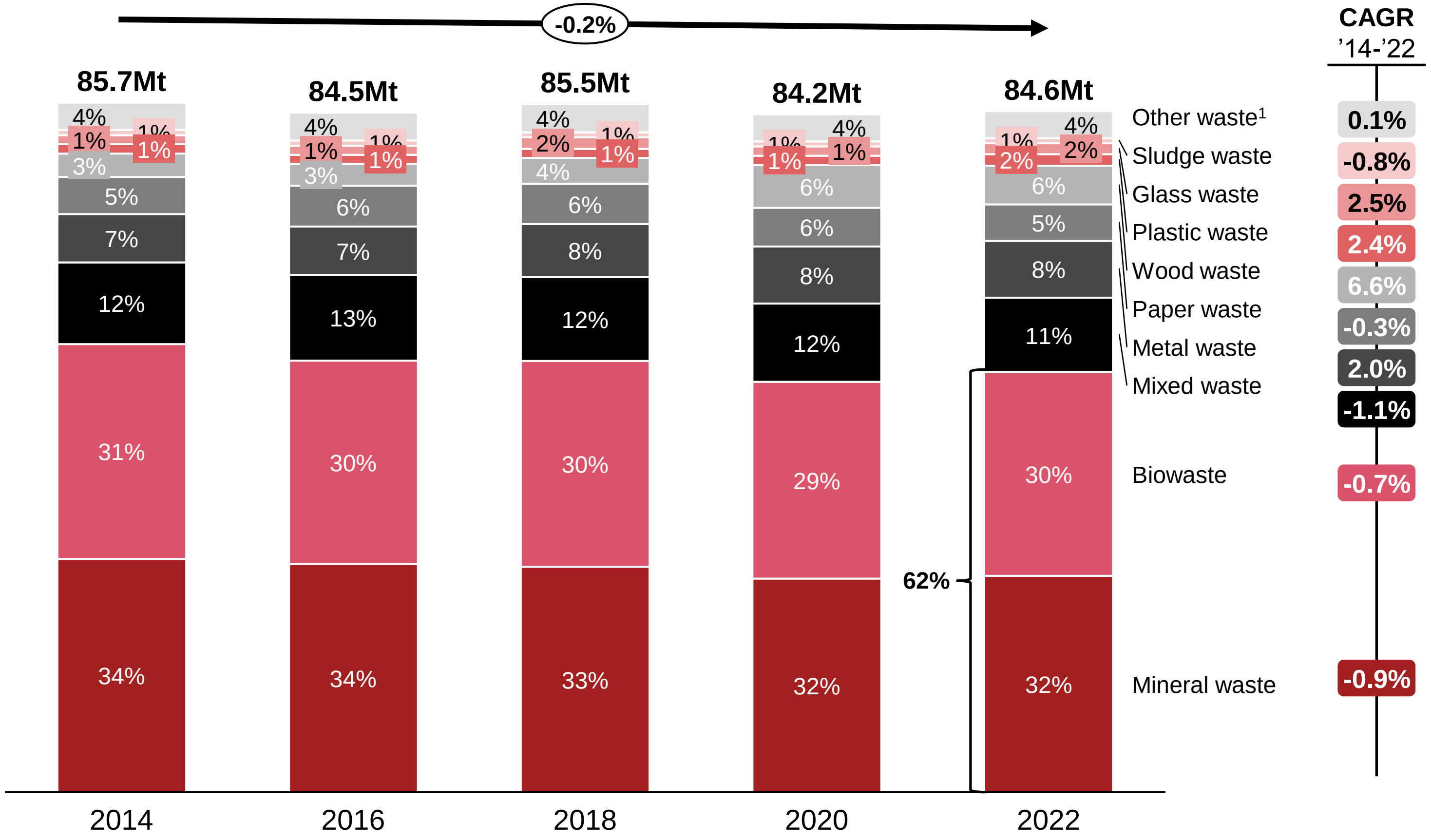
Source: CBS; Eurostat; Strategy& analysis

The volume distribution over waste types also remained stable over time, with mineral and biowaste accounting for 62%

2 Dutch waste market: waste volume per waste type

Generated waste volume in the NL per waste type

(2014 – 2022, in Mt and %)



Key insights

- In the past decade, the **waste volume distribution over waste type remained stable,** but there have been **some changes in the composition**
- Waste types becoming **relatively less dominant:**
  - **Mineral waste** decreased from 34% to 32%, likely driven by the increased reuse of mineral waste on construction sites
  - **Biowaste** decreased from 31% to 30% as this is increasingly reused in industrial processes (e.g., orange peels or cocoa shells) and subsequently not registered as waste
  - **Mixed waste** decreased from 12% to 11%, following municipalities efforts to stimulate separation-at-source
- Waste types becoming **relatively more dominant:**
  - **Wood waste** increased from 3% to 6%, driven by increased separation-at-source at e.g., municipal sorting centres
  - **Plastic waste** increased from 1% to 2%, driven by an increase in plastic packaging use
  - **Metal waste** increased from 7% to 8%, mostly driven by a rise in ferrous waste (iron)

---

1) Other consists of rubber, textile and discarded waste

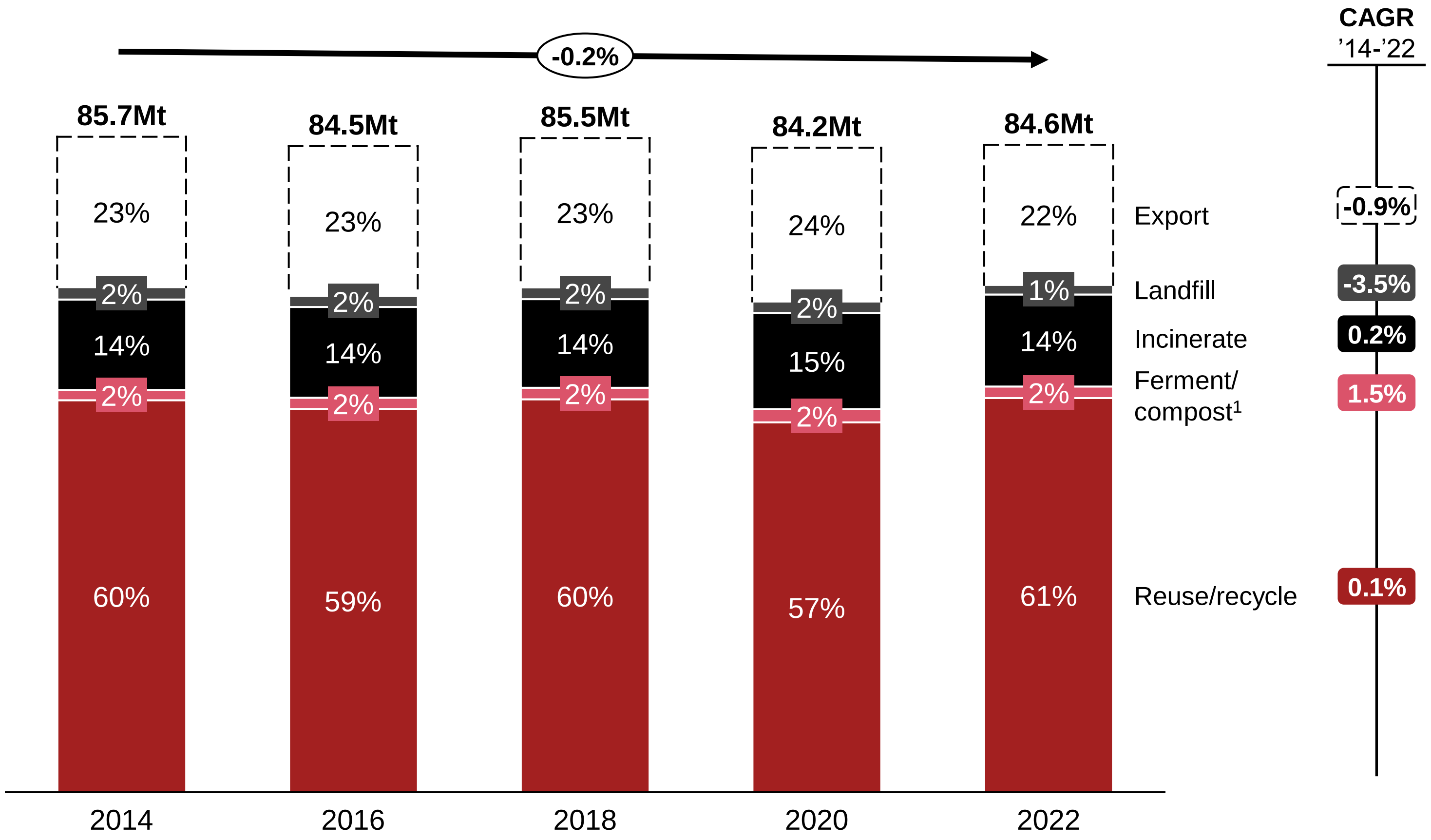
Source: CBS; Afvalmonitor; Verpact; CE Delft; Strategy& analysis

The volume distribution over processing method remained stable over time; the NL is frontrunner in the EU with a 61% reuse and recycle rate

③ Dutch waste market: waste volume per processing method

Processed waste volume in the NL per processing method

(2014 – 2022, in Mt and %)



Key insights

- In the past decade, the waste volume **distribution** over processing method **remained stable,** but there have been **some changes in the composition**
  - ○ **Less waste is landfilled** (-3.5% CAGR) following policies at the EU and NL level (e.g., closure landfill sites)
  - ○ **Less waste is exported** (-0.9% CAGR) following e.g., the ban to export waste from the EU to non-OECD countries
  - ○ **More waste is fermented/composted** (1.5% CAGR) following e.g., improved biowaste separated at source
  - ○ **Slightly more waste is incinerated (0.2% CAGR) and reused/recycled (0.1% CAGR)**
- **The NL is a frontrunner in the EU** with a 61% reuse/recycle rate vs. 55% as EU average

Reuse and recycle rate the NL vs. EU

(2022, in %)

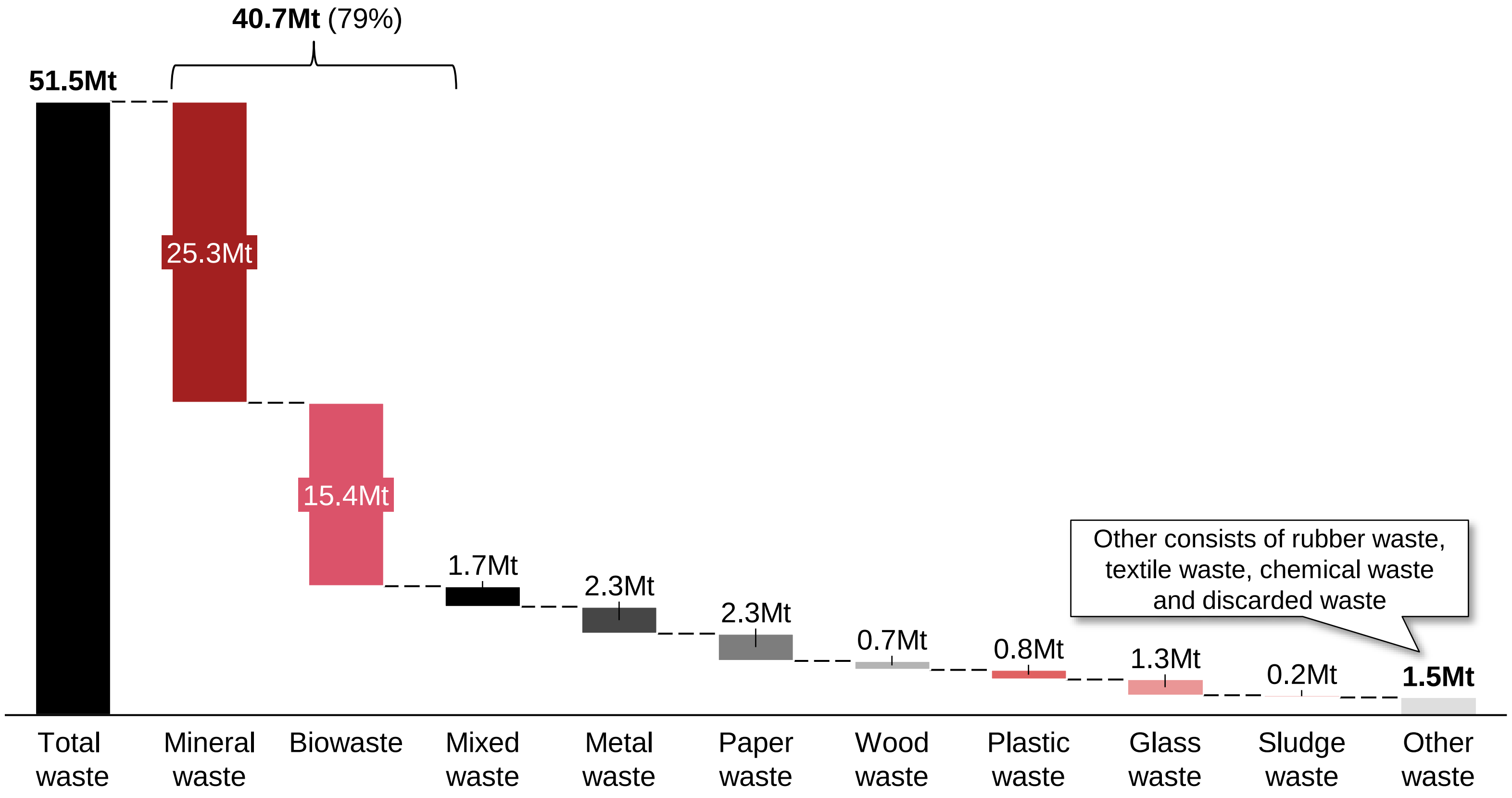
---

1) As documented in ’Afvalverwerking in Nederland’, as CBS numbers were unavailable;
Source: CBS; Afvalverwerking in Nederland reports; CLO; Strategy& analysis

Reuse and recycle in the NL is driven by mineral and biowaste: the reuse and recycle rate is 13% when these waste types are excluded

4 Dutch waste market: reuse and recycle

Reused and recycled waste volume in the NL per waste type
(2022, in Mt and %)

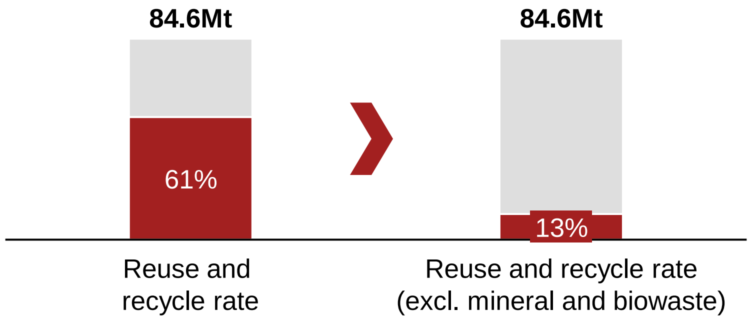


Other consists of rubber waste, textile waste, chemical waste and discarded waste

Key insights

- The reused and recycled waste volume in the NL consists for 79% of:
  - **Mineral waste: construction and demolition waste** and is often used as **backfilling** in new construction projects (e.g., roads, infrastructure)
  - **Biowaste:** mostly **C&I** waste that emerges during **food production processes**, which is reused as **animal feed** or recycled during other processes
- When these **two waste types are excluded**, the **reuse and recycle rate in the NL is 13%**

Reuse and recycle rate the NL (excl. mineral and biowaste) *(2022, in Mt and %)*



Source: CBS; Strategy& analysis

The NL is expected to have substantial volumes of non-recyclable waste in the future based on different perspectives

Future Dutch waste market

Details on next pages

In the future waste market in the NL, there is expected to be substantial volumes of non-recyclable waste based on two perspectives

1

Bottom-up evaluation future waste volume in the NL: in the future waste landscape, there is expected to be a substantial waste volume as it will be challenging to substantially reduce the total waste volume in the NL due to amongst others population growth and economic growth

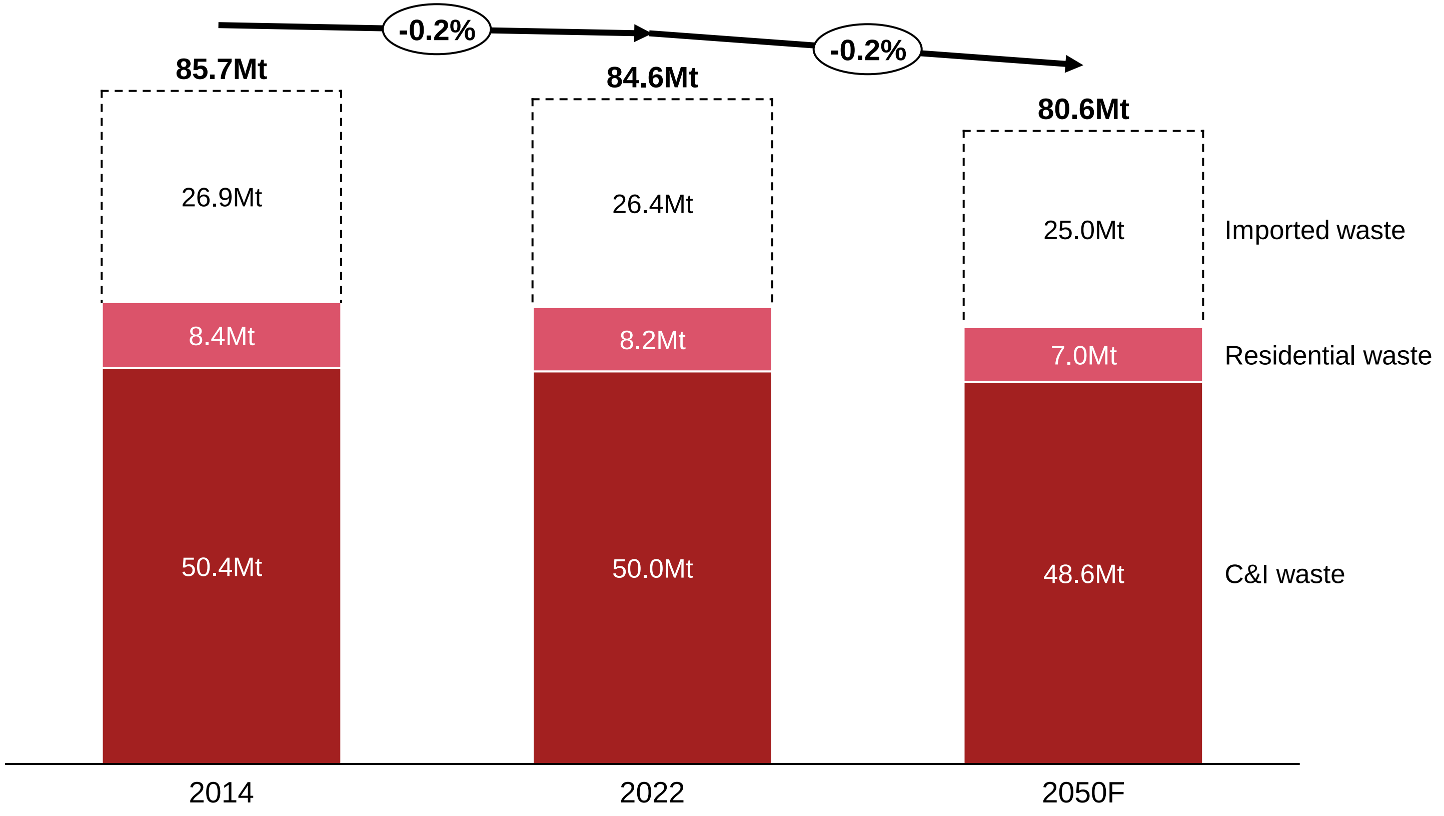
2

Study on future non-recyclable waste volume in the NL: as the NL transitions to circular economy, primary raw materials will be replaced by secondary alternatives, therefore more waste will be recycled resulting in more non-recyclable waste from the recycling process

The total waste volume is expected to slightly decline from 84.6Mt in 2022 to 80.6Mt in 2050

❶ Bottom-up evaluation future waste volume in the NL (1/2)

Projected generated waste volume in NL per waste source
(2014 – 2050F[1], in Mt)



Key insights

- Between 2014 and 2022, the NL has **not been able to substantially reduce the total waste volume** despite active government efforts
- Going forward, it will be **challenging to substantially reduce the total waste volume** (see details on next page):
  - ○ **Residential waste is expected to remain stable**: the effect of the growing population is offset by the effect of the decreasing average waste per capita
  - ○ **C&I waste is expected to remain stable**: the effect of the growing economic output is offset by the effect of the increasing material efficiency
  - ○ **Imported waste is expected to remain stable**: the NL will continue to use foreign waste to compensate for shortages

Source: CBS; Eurostat; Strategy& analysis

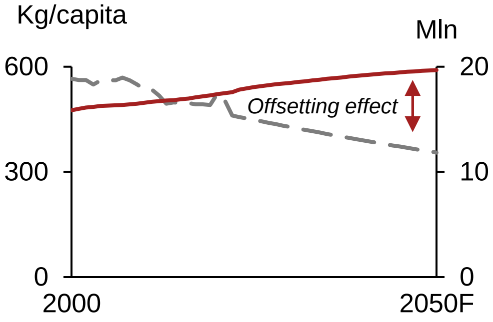
It will be challenging to substantially reduce residential, C&I and imported waste, mainly due to population and economic growth

1 Bottom-up evaluation future waste volume in the NL (2/2)

Residential waste dynamics

- Residential waste is driven by **population size and average residential waste per capita**
- Historically and in the future, the **effect from the growing population is offset by the effect from the decreasing average waste per capita**
    - The **population** has steadily grown since 2000, and is expected to continue this trend to 2050
    - The **average waste per capita** has steadily decrease (except for COVID-19 hick-up), and is expected to continue this trend following successful efforts to produce less waste

Population size vs. average waste per capita
(2000 – 2050F^1)

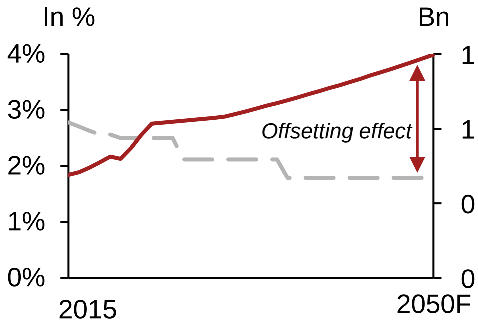


Residential waste volume NL
(2022 – 2050F)

C&I waste dynamics

- C&I waste is driven by **economic growth and material efficiency**
- In the future, the **driving effect from growing economy** on C&I waste is expected to be **offset by the increasing material efficiency**
    - Dutch GDP has steadily grown since 2015, and is expected to continue this trend to 2050
    - Material efficiency has increased in the past years, but PBL projects that efficiency gains will experience a growth decline going forward

GDP development vs. material efficiency growth
(2015 – 2050F^2, in Mt)

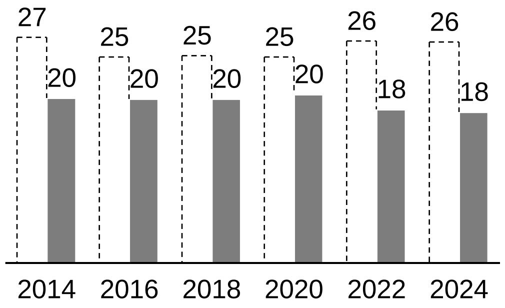


C&I waste volume NL
(2022 – 2050F)

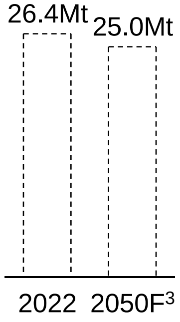
Imported waste dynamics

- Historically, the Netherland has been **one of the top waste importing countries in the EU**
- In addition, **much imported waste is exported** as NL functions as **transit country** in global trade
- In the future, NL is expected to continue importing substantial amounts of waste to continue its role as transit country and to meet the growing demand of secondary raw materials

Imported vs. exported waste volumes NL
(2014 – 2050F, in Mt)



Imported waste volume NL
(2022 – 2050F^3)



---

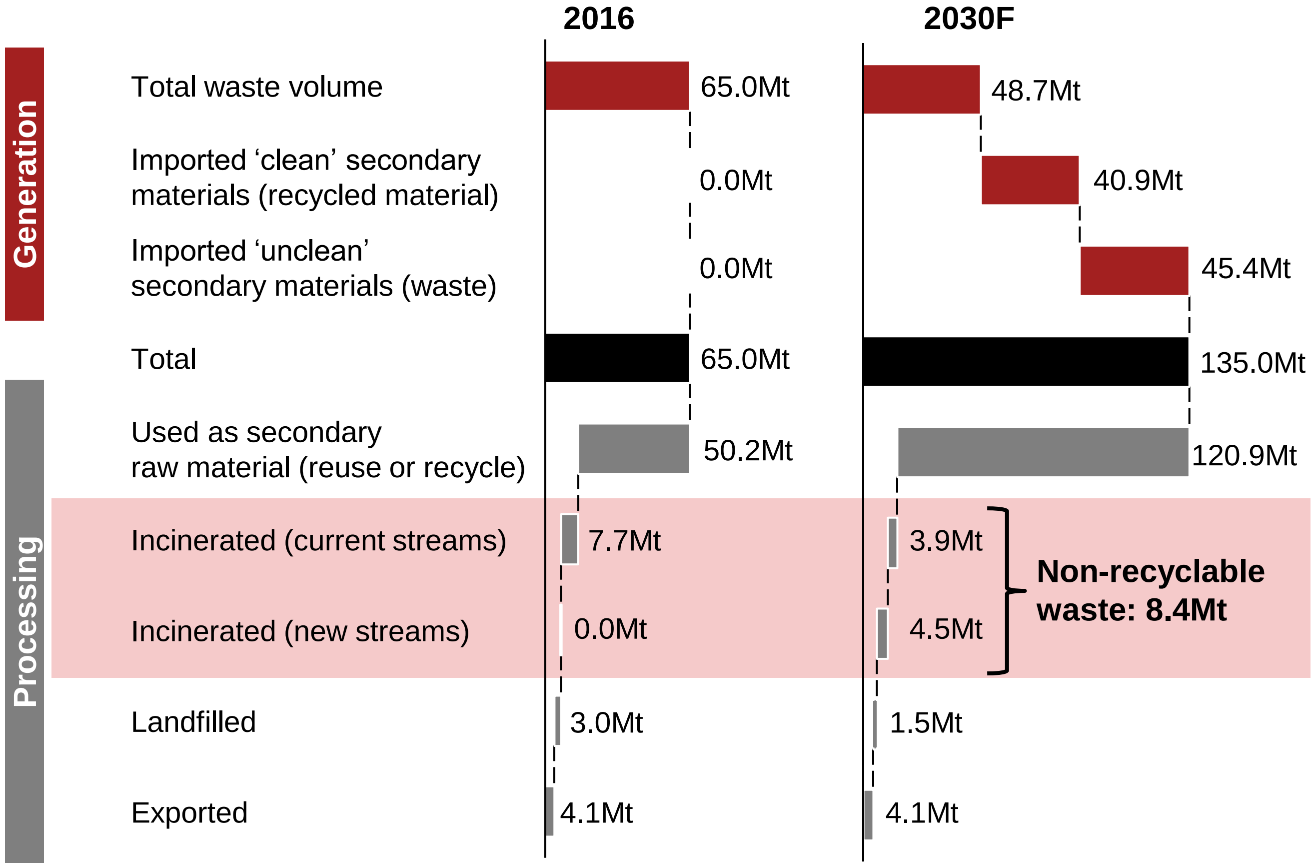
1) Assumptions 2050F: population size based on CBS projections and average waste per capita based on extrapolation 2000-2022 CAGR to 2050; 2) GDP growth has been projected in accordance with PwC 2050 estimations for NL; Material efficiency growth has been extrapolated in line w/PBL trends; 3) Assumption 2050F: waste import based on extrapolation 2014-2024 CAGR to 2050
Source: CBS; Roland Berger; PBL - 'Integrale Circulaire Economie Rapportage 2023'; The Long View: How will the global economic order change by 2050? (PwC); Strategy& analysis

To meet the growing demand for secondary raw materials, more waste will be recycled in the NL resulting in more non-recyclable waste

❷ Study future non-recyclable waste volume in the NL

Projected non-recyclable waste volume in the NL

(2016 vs. 2030F, in Mt)



Key insights

- To achieve a 100% circular, climate-neutral by 2050, **primary abiotic raw materials are expected to be replaced by secondary (waste recycling) and bio-based alternatives**
- The NL must find **new sources for secondary raw materials** to meet the growing demand: these are assumed to be **partly clean** that can be used directly in the production process and **partly unclean** (require processing before recycling)
- In the past, **recycling has always led to a non-recyclable waste** from the recycling process that would be incinerated in W2E-plants given the low quality and energy potential
- Therefore, **as more waste in the NL will be recycled in the future** to meet with the growing secondary raw material demand, **the non-recyclable waste volume will also increase**
- The **non-recyclable waste volume is expected to increase to from 7,7Mt in 2016 to 8,4Mt in 2030**[1]
- Evidently, there is expected to be **non-recyclable waste in the future waste landscape in the NL**

---

1) Projection based assumptions: 85% recycling rate for waste and unclean raw materials and 10% processing loss following pre-treatment unclean materials;
Source: E. Dijkgraaf – 'Afvalenergiecentrales ook nodig in circulaire economy' (2023); PBL – 'Integrale circulaire economy rapportage' (2023)

Appendix

Emerging alternative waste processing technologies are shaping the future waste market

Alternative waste processing technologies overview

Technology	**Advanced sorting**	**Plastic chemical recycling**	**Biowaste processing**	**W2E incineration with CCS/U**
Description	Sorting unsorted waste streams on characteristics beyond material type and colour, such as material shape or previous use of material	Breaking down plastic waste into raw materials/molecules that can be reused again in the production of new products	Breaking down (organic) biowaste in the absence of oxygen, by using microorganisms (e.g., fungi, bacteria) or through chemical processes	Safely storing the produced CO2 from waste incineration underground, or reusing the CO2 in the production process
Key technologies *Non-exhaustive*	• AI technology • Robotic technology • Advanced sensor technology	• Pyrolysis • Gasification • Depolymerization • Solvolysis	• Anaerobic digestion (AD)/fermentation • Composting • Microbial Fuel Cells (MFCs) • Pyrolysis	• Incineration with carbon capture storage (CCS) • Incineration with carbon capture utilization (CCU)
Input	Mixed waste	Plastic waste	Biowaste	Mixed waste
Output	Cleaner, well-sorted waste streams	Molecules	Depends on technology	Must run energy products and CO_2
Limitations	• High investment and operational costs • Technical malfunctions	• Requires specific and clean waste streams (except gasification) • Does not achieve 100% yield (e.g., 50% for pyrolysis[1])	• Requires specific and clean waste streams • Long processing time (e.g., weeks/months for AD/fermentation)	• Complex infrastructure and logistical requirements • Energy loss from CCS/U technology
Players *Non-exhaustive*	myne TOMRA RECYCLEYE NIHOT MACHINEX	DOW سابك sabic BLUEALP GR3N MURA PLASTIC ENERGY ubq	BioBTX ArcelorMittal SONNENERDE Biogas- PyroCore Move to circularity Biogreen® PYREG NET ZERO TECHNOLOGY KF Krieg & Fischer Ingenieure GmbH	Twence® TOSHIBA AVR fortum SINTEF

1) Plastic-to-plastic yield (amount of new plastic produced from plastic waste sent to recycling) is approximately 50%

Source: Nationaal Testcentrum Circulaire Plastics – ‘Recycling pathways of post-consumer plastic packaging waste in Europe’ (2022); Journal of Cleaner Production; PBL & TNO – ‘Decarbonisation options for the Dutch waste incineration industry’ (2022); Renewable Carbon Publications; CE Delft; Company websites; Strategy& analysis

AI, robotics and advanced sensors are emerging technologies, allowing waste sorting on attributes, beyond material type and colour

Advanced sorting (1/2): technology overview

Advanced sorting

Technology	Description	Input	Output	Pros	Cons
AI technology	• Artificial Intelligence (AI) employs computer vision, machine learning, and data analytics to enhance the sorting and recycling process • By leveraging AI algorithms, this technology can automatically identify and sort various material types from mixed waste streams, and detect and remove contaminants • AI algorithms can analyze large amounts of data to optimize the process and make it more efficient	Mixed unsorted waste streams	Cleaner, well-sorted waste streams	✓ Sorting on attributes beyond material type and colour ✓ Higher sorting speed ✓ Higher sorting accuracy	× High investment and operational costs (e.g., hardware and training) × Comprehensive and up-to-dataset required
Robotic technology	• Robotic technology use a mechanical system coupled to sensors to detect, classify and remove objects of interest from an unsorted waste stream • The most common type is the pick and place robot, which has one or more robotic arms that are equipped with a gripper	Mixed unsorted waste streams	Cleaner, well-sorted waste streams	✓ Sorting on attributes beyond type and colour ✓ Simultaneously sort multiple type of objects (e.g., air jets are binary) ✓ Higher sorting quality, consistency and availability ✓ Lower human labour	× Low sorting speeds (than e.g., air jets) × High investment and operational costs (e.g., infrastructure and maintenance) × Operational challenges (e.g., malfunction)
Advanced sensor technology	• Currently, NIR and RGB sensors are typically used to classify material based on their material type and colour • New sensor technologies such as LIBS, MIR and THz can gather more information on materials by using innovative techniques such as different or wider range of the electromagnetic spectrum	Mixed unsorted waste streams	Cleaner, well-sorted waste streams	✓ Sorting on attributes beyond material type and colour ✓ Higher sorting accuracy	× Typically slower response time than current sensors × Higher costs than conventional sensors × Some sensors have low maturity

Source: Nationaal Testcentrum Circulaire Plastics – 'Recycling pathways of post-consumer plastic packaging waste in Europe' (2022); Journal of Cleaner Production; Company websites (see next pages); Strategy& analysis

Many advanced sorting companies are emerging that promise improved sorting performance

Advanced sorting (2/2): market examples

Advanced sorting

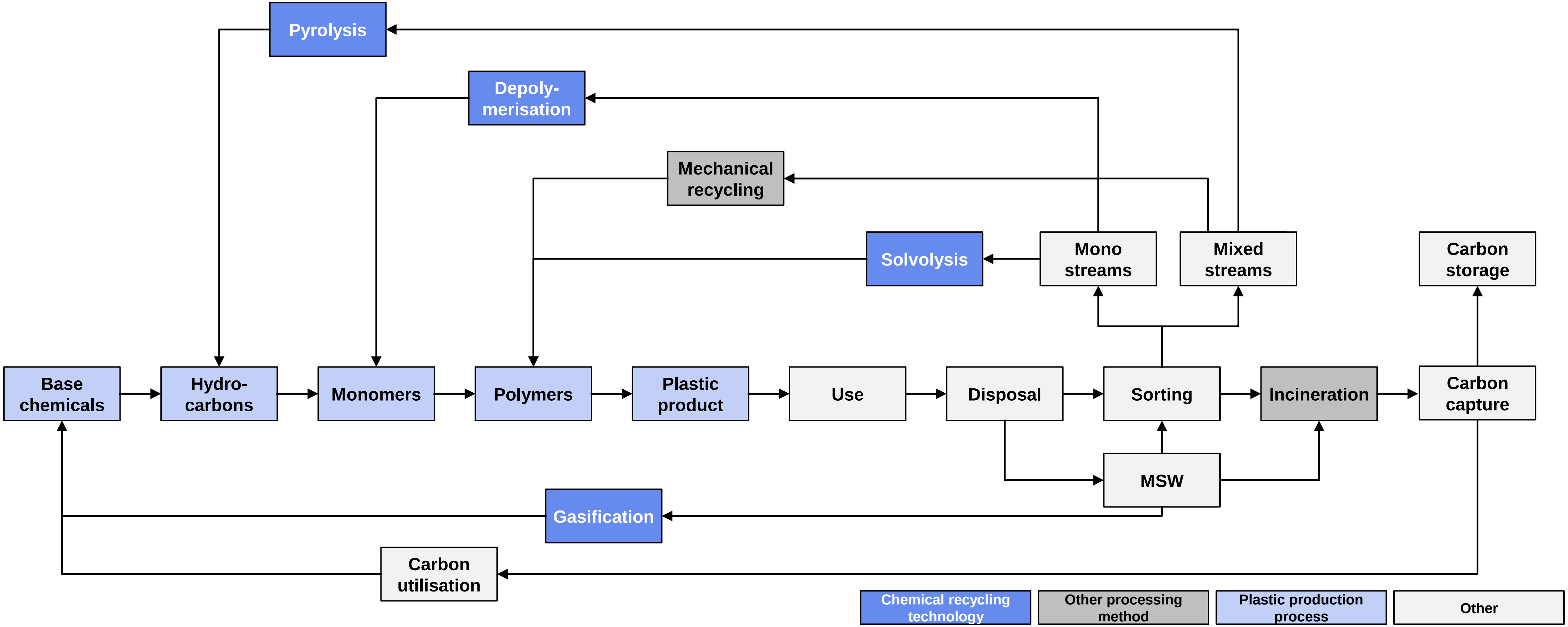
	Myne Xorter	RecycleEye QualiBot	Nihot Max-AI Robotic Sorter	MachineX SamurAI Robot	TOMRA Technologies
Input	Post-consumer aluminum waste	Mixed waste	Mixed waste	Mixed waste	Mixed waste
Process	AI-powered metals waste sorting facility: Xorter machine sorts aluminium, e-waste and copper waste by alloy	AI-powered robot technology that separates recyclable materials from a mixed waste stream with up to 55 picks per minute	Sorting technology that uses AI, robotics and machine learning technology to separate valuable materials from mixed waste streams	AI-powered robot technology that separates recyclable materials from a mixed waste stream with up to 70 picks per minute and 95% efficiency	Multifunctional sensor technology combined with near-infrared spectroscopy, visual spectrometry and deep learning to identify and sort various material types
Output	Aluminium metal alloys	Sorted recyclable waste: non-ferrous metals, fiber and plastics	Sorted recyclable waste: plastics, cardboard, paper and aluminum/steel cans	Sorted recyclable waste (various waste types)	Sorted recyclable waste: plastic, e-waste, wood, paper, packaging and textiles
Players	myne	RECYCLEYE	NIHOT®	MACHINEX	TOMRA
Country	🇳🇱	🇬🇧	🇳🇱	🇨🇦	🇳🇴

Source: Company websites; Strategy& analysis

Pyrolysis, depolymerisation, solvolysis and gasification are emerging chemical recycling technologies for plastic waste

Plastic chemical recycling (1/3): chain

Plastic chemical recycling



Source: PBL & TNO – 'Decarbonisation options for the Dutch waste incineration industry' (2022); Renewable Carbon Publications; Strategy& analysis

These technologies recover molecules from plastic waste – most require relatively clean plastic waste streams to yield high-quality outputs

Plastic chemical recycling (2/3): technology overview

Plastic chemical recycling

Technology	Description	Input	Output	Pros	Cons
Pyrolysis	Thermal decomposition process that involves heating waste (typically >500°C) in an oxygen-free environment, providing enough heat to deconstruct plastic waste into smaller molecules that can be further processed into new chemicals	Plastics (e.g., PET, PP, PS, PA)	Naphtha/feedstock	✓ Able to process mixed and contaminated plastic waste streams ✓ Output can be reprocessed into virgin-like material	✗ High investment and operational costs (e.g., high energy use) ✗ Strict requirements on quality input feed (specific and clean waste) ✗ 50% plastic-to-plastic yield
Gasification	Chemical process where waste materials are heated to an extremely high temperature (1000 – 1500 °C) with a limited amount of oxygen, breaking down the molecules and producing syngas (mainly hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen)	All plastic types (also able to process non-recyclable waste)	Syngas and other residual products	✓ Output (syngas) can be used for various applications (e.g., methanol, ammonia) ✓ No requirement on quality input feed	✗ High investment and operational costs (e.g., high energy use) ✗ Complex technology and infrastructure
Depoly-merization	Chemical process that uses controlled chemical or thermal reactions and heat to break down/depolymerize plastic polymers in their constituent monomers and oligomers	Plastics (e.g., PET, PA)	Monomers/oligomers	✓ High quality monomer recovery ✓ Less energy intensive then e.g., pyrolysis and gasification	✗ Strict requirements on quality input feed (specific and clean waste) ✗ High operational costs ✗ Complex by-product handling to avoid environmental harm
Solvolysis	Chemical process that uses a solvent to depolymerize plastics into smaller molecules (not always classified as chemical recycling)	Plastics (e.g., PET)	Polymers	✓ High quality polymer recovery ✓ No/little energy consumption	✗ Strict requirements on quality input feed (specific and clean waste) ✗ Use of potentially hazardous solvents
Fluid catalytic cracking (FCC)	Process that breaks down long polymer chains, particularly non-recyclable types like polyethylene and polypropylene, into smaller hydrocarbon molecules using a catalyst at medium high temperatures (>350°C)	Plastic (e.g., PE, PP)	Liquid and gaseous hydrocarbons, waxes	✓ High value output	✗ High energy consumption

Source: PBL & TNO – 'Decarbonisation options for the Dutch waste incineration industry' (2022); Nationaal Testcentrum Circulaire Plastics – 'Recycling pathways of post-consumer plastic packaging waste in Europe' (2022); CE Delft – 'Monitoring Chemical Recycling' (2022); Company websites (see next page); Strategy& analysis

Recently, investor appetite in these chemical recycling technologies is growing

Plastic chemical recycling (3/3): market examples

Plastic chemical recycling

	DOW & Mura	SABIC – Plastic Energy	BlueALP - Shell	GR3N	UBQ
Input	End-of-life plastic waste	End-of-life plastic waste	End-of-life plastic waste	End-of-life plastic (PET) waste	Non-recyclable waste (incl. plastic)
Process	Advanced pyrolysis plant that will convert mixed plastic waste into hydrocarbon liquids (used to build plastics)	Advanced recycling plant with capacity of 20Kt per year, applying pyrolysis for conversion of plastic waste	Two new pyrolysis units with a capacity of 17Kt per year (BlueAlp has a patented pyrolysis process)	Microwave-assisted depolymerization (MADE) technology to produce PET and polyester from recycled monomers	Conversion of non-recyclable waste into thermoplastic composite without residual fraction via patented waste conversion process
Output	Hydrocarbon oil	TACOIL, alternative feedstock to create virgin-quality food-grade plastics	High-quality pyrolysis oil (with low energy consumption)	Virgin-quality monomers	Thermoplastic composite (fossil-based plastic alternative)
Players	DOW MURA TECHNOLOGY	سابك sabic PLASTIC ENERGY	BLUEALP Accelerating Plastic Recycling Shell	GR3N	ubq
Country	🇩🇪	🇳🇱	🇳🇱	🇪🇸	🇮🇱

Source: Company websites; Strategy& analysis

AD/fermentation, composting, MFCs and pyrolysis are emerging technologies to process biowaste

Biowaste processing (1/2): technology overview

Biowaste processing

Technology	Description	Input	Output	Pros	Cons
Anaerobic digestion (AD)/fermentation	Biological process that breaks down biowaste by bacteria to produce biogas (a mixture of methane and carbon dioxide which can be used as a renewable energy source) and digestate (which can be used as a nutrient-rich fertilizer)	Biowaste	Biogas and digestate	✓ Alternative for fossil-based natural gas ✓ Output can be used for various applications (e.g., fuel, biomethane) ✓ Avoids damaging methane emissions in the atmosphere	× Strict input requirements: only applicable for well-sorted uncontaminated waste stream × High investment and operational costs × Long processing time (weeks/months) × Environmental concern (e.g., toxic spills)
Composting	Biological process that decomposes organic waste by microorganisms (e.g., fungi and bacteria), resulting in the production of nutrient-rich soil amendment (compost) that can be used as fertilizer	Biowaste	Compost	✓ Replaces chemical fertilizers ✓ Low cost compared to other technologies ✓ Can be done on small scale (e.g., households)	× Strict input requirements: only applicable for well-sorted uncontaminated waste × Low output flexibility (can only be used as fertilizer) × Long processing time (months)
Microbial Fuel Cells (MFCs)	Biological process that uses microorganisms to break down the organic matter and release electrons, which can be captured and used to generate electricity	Biowaste	Electricity	✓ Alternative source of fuel ✓ Low carbon emission ✓ Can be applied in area lacking electricity	× High investment and operational costs × Lower power output × Electrodes lack durability and strength × Low growth rate of microbes
Pyrolysis	*See plastic waste chemical recycling technologies*				

Source: Renewable and Sustainable Energy Reviews; Company websites (see next page); Strategy& analysis

The potential for these biowaste processing technologies is illustrated by recent market examples

Biowaste processing (2/2): market examples

Biowaste processing





	BioBTX	Pyrocore	ArcelorMittal & Biogreen	Sonnenerde & Pyreg	Werlte Biogas Plant
Input	Biowaste (and plastic waste)	Biowaste	Biowaste (mainly wood)	Biowaste (e.g., grain husks, sunflower shell, pulp mud)	Biowaste (e.g., corn and grass silage, cattle and poultry manure)
Process	Conversion of biomass (and mixed plastic waste) into renewable carbon via pyrolysis and catalytic upgrading	Conversion of biowaste by using pyrolysis technology in which waste is heated under high temperatures (600-900°C) without oxygen	Clean syngas production plant to reduce CO2-emissions produced during the steelmaking process	Industrial biochar production plant leveraging Pyreg's pyrolysis technology	Anaerobic digestion installation to transform biowaste into biomethane and digestate with 110,000 m3 throughput per year
Output	Renewable carbon	Syngas and bio-char	Biogas and biochar	Biochar	Biomethane and digestate
Players	BioBTX	PyroCore Move to circularity	ArcelorMittal Biogreen®	SONNENERDE www.sonnenerde.at PYREG NET ZERO TECHNOLOGY	Biogas- Krieg & Fischer Ingenieure GmbH
Country	🇳🇱	🇧🇪	🇱🇺	🇦🇹	🇩🇪

Source: Company websites; Strategy& analysis

W2E-plants are increasingly accompanied with CCS/U technology to avoid CO2-emissions from the waste incineration process

W2E incineration with CCS/U (1/2): technology overview

W2E incineration with CCS/U

Technology	Description	Input	Output	Pros	Cons
W2E incineration with CCS	W2E-plant that incinerates waste to generate baseload energy products, can be extended with carbon capture storage (CCS) technology in which CO2 is captured and safely stored underground	Non-recyclable waste	Baseload energy products (steam and electricity)	✓ No CO2-emission in the atmosphere from W2E-plant (climate-neutrality) ✓ Scalable technology to other applications (e.g., industry, transport) ✓ No waste input requirement	× CO2 is not reused to produce new products × Complex infrastructure and logistical requirements (e.g., storing CO2 in empty gas fields under north sea) × High costs for CCS tech × Energy loss from CCS tech
W2E incineration with CCU	W2E-plant that incinerated waste to generate baseload energy products, can be extended with carbon capture utilization (CCU) technology in which CO2 is captured and used directly (i.e., not chemically altered) or indirectly (transformed) in various products (e.g., synthetic fuels, chemicals or building aggregates)	Non-recyclable waste	Baseload energy products (steam and electricity) and CO2	✓ No CO2-emission in the atmosphere from W2E-plant (climate-neutrality) ✓ CO2 is reused to produce new products ✓ Scalable technology to other applications (e.g., industry, transport) ✓ No waste input requirement	× Complex infrastructure and logistical requirements (e.g., transporting CO2 from W2E-plants to users) × High costs for CCU tech × Energy loss from CCU tech

Source: International Energy Agency; Company websites (see next page); Strategy& analysis

The potential for these technologies is illustrated by recent market examples

W2E incineration with CCS/U (2/2): market examples

W2E incineration with CCS/U

	Twence	AVR Duiven	Saga City Plant	Klementsrud	NETOX
Input	Non-recyclable waste	Non-recyclable waste	Non-recyclable waste	Non-recyclable waste	Non-recyclable waste
Process	W2E-plant that captures, stores and reuses CO2 as raw material in the greenhouse horticulture sector and dry ice production,n using CCU technology	W2E-plant that captures, stores and reuses 60k tonnes of CO2 per year as raw material in the greenhouse horticulture sector, using CCU technology	W2E-plant that captures, stores and reuses 10 tonnes CO2 per day to cultivate crops and create algae cultures at nearby farms, using CCU technology	W2E-plant that captures and stores 400k tonnes of CO2 to become reality in 2026, by using CCS technology	W2E-plant that captures and stores CO2 to become reality in 2030, by using CCS technology
Output	Baseload energy products and circular CO2	Baseload energy products and circular CO2	Baseload energy products and circular CO2	Baseload energy products	Baseload energy products
Players	Twence®	AVR.	TOSHIBA	fortum	SINTEF
Country	🇳🇱	🇳🇱	🇯🇵	🇳🇴	🇳🇴

Source: Company websites; Strategy& analysis

Appendix

Societal case: strategic fit with EU and NL ambitions

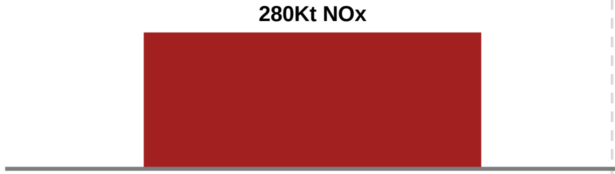
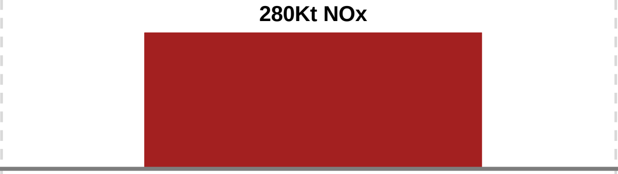
Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	W2E incineration	W2E incineration + CCS	Gasification (FUREC)
Strategic fit with EU and NL ambitions	**Circularity**	**Production of electricity and heat** • W2E incineration is classified as R1 with energy recovery producing heat and electricity without producing molecules. Some EU countries remain reliant on W2E incineration, others (e.g., NL) are focused on reducing incinerated waste • W2E incineration supports a scalable waste management strategy, with large scale facilities (400-600Kt capacity), best-suited to process waste closer to its source	**Production of electricity and heat** • No contribution for CCS as carbon is stored, but not reused • W2E incineration plants, whether original or retrofit, are becoming more scalable, with CCS capacities ranging from 50 to 400Kt CO_2 per year	**Production of circular feedstock** • Gasification (FUREC) is classified as R3 and R4, using non-recyclable waste to produce circular secondary raw materials (e.g., hydrogen, carbon) to produce new (chemical) products • Gasification (FUREC) enables a scalable waste management strategy, with large-scale facilities (800Kt capacity), with the ability to process waste from multiple regions via efficient transport (eliminated moisture via pelletization)
	Climate neutrality	**Significant CO_2 emissions** • W2E incineration leads to substantial CO_2 emissions, but saves significant methane emissions (compared to landfilling waste)	**Limited CO_2 emissions** • W2E incineration with CCS has limited CO_2 emissions as well as saving significant methane emissions (compared to landfilling waste)	**Production of CO_2 free outputs** • Gasification (FUREC)'s output (circular hydrogen) is an alternative for grey hydrogen, avoiding substantial CO_2 emissions. FUREC with CCS avoids further emissions
	Raw material security	**Production of heat & electricity (W2E)** • W2E incineration with energy recovery contributes to a stable supply of electricity and heat	**Production of heat & electricity (W2E)** • W2E incineration with energy recovery contributes to a stable supply of electricity and heat • No contribution for CCS as carbon is stored but not reused	**Local production of raw materials** • Gasification (FUREC) produces circular secondary raw materials locally (e.g., hydrogen, carbon), reducing dependency on foreign countries to achieve a stable supply of raw materials
	Competitive position (chemical) industry	**Improving supply security** • Incinerators may supply heat to the chemical industry	**Improving supply security** • Incinerators may supply heat to the chemical industry	**Enhancing circularity position** • Gasification (FUREC) enables the chemical industry to adopt circular production, meet regulations, and enhance its circularity position
	Conclusion	**Moderate strategic alignment** Moderate contribution to ambitions: strong scalability for waste processing, production of electricity and heat with substantial CO_2 emissionsy	**High strategic alignment** High contribution to ambitions: increasing scalability for waste processing and CC capture, CO_2 free production of electricity and heat	**Very high strategic alignment** Significant contribution to ambitions: strong scalability for efficient waste processing, local CO_2 free production of circular feedstock, and strong position for the chemical industry

Source: RWE input; Eurostat; EU Directive 2008/98/EC; Directive 1999/31/EC; Strategy& analysis

Sustainability case: environmental impact (1/5)

Gasification evaluation is based on data shared by FUREC

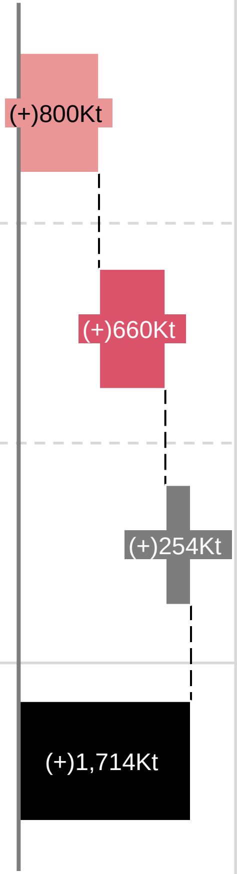
Criteria	Sub-criteria	W2E incineration	W2E incineration + CCS	Gasification (FUREC)
Environmental impact	**Treatment of by-products**	**Fly ash and bottom ash** • By-products are fly ash and bottom ash, constituting ~25% of input mass and requiring additional treatment • While the treatment of bottom ash is standard and cost-effective, treatment of fly-ash is more intensive due to hazardous substances	**Fly ash and bottom ash** • By-products are fly ash and bottom ash, constituting ~25% of input mass and requiring additional treatment • While the treatment of bottom ash is standard and cost-effective, treatment of fly-ash is more intensive due to hazardous substances • Additional complexity (handling, processing, disposal) from storage or utilization of captured CO_2	**No residual stream** • By-products are inert slag, mineral, salt, filter cake without any residual stream – all outputs are sold to chemical industry • Filtration and scrubbing systems are limited – by-products are periodically disposed-of
	NOx (nitrogen) emissions *Per 800Kt processed non-recyclable waste*	**280Kt NOx** • W2E incineration generates the following NOx emissions 	**280Kt NOx** • W2E incineration with CCS generates the following NOx emissions with potential for further reduction: 	**13Kt NOx** • Gasification (FUREC) generates the following NOx emissions: 
	Conclusion	**High environmental impact** 280Kt of NOx emissions and (+)1,500Kt of	**High environmental impact** 280Kt of NOx emissions	**Limited environmental impact** Limited +13Kt NOx emissions

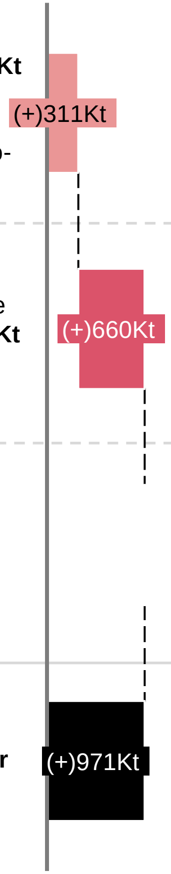
Source: RWE Input; Strategy& analysis, PBL – 'Decarbonization options for the Dutch Waste Incineration Industry' (2022)

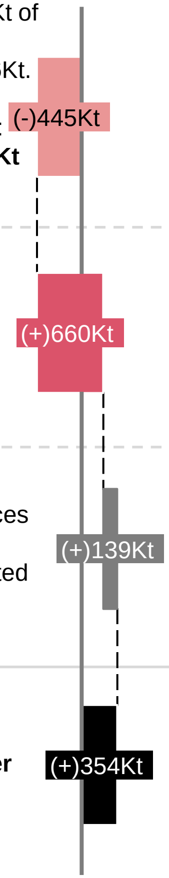
Sustainability case: climate impact (2/5)

Landfill, W2E incineration and W2E incineration with CCS

Criteria	Sub-criteria	Landfill	W2E incineration	W2E incineration with CCS
Climate Impact`[1]	**CO_2 emissions[2]**	Landfilling waste generates significant amount of methane equivalent to ~1.0 CO_2 eq. kg/per kg of waste or **(+)800Kt CO_2** for 800Kt of waste	W2E incineration generates 1.05 CO_2 kg/per kg of waste or **(+)840Kt CO_2** for 800Kt of waste, of which **(+)311Kt CO_2** (37%) are fossil-based emissions (rest is bio-based)	W2E incineration generates 840Kt of CO_2 emissions. With CCS, W2E captures ~90% of emissions: 756Kt. 63% of emissions are bio-based and count as negative emissions: **(-)476Kt,** partially offset by **(+)31Kt** fossil-based CO_2 emissions (not captured)
	Hydrogen CO_2 emissions opportunity cost *10 -14 CO_2 kg /1 kg of Grey hydrogen*	Landfilling waste cannot generate 55Kt of hydrogen, requiring +**660Kt CO_2** As green hydrogen becomes more prevalent, CO_2 emissions will decrease	W2E incineration cannot generate 55Kt of hydrogen, requiring +**660Kt CO_2**	W2E incineration plants cannot generate 55Kt of hydrogen, requiring **(+)660Kt CO_2**
	Electricity & heat CO_2 emissions opportunity cost *0.40 CO_2 kg /1 kWh net electricity* *0.23 CO_2 kg /1 kWh net heat*	W2E incineration generates electricity and heat, requiring +**254Kt CO_2** As energy mix becomes more sustainable with renewable energy sources (NL: 70% by 2030, and 100% by 2050), opportunity cost will disappear	W2E incineration generates electricity and heat – no CO_2 opportunity cost	W2E incineration with CCS reduces net efficiency by ~10%-pt., consuming almost half of generated electricity and heat
	Conclusion	**(+)1,714Kt of CO_2 is produced per year**	**(+)971Kt of CO_2 is produced per year**	**(+)354Kt of CO_2 is produced per year**







---

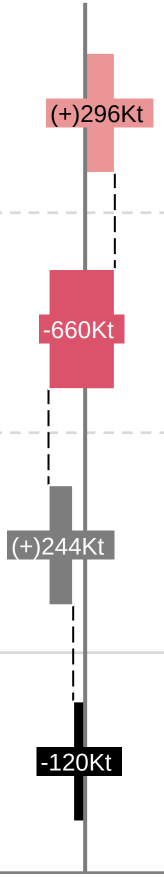
1) Climate impact is measured yearly, per ~800Kt of processed waste to ensure like-for-like comparison; 2) To ensure like-for-like comparison, for gasification (FUREC) and W2E incineration (with and without CCS), 37% of emissions from MSW are considered to be fossil-based (as indicated for NL in mentioned PBL report); Source: RWE Input; Strategy& analysis, PBL – 'Decarbonization options for the Dutch Waste Incineration Industry' (2022); Institute for Energy Economics and Financial Analysis (IEEFA) – 'Carbon Capture at Boundary Dam 3: Still Underperforming, a Failure' (2021); International Energy Agency (IEA) – 'Carbon Capture, Utilisation and Storage' (2023); NV afvalzorg Holding – 'Landfilling of waste: accounting of greenhouse gases and global warming contributions' (2009)

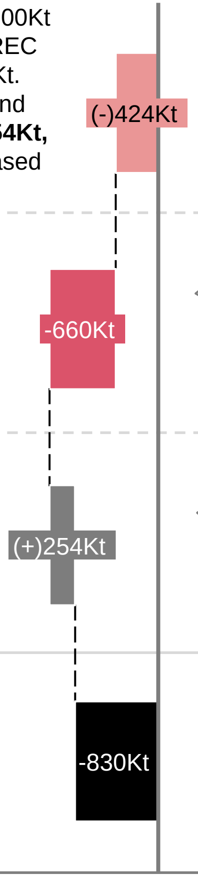
Sustainability case: climate impact (3/5)

Gasification (FUREC) with/without CCS

Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	Gasification (FUREC) without CCS	Gasification (FUREC) with CCS
Climate Impact`[1]	**CO_2 emissions[2]**	Gasification (FUREC) generates 800Kt of CO_2 emissions for 800Kt of waste, of which **(+)296Kt CO_2** (37%) are fossil-based emissions (rest is bio-based)	Gasification (FUREC) generates 800Kt of CO_2 emissions. With CCS, FUREC captures ~90% of emissions: 720Kt. 63% of emissions are bio-based and count as negative emissions: **(-)454Kt,** partially offset by **(+)30Kt** fossil-based CO_2 emissions (not captured)
	Hydrogen CO_2 emissions opportunity cost *10 -14 CO_2 kg /1 kg of Grey hydrogen*	Gasification (FUREC) generates 55Kt of hydrogen, saving **(-)660Kt CO_2**	Gasification (FUREC) generates 55Kt of hydrogen, saving **(-)660Kt CO_2**
	Electricity & heat CO_2 emissions opportunity cost *0.40 CO_2 kg /1 kWh net electricity* *0.23 CO_2 kg /1 kWh net heat*	Gasification (FUREC) cannot generate ~1.3 PJ of electricity & 1.6 PJ of net heat, with an opportunity cost of **(+)244Kt of CO_2**	Gasification (FUREC) cannot generate ~1.3 PJ of electricity & 1.6 PJ of net heat, with an opportunity cost of **(+)244Kt of CO_2. ** An additional **(+)10Kt of CO_2** results from the CCS efficiency loss
	Conclusion	**(-)120Kt of CO_2 is avoided per year**	**(-)830Kt of CO_2 is avoided per year**





As green hydrogen becomes more prevalent, CO_2 emissions will decrease

As energy mix becomes more sustainable with renewable energy sources (NL: 70% by 2030, and 100% by 2050), opportunity cost for FUREC will disappear

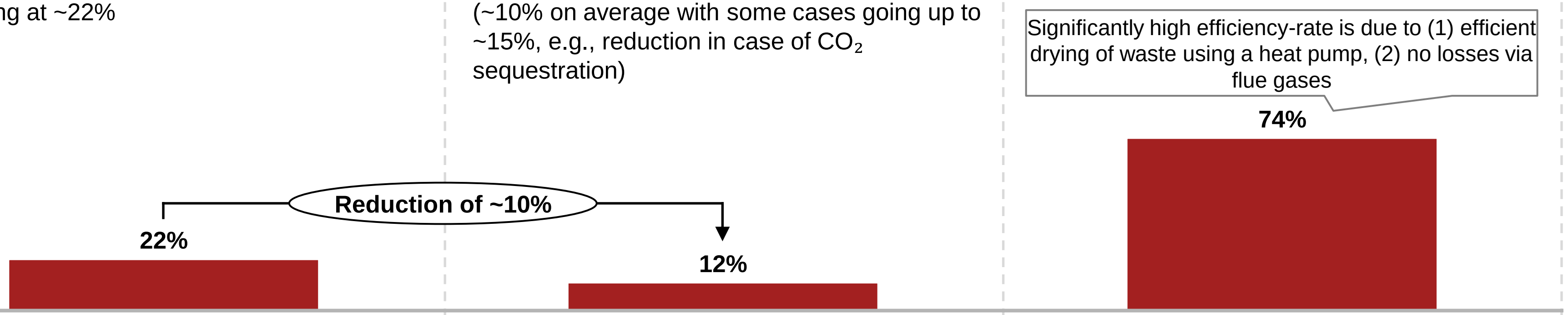
---

1) Climate impact is measured yearly, per ~800Kt of processed waste to ensure like-for-like comparison; 2) To ensure like-for-like comparison, for gasification (FUREC) and W2E incineration (with and without CCS), 37% of emissions from MSW are considered to be fossil-based (as indicated for NL in mentioned PBL report); Source: RWE Input; Strategy& analysis, PBL – 'Decarbonization options for the Dutch Waste Incineration Industry' (2022); Institute for Energy Economics and Financial Analysis (IEEFA) – 'Carbon Capture at Boundary Dam 3: Still Underperforming, a Failure' (2021); International Energy Agency (IEA) – 'Carbon Capture, Utilisation and Storage' (2023)

Sustainability case: energy efficiency (4/5)

Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Energy Efficiency	**Estimated Net Efficiency** *(Deep-dive on W2E incineration efficiency rate on next page)*	**Energy efficiency of ~22%** • Energy is exported in the form of net electricity(1.3 PJ) and net heat (1.6 PJ) for industrial uses. Net heat is converted to electricity for standardized outputs, with typical power generation achieving only about 25% thermal-to-electric efficiency due to conversion losses • Varying estimated net efficiency across W2E incinerators in NL between 17% and 28% - averaging at ~22%	**Energy efficiency of ~12%** • Energy is exported in the form of net electricity and heat for industrial uses- Net heat is converted to electricity for standardized outputs, with typical power generation achieving only about 25% thermal-to-electric efficiency due to conversion losses • Estimated net efficiency for incineration CCS is taken as ~12% due to a ~10% average penalty of energy efficiency due of CCS technology (~10% on average with some cases going up to ~15%, e.g., reduction in case of CO_2 sequestration)	**Energy efficiency of 71-74%** • Significant energy is exported in the form of hydrogen (~64%), steam (~10%), and Sulfur (<1%) – Approximately 3% of energy efficiency is lost when implementing CCS with FUREC due to the addition of a compressor • ~25% of the energy is lost in refrigeration (mainly from the syngas, compressors, the air separator, and the drying air from pelletizing)
	Conclusion	**Low efficiency (~22%)** Primarily due to waste conversion into heat and electricity with limited raw material recovery	**Low efficiency (~12%)** Primarily due to waste conversion into heat and electricity with limited raw material recovery, with additional loss due to CCS	**High efficiency (~74%)** Primarily due to waste conversion into valuable raw materials, maximizing raw material recovery

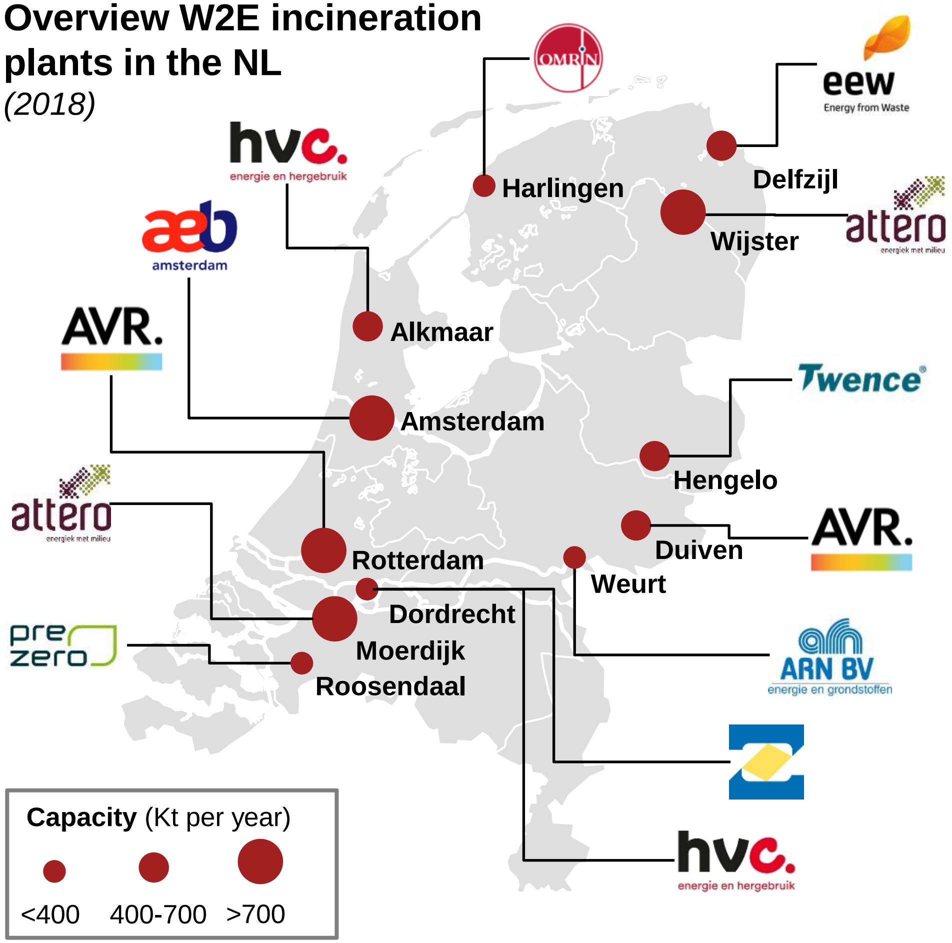


Significantly high efficiency-rate is due to (1) efficient drying of waste using a heat pump, (2) no losses via flue gases

Source: RWE Input; PBL – 'Decarbonization options for the Dutch Waste Incineration Industry' (2022); P.Wienchol, A.Szlek, M. Ditaranto – 'Waste-to-energy technology integrated with carbon capture: challenges and opportunities' (2020); Strategy& analysis

Sustainability case: deep-dive energy efficiency (5/5)

Overview W2E incineration plants in the NL
(2018)



Name W2E Facility	**Prod. and cap. volume**[1] *(2018, in kt)*	**LHV of waste** (GJ/t of waste)	**Net electricity**[2] *(2018, TJ)*	**Net heat converted to electricity**[3] *(2018, in TJ)*	**Net energy efficiency** *(% 2018)*
AEB Amsterdam	1,487Kt **1,487Kt**	9.5	2864	278	22%
AVR Rijnmond	1,323Kt **1,323Kt**	9.1	1,273	1,122	20%
AEC Moerdijk	887Kt **1,200Kt**	10.0	1,888	405	26%
Attero Wijster	649Kt **719Kt**	9.3	1,193	82	21%
HVC Alkmaar	642Kt **675Kt**	9.9	1,377	73	23%
Twence	608Kt **650Kt**	11.3	1,050	380	21%
AVR Duiven	394Kt **400Kt**	9.2	441	175	17%
EEW Delfzijl	382Kt **576Kt**	8.6	566	314	27%
PreZero Energy	366Kt **366Kt**	10.0	854	25	24%
HVC Dordrecht	280Kt **396Kt**	13.1	413	243	18%
ARN BV	233Kt **310Kt**	12.8	517	203	24%
REC Harlingen	217Kt **280Kt**	13.9	431	426	28%
Total	**7,468kt (prod) out of 8,202kt (capacity)**	**10.0**	**14,903**	**12,115**	**Weighted average** **22%**

---

1) Production volumes exceeding the stated capacity are expressed as 100% of capacity in this overview; 2) Net electricity is calculated as 85% of gross generated electricity; 3) Net heat is converted to electricity to ensure outputs are standardized. In typical power generation, only about 25% of thermal energy is converted into electricity due to conversion losses; Source: Strategy& analysis; PBL – 'Decarbonisation options for the Dutch industrial gases production' (2022); Rijksoverheid – 'Afvalverwerking in Nederland' (2018); Annual reports of W2E-plants; Strategy& analysis

Business case: key financials (1/3)

Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Key financials[1]	**Capital expenditures**	**€900-1,200 per ton of waste** • W2E incinerators' capital expenditures are ~€1000 per ton of waste, decreasing as overall plant capacity increases due to economies of scale • W2E incinerators have an average capacity of 170Kt of waste processing per year, with a wide range of 80-500Kt of waste per year. Examples of W2E incinerators include: **~1,200€/kt** Allerton Waste Recovery Park (UK) Capex : €384M Capacity: 320Kt per year **~1,000€/kt** Slough Multifuel Project (UK) Capex : €480M Capacity: 480Kt per year **~950€/kt** Avonmouth Resource Recovery (UK) Capex : €300M Capacity: 320Kt per year	**€1,400-3,000 per ton of waste** • W2E incineration plants with CCS (original or retrofit installations) require significant investments due to the required additional infrastructure (e.g., compression, liquefaction, transport to storage or utilization facilities) • Capex requirements rise with higher carbon capture targets, requiring more extensive upgrades or adaptations of existing systems • Capacity of W2E incinerators (new and/or retrofitted CCS) varies widely from 50 up to 400Kt CO_2 per year (retrofitted project often have less carbon capture capacity). Examples W2E incinerators with CCS include: **~2,700€/kt** Klemetsrud project (Norway) Capex : €1,050M Capacity: 400Kt per year **~1,400€/kt** Amager Bakker Plant (Denmark) Capex : €550M (pilot for CC) Capacity: 400Kt per year	**€1,000-1,400 per ton of waste** • Gasification (FUREC) has a larger scale of operations, with plant capacity (up to 800Kt of waste per year) far exceeding other chemical recycling processes • Gasification (FUREC)'s capex per ton of waste incorporates the logistical and ecosystem requirements (e.g., waste separation, compression, torrefaction) in a cost-effective waste processing technology • As plant size increases, economies of scale allow gasification (FUREC) for greater efficiency in handling larger volumes of waste, further reducing capex per ton
	Conclusion	**€900-1,200 per ton of waste** Cost-effective waste processing technology and high waste processing capacity (up to 500Kt of waste per year)	**€1,400-3,000 per ton of waste** Significant additional investment due to CCS technology and improving waste processing capacity (up to 400Kt CO_2 per year)	**€1,000-1,400 per ton of waste** Cost-effective waste processing technology and high waste processing capacity (up to 800Kt of waste per year)

---

1) Conversion from £ to € is taken as 1.20; Source: RWE Input; Strategy& analysis; Mentioned projects' websites; PBL – 'Decarbonization options for the Dutch waste incineration industry' (2022); PBL; Datasets SDE++, SCE & 2024UK; Strategy& analysis

Business case: value of outputs (2/3)

Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Value of outputs[1]	**Overview of outputs**	**Must-run energy products and by-products** • Incineration converts 800Kt of waste into heat and electricity and by-products: By-products **20Kt Metals** **180Kt Bottom ash** **10Kt Fly ash** • By-products (metals, bottom & fly-ash) constitute 20-30% of input mass – these require treatment • CO_2 is emitted and not captured + stored	**Must-run energy products, by-products & CO_2** • Incineration converts 800Kt of waste into the following products: By-products **20Kt Metals** **180Kt Bottom ash** **10Kt Fly ash** • By-products (metals, bottom & fly-ash) constitute 20-30% of input mass – these require treatment • CO_2 (840Kt) is captured + stored	**Syngas and by-products** • FUREC converts 800Kt of waste into syngas (incl. 55Kt of hydrogen) and by-products: By-products **135Kt inert slag** **Nitrogen** **24Kt metals** **36Kt minerals** • No residual stream: all by-products are sold to the (chemical) industry
	Value of primary output *(Deep-dive on next page)*	**€41M per 800Kt of waste per year** • Heat and electricity are must-run energy products (with available alternative sources such as nuclear, solar, wind, etc.) • Value of generated electricity and heat is €41M (2030)	**€22M per 800Kt of waste per year** • Heat and electricity are must-run energy products • Value of generated electricity and heat is €22M (2030)	**€190M per 800Kt of waste per year** • Circular hydrogen commands higher market prices. Potential for demand for secondary raw materials is high with few available alternatives • Value of generated hydrogen by FUREC – considered to be green – would be €190M
	Conclusion	**Outputs are must-run energy products (heat and electricity) with value of €41M**	**Outputs are must-run energy products (heat and electricity) with value of €22M**	**Outputs is valuable syngas for chemical industry with value of €190M**

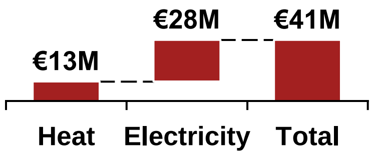
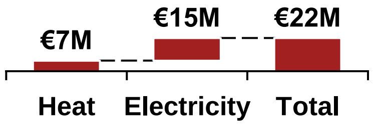
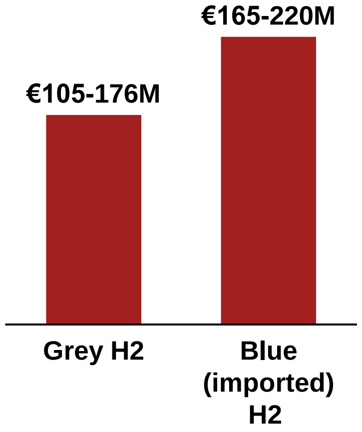
---

1) Value of outputs is measured yearly, per ~800Kt of processed waste to ensure like-for-like comparison

Source: RWE Input; Strategy& analysis

Business case: deep-dive on value of primary output (3/3)

Gasification evaluation is based on data shared by FUREC

Criteria	Sub-criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Value of outputs	**Value of primary output**	**€41M per 800Kt of waste per year** - Value of generated thermal capacity and generated electricity is €41M (2030) *Unit price - 2030 (€/MWh)*[1,2]: 28.9, 78.0 *Estimated value for total generated heat and electricity (2030)*  	**€22M per 800Kt of waste per year** - Value of generated thermal capacity and generated electricity is €22M (2030); corrected for energy efficiency loss from CCS technology *Unit price - 2030 (€/MWh)*[1,2]: 28.9, 78.0 *Estimated value for total generated heat and electricity (2030)*  	**€190M per 800Kt of waste per year** - Value of generated hydrogen by FUREC would be €165-220M (2030) *Price per 1kg of hydrogen - 2030 (€/kg)*[3]: 1.9-3.2, 3.0-4.0 *Prices for feedstock competitive with grey/ blue hydrogen given market conform gate fees* *Estimated value for total produced hydrogen* 

---

1) Price of generated heat is based the forward price in the market for year 2027 – assumed to be remain in the same order of magnitude in 2030; 2) Price of generated electricity is based the forward price in the market for year 2027 – assumed to be remain in the same order of magnitude in 2030; 3) Price of grey and blue hydrogen are based on cost of production in 2030 from the PBL report below. Importing blue hydrogen as blue ammonia incurs additional costs due to conversion, transportation, and reconversion processes; Source: RWE input; RVO; PBL – 'Productie, import, transport en opslag van waterstof in Nederland' (2024); EHB (Energy Delta Institute) – 'Analysing the future demand, supply, and transport of hydrogen' (2021); European Energy Exchange (EEX) – 'Market Data for Power Futures: Unit price (€ per MWh) for electricity based on last recorded baseload price.' (Accessed November 2024); Strategy& analysis

Technological case: deep-dive on TRL

Criteria	W2E incineration	W2E incineration with CCS	Gasification (FUREC)
Technological readiness levels[1]	**Commercial technology, TRL = 9** • W2E incineration is an established and mature technology with a significant commercial deployment **W2E incineration:** TRL = 9	**Commercial technology, TRL = 9** • W2E incineration with CCS are successfully demonstrated prototype[2] (TRL=7-9) with increasing levels of commercialization **W2E incineration:** TRL = 9 **CCS treatment[2]:** TRL= 7-9 • Additional improvement are required to reduce costs and increase efficiency	**Commercial technology, TRL = 9** **Successful pilot TRL= 8, each with a TRL > 8** • Gasification (FUREC)'s individual technologies are widely used and commercially available – overall technology has a TRL=8 **Pelletization:** TRL = 8-9 **Torrefaction[3]:** TRL = 8 **Entrained Flow Gasification[4]:** TRL = 9

1) Technology Readiness Levels (TRL) is a scale from 1 to 9 to assess the maturity of a technology, TRL 1 is earliest stages of research, and TRL 9 is fully mature, commercially deployable technology; 2) Literature indicates 7-9 levels. However, TRL is assumed as 9 due to successful commercial deployment of CCS technology; 3) Torrefaction as a stand-alone process is classified at TRL 8-9, with some mature applications reaching TRL=9. To remain conservative, we have opted for TRL 8; 4) Literature indicates that entrained flow gasification has reached TRL=8. However wide commercial deployment in China is indicative of a TRL =9; Source: RWE input; PBL – 'Decarbonization options for the Dutch waste incineration industry' (2022); Waste Management Symposium – 'Technical Paper on Waste Processing Technologies' (2008); Waste Recycling Magazine – 'Waste Pelletization Feature' (2023); TTU-IR – 'Study Comparing Trash-to-Gas (TtG) Systems' (2021); IEA –'Assessment of successes and lessons learned for biofuels deployment' (2023); Rudolfsson et al. – 'Combined effects of torrefaction and pelletization parameters on the quality of pellets produced from torrefied biomass' (2017); Schotgroep BV – 'Ketenanalyse torrefactie conversietechnologie' (2021); Samani et al. – 'Numerical simulation of lignin gasification: The role of gasifying agents in entrained-flow reactors' (2024)

Appendix

Details scope of study and availability and quality of information

Scope

We have carried out the work as agreed with you in the Engagement Letter (17 September 2024). In accordance with the Engagement Letter, our scope included the chemical raw material demand from the EU chemical industry, the supply of (non-recyclable waste) in the EU, the role of alternative waste processing technologies and recommendations to stimulate these alternative waste processing technologies. The scope of the work as agreed in the order confirmation remains unchanged.

We have not conducted a review of the technology, the business case and the sourcing strategy of FUREC.

We have completed our analysis work on 11th November 2024. Therefore, this report does not include the consequences of events after that date or the impact of information that became available later.

Availability and quality of information

Our information is based on expert information, public sources and RWE management information regarding FUREC (see sources in footnotes).

The provided information has allowed us to gain insight and understanding into the raw material demand from the EU chemical industry, the (non-recyclable waste) supply in the EU, the role of alternative waste processing technologies, and recommendations to stimulate these technologies.

Starting point for our work

We have based our work on the information made available to us. We have assumed that this information is accurate, complete, and not misleading. We have not performed an audit of this information, nor have we conducted a review to determine its completeness and accuracy in accordance with international audit or review standards.

Access to our report

Our report is specifically prepared for the client with whom we have agreed on the purpose and scope of our work, or to whom we have explained the nature and extent of our work and the limitations therein. We do not accept any responsibility, duty of care, or liability - contractually, in tort (including negligence), or otherwise - for the use of the report by parties other than the client.

As agreed in our Engagement Letter, our report may only be shared with third parties for informational purposes.

Other comments

This report, as well as any dispute arising from or relating to (the content of) the Report, shall be exclusively governed by Dutch law.

strategy&
Part of the PwC network

Thank you

strategyand.pwc.com