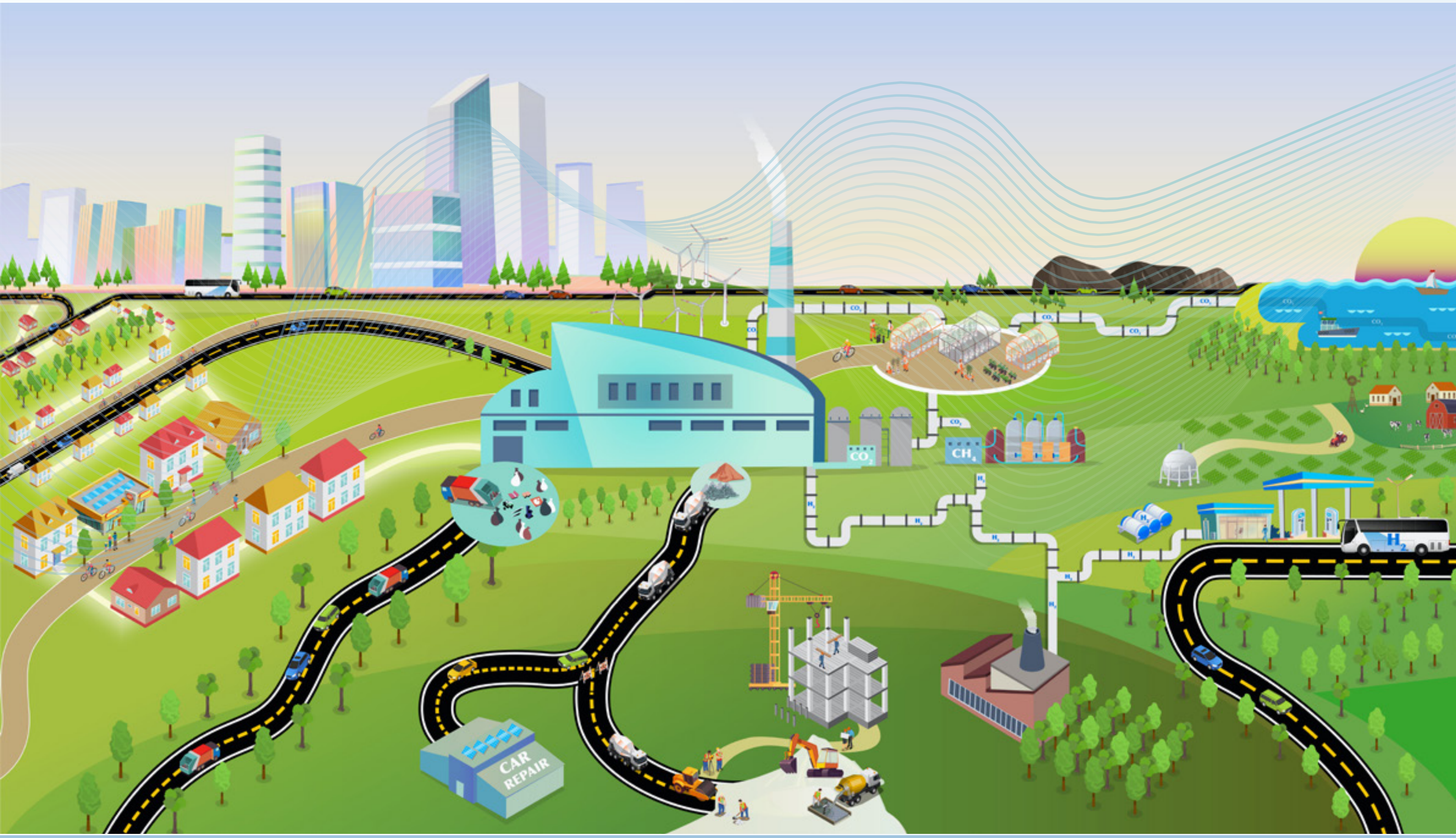
RECOVERING THE NON-RECYCLABLE

From Waste-to-Energy to Integrated Resource-Recovery Facility



ESWET

European Suppliers of Waste-to-Energy Technology

Recovering the non-recyclable:

From Waste-to-Energy to Integrated Resource-Recovery Facility

ESWET

European Suppliers of Waste-to-Energy Technology

ACKNOWLEDGMENTS

The completion of this report could not have been possible without the contributions and expertise of the ESWET members and representatives, but also the data and work done by CEWEP and quoted accordingly in the document.

All graphic images in the report belong to ESWET except Figures 2 and 3, courtesy of CEWEP, and pictures on pages 7 and 10, courtesy of ESWET members.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Complementary to waste prevention and recycling, Waste-to-Energy facilities currently represent the most sustainable solution to treat non-recyclable waste.

Waste-to-Energy (WtE) diverts waste from landfills, contributes to the circular economy, and produces reliable and local energy. WtE plants also play an important hygienisation role for the community. But the sector is still full of new opportunities.

ENERGY SECURITY

The generation of baseload, reliable, local, and partially renewable energy is crucial today in Europe, as it contributes to the energy transition and energy security. Increasing energy efficiency of both heat and electricity production will also help to reduce European reliance on third countries.

"When WtE technologies are equipped with proper air pollution reduction facilities they can contribute to clean electricity production and reduction of GHG emissions.", IPCC, 2022[1]

WASTE-TO-HYDROGEN

However, the utilisation of residual waste is not only limited to heat and electricity. Indeed, renewable and low-carbon hydrogen and e-fuels are now on the table. Via electrolysis or certain types of gasification, but also by coupling captured carbon and hydrogen to produce methane (gas) and methanol (liquid), new technologies are ready to contribute to decarbonising other sectors such as transport. Furthermore, hydrogen can be used as intermediate storage to manage fluctuating electricity load.

As about half of the energy produced by plants is of biogenic origin, Waste-to-Hydrogen is partly renewable, partly low-carbon.

CARBON CAPTURE

Given the plants' share of biogenic emissions, widespread implementation of carbon capture technologies currently has the potential to make WtE plants carbon negative. The captured CO_2 will then contribute to the circular economy by producing e-fuels or be directly used in various applications, e.g., greenhouses.

MATERIALS RECOVERY

Securing raw materials is a major strategic and environmental issue in Europe. By increasing the quantity and quality of materials recovered from incineration bottom ash (IBA), plants can contribute to the availability of secondary raw materials. But metals and minerals are not the only valuable resources from residual waste: with new technologies, flue gas cleaning residues become a source of circular raw materials to be used in the chemical sector.

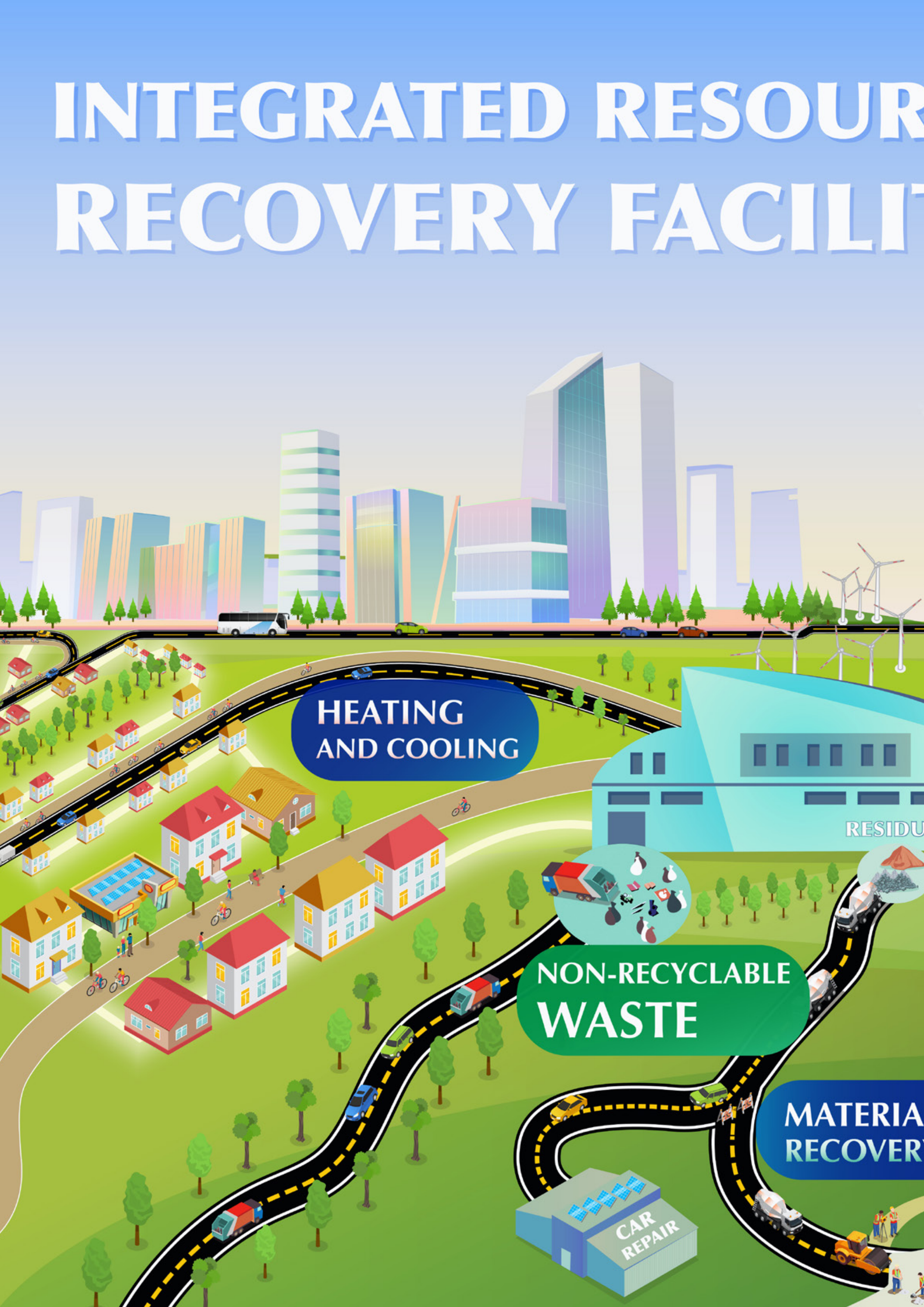
A NEW CONCEPT

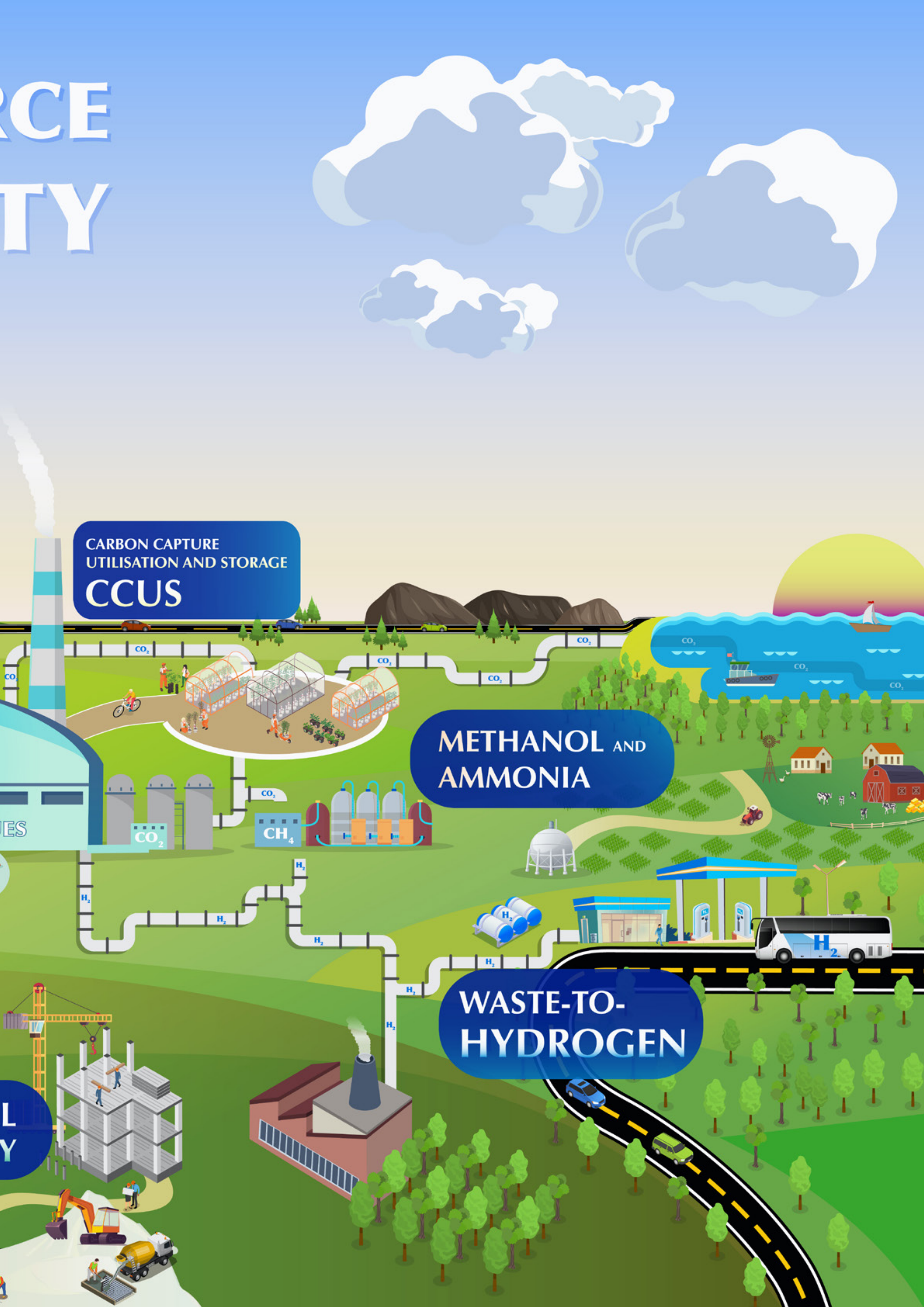
The integration of these innovative technologies to current installations, while taking into account their locations, size, specificities and their near environment, is maximising their contribution to circularity and decarbonisation by going from standard WtE plants to Integrated Resource-Recovery Facilities.

Depending on the plant's characteristics, however, some added equipment will be more relevant than others, such as an electrolyser if there is a local demand for hydrogen.

The Integrated Resource-Recovery Facility (IRF) represents a new model of plant and a step-change evolution in waste thermal treatment.

This holistic project, first introduced in 2019 by ESWET in its 2050 Vision, can now be implemented thanks to state-of-the-art European engineering.


INTEGRATED RESOUR
RECOVERY FACILIT
HEATING
AND COOLING
RESIDU
NON-RECYCLABLE
WASTE
MATERIA
RECOVER
CAR
REPAIR



RCE
TY
CARBON CAPTURE UTILISATION AND STORAGE
CCUS
METHANOL AND AMMONIA
WASTE-TO-HYDROGEN

INTRODUCTION

Our society cannot be truly sustainable without fully addressing waste challenges.

Undoubtedly, the best solution is the reduction of waste at source, meaning less waste production. That process includes first prevention, then an increase of the proportion of reusable products on the market.

Secondly, measures are also needed to increase and improve sorting and recycling processes.

Even with the best technologies in place, recycling is not always the preferred option as it can sometimes have a higher environmental impact than recovery, and is not eternally possible or even economically viable for some residual waste streams.

From such non-recyclable waste fractions, its valuable energy content shall be recovered to minimise the least attractive option, disposal.

With the Green Deal, launched in 2019, the goal is to steer EU policy towards three main objectives: decarbonisation, pollution reduction, and circularity.

This substantial shift applied to all economic activities requires securing the necessary resources to achieve a sustainable transition in the EU and significantly reduce GHG emissions so that Europe becomes carbon neutral by 2050.

The goal of this report is two-fold:

1 to present the main features of Integrated Resource-Recovery Facilities as a solution for carbon negative residual waste treatment

2 to highlight the EU policy framework needed to support those Integrated Resource-Recovery Facilities.

To ensure the success of the green transition, a new approach to waste management of non-recyclable waste is required!

1 CARBON SAVINGS

There are two options for the treatment of non-recyclable and residual waste: thermal treatment, or landfilling. The former is recognised as part of the 'recovery' operations, above 'disposal' (see Figure 1 below).

WASTE HIERARCHY

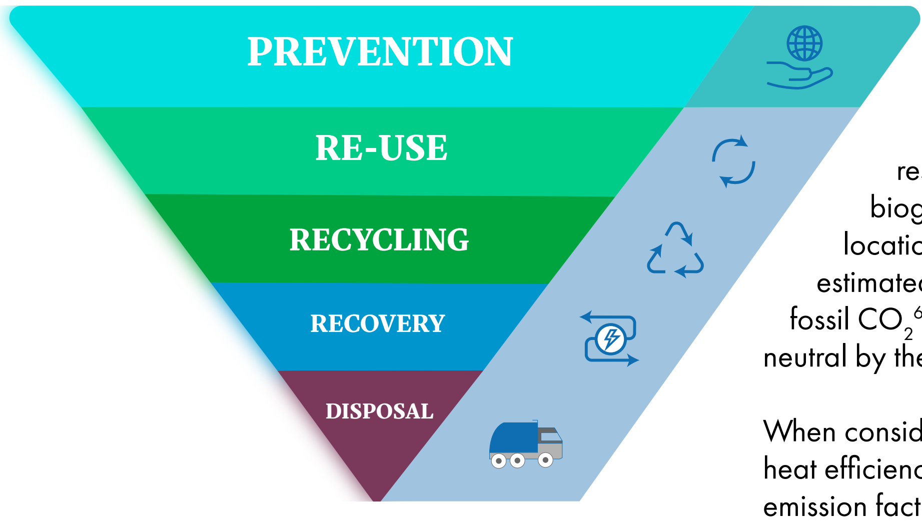


Figure 1: Waste Hierarchy

Landfills, when not designed properly, are indeed a leading source of uncontrolled methane emissions, and of air, soil, and water (including groundwater) pollution.

More modern landfill installations can be equipped with methane recovery, but energy recovery from landfills is not common practice and the efficiency in terms of energy recovery is much lower than the energy yield obtained in thermal waste treatment plants[2], and provides less environmental benefits[3].

The difference is even greater when considering a 20-year time frame as recognised by the IPCC in April 2022, which is the most urgent timeline to consider when tackling climate change.

Indeed, methane emissions at the 20-year horizon are 84-87 times more harmful than CO_2 emissions, whereas they are 28-36 times more harmful at the 100-year horizon[4]; still a considerable magnitude.

While the treatment of 1 tonne of municipal waste generates about 1 tonne of CO_2 emissions, direct emissions do not show the full picture.

When considering thermal treatment with a Life Cycle Approach (LCA), carbon savings should also be taken into account to show the full picture of related emissions[5].

WtE plants emit both fossil CO_2 (for instance, from treating residual plastics) and biogenic CO_2 (from residual paper or food). The share of biogenic carbon varies depending on location, seasonality, etc., but is generally estimated at up to 60% meaning only 40% is fossil CO_2[6]. Biogenic CO_2 is considered carbon neutral by the IPCC.

When considering the overall net electricity and heat efficiency combined with the current CO_2 emission factor of the European electricity and heat grid mix, energy from waste substitutes fossil fuels[7] and, depending on the energy grid, it is estimated to save 360kg of CO_2eq per tonne of waste treated, according to CEWEP and as shown in Figure 2.

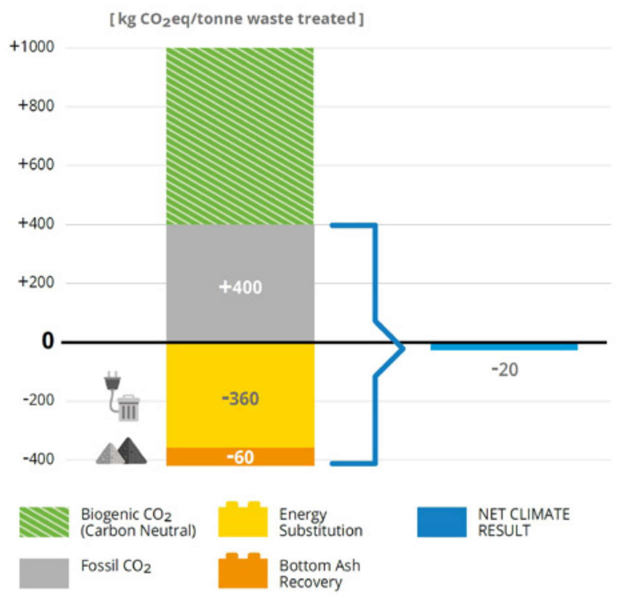


Figure 2: Current net carbon balance of the European WtE sector, excluding landfill diversion (Credits: CEWEP Climate Roadmap 2022)

CO_2 savings are also achieved by the recovery of valuable materials from incineration bottom ash, the residues of the combustion process. Recovery of metals brings an additional reduction of 60kg of CO_2eq per tonne of waste treated, according to CEWEP, which already gives a modest climate positive result through less emissions.

Adopting a Life Cycle Assessment and taking into account CO_2eq savings by WtE, the climate balance can be considered already carbon neutral today, as also recognised by the International Energy Agency (IEA) Greenhouse Gas R&D Programme[8].

When the diversion of non-recyclable waste from landfills is also taken into account, carbon savings are even more significant, according to CEWEP and as shown in Figure 3.

However, with the integration of new technologies, the sector can go from carbon neutral to carbon negative, even in countries where energy substitution or landfill diversion are not as relevant anymore.

That is where the discussion on the Integrated Resource-Recovery Facility becomes more pertinent.

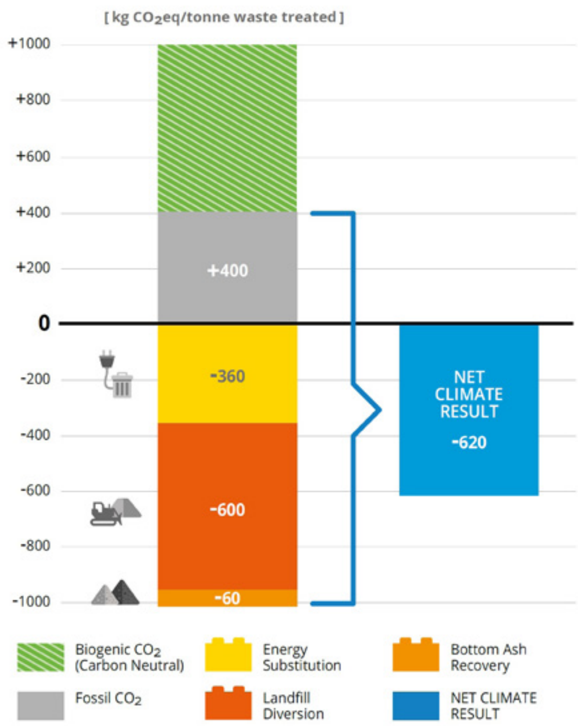


Figure 3: Current net carbon balance of the European WtE sector, considering landfill diversion (Credits: CEWEP Climate Roadmap 2022)

INSIDE A WASTE-TO-ENERGY PLANT

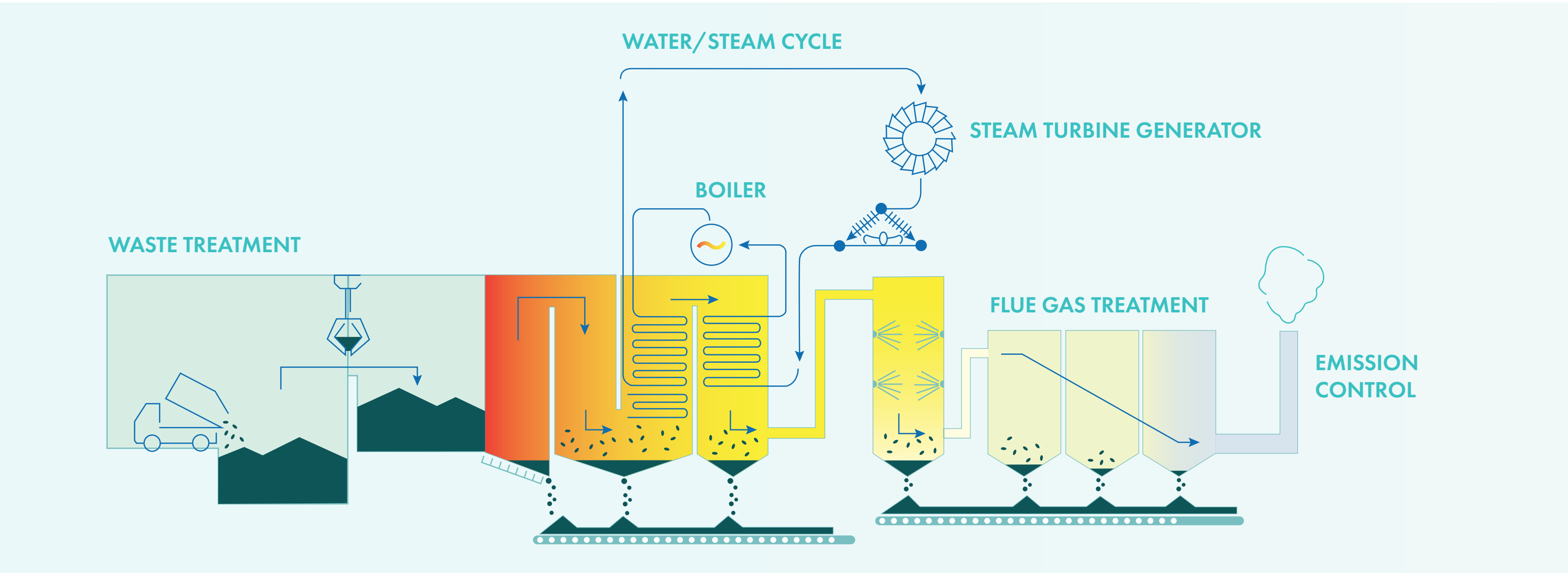


Figure 4: Inside a Waste-to-Energy plant

POLICY

Policy Recommendations for recognising the carbon savings of WtE & IRF:

1) Adopt an approach based on the Life-Cycle Assessment of Emissions in relevant pieces of EU legislation, including the EU ETS Directive, the Renewable Energy Directive and the Delegated Act on GHG emission savings of Recycled Carbon Fuels.

2) Adapt the EU rules on monitoring, reporting and verification of emissions to the WtE & IRF specificities, especially by considering the complexities, uncertainties and high costs of the prescribed methods and frequencies of controls, all stemming from the heterogeneous nature of the mixed waste.

3) Establish a methodology for the calculation of GHG emissions savings of fuels produced from WtE & IRF that considers the particularities of mixed non-recyclable waste as a feedstock.

4) Amend the Waste Sector Protocol[9] to allow for the recognition of the avoided emissions from WtE & IRF processes (mainly through material and energy recovery, as well as landfill diversion).

2 ENERGY SECURITY

Thermal treatment plants are able to recover energy in the form of steam, electricity or hot water. Therefore, Waste-to-Energy constitutes a link between the circular economy and renewable energy.

Since the waste treated in WtE plants is mixed, the majority of it is of biogenic nature, meaning biomass[10]. This biodegradable fraction of the waste is recognised as a renewable source of energy replacing fossil energy carriers and feedstocks in energy-intensive industries.

Recent studies estimate that the renewable energy output from WtE plants is more than 50%[11], contributing substantially to substituting fossil fuels in the electricity, district heating, industrial steam supply and transport sectors.

The supply of high-temperature heat produced by WtE systems is typically used by nearby industry processes, such as factories. A steam turbine-powered generator is used in this process to generate electricity that is fed into the national grid.

According to CEWEP's calculation, in 2019 in Europe, WtE plants produced 43 billion kWh of electricity, which provided 20 million citizens with electricity[12].

The amount of primary energy produced by WtE in 2019 was equivalent to 13.8 billion m³ of natural gas. This corresponds to approximately 9% of the imports to the EU from Russia (155 billion m³ in 2021)[13].

According to CEWEP, by 2035 European WtE plants could produce 189 TWh of useful energy per year from residual waste, which would be equivalent to 19.4 billion m³ of natural gas in terms of primary energy and 12,5% of gas imports from Russia, while respecting the recycling targets.

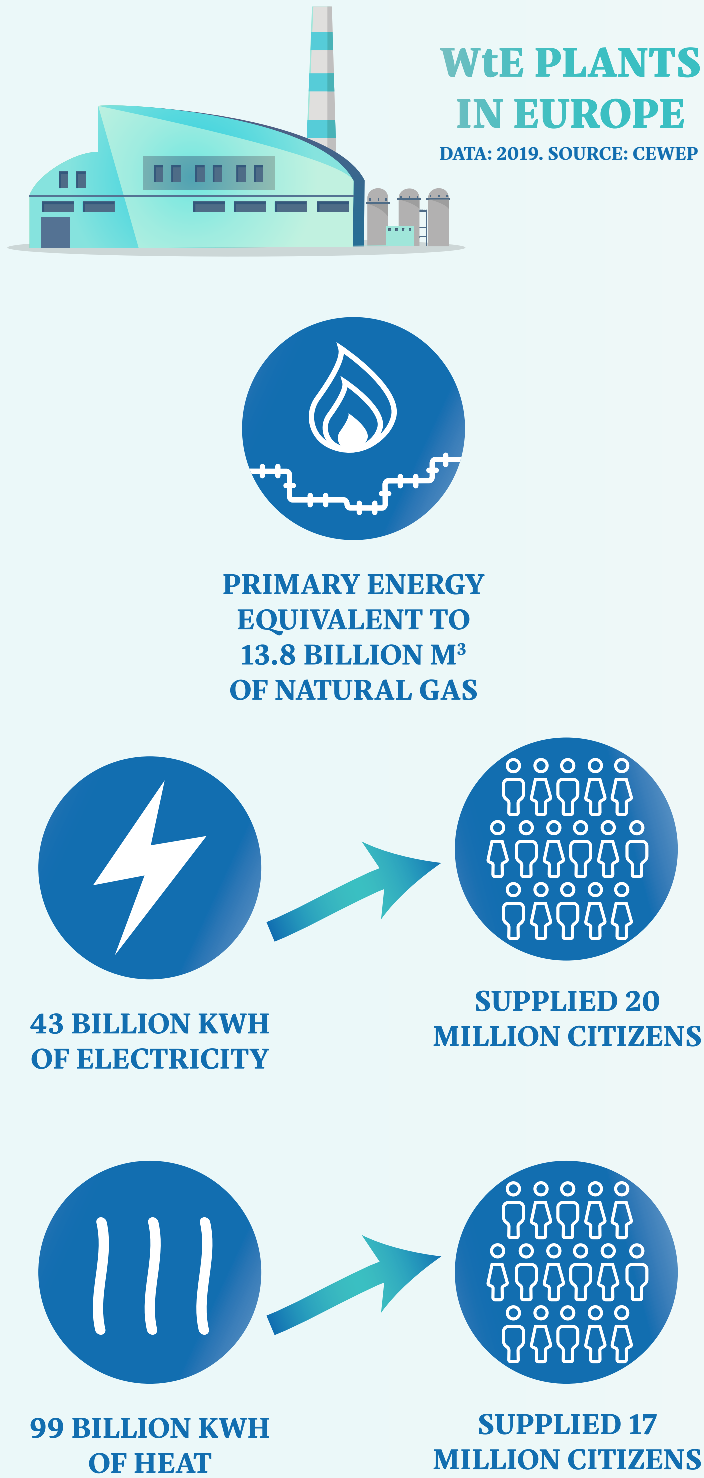


Figure 5: Waste-to-Energy plants in Europe - Electricity and Heating generation

Depending on the WtE system infrastructure, hot water is often sent to the local district heating and cooling network to heat or cool buildings, offices, hospitals and so on, or directly used in industrial processes regardless of a connection to a district heating network.

The majority of WtE plants in Europe also provide heat to homes and industry, maximising heat recovery.

One of the major advantages of energy produced from waste is that the energy carrier is not subject to price fluctuations of fuels, such as gas, while being less vulnerable to relative supply problems. In a context of rising energy prices, energy from waste remains a financially reliable energy.

Moreover, energy from waste is a partly renewable and secure baseload energy source offering flexibility and stability to the energy grid, because of its complementary role to variable renewable energy sources, such as wind and solar.

Another major advantage of energy produced from waste is that it is by essence a geographically distributed source of energy. WtE facilities are built and operated within high density urban area to reduce the environmental and financial costs associated to transportation of the waste.

The production of energy from non-recyclable waste is now diversifying, with the generation of renewable and low-carbon hydrogen, and synthetic fuels, which are crucial in reaching the climate objectives and the renewable energy targets.

Increasing energy efficiency is also an important topic and one of the main economic, political and environmental challenges in Europe.

Expanding current WtE plants into Integrated Resource-Recovery Facilities (IRF), and maximising the production and local usage of heat or hot water, will deliver an important contribution to both efficiency and energy security.

POLICY

Policy Recommendations for safeguarding and promoting WtE & IRF's role in energy security:

1) Safeguard the partly renewable feature of the energy - both heat and electricity - produced from WtE & IRF in the Renewable Energy Directive and related legislation.

2) Recognise the heat recovered from the fossil fraction of the residual waste treated in WtE & IRF as waste heat in the definition of the latter in the Renewable Energy Directive (in that it is unavoidable and not produced intentionally but as part of the process of treating waste).

3) Acknowledge the role of WtE & IRF as cogeneration facilities and continue supporting the sector in all relevant energy-efficiency legislation (e.g., Energy Efficiency Directive, Harmonised Efficiency Reference Values for calculating energy savings through cogeneration, etc.).

4) Support and incentivise the use of IRF to reduce Europe's dependency on gas imports, by including it in RePowerEU-related legislation.

5) Allow for state aid support for bioenergy production from WtE & IRF and ensure such support for high-efficiency cogeneration projects.

6) Recognise the bioenergy supplied by WtE & IRF as Taxonomy-eligible.

3 MATERIAL RECOVERY

Securing raw materials without over-relying on third countries has become a major environmental and geopolitical challenge for the EU. In this context, material recovery from IRF has a significant role to play in the circular economy and the decarbonisation by providing secondary raw materials and chemicals.

In the EU, Norway and Switzerland, around 500 WtE plants generate around 17.6 Mt/ per year of incineration bottom ash (IBA)[14].

IBA represents about 20 to 25% by weight of the waste input to incineration and contains metals and minerals in various proportions that can substitute the energy-intensive extraction of virgin material.

On average, IBA is composed of 80 to 85% by weight of minerals, 10 to 12% by weight of ferrous metals (steel and iron) and 2 to 5% of non-ferrous metals (aluminium, copper, etc.), and even precious metals, such as silver and gold[15].

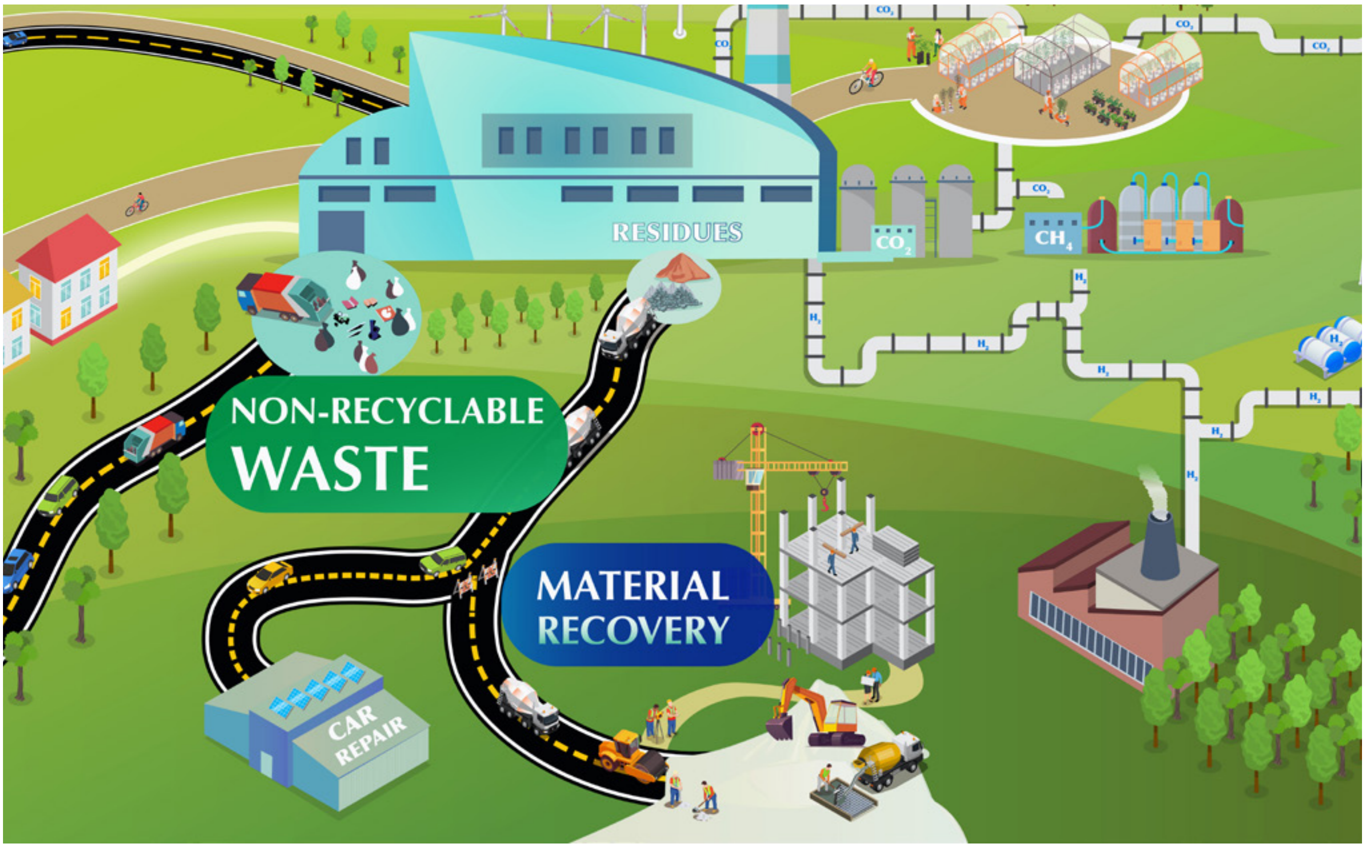
However, metal recovery systems and technologies differ significantly from one region to another (see Table 1 below). Furthermore, IBA composition is very heterogeneous and depends on the composition of the waste input as well as the operating conditions of incineration.

Two treatments are used: dry or wet. The choice between dry or wet depends on the IBA discharge system, which can also be wet-based or dry-based.

IBA TREATMENT TECHNOLOGIES

TECHNOLOGY	CHARACTERISTICS	CURRENT USE
WET PROCESSING OF WET-DISCHARGED BOTTOM ASH	• Consumption of water • Provides efficient recovery of heavy and non-ferrous metals and minerals that have great potential for recycling and reuse • When treating wet-discharged fresh ash, metal recovery can start from a grain size of 0.05 mm • Fresh ash yields higher metal recovery rates as it limits the time for carbonisation or solidification	Started in the Netherlands Limited number of plants are applying this technology
DRY PROCESSING OF WET-DISCHARGED BOTTOM ASH	• Technically mature • Possible reuse of mineral matter for construction • Recover metals below 2.0 mm • Depending on the technology, can recover precious metals (gold, silver) from 0.5 to 2.0 mm • High operating costs covered by metal revenues • Good potential for aggregates recycling	Established solution Recovery depth and maturation demand depending on the local market situation for aggregates and political framework
DRY PROCESSING OF DRY-DISCHARGED BOTTOM ASH	• Possible reuse of mineral matter for construction • High recovery efficiency of nonferrous metal below 0.2 mm • High quality of materials recovered • Zero water costs and less material transport • Allows for better metal recovery rates • Higher CAPEX and operating costs covered by metal revenue • Can lead to 140kg of CO_2 savings per ton of waste for enhanced metal recovery	High-end recycling facilities in operation in Switzerland and Sweden. High recovery efficiency Gaining interest in the rest of Europe

Table 1: IBA Treatment Technologies



In thermal treatment plants, the bottom ash is typically removed from the furnace via a wet-type discharger. Dry discharge of bottom ash, which facilitates the subsequent use of recovered materials, is nonetheless developing in some European countries, and could be further deployed in an IRF.

Apart from metals, minerals are also recovered from IBA as aggregates mainly used in the construction sector. The recovery and utilisation of minerals should be incentivised by being recognised at EU level as recycling, equal to the recycling of metals today from IBA.

For instance, in the Netherlands all operators of plants signed a “Green deal on bottom ash” public-private partnership with the Dutch government, including the full recovery of all minerals from 2020. Applications can be in road construction, bridges and sound walls, or in concrete products such as bricks.

METAL RECOVERY FROM IBA

The recovery of metals from plants is currently recognised as recycling at EU level[16], and constitutes an additional source of revenue. However, the utilisation rate of materials from IBA differs significantly among Member States as there is no harmonisation at EU level. It appears that the utilisation rate is rather a result of political commitment for IBA recycling[17].

The full recovery of metals represents a potential market of €2 billion[18] in 2021, of which 98% is from non-ferrous metal (based on the dry extraction and treatment of IBA as made in Switzerland) and a potential CO_2 emissions reduction of 14.5 million tonnes[19].

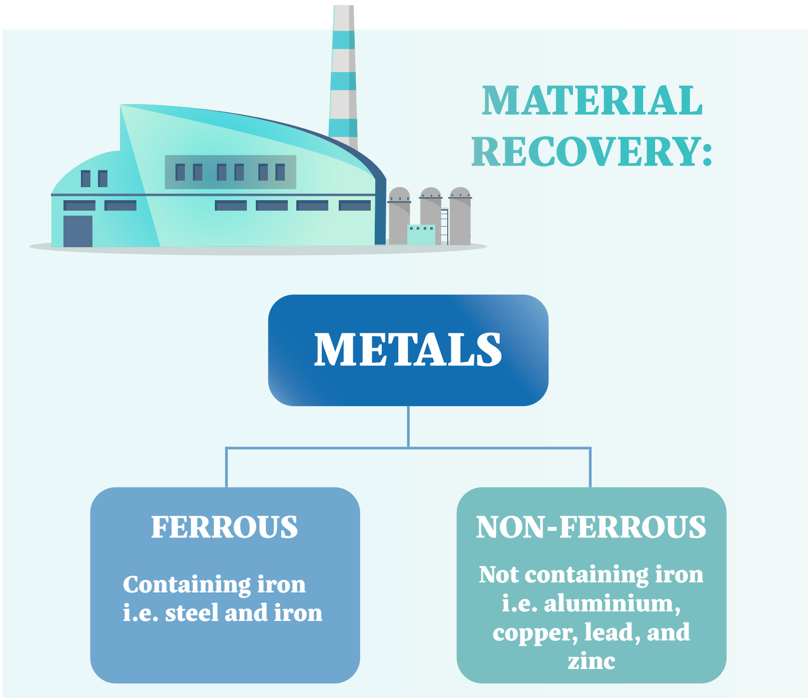


Figure 6: Waste-to-Energy and Material Recovery

The quality of the material recovered is ensured by cleaning and upgrading processes (such as drying, mechanical removal of remaining dust, etc.), prior to being sold to foundries. This allows for a higher purity and quality[20] at the end of the process.

While almost all metals in IBA are effectively recovered and recycled, the utilisation of minerals highly depends on the country or region. This means that there is an opportunity to significantly increase, and improve, the recovery yield of minerals and their use in construction materials, aggregates, etc.

RECOVERY OF ALUMINIUM AND IRON

From the 2 to 5 wt% of non-ferrous metals, around 2/3 is aluminium (Al)[21]. The full volume of IBA potentially available for recovery with advanced technologies such as dry discharge systems in Europe is up to 0.7 million tons of aluminium[22] (which would represent up to 11% of all European imports).

Iron is the main metal component in IBA and represents a significant source of secondary raw materials. In 2017, 35.5% of global raw steel was produced from secondary raw materials. Steel scrap consumption for steelmaking was 93.8 tonnes in the EU in 2018[23].

Nowadays, out of 20 million tons of IBA annually produced by European WtE plants, only about a third of the valuable non-ferrous metals found in the IBA is recycled.

Sending for recycling the additional 300,000 tons of aluminium, copper, zinc and lead currently destinated for landfilling and road construction[24] would definitely increase the domestic production of raw materials in Europe, and would thus reduce the dependency on imports.

RECOVERY OF FLY ASHES

Thermal treatment produces two solid residues: bottom ashes and fly ashes. Fly ashes are the residues resulting from the flue gas purification system, that follows the waste combustion process. Pollutants not destroyed by the combustion process concentrate in the fly ashes, hence the latter are classified in the EU as hazardous waste. Fly ashes represent about 15kg per tonne of waste treated, and because of their hazardous status, they are generally disposed of in special landfills after pre-treatment (e.g., stabilisation or solidification). Currently, many efforts are being made in order to extract resources from fly ashes

However, a few technologies allow for the extraction of salts and heavy metals from fly ash, which entered the process embedded in the waste.

Various treatment methods of fly ash exist and can be further deployed. These include neutral and acidic washing, thermal treatment, pyrolysis processes, hydrothermal treatment, solidification/stabilisation (S/S) method, and leaching processes[25].

Some of these processes enable the recovery of valuable resources such as silicates[26]. With washing processes, commercial salts (potassium chloride, sodium chloride, etc.) are extracted from the fly ash and utilised in other industries.

In general, the material and metal recovery possibilities from fly ash depend on the setup of the flue gas cleaning system of a plant.

FLY ASH FOR BUILDING MATERIAL

Another way to recover fly ash is to use it as a base for construction materials. Accelerated carbonation technology (ACT) is used to combine captured CO_2 and thermal residues, including fly ash, to create a carbon negative aggregate for the construction sector. But this is not commonly applied yet.

It also allows for the permanent capture of CO_2 used in the process, hence contributing to decarbonisation via carbon capture and utilisation. An 'end-of-waste' status was granted for this aggregate by the UK's Environment Agency in 2011[27], meaning that it can be considered as a product at the legislative and commercial level.

This technology contributes to the circular economy by using fly ash as a resource and reducing the amount of residues sent to landfills. Projects are now developing in the EU as well, with, for instance, a new ACT plant in Spain which was awarded funding from the EU Innovation Fund[28].

THE RECOVERY OF HEAVY METALS

Recovering heavy metals from waste, and - in this case - fly ash, also substitutes the use of virgin materials in the chemical industry. The process of selective zinc recovery from the acidic-scrubbed fly ash from plants is one example of a process-integrated method for recovering economically profitable heavy metals.

Cadmium, lead and copper are separated using a reductive process and recovered as a metal mixture in lead works. Zinc is separated from the "pre-cleaned filtrate using a selective extraction method", and then concentrated and recovered electrolytically as pure zinc (Zn > 99.995%)[29].

The synergies associated with the residues occurring with wet flue gas cleaning are used during the process. During acidic ash extraction, the heavy metals in the fly ash are mobilised and extracted by the acidity of the quench water. At the same time, the excess acid content of the quench water is neutralised by the alkalinity of the fly ash.

After acidic fly ash scrubbing, the filter ash cake has an extremely low heavy metal content. Any organic matter that remains in the cake subsequent to scrubbing can be returned to the combustion system so that it can be destroyed and energy can be recovered from it.

In Switzerland, filter ashes are mainly treated by acidic ash extraction transferring the metals in a zinc-containing hydroxide sludge[30]. The development and establishment of a central large-scale processing facility for a metal recovery from hydroxide sludge is currently taking place.

POLICY

Policy Recommendations for safeguarding and promoting WtE & IRF's role in material recovery

1) **Recognise the recovery of minerals from IBA in the Member States' recycling target, similarly to the recycling of metals from IBA.**

2) **Address both critical raw materials and non-critical raw materials in EU legislation on secondary raw materials (Critical Raw Materials Act, Waste Framework Directive revision, etc.).**

3) **Address the untapped potential of EU supply by facilitating the use of materials from waste streams, including WtE & IRF residues.**

4 WASTE-TO-HYDROGEN AND WASTE-TO-FUELS

As previously stated, Waste-to-Energy covers a wide range of different technologies with proven advantages to the European energy mix.

WtE presents a significant versatility as it may produce not only heat and electricity but also renewable and low carbon hydrogen and fuels, i.e., Waste-to-Hydrogen (WtH) and Waste-to-Fuel (WtF), whereby WtE processes provide some or all energy required for the generation of hydrogen and fuels.

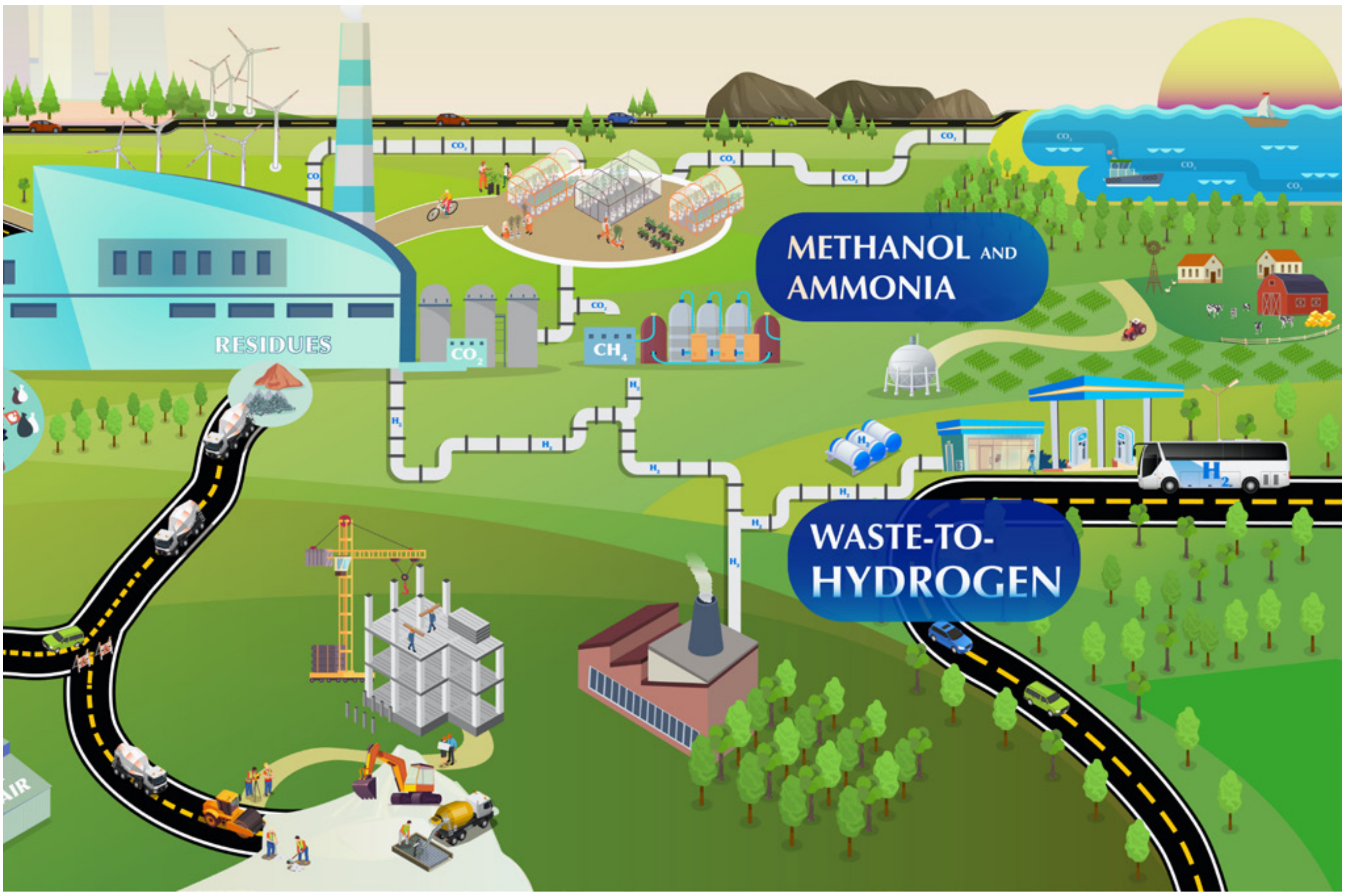
Waste-to-Hydrogen can be realised either by combining a combustion-based WtE plant with electrolysis or by certain processes based on gasification (for pre-treated waste).

Waste-to-Fuel is characterised by the production of any synthetic fuel (liquid or gaseous) typically from a combination of captured carbon dioxide and Waste-to-Hydrogen.

These synthetic fuels denote a form of carbon capture and utilisation (CCU). The produced fuels include methane (gas), methanol and ethanol (both liquid), which all are formed through hydrogenation of carbon dioxide.

WASTE-TO-HYDROGEN / WASTE-TO-FUEL AND CLIMATE OBJECTIVES

Renewable and low carbon hydrogen and fuels are considered key to the climate objectives, especially in energy-intensive industries and transport.



Hydrogen and fuels produced from waste are partly bio-based fuels (derived from the biogenic share of the energy from WtE) and partly recycled carbon fuels. Accordingly, they should be recognised as partly renewable hydrogen/fuel and partly low carbon hydrogen/fuel, if they meet the required sustainabily criteria.

Waste-derived fuels increase the waste management sector's contribution to the decarbonisation of Europe.

They also reduce land competition between energy and food crops[31], with a JRC 2016 report further stating that "*life-cycle CO_2 costs are lower than for fossil fuels or crop-based biofuels*[32]." In many parts of Europe where municipal solid waste is still predominantly landfilled, its conversion to biofuels would provide significant GHG savings. The displacement of GHG emissions for ethanol from municipal solid waste is estimated at -225g CO_2e/MJ[33].

WASTE-TO-HYDROGEN & WASTE-TO-FUEL APPLICATIONS

Hydrogen from WtH powering fuel cells represents a significant alternative to fossil fuel powered engines in buses and trucks in cities or refuse trucks collecting municipal waste.

Several hundreds of refurbished or new plants treating municipal waste throughout Europe can thus become local sources of renewable and low carbon hydrogen, located closely to consumers in urban centres. Already, promising pilot demonstrations and projects at various stages of development exist in Europe.

Waste-to-Hydrogen has been proven in Wuppertal, Germany[34]. There, the WtE plant can generate enough hydrogen to power 20 public transport buses (with a goal of 70 buses by 2025), contributing to the decarbonisation of heavy transport vehicles, and avoiding particle matter emissions.

Thanks to this facility, it is estimated that the city of Wuppertal saves more than 700 tons of CO_2 per year. The produced electric power from the WtE plant is sold on the spot market. This allows them to produce H_2 when spot prices are low and store it in their H_2 storage.

Methane and methanol as synthetic fuels produced from WtH can also be used in transportation as alternative fuels, contributing to decarbonisation efforts.

A Waste-to-Methane project is up and running in Dietikon, Switzerland[35], and has recently been awarded the Watt d'Or. With an electrolysis capacity of 2.5MWh or 450 m³ of hydrogen per hour, the plant produces around 18,000MWh of synthetic gas per year.

This enables end customers to heat, cook, or refuel vehicles with a CNG engine – from small cars to large trucks – and thus operate in a CO_2-neutral way. As a result, the plant makes an important contribution to decarbonisation, as its green gas can result in up to 5,000 fewer tonnes of CO_2 emissions per year, which corresponds to the CO_2 emissions of approximately 2,000 households.

H_2 GENERATION FROM WtE

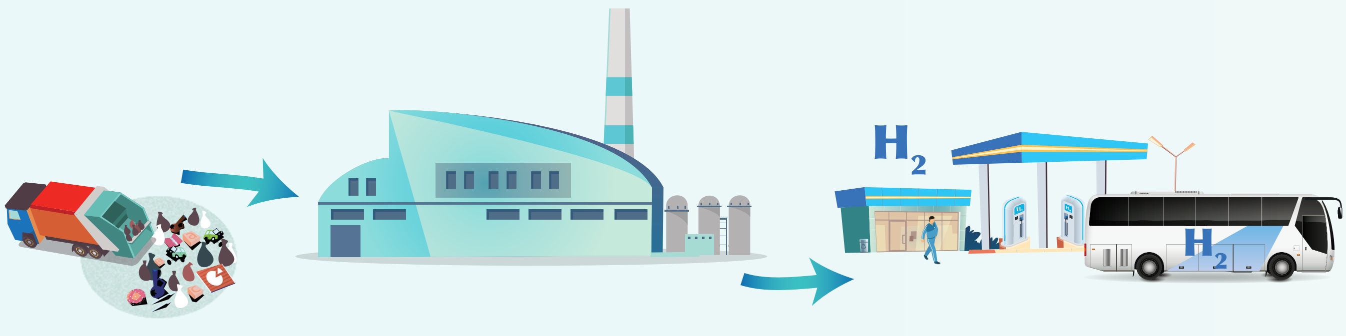


Figure 7: H_2 generation from Waste-to-Energy

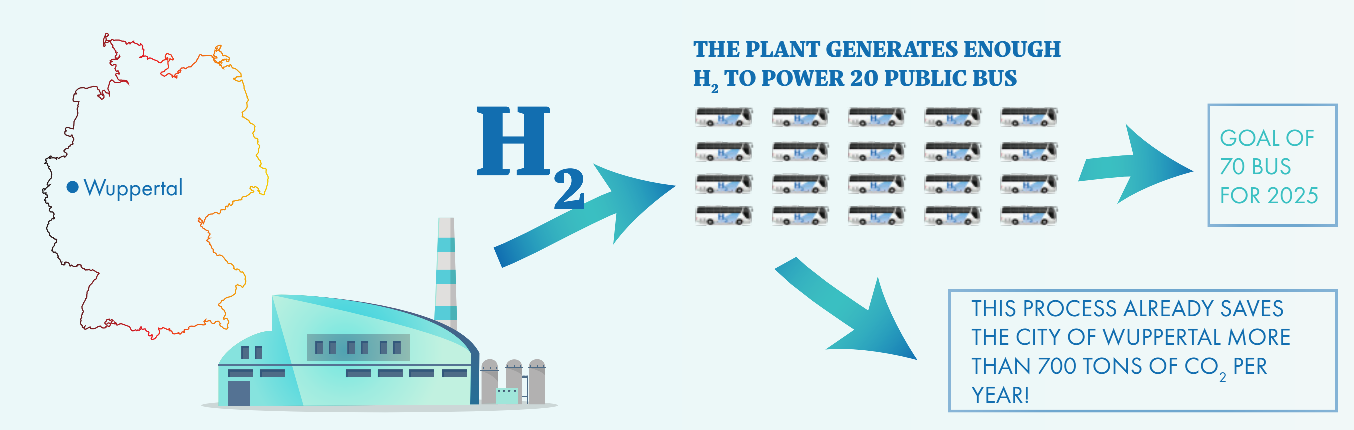


Figure 8: H_2 generation from the Waste-to-Energy plant in Wuppertal,Germany

Apart from its use in transportation, WtH can also be used in industries, for instance in the steel, cement, and chemicals industries, to help them decarbonise. These industries cannot rely only on electrification but need energy-dense fuels to generate high-temperature heat for their industrial processes.

Hydrogen and methane can also be blended with natural gas for various applications, essentially decreasing the overall environmental and climate footprint of the blend, given the partly renewable and partly low carbon feature of the hydrogen and methane produced by WtH and WtF.

Hydrogen can also be coupled with nitrogen to produce ammonia for agricultural fertilisers, avoiding the use of fossil fuels or natural gas. Ammonia has a higher energy density than liquid hydrogen, thus it can be used efficiently as a new form of energy storage or as a fuel, which does not emit CO_2 when burned.

BENEFITS OF WASTE-TO-HYDROGEN & WASTE-TO-FUEL

Apart from the environmental and climate benefits analysed above, WtH and WtF offer many other benefits.

To start with, WtH can be used to manage the fluctuating load of the energy grid: when the electricity cannot be fed into the grid, it can be used for the hydrogen production.

In that way, WtH contributes to a stronger electricity grid: it offers additional flexibility as it has the potential to actively participate in stabilising the grid electrical frequency, helping WtE plants offer primary and secondary frequency control services, while playing the role of intermediate energy storage.

In addition, as WtH is produced from a controllable baseload energy, it supports the integration of variable renewable energy sources, such as solar or wind, in the energy system, as these fluctuating power sources increasingly require being counterbalanced by controllable baseload sources of power.

Furthermore, WtH is a holistic example of circular economy in action if we consider the use in waste collecting trucks and municipal buses. It also helps decarbonise grid detached mobile equipment, which may be inconvenient to be decarbonised using batteries.

Another benefit from WtH can be the use of the oxygen (O_2), a by-product from the electrolysis of water, to increase the efficiency of incineration or its application in waste-water treatment facilities.

THE MARKET CASE FOR WASTE-TO-HYDROGEN & WASTE-TO-FUEL

Considering the need for renewable energy and the inequality of resources varying from one Member State to another, WtH and WtF has the advantage, contrary to other renewable sources, e.g., wind and solar, of being a plannable energy source.

Hydrogen produced from intermittent renewable energy sources requires investments in larger plant capacities to compensate for the lower Capacity Utilisation Factors (CUF) of these power plants[36]. Hydrogen storage and transport costs – if produced offshore or far from consumers - are still a significant challenge on the growth of a hydrogen economy as they can represent a significant portion of the levelised cost of hydrogen for the end-customers.

On the contrary, WtH and WtF habe the potential to be an economically competitive and locally produced fuel as WtE is in a "sweet spot" that combines both advantages: a baseload power, with CUF close to 100%, and low transport costs of the produced hydrogen (from production point to end-customer).

Most WtE plants are ideally located geographically close to end-customers in the outskirts of cities. With hydrogen transportation infrastructure (pipelines, distribution network, hydrogen trailers) still under-developed, WtH can become a catalyst of the hydrogen economy.

In addition, the demand for renewable and low-carbon hydrogen will be on the rise for years to come. Biofuels' demand will also increase significantly by 2050. These projections create a favourable market case for the development of WtH and WtF projects and prove the IRF's rightful aim to be at the forefront of decarbonisation strategies.

This tendency is similar in the WtE sector as well, with the 2021 Ecoprog barometer[37] of the WtE sector showing that the interest in hydrogen is high in the sector. Around 90% of the EU WtE operators interviewed declared they are either already considering plans for production or following the topic closely.

COSTS AND CHALLENGES OF WASTE-TO-HYDROGEN AND WASTE-TO-FUEL

The cost of WtH is still relatively high: 1MWe electrolysis plant requires a total investment of approximately 6 million EUR, when including all storage and distribution equipment.

In the short term, the optimal size for WtH projects should be in the range of 3 to 10MW, a scale allowing cost effective production while securing local hydrogen off-takers.

According to internal estimations, the complete CAPEX cost for a current 3MW project is between 10 and 15 million EUR, with hydrogen being sold at around 8 to 20 EUR/kg significantly depending on power costs.

It is important to make WtH cost-competitive through standardisation that can lead to economies of scale, and that is why access to finance is crucial for WtH.

On the other hand, CAPEX for a methanation unit is estimated for 2030 at 500,000 EUR per MWMethane and OPEX at 5% of CAPEX[38].

Despite that methanation requires an additional conversion step to the WtH process, with a resulting decrease in the overall efficiency[39], it has many benefits:

i) Methane's volume energy density (> 1000kWh/m^3) is much higher than hydrogen's (270kWh/m^3)[40];

ii) Methane can be better injected into the existing gas infrastructure;

iii) It has a lower risk of ignition than hydrogen, thus it is safer for domestic utilisation; and

iv) Methane production can encourage CO_2 capture and utilisation technologies.

Both conversion processes for hydrogen and then methane have as losses mainly waste heat.

However, waste heat can be recovered to increase efficiency of the processes themselves or to feed an existing district heating system[41]. The heat produced from methanation reaction is also enough to allow for carbon capture processes at the WtE plant.

In conclusion, like all decarbonisation activities, there is a higher initial cost to install and operate such facilities, but similar to other renewable energy sources, the learning curve will be very steep, which will allow IRF plants eventually to offer WtH & WtF at more competitive prices.

That is why the legal framework, and the financial support are crucial at this initial stage, to provide the necessary security and incentives to the projects to take off.

POLICY

Policy Recommendations for safeguarding and promoting IRF's role in hydrogen and fuel production:

1) Safeguard the partly renewable feature of hydrogen and fuels produced from WtE & IRF processes and acknowledge them as partly biomass/ bio-based fuels and partly recycled carbon fuels in the Renewable Energy Directive, the Gas Directive, the Energy Taxation Directive, and related legislation.

2) Acknowledge the emission savings resulting from landfill diversion in fuel-related legislation and recognise WtH & WtF as renewable and low-carbon fuels.

3) Establish a clear certification framework for hydrogen and fuels produced from WtE & IRF processes treating mixed waste feedstock.

4) Identify hydrogen and biofuels supplied by WtE & IRF as Taxonomy-eligible.

5) Recognise the contribution of WtE & IRF in hydrogen and biomethane production in RePowerEU legislation.

6) Grant state aid support for biofuels and low-carbon fuels produced from WtE & IRF processes

5. CARBON CAPTURE UTILISATION & STORAGE

Carbon capture, utilisation and storage (CCUS) technologies are widely recognised as a necessity to decrease GHG emissions[42].

As recognised by the latest IPCC report, the implementation of CCUS for plants can "enable waste to be a net zero or even net negative emissions energy source", with the potential to capture "about 60 to 70 million tons of carbon dioxide annually" in Europe[43].

With the 2050 carbon neutrality objective set by the Green Deal, the development of CCUS gained positive political momentum, with the launch of new projects starting in 2019.

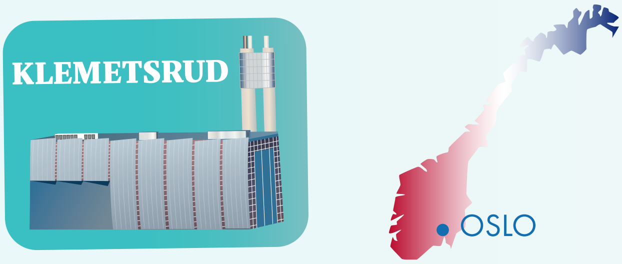
The integration of CCUS in WtE represents an opportunity for bioenergy with carbon capture and storage (BECCS), one of the few abatement technologies that can be carbon negative, and an essential part of the IRF. Furthermore, the sector is one of the cost-competitive options for CCUS[44].

CCUS projects are now fairly advanced in Europe, such as the Klemetsrud plant, part of the Longship project supported by the Norwegian government, which will capture up to 400,000 tons of CO_2 per year[45].

Another project at the Amager Bakke plant is planning to capture up to 500,000 tonnes of CO_2 each year. While the viability of the capture process was proven with a pilot demonstration in 2022[46], the plant is still looking for funding to ensure the future of the project.

In total, more than a dozen projects to implement carbon capture for European plants are in the pipeline.

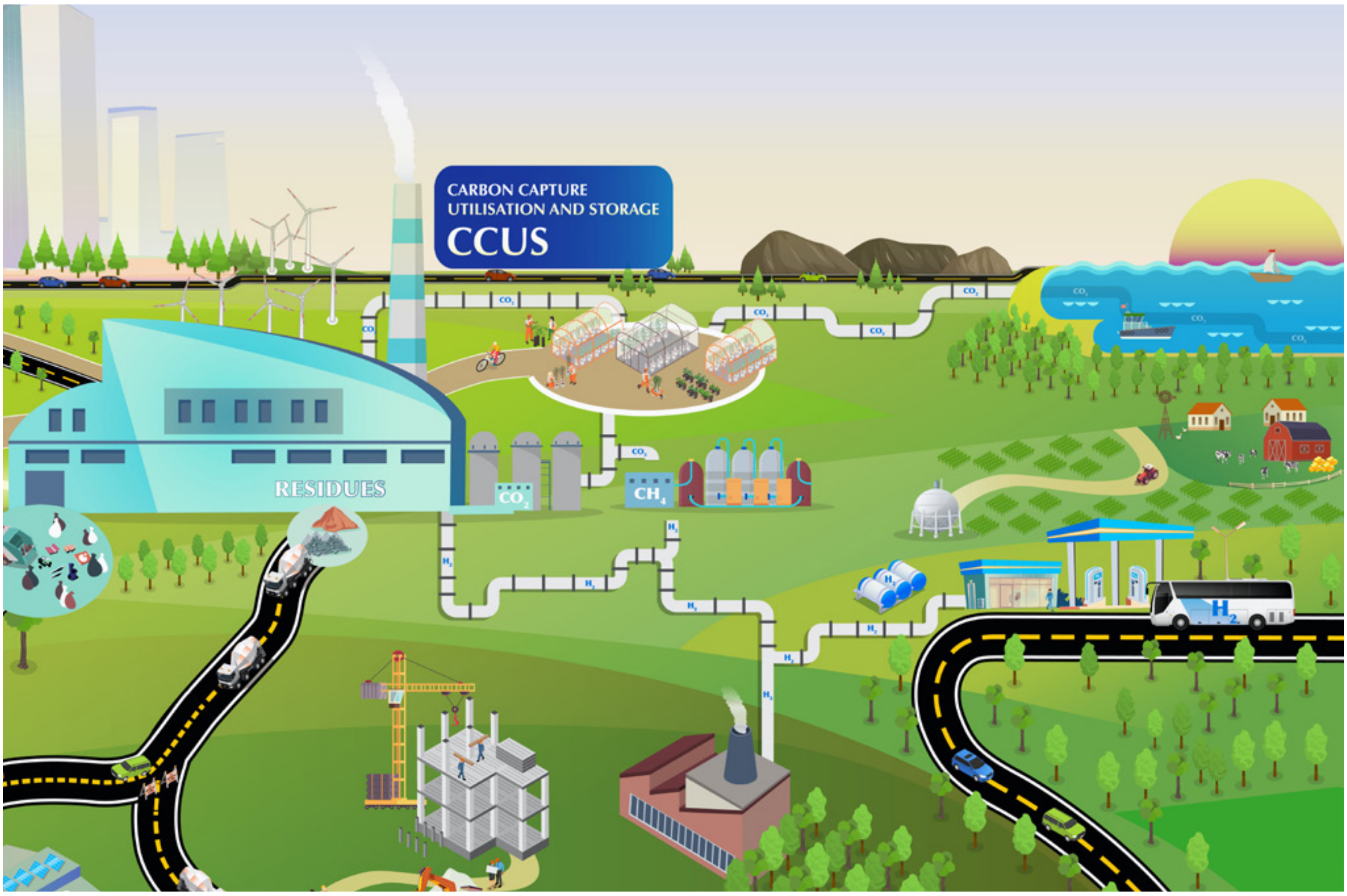
EXAMPLES OF CURRENT PROJECTS IN EUROPE



Part of the Longship project - supported by the Norwegian government - the Klemetsrud plant will capture up to 400,000 tons of CO_2 per year.

The Amager Bakke plant is planning to capture up to 500,000 tonnes each year. The viability of the capture process was proven with a pilot demonstration in 2022.

Figure 9: Current CCUS projects in Waste-to-Energy plants in Europe



CARBON CAPTURE

When capturing CO_2 from facilities, two options are mainly explored:

1) Amine-based capture: flue gas is first cooled, then brought into contact with amine-based solvents that will separate gases and retain the CO_2.

2) Enzymes-based capture: a similar process as amine-based is used, but with biological enzyme carbonic anhydrase instead of conventional solvents.

The use of biological enzymes brings environmental benefits, but is currently considered as an emerging technology (Technology Readiness Level 8). Post-combustion, solvent-based capture technology is currently the solution most deployed or to be deployed in projects[47].

The overall impact of implementing carbon capture depends on the integration of the technology in the plant and its specificities.

The energy spent on the capture process will be different from one plant to another, depending on criteria such as the technology used, if the waste heat generated by the capture can be recovered, the potential need to adapt the flue gas cleaning process, etc..

It can be estimated that the capture process reduces the electricity output by 22,1% to 16,5%, but with the addition of heat pumps or post-capture flue gas condensation[48] the heat recovery can balance this loss.

CARBON TRANSPORT AND STORAGE

Transportation can be done within a network of pipelines, using shipping or other means of transport, such as trucks or rail freight. Transport via pipeline is a largely established technology.

Using ships is also an option, but they have to be adapted to CO_2 transport and necessitate large buffer stocks.

The cost of transport depends on the means used and the distance. However, with economies of scale this cost can be significantly reduced[49].

The captured CO_2 has two possible routes: storage or utilisation. In case of storage, the CO_2 is permanently stored in geological formations, such as saline aquifers.

CARBON UTILISATION

Among the possibilities of using CO_2, sending it to greenhouses is already applied in thermal waste treatment, mainly in the Netherlands.

The AVR Duiven plant in the Netherlands can capture up to 100,000 tonnes of CO_2 per year. The Twence plant, in Hengelo, is developing a larger scale unit to also reach this capture capacity. Both facilities send the carbon to nearby greenhouses to promote plant growth[50].

Mineralisation is another possible route for carbon captured from IRF for building aggregates. Other uses include:

- Fertiliser with lower environmental impact
- Carbonated soft drinks
- Methanol production
- E-fuels, when coupled with hydrogen.

OVERALL COST OF CCS

The overall cost of CCS for thermal waste treatment is estimated from 76 EUR/tCO_2 to 127 EUR/tCO_2, which would be at least as cost-effective as other sectors such as glass or refining[51]. Current developments in solvent innovation, process integration and intensification will lower the CO_2 capture cost over time.

ESTIMATION OF CCS COSTS[52]

CAPTURE	The costs from capture vary depending on the type of capture and on whether economies of scale are possible. Studies estimate the cost to be around 48 EUR/tCO_2 to 60 EUR/tCO_2.
TRANSPORT	The cost of transport depends on the distance travelled and the type of transport. For transport via pipelines in CCS projects in general, it is estimated from 1 EUR to 2 EUR/tonne, with a distance travelled of less than 180 km, and a compression cost of about 9 EUR/tonne[53]. For specific energy from waste facilities, studies estimate the cost to be between 17 EUR/tCO_2 to 32 EUR/tCO_2. Pipelines are the cheapest option currently, with the trucks being the most expensive.
STORAGE	Studies estimate the cost to be around 9 EUR/tCO_2.

Table 2: Estimation of CCS costs

The CAPEX is determined by the plant size, the degree of modularisation, the possible degree of prefabrication and the solvent used. Fully deployed networks, and proper CO_2 transport infrastructure will help to achieve economies of scale.

It was estimated that for a plant treating 240,000 tonnes of waste per year, with amine-based capture technology the CAPEX would be around €50 million EUR and the Operation & Maintenance (O&M) cost of 1 million EUR per year. With the addition of a large heat pump to recover the waste heat, the CAPEX would be of 65 million EUR and the O&M cost of 2 million EUR per year[54]. However, the heat pump allows to reduce the loss of energy.

Disclaimer: *The cost figures presented in this section have been sourced from sources cited in the report and refer to estimations conducted and published in the past. It is important to note that these figures may not accurately represent current market conditions, economic factors (including currency and inflation), or other variables and external factors that could influence these costs in the present day. It is recommended that these figures be used as a general reference point rather than precise, up-to-date information. For the most accurate and current cost estimates, readers are encouraged to consult recent industry reports, market analyses, and official sources. ESWET and its members do not bear responsibility for any decisions made based on the information provided in this section on costs of CCS.*

POLICY

Policy Recommendations for further promoting WtE & IRF's contribution to circular economy and decarbonisation:

---

1) **Safeguard the access to EU funding for CCUS projects for WtE & IRF.**

2) **Ensure that the rules for monitoring of carbon removals take into account the specificities of WtE & IRF, e.g., the heterogeneous nature of the feedstock.**

3) **Acknowledge the full spectrum of CCU applications in WtE & IRF in the EU legislation.**

ENDNOTES

1) Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, p. 990.

2) Based on US data, the production of electricity from MSW in WtE ranges from 470 to 930 kW/h per ton of waste, while landfill gas recovery ranges from 41 to 84 kW/h per ton of waste. Kaplan, DeCarolis & Thorneloe (2009), Is it better to burn or bury waste for clean electricity generation?, Environmental Science & Technology 43, available here. See also Oonk (2012), Efficiency of landfill gas collection for methane emission reduction, Greenhouse gas measurement and management 2.

3) Kaplan, DeCarolis & Thorneloe (2009), Is it better to burn or bury waste for clean electricity generation?, Environmental Science & Technology 43.

4) Lee, Han and Wang (2017), Evaluation of landfill gas emissions from municipal solid waste for the life-cycle analysis of waste-to-energy pathways, Journal of Cleaner Production 166.

5) Figure 2 & 3 and related explanations from CEWEP (2022), Climate Roadmap and Technical Annex.

6) See for instance Frédéric GIOUSE, Elise RAVACHE et Léa MOUTTE. 2020. Détermination des contenus biogène et fossile des ordures ménagères résiduelles et d'un CSR. [ADEME - Cabinet Merlin – ENVEA. Détermination Des Contenus Biogène Et Fossile Des Ordures Ménagères Résiduelles Et D'un Csr, A Partir D'une Analyse 14c Du CO_2 Des Gaz De Post-Combustion. Programme UIOM 14C – Campagne de mesures sur UIOM et chaufferie CSR.

7) The IEA also considers that the substitution of fossil energy is an important carbon offset of WtE, see IEA (2020), IEAGHG Technical report CCS on Waste-to-Energy, 2020-06.

8) https://ieaghg.org/about-us/what-do-we-do

9) The Waste Sector Protocol, which was developed based on the Greenhouse Gas Protocol Corporate Standard, elaborated by the WBCSD and the WRI.

10) IPCC, Climate Change 2007: Working Group III: Mitigation of Climate Change, 4.3.3.3 Biomass and bioenergy.

11) Frédéric GIOUSE, Elise RAVACHE et Léa MOUTTE. 2020. Détermination des contenus biogène et fossile des ordures ménagères résiduelles et d'un CSR. [ADEME - Cabinet Merlin – ENVEA. Détermination Des Contenus Biogène Et Fossile Des Ordures Ménagères Résiduelles Et D'un Csr, A Partir D'une Analyse 14c Du CO_2 Des Gaz De Post-Combustion. Programme UIOM 14C – Campagne de mesures sur UIOM et chaufferie CSR.

12) CEWEP (2022), Waste-to-Energy Climate roadmap.

13) CEWEP factsheet on energy and climate, updated in March 2022.

14) Blasenbauer et al. (2020), Legal situation and current practice of waste incineration bottom ash utilisation in Europe, Waste Management 102.

15) Muchova, Bakker & Rem (2009), Precious metals in municipal solid waste incineration bottom ash, Water Air Soil Pollution:Focus 9

16) EC Implementing Decisions 2019/1004, WFD, metals separated and recycled after incineration are considered as recycled.

17) Blasenbauer et al. (2020), Legal situation and current practice of waste incineration bottom ash utilisation in Europe, Waste Management 102.

18) From internal calculation based on figures from Geschäftsbericht der ZAV Recycling AG (2020).

19) Based on internal calculations derived from Mehr et al. (2020) The environmental performance of enhanced metal recovery from dry municipal solid waste incineration bottom ash, Waste Management 119. Based on advanced metal recovery with the latest technologies from the Hinwil plant in Switzerland.

20) Syc et al, (2020), Metal recovery from incineration bottom ash, State-of-the-art and recent developments, Journal of Hazardous Materials 393.

21) CEWEP factsheet on bottom ash (data from 2018)

22) For reference, a tonne of aluminium is worth about 2 209 € (February 2023).

23) EuRIC, Metal Recycling Factsheet, available at: https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf

24) https://www.tudelft.nl/citg/over-faculteit/afdelingen/engineering-structures/sections-labs/resources-recycling/research-innovation/recycling-technologies/incinerator-bottom-ash-recycling

25) Xue and Liu (2021), Detoxification, solidification and recycling of municipal solid waste incineration fly ash, Journal of Chemical Engineering 420.

26) See for instance the patented Ash2Salt process by EasyMining.

27) Gunning P., Hills C.D. and Carey P.J. (2013), Commercial application of accelerated carbonation: Looking back at the first year, ACEME.

28) For the full list of projects in Waste-to-Energy approved for EU funding within the Innovation Fund, see the article published on the ESWET website: " Innovative Waste-to-Energy projects approved for EU funding".

29) Quina, M. et al. (2018), Technologies for the management of MSW incineration ashes from gas cleaning: New perspectives on recovery of secondary raw materials and circular economy, in Science of the Total Environment 635, pp. 536-542.

30) See the SwissZinc project in Switzerland.

31) Fully exploiting the potential of waste-derived fuels help to reorient food crops towards food production, instead of biofuels.

32) Saveyn, H., Eder, P., Ramsay, M., Thonier, G., Warren, K. and Hestin, M., Towards a better exploitation of the technical potential of waste-to-energy, EUR 28230 EN, Publications Office of the European Union, Luxembourg, 2016, page 240 and 242, citing: Recreate: Policy Brief No. 2, November 2015, Producing Bioethanol from residues and wastes.

33) Ibid, citing: Wasted: Europe's Untapped Resource – An Assessment of Advanced Biofuels from Waste & Residues.

34) For more details, see AWG's press release: " Müll macht mobil: WSW-Busse fahren mit Wasserstoff aus dem MHKW".

35) More information on the article by Swisspower: " Projet phare chez Limeco à Dietikon : Inauguration de la première installation industrielle Power-to-Gas de Suisse".

36) For a Solar Photovoltaic (SPV) project, the Capacity Utilisation Factor (CUF) is the ratio of actual energy generated by SPV project over the year to the equivalent energy output at its rated capacity over the yearly period.

37) 2021 Ecoprog Industry Barometer Waste-to-Energy.

38) Gabriele Fambri, Cesar Diaz-Londono, Andrea Mazza, Marco Badami, Teemu Sihvonen, Robert Weiss, Techno-economic analysis of Power-to-Gas plants in a gas and electricity distribution network system with high renewable energy penetration, Applied Energy, Volume 312, 2022, 118743, ISSN 0306-2619.

39) Electrolysis and methanation typically have an overall energy conversion efficiency of only 50% (60 to 70% for electrolysis and about 80% for methanation), meaning that 50% of the electrical energy is lost in the conversion process (in heat).

40) Herib Blanco, Wouter Nijs, Johannes Ruf, André Faaij, Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization, Applied Energy, Volume 232, 2018, Pages 323-340, ISSN 0306-2619.

41) Weiss R, Saastamoinen H, Ikäheimo J, Abdurafikov R, Sihvonen T, Shemeikka J. Decarbonised District Heat, Electricity and Synthetic Renewable Gas in Wind- and Solar-based Energy Systems. J Sustain Dev Energy Water Environ Syst. 2021; 9(2):1080340.

42) As pointed out by the Global CCS Institute in their report Waste-to-Energy with CCS: A pathway to carbon-negative power generation (2019).

43) Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, p. 990.

44) Eunomia (2021), CCUS Development pathway for the EfW sector, commissioned by Viridor.

45) Fortum, press release on the project: "Fortum Oslo Varme and our Carbon Capture Project".

46) Envirotec magazine (March 2022), New heights for CCS.

47) Global CCS Institute (2019), Waste-to-Energy with CCS: a pathway to carbon negative power generation.

48) See for instance: Bisinella V, Nedenskov J, Riber C, Hulgaard T and Christensen TH (2022), Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage, Waste Management & research 40, pp. 79-95.

49) When going from 1 to 3 million of tonnes of CO_2, the cost of pipeline transport can be lowered by 50% according to Rambøll's estimations.

50) Newest-CCUS article (2022), "No time to waste: WtE operators in the Netherlands turn up the heat on decarbonisation".

51) Eunomia (2021), CCUS development pathway for the EfW sector, scenario and costs based on UK facilities, original figures in £, converted in € on 03.11.2022.

52) Eunomia (2021), CCUS development pathway for the EfW sector, scenario, and costs based on UK facilities, original figures in £, converted in € on 03.11.2022.

53) Zero Emissions Platform (2019), The cost of subsurface storage of CO_2.

54) Ramboll (2020), CO2 fangst på danske affaldsenergianlæg, commissioned by Dansk Affaldsforening, original figures in DKK, converted into EUR in December 2022.

ESWET

European Suppliers of Waste-to-Energy Technology

WWW.ESWET.EU
INFO@ESWET.EU