



# Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage

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## Abstract

Amending municipal solid waste incineration with carbon capture and storage (CCS) is a new approach that can reduce the climate change impacts of waste incineration. This study provides a detailed analysis of the consequences of amending the new Amager Bakke incinerator in Copenhagen (capacity: 600,000 tonnes waste per year) with CCS as a post-combustion technology. Emphasis is on the changes in the energy flows and outputs as well as the environmental performance of the plant; the latter is assessed by life cycle assessment. Amending Amager Bakke with CCS of the chosen configuration reduces the electricity output by 50% due to steam use by the capture unit, but introducing post-capture flue gas condensation increases the heat output utilized in the Copenhagen district heating system by 20%. Thus, the overall net energy efficiency is not affected. The CCS amendment reduces the fossil CO<sub>2</sub> emissions to 40 kg CO<sub>2</sub> per tonne of incinerated waste and stores 530 kg biogenic CO<sub>2</sub> per tonne of incinerated waste. Potential developments in the composition of the residual waste incinerated or in the energy systems that Amager Bakke interacts with, do not question the benefits of the CCS amendment. In terms of climate change impacts, considering different waste composition and energy system scenarios, introducing CCS reduces in average the impact of Amager Bakke by 850 kg CO<sub>2</sub>-equivalents per tonne of incinerated waste. CCS increases the environmental impacts in other categories, but not in the same order of magnitude as the savings introduced within climate change.

## Keywords

Carbon capture, carbon storage, waste to energy, municipal solid waste, incineration

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## Introduction

Municipal solid waste incineration (MSWI) is the main treatment for residual municipal solid waste (MSW) in Denmark, providing hygienic treatment of the waste, air pollution control (APC) and recovery of energy from the combustion process. Although 71% of the waste generated in Denmark today is collected for recycling and recovery, MSWI still provides the important function of treating non-recyclable waste fractions. Between 2015 and 2019, MSWI treated around 25% of the waste generated in Denmark per year, corresponding to more than 3,000,000 tonnes of waste per year excluding imports (Miljøstyrelsen, 2020). Energy recovery from the combustion process, which occurs via cogeneration of electricity and heat, covers around 6% of the Danish electricity supply and 24% of the Danish heat supply, contributing to Denmark's mission in reducing domestic energy supply from fossil energy sources (Energinet, 2020; Energistyrelsen, 2020).

The newly-built Amager Bakke incineration facility in Copenhagen (operated by Amager Resource Center (ARC) and owned by five municipalities of the Greater Copenhagen

area: Copenhagen, Frederiksberg, Hvidovre, Tårnby and Dragør) is a state-of-the-art MSWI plant with one of the highest energy recovery efficiencies in Europe and is the largest of its kind in the Nordic countries (Hulgaard and Søndergaard, 2018). Famous for its iconic design including a ski slope (Bjarke Ingels Group, 2019), Amager Bakke is designed to treat a large share of the Danish residual waste, with a treatment capacity of around 600,000 tonnes of waste per year. Located close to residential areas and connected to the urban district heating (DH) network, Amager Bakke supplies

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electricity and heat to the Greater Copenhagen area, thereby reducing its dependency on fossil energy sources such as coal and natural gas. Amager Bakke contributes to the initiatives of the Danish capital to become carbon-neutral by 2025–2030 and is foreseen to constitute one of the foundations for the heat supply for the Greater Copenhagen area beyond 2025 (Københavns Kommune, 2012).

However, due to the fossil carbon present in the residual MSW (e.g. non-recyclable plastic and synthetic textiles), MSWI is a net fossil CO<sub>2</sub> emitter. The carbon in the waste is almost completely combusted into CO<sub>2</sub>, resulting in emissions close to 1 tonne of CO<sub>2</sub> per tonne of residual MSW. The fossil carbon content in the flue gas of Danish incinerators is around one-third of the emitted CO<sub>2</sub> (Larsen et al., 2013). Considering the principles of CO<sub>2</sub>-accounting for waste management systems (Christensen et al., 2009), the flue gas emission thus contributes with a climate change impact in the order of 350 kg CO<sub>2</sub>-equivalents (CO<sub>2</sub>-eq) per tonne of incinerated MSW.

The climate change benefit of energy recovery from MSWI outbalances the climate change impacts of the emitted fossil CO<sub>2</sub> when the recovered energy substitutes for the production of electricity and heat from fossil energy sources, such as coal and natural gas (e.g. Astrup et al., 2009). However, with the Danish energy system becoming increasingly less fossil fuel dependent (Energinet, 2020; Kofoed-Wiuff et al., 2020), the energy recovered from MSWI may substitute for the production of energy from renewable sources with a low carbon footprint. As a consequence, the fossil CO<sub>2</sub> emissions from incineration of waste are no longer outbalanced and incineration of waste provides a net climate change impact (Bisinella et al., 2021b).

Amending existing MSWI with carbon capture and storage (CCS) can be a solution to this challenge. ARC is investigating the installation of carbon capture (CC) as a post-treatment technology at Amager Bakke, aiming to be fully operative by 2025 and compliant to Copenhagen's carbon-neutrality mission and to the ambitious goals of the Danish Government for reducing climate change impacts connected to the Danish waste management and energy sectors (Danish Government, 2020a, 2020b). CC is an APC technology already applied in industry for capturing CO<sub>2</sub> from high concentration sources (e.g. ammonia production, fermentation; IPCC (2005)). CC applied to MSWI with subsequent storage of the captured CO<sub>2</sub> reduces climate change impacts by reducing fossil CO<sub>2</sub> emissions to the atmosphere, but also provides a climate change benefit by capturing the biogenic CO<sub>2</sub> from the flue gas and removing it from the carbon cycle (Christensen et al., 2009). The captured CO<sub>2</sub> can be stored underground (Bisinella et al., 2021b) or utilized for chemical products or fuels (Christensen and Bisinella, 2021). Currently, only three operating MSWI plants capture CO<sub>2</sub> for local reuse: AVR and Twence in the Netherlands and Saga City in Japan (Huttenhuis et al., 2016; Kearns, 2019; Wienchol et al., 2020). CCS is at its pilot stage at Fortum Oslo Varme, Norway (Fagerlund et al., 2021). In all cases, the climate change impacts of MSWI were not only considerably reduced but also converted into net climate

change benefits. Converting Amager Bakke to carbon-negative would thus constitute a net benefit for the climate budget of the ARC municipalities, and allow for potential future utilization of the captured CO<sub>2</sub> for chemicals and fuels (Danish Government, 2020b).

The environmental benefits and potential trade-offs of amending Amager Bakke with CCS can be systematically assessed using life cycle assessment (LCA) as early as the planning stage (Christensen et al., 2020; ISO, 2006a, 2006b). Bisinella et al. (2021b) carried out an LCA on different hypothetical MSWI configurations amended with CCS via monoethanolamine (MEA). The study showed how CCS not only reduces the climate change impacts of MSWI by reducing fossil CO<sub>2</sub> emissions to atmosphere, but also provides net climate change savings for the captured and stored biogenic CO<sub>2</sub>. The difference in climate change impacts of MSWI and MSWI amended with CCS, without significant changes in the MSWI configuration, was found proportional to the capture efficiency and to the content of carbon in the waste.

However, such findings cannot be directly generalized to Amager Bakke. The performance of MSWI amended with CCS in terms of energy recovery is largely influenced by the integration of the CCS technology in the MSWI plant and its case-specific effects on the MSWI's energy balance. The energy penalty in terms of steam use for operating the capture unit can reduce the overall energy recovery up to 50% (Bisinella et al., 2021b; Wienchol et al., 2020) and, as a consequence, limits the climate change benefits of substituting energy production from other energy sources. Moreover, the content of biogenic carbon in the waste governs the benefit from capturing biogenic CO<sub>2</sub>. With a lifetime of CCS at Amager Bakke of around 30 years, an LCA needs to take into account not only the conditions at installation, but also the potential future conditions in which Amager Bakke amended with CCS may operate, in terms of potential changes in residual waste composition as collection and recycling systems develop, as well as in terms of the energy systems with which the plant interacts. Only few scientific reports exist on the amendment of CCS to actual waste incinerators (Lousselet et al., 2017; Tang and You, 2018), and to our knowledge no reports exist addressing the energy consequences where also heat recovery is in focus.

The aim of this study is to provide an environmental assessment of amending the Amager Bakke MSWI plant in Copenhagen with CCS utilizing the LCA methodology. The goal of the LCA is to compare the environmental burdens and benefits connected to MSWI at Amager Bakke with and without CCS. The assessment takes into account the different configuration scenarios for integration of CCS with the existing plant, with specific attention to the effects on the energy balance. The assessment makes use of scenario analysis to assess effects of potential changes in the composition of the treated waste (e.g. increased source segregation and collection of recyclables or introduction of a material recovery facility (MRF)), and in the energy system interacting with the MSWI plant (e.g. fossil-free energy system scenarios (ES)) throughout the lifetime of the technology.

## Materials and methods

The environmental assessment of amending Amager Bakke with CCS is carried out with LCA. The LCA compares two configurations of the MSWI plant without CCS to two configurations with CCS, with specific attention to differences of the MSWI energy balance and their effects on the LCA results. Moreover, the interpretation of the LCA results makes use of sensitivity and scenario analyses to assess the variations in environmental impacts of Amager Bakke (with and without CCS amendment) in potential operative conditions throughout its lifetime (2025–2055), which involve changes in the composition of the incinerated waste and developments in the energy system that Amager Bakke interacts with details on LCA methodology, configurations of the MSWI plant, and on waste and energy system scenarios are presented in the following sections.

### LCA methodology

*Goal and scope of the LCA.* The goal of the LCA is to provide a systematic assessment of the potential environmental impacts of introducing CCS at Amager Bakke as post-treatment technology. The aim of the LCA is to compare the environmental impacts of Amager Bakke with and without CCS, considering variations to the MSWI's energy balance and potential effects of changes in the composition of the incinerated waste and the local energy system throughout the lifetime of the CCS amendment. The intended application of the LCA is to support sustainable development of waste management and incineration practices in the Greater Copenhagen area in Denmark.

The LCA analyses one configuration at a time. The functional unit of the study is the treatment of residual Danish MSW with incineration at the Amager Bakke plant in Copenhagen, Denmark, in 2025–2055. The temporal scope of the assessment is the estimated lifetime of the amended CCS technology (30 years). The reference flow is 1 tonne (1000 kg) wet weight (ww) of residual MSW. The composition of the waste is presented in the following dedicated section and in the Supplemental Material.

The system boundaries include ancillary materials (e.g. chemicals) and energy (e.g. start-up fuel and internal energy use) required for the treatment of the waste with incineration, direct emissions from incineration of the waste, as well as ancillary materials and energy required for the treatment of the residues from the incineration process. Additional functionalities (e.g. recovery of energy from the incineration process and recovery of scrap metals from the bottom ashes) are included in the system via system expansion (the assessment includes the benefits from the avoided production of energy and materials recovered from the waste treatment process). Transportation of recovered materials is included. The configurations where MSWI is amended with CCS include emissions related to CO<sub>2</sub> capture, transportation and storage. The study focuses on waste incinerated at Amager Bakke; the system boundaries exclude collection and transportation of waste to the MSWI plant, as well as treatment of source

segregated and collected waste sent to other waste treatments. Increased collection, sorting and recycling in the future is included in the study through the effects on the composition of the incinerated waste. The system boundaries exclude emissions connected to production and end-of-life of equipment and facilities.

The life cycle inventory modelling (LCI) for the MSWI configurations assessed is reported in the following sections and in the Supplemental Material. The LCI modelling approach is consequential, since the aim of the LCA is to analyse potential environmental consequences of introducing CCS at Amager Bakke. The resources utilized and recovered are *marginal* resources expected to change in the long-term, following a small change in demand. The inventories for the resources utilized and recovered in the modelling were retrieved from the Ecoinvent database, version 3.7.1, system expansion, consequential, long-term (Wernet et al., 2016).

The study was carried out with Microsoft Excel and the LCA model EASETECH, developed at the Technical University of Denmark (Clavreul et al., 2014). Microsoft Excel was used to perform calculations on materials and energy balances, and for the interpretation and analysis of the results of the LCA model. EASETECH was used for the LCA model of Amager Bakke, with and without CCS. EASETECH allows specifying the composition of the waste in terms of material fractions (e.g. paper and glass) and physico-chemical properties (e.g. energy content and carbon content), as well as detailed process-specific modelling of waste management technologies. The process-specific modelling of Amager Bakke in this study was linked to the waste composition in terms of emissions, captured carbon and energy recovery. Modelling of other treatment technologies for the residues of MSWI was performed using process models included in the EASETECH database.

The process modelling of Amager Bakke was performed in collaboration with ARC and Ramboll Group and it is considered to be representative for the operation of the MSWI plant for 30 years, 2025–2055. The main technical features of the Amager Bakke configurations are reported in the following dedicated sections. The inventory of emissions was compiled according to ARC observed emissions and operational data from 2020 and to waste material mass balances performed in EASETECH. The energy and mass balances for baseline and future operation modes were modelled by Ramboll Group with the commercial Thermoflex<sup>®</sup> thermodynamic modelling software developed by Thermoflow Inc., USA (Thermoflow, 2021). The composition of the waste treated and the ES in which Amager Bakke operates are studied with scenario analysis and are considered representative of the conditions in the 2025–2055.

*LCA results interpretation.* The study assumes the following characterization factors for the contribution of CO<sub>2</sub> to climate change (Bisinella et al., 2021b; Christensen et al., 2009): (i) emission of biogenic CO<sub>2</sub> from waste bio-products (e.g. food waste): 0 kg CO<sub>2</sub>-eq per kilogram biogenic CO<sub>2</sub>; (ii) emission of

fossil CO<sub>2</sub> from materials based on fossil carbon (e.g. plastic): 1 kg CO<sub>2</sub>-eq per kilogram fossil CO<sub>2</sub>; (iii) storage of biogenic CO<sub>2</sub> permanently (>1000 years): -1 kg CO<sub>2</sub>-eq per kilogram biogenic CO<sub>2</sub>; (iv) storage of fossil CO<sub>2</sub> permanently (>1000 years): 0 kg CO<sub>2</sub>-eq per kilogram fossil CO<sub>2</sub>.

The life cycle impact assessment (LCIA) phase utilizes the European Commission's recommended Environmental Footprint LCIA methods (EF.3), including 16 midpoint impact categories (Fazio et al., 2018; Saouter et al., 2018). The time horizon of the impact characterization is 100 years. The impact categories included are climate change, ozone depletion, human toxicity (cancer and non-cancer effects), particulate matter, ionizing radiation, photochemical ozone formation, acidification, eutrophication (terrestrial, aquatic freshwater and marine), freshwater ecotoxicity, land use, water use and resource use (minerals, metals and energy carriers). The results presented in this LCA study are midpoint impact potentials and do not represent impacts on category endpoints, threshold levels, safety margins or risk levels. The LCA results are further normalized as person equivalents (PE) based on the global normalization factors of Sala et al. (2017). PE is the annual environmental load in the specified categories by one average person covering all life activities (food, housing, travel, etc.). The discussion of the results emphasizes the climate change impact category, as this is believed to be the main focus when addressing CCS. The characterized and normalized results for all impact categories are reported in the Supplemental Material and discussed in the results section.

The LCA results for two Amager Bakke configurations without CCS and for two Amager Bakke configurations with CCS were calculated with a baseline waste composition (WC2, see dedicated section) and within a baseline ES (ES3, see dedicated section). The LCA results interpretation phase involved identifying the processes contributing the most to the results, for each configuration assessed and impact category. Moreover, the study systematically analysed potential variations in LCA results caused by changes in waste composition and energy system (epistemic uncertainty) and by input values in the model (parameter uncertainty).

The robustness of the results with respect to changes in waste composition and energy system (epistemic uncertainty) was tested with scenario analysis. Scenarios offer the structured framework for addressing the epistemic uncertainty of the future conditions in which Amager Bakke will operate (Mendoza Beltran et al., 2018). In this study, scenarios do not provide predictions of the future, but rather are used to describe potential operative conditions for Amager Bakke. Scenarios are a 'rehearsing space' intended to highlight central elements of possible futures and draw attention to important waste composition and energy system aspects that can affect the sustainability assessment and performance of the MSWI when introducing CCS (Bisinella et al., 2021a). The sensitivity of the LCA results with respect to input values used in the LCA modelling (parameter uncertainty) was analysed with sensitivity analysis. This involved

calculating normalized sensitivity ratios (SRs) for each input value used in the model for each environmental impact assessed and energy scenario, as described in Bisinella et al. (2017, 2016), in order to identify potential environmental hotspots.

### *Amager Bakke MSWI*

The Amager Bakke plant includes two identical lines each with a furnace with a moving grate followed by a high-pressure steam boiler (Hulgaard and Søndergaard, 2018). The main technical elements of ARC for material use, air emissions and APC are listed in Table 1 ('baseline' and 'baseline heat pump (HP)'). After particle removal in an electrostatic precipitator (ESP), the flue gas is treated with selective catalytic reduction (SCR) that reduces nitrogen oxides (NO<sub>x</sub>; NO and NO<sub>2</sub>) to a low level by use of ammonia water, and also destroys dioxin, prior to a four-stage wet flue gas treatment. A first-stage acidic scrubber targets hydrogen chloride (HCl), hydrogen fluoride (HF) and residual heavy metals (including mercury) after the ESP. A second-stage limestone alkaline scrubber removes sulphur dioxide (SO<sub>2</sub>) before a two-stage flue gas condensation with additional polishing of the flue gas with activated carbon injection in the scrubber system.

Energy flows in Amager Bakke are illustrated in Figure 1 and Table 2. Energy recovery from the waste occurs by combined heat and power generation with a highly efficient steam turbine that is common for the two lines. In the baseline configurations without CCS, Amager Bakke can operate in two different modes with different energy recovery in terms of power and heat production, depending on the flue gas condensation stages. In the first configuration ('baseline', Table 2), the power generation efficiency is 25.4% of the lower heating value (LHV) of the treated waste. The turbine condenser produces DH corresponding to 63% of thermal input. Additional heat is recovered by direct flue gas condensation which is characterized by heat exchange between the warm liquid of the scrubber of flue gas condenser and the less warm DH return flow, adding 9%-point to the thermal efficiency of the plant. The total gross thermal efficiency of this operating mode is 98%. Around 70 kWh of electricity per tonne of incinerated waste is used in the operation of furnace, APC and direct flue gas condensation.

In the second operating mode ('baseline HP', Table 2), the heat recovery of the flue gas condensation is extended by using an absorption HP for a second-stage flue gas condensation. The HP uses steam that is extracted from the turbine at around 7 bar(a), causing the power generation efficiency to drop to 22.8% of the thermal input. The turbine condenser output drops to 49%, but the direct and HP-driven flue gas condensation add a total of 20%, and the steam used for the HP adds another 15% to the DH output, making a total gross thermal efficiency of 107% (23 + 49 + 20 + 15 = 107). Although this appears to conflict with the fundamental laws of thermodynamics, it does not. The explanation is that it is common practice (in Europe) to refer to the thermal efficiency as energy input measured by the LHV of input waste. This definition implies that the water vapour released

**Table 1.** Inventory of Amager Bakke plant with and without CCS amendment. The table includes main technical features of the APC system, material use and air emissions. Water emissions are reported in the Supplemental Material.

Amager Bakke configuration	Baseline		CCS	
	Baseline	HP**	Net zero	Net zero, lower T***
<b>Technical features APC</b>				
Particle removal	Yes	Yes	Yes	Yes
APC system (scrubbing)	Wet	Wet	Wet	Wet
Dioxin filter	Yes	Yes	Yes	Yes
deNO <sub>x</sub> technology	SCR	SCR	SCR	SCR
CC	No	No	Yes, MEA	Yes, MEA
<b>Material use</b>				
Diesel (m <sup>3</sup> tonne <sup>-1</sup> ww)	0.001 <sup>1</sup>	0.001 <sup>1</sup>	0.001 <sup>3</sup>	0.001 <sup>3</sup>
Activated carbon (kg tonne <sup>-1</sup> ww)	0.3 <sup>1</sup>	0.3 <sup>1</sup>	0.3 <sup>3</sup>	0.3 <sup>3</sup>
Ammonia water (24.5%) (kg tonne <sup>-1</sup> ww)	2 <sup>1</sup>	2 <sup>1</sup>	2 <sup>3</sup>	2 <sup>3</sup>
CaCO <sub>3</sub> (95%) (kg tonne <sup>-1</sup> ww)	11 <sup>1</sup>	11 <sup>1</sup>	11 <sup>3</sup>	11 <sup>3</sup>
FeCl <sub>3</sub> (40%) (kg tonne <sup>-1</sup> ww)	0.06 <sup>1</sup>	0.06 <sup>1</sup>	0.06 <sup>3</sup>	0.06 <sup>3</sup>
NaOH (27%) (kg tonne <sup>-1</sup> ww)	0.4 <sup>3</sup>	0.4 <sup>3</sup>	0.5 <sup>3</sup>	0.5 <sup>3</sup>
MEA (kg tonne <sup>-1</sup> ww)	0	0	1 <sup>4</sup>	1 <sup>4</sup>
Polymer* (100%) (kg tonne <sup>-1</sup> ww)	0.007 <sup>1</sup>	0.007 <sup>1</sup>	0.007 <sup>3</sup>	0.007 <sup>3</sup>
TMT-15* (15%) (kg tonne <sup>-1</sup> ww)	0.02 <sup>1</sup>	0.02 <sup>1</sup>	0.02 <sup>3</sup>	0.02 <sup>3</sup>
Water (m <sup>3</sup> tonne <sup>-1</sup> )	0.06 <sup>1</sup>	0.06 <sup>1</sup>	0.06 <sup>3</sup>	0.06 <sup>3</sup>
<b>Air emissions</b>				
SO <sub>2</sub> (g tonne <sup>-1</sup> ww)	10 <sup>1</sup>	10 <sup>1</sup>	10 <sup>2</sup>	10 <sup>2</sup>
HCl (g tonne <sup>-1</sup> ww)	3 <sup>1</sup>	3 <sup>1</sup>	3 <sup>2</sup>	3 <sup>2</sup>
NO <sub>x</sub> (g tonne <sup>-1</sup> ww)	158 <sup>1</sup>	158 <sup>1</sup>	158 <sup>2</sup>	158 <sup>2</sup>
NH <sub>3</sub> (g tonne <sup>-1</sup> ww)	1 <sup>3</sup>	1 <sup>3</sup>	1 <sup>2</sup>	1 <sup>2</sup>
Particles (g tonne <sup>-1</sup> ww)	7 <sup>1</sup>	7 <sup>1</sup>	7 <sup>2</sup>	7 <sup>2</sup>
Hg (g tonne <sup>-1</sup> ww)	0.008 <sup>1</sup>	0.008 <sup>1</sup>	0.008 <sup>2</sup>	0.008 <sup>2</sup>
Pb (g tonne <sup>-1</sup> ww)	0.0006 <sup>1</sup>	0.0006 <sup>1</sup>	0.0006 <sup>2</sup>	0.0006 <sup>2</sup>
Cd (g tonne <sup>-1</sup> ww)	0.001 <sup>1</sup>	0.001 <sup>1</sup>	0.001 <sup>2</sup>	0.001 <sup>2</sup>
As (g tonne <sup>-1</sup> ww)	0.008 <sup>1</sup>	0.008 <sup>1</sup>	0.008 <sup>2</sup>	0.008 <sup>2</sup>
HF (g tonne <sup>-1</sup> ww)	0.0004 <sup>1</sup>	0.0004 <sup>1</sup>	0.0004 <sup>2</sup>	0.0004 <sup>2</sup>
CO (g tonne <sup>-1</sup> ww)	0.03 <sup>1</sup>	0.03 <sup>1</sup>	0.03 <sup>2</sup>	0.03 <sup>2</sup>
PAH (mg tonne <sup>-1</sup> ww)	0.0002 <sup>1</sup>	0.0002 <sup>1</sup>	0.0002 <sup>2</sup>	0.0002 <sup>2</sup>
Ni (mg tonne <sup>-1</sup> ww)	0.004 <sup>1</sup>	0.004 <sup>1</sup>	0.004 <sup>2</sup>	0.004 <sup>2</sup>
Mn (mg tonne <sup>-1</sup> ww)	0.007 <sup>1</sup>	0.007 <sup>1</sup>	0.007 <sup>2</sup>	0.007 <sup>2</sup>
Dioxin (µg tonne <sup>-1</sup> ww)	0.009 <sup>1</sup>	0.009 <sup>1</sup>	0.009 <sup>2</sup>	0.009 <sup>2</sup>

Source: The MEA consumption is estimated in accordance with The Danish Energy Agency and Energinet (2020).

<sup>1</sup>Data derived from Amager Bakke operation in 2020, obtained from ARC. Air emissions are rounded up or the detection limit is used as basis whenever the measurements are below the respective detection limits.

<sup>2</sup>Conservatively estimated not to change after amendment with CC. The assessment is conservative because the CC system is an add-on to the existing APC-system, including an absorber and a post-absorber flue gas condensation stage which acts as an additional APC-stage that removes pollutants, including breakdown products of MEA.

<sup>3</sup>Material use is estimated not to change except for the ones used in the CC-process.

<sup>4</sup>Changes after amendment with CC. Ramboll's own calculations based on MEA capture process with a 90% capture efficiency.

\*Not included in the LCA modelling due to lack of inventories for production data.

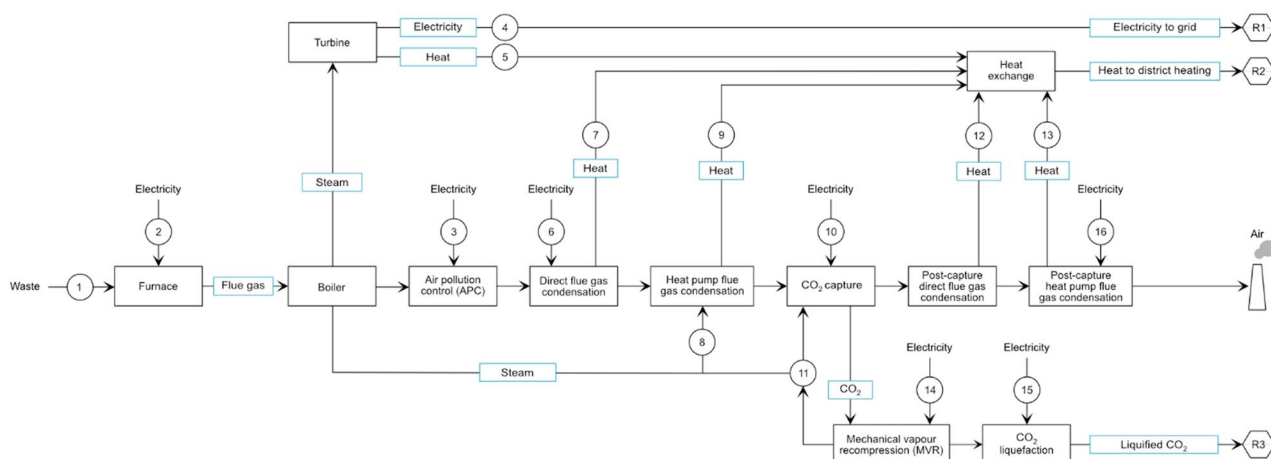
\*\*HP: Additional heat pumps are introduced in the baseline configuration.

\*\*\*Lower T' differs from the main CCS-case only by operation against lower DH temperatures – which does not affect material use or air emissions.

during combustion leaves the system in an evaporated state. The LHV does, thus, not include the heat of condensation. When flue gas condensation is applied, this precondition is violated and values above 100% are possible (Hulgaard and Søndergaard, 2018). The internal electricity use is unaffected at 70 kWh tonne<sup>-1</sup> of treated waste, for electricity use in the furnace, APC and flue gas condensation.

The residues from Amager Bakke are APC residues (APC; fly ash, gypsum and sludge), bottom ash, scrap metals,

wastewater and condensate. Fly ashes are currently utilized in Norway for neutralization of waste acid, substituting limestone (Maresca et al., 2021). Ferrous and non-ferrous metals are separated from the bottom ash and sent to recycling processes. Bottom ash is used for road construction, substituting gravel. Dry gypsum formed by absorption of sulphur dioxide by limestone in the scrubbing system is collected and recycled as gypsum mineral. Process wastewater from the plant is treated on site at Amager Bakke. Sludge generated from waste water treatment is disposed



**Figure 1.** Energy flows in Amager Bakke with the modelled CC-system. The values corresponding to the numbered flows 1–16 are reported in Table 2.

R1: electricity grid; R2: DH network; R3: CO<sub>2</sub> storage.

**Table 2.** Technical features of energy production in Amager Bakke and technical energy flows, for configurations with and without CCS. The energy flows correspond to numbered flows 1–16 illustrated in Figure 1. Data derived from calculations performed by Ramboll Group, own experience from commercial flue gas condensation installations and in line with data of Danish Energy Agency and Energinet (2020).

Amager Bakke configuration	Baseline		CCS	
	Baseline	HP	Net zero	Net zero, lower T
Technical features, energy production				
Power production	Yes	Yes	Yes	Yes
Heat production	Yes	Yes	Yes	Yes
Direct flue gas condensation	Yes	Yes	Yes	Yes
Absorption HP flue gas condensation	No	Yes	No	Yes
Post-CC direct flue gas condensation	No	No	Yes	Yes
Post-CC electricity driven HP	No	No	Yes	Yes
Technical energy flows				
1. Waste input, LHV, GJ tonne <sup>-1</sup> ww	10.8	10.8	10.8	10.8
2. Electricity use, furnace, kWh tonne <sup>-1</sup> ww	34	34	34	34
3. Electricity use, APC, kWh tonne <sup>-1</sup> ww	27	27	27	27
4. Electricity recovery, turbine, gross, % of LHV	25.4	22.8	22.5	22.5
5. Heat recovery, turbine condensation, gross, % of LHV	62.9	49.3	44.5	44.5
6. Electricity use, direct flue gas condensation, kWh tonne <sup>-1</sup> ww	7	7	7	7
7. Heat recovery, direct flue gas condensation, % of LHV	9	9	9	10
8. Steam use, HP flue gas condensation (GJ tonne <sup>-1</sup> ww)	–	1.63	–	–
9. Heat recovery, HP flue gas condensation (% of LHV)*	–	26.0	–	–
10. Electricity use, CO <sub>2</sub> capture kWh tonne <sup>-1</sup> ww	–	–	42	44
11. Steam use, CO <sub>2</sub> capture GJ tonne <sup>-1</sup> CO <sub>2</sub>	–	–	2.49	2.49
12. Heat recovery, CO <sub>2</sub> capture, heat exchange GJ tonne <sup>-1</sup> CO <sub>2</sub>	–	–	2.03	2.55
13. Heat recovery, CO <sub>2</sub> capture, compression HP GJ tonne <sup>-1</sup> CO <sub>2</sub>	–	–	2.06	1.92
14. Electricity use, MVR kWh tonne <sup>-1</sup> ww	–	–	105	104
15. Electricity use, CO <sub>2</sub> liquefaction, kWh tonne <sup>-1</sup> ww	–	–	42	42
16. Electricity use, electricity driven HP of CC-system, kWh tonne <sup>-1</sup> ww	–	–	109	101
Total gross thermal efficiency, % of LHV	98	107	111	115

\*including driving energy (steam).

MVR: mechanical vapour recompression.

of in a landfill for hazardous waste in Denmark. Condensate extracted from the flue gas condensation stage is used to cover losses in the DH network, substituting for demineralized water. The inventories for the treatment of residues are available in the Supplemental Material.

### Amager Bakke MSWI with CCS

CC at Amager Bakke. CC is a flue gas treatment technology for post-combustion separation and capture of CO<sub>2</sub>. Several CC technologies exist: MEA scrubbing, pressure swing operation,

hydrate-based, cryogenic distillation and membrane filtration. The CC technology considered for amendment to Amager Bakke is based on MEA; often used in the context of MSWI (Bisinella et al., 2021b).

The MEA-based CC amendment for Amager Bakke was modelled by Ramboll Group. After direct flue gas condensation (one-stage only, Table 2), the cooled flue gas at around 55°C is fed into a CO<sub>2</sub> absorber containing a 30% MEA solution, which absorbs around 90% of the CO<sub>2</sub> in the flue gas at 1 bar. After the CO<sub>2</sub> absorber, the flue gas is condensed to 30–35°C with a two-stage post-capture flue gas condensation before being emitted through the stack. The CO<sub>2</sub>-rich MEA-solution from the CO<sub>2</sub> absorber is heated to 104°C and fed into a CO<sub>2</sub> stripper at 1.8 bars, which makes use of steam extracted from the turbine at 170°C and 7 bar(a), the pressure of which is reduced to the reboiler pressure of 3 bar(a). In the stripping process, the CO<sub>2</sub> desorbs from the MEA and leaves saturated with water vapour. The CO<sub>2</sub>-rich water vapour is then fed into a MVR step, which in two stages compresses the mixture causing the temperature to rise. After each stage, the mixture is cooled by heat exchange with condensate that vaporizes to be used as part of the feed to the reboiler, effectively reducing the need of extraction steam to supply the reboiler. Water condenses out of the CO<sub>2</sub> per water vapour mixture when cooling. After the MVR system the CO<sub>2</sub>-pressure is 15 bar(a) at which pressure the CO<sub>2</sub> is cooled and liquefied in a conditioning stage, and leaves the system at –30°C and 14 bar(a) as liquid CO<sub>2</sub> for transportation in pipes. We assume that the refrigerant used has no significant environmental impact.

Additional material use and air emissions due to the CC amendment are reported in Table 1, ‘CC net zero’ and ‘CC net zero, lower T’. After the stripping process, the MEA is cooled and reused for CO<sub>2</sub> absorption. However, part of the MEA degrades during the process (releasing 0.1 kg NH<sub>3</sub> per tonne CO<sub>2</sub> captured, which is separated in the post-absorber flue gas condensation stages), or is lost due to formation of heat-stable salts or as vapour and aerosols during stripping. This study considers a MEA use of around 1 kg tonne<sup>-1</sup> of CO<sub>2</sub>. This value is lower than the 4 kg tonne<sup>-1</sup> of CO<sub>2</sub> in Bisinella et al. (2021b) because some suppliers will guarantee lower values and hence new units can have lower consumption. NaOH is also added at the stripping step (Table 1, materials use). In total, CC produces around 1 kg (dry matter) of residue per tonne of CO<sub>2</sub> captured. This waste is disregarded in this study but will probably be incinerated in the facility and hence we assume that the amount and composition of residues will not change significantly after amending Amager Bakke with CC.

*Effect of CC on energy balance.* The effects of the CC amendment on the Amager Bakke energy balance are summarized in Table 2, ‘CCS net zero’ and ‘CCS net zero, lower T’. The CO<sub>2</sub> stripper requires steam extraction from the turbine, which has shown to lower the overall energy efficiency of MSWI plants (Bisinella et al., 2021b; Wienchol et al., 2020). For this reason, the CC amendment for Amager Bakke was modelled by Ramboll

Group in order to maximize heat recovery from the capture process and reach as close as possible an overall ‘net zero’ difference in terms of overall net energy efficiency with the baseline configurations without CCS.

In a first configuration (Table 2, ‘CCS net zero’), the steam extraction from the turbine for the CC process lowers the power generation to 22.5% of the LHV of the treated waste, and lowers the DH production from the turbine condenser system and direct flue gas condensation to a DH output of 53.5% of thermal input. The HP flue gas condensation stage is taken out of operation because the cooling provided in this stage is not necessary for the functioning of the absorber, the same amount of heat may be extracted in the post-absorber condensation by heat exchange (without using HPs), and to save the extraction steam for the stripper. Instead, additional heat recovery takes place with a two-stage post-capture flue gas condensation (Figure 1), with a direct condensation stage followed by a HP driven condensation stage – in this case cooled by an electricity-driven HP. This two-stage post-capture flue gas condensation allows recovering 4 GJ tonne<sup>-1</sup> of captured CO<sub>2</sub>, for a total gross thermal efficiency of 111%. The total electricity use in this configuration is 367 kWh tonne of incinerated waste, due to use in the CO<sub>2</sub> capture and MVR-system and liquefaction, but also for the second post-combustion flue gas condensation via electricity-driven vapour compression HP.

In another possible operating case (Table 2, ‘CCS net zero’, lower T), representing a likely future development, the temperature level of the DH network is lowered to yield a return temperature of 45°C and requires a flow temperature of 95°C instead of 108°C used in the other cases. Lowering of the DH temperature level facilitates the integration of the large amounts of low temperature heat that may be recovered from the CC-system, limiting the need of using HPs for the recovery. The lower DH temperature level increases the heat recovery from the CC-system to 4.5 GJ tonne<sup>-1</sup> of captured CO<sub>2</sub> (or 38% of thermal input to the MSWI-plant) and slightly lowers the internal electricity use to 360 kWh tonne<sup>-1</sup> of incinerated waste due to less energy required for energy reclamation via electricity-driven vapour compression HP. The total gross thermal efficiency of this operating mode is 115%.

The heat recovery opportunities are not fully exhausted with the considered system, for example, recovering the heat from the liquefaction process would add around 4%-point plant efficiency increase.

*Transport and storage of CO<sub>2</sub>.* After compression to 14 bar and cooling to –30°C, liquid CO<sub>2</sub> can be transported to a suitable storage site where it is injected and permanently stored. In general, the transportation of CO<sub>2</sub> may take place in road tankers, railroad tankers, sea carriers (similar to liquefied natural gas carriers) or by pipeline. The choice of transportation depends on the amount of CO<sub>2</sub>, the lifetime of the transportation scheme, the destination, transport logistics (e.g. harbours, railroads and roads) and, ultimately, the costs involved. Pipeline transport is usually

possible within the supercritical envelope of CO<sub>2</sub> – the typical range is between 85 and 150 bar, and between 13 and 44°C, to ensure a stable single-phase flow through the pipeline (Leung et al., 2014). Transport by small vessels may take place at low temperatures (from –22 to –28°C) and moderate pressures (15–18 bar), according to Haugen et al. (2017), IPCC (2005) suggests that the physical CO<sub>2</sub>-loss by transportation by pipeline amounts to 1%–2% of the transported CO<sub>2</sub> per 1000 km, and approximately 2.5% by ship. Pour et al. (2018) calculated that CO<sub>2</sub> transportation from an MSWI plant, although details were not specified, amounted to a net climate change load of 30 kg CO<sub>2</sub> per tonne of MSW. Suitable storage sites are geological formations such as depleted oil and gas reservoirs, un-mineable coal beds, saline aquifers or basalts, where liquid CO<sub>2</sub> is injected about 1 km below the Earth's surface (European Parliament, 2009).

The liquid CO<sub>2</sub> captured at Amager Bakke is assumed transported by means of a 1.5 km concrete-covered steel DN125 pipeline to the nearby harbour of Prøvestenen. Here it can be stored for short term before transportation by sea carrier: 12 cylindrical tanks of 760 m<sup>3</sup> each, allow short-term storage for a maximum of 5 days. CO<sub>2</sub> is then transported in tanks by dedicated ships to the storage site from existing harbour facilities at Prøvestenen. The ships are assumed to be similar to existing ships used to transport liquefied natural gas.

The selection process for the storage site is still ongoing. Potential locations are exhausted oil and gas fields in the Northern Sea. The Northern Lights Project would allow storing CO<sub>2</sub> in geological structures off the coast of Norway. The CO<sub>2</sub> is transported by ship to a receiving station on the coast. From the coast, an 110 km pipeline transports CO<sub>2</sub> to storage site, which stores CO<sub>2</sub> 3 km into the geological formation. A second potential site is the former gas field Cecilie in the Danish part of the North Sea, operated by the gas company Ineos. CO<sub>2</sub> is transported by ship to a floating platform and injected from there.

We assume that the transport involves 1150 km, which is the average distance from Amager Bakke to the potential storage sites, assuming an emission of 0.02 kg CO<sub>2</sub>-eq per metric tonne transported per km (Ecoivent 3.7.1, sea carrier transportation with cooling). With 931 kg CO<sub>2</sub> captured per tonne ww waste, this amounts to around 20 kg CO<sub>2</sub>-eq per tonne ww. Moreover, we assume that the transportation process causes a loss of 2.5% of the transported CO<sub>2</sub>. These assumptions are in accordance with IPCC (2005) and Pour et al. (2018). IPCC (2005) assumes that a good storage site can keep 99% of CO<sub>2</sub> confined for more than 1000 years. Leakage may take place while injecting and closing off injection wells, while off-site migration is marginal. We assume that at a suitable permanent storage site, 2% of CO<sub>2</sub> will be lost due to injection and off-site migration.

### Waste composition scenarios

The composition of the incinerated waste material in terms of material fractions (e.g. paper and glass) and physico-chemical

composition associated to each waste material fraction (e.g. water content and carbon content) affects MSWI emissions, materials and energy required, as well as recovered energy and materials (Bisinella et al., 2017). Key physico-chemical characteristics are the water content and energy content (LHV) of the waste, which allow estimating the energy recovered from the MSWI plant. The carbon content of the incinerated waste and the share of fossil and biogenic carbon affect the climate change impacts of MSWI, and the performance of MSWI amended with CCS.

The characteristics of the incinerated waste material cannot be generalized a priori, since the overall physico-chemical composition is a result of the relative contribution of different waste material fractions. This relative contribution depends on multiple factors (e.g. waste type, geography and type of dwellings), especially the waste collection and recycling schemes in place in the MSWI plant catchment area and any pre-sorting before incineration (e.g. utilization of a MRF) (Edjabou et al., 2021).

Currently, Amager Bakke treats approximately 600,000 tonnes of waste per year, composed of different waste types, in varying amounts: residual household waste, residual commercial waste and other residual waste from Denmark or Europe. Imported waste needs to comply with import restrictions (e.g. low organics and plastic content) set by ARC's climate strategy, aiming at importing only low-carbon waste (details in Supplemental Material). The composition of the incinerated waste is expected to vary during the lifetime of the CCS amendment, due to variations in relative share of the waste types incinerated and variations in their fractional and physico-chemical composition. Instead of providing a precise estimate of how the waste composition will vary during the lifetime of the CCS amendment, we provide three compositions based on plausible collection schemes and share between waste types that cover the operative range of Amager Bakke in terms of LHV and provide different carbon content and share between biogenic and fossil carbon.

The waste compositions utilized for this study are presented in Table 3, ordered from left to right based on the overall LHV. The three compositions all represent residual MSW after collection of recyclables (paper, cardboard, metal and glass) and organic waste. The first composition on the left (WC1) represents a scenario where the collection of recyclables does not increase with respect to the current situation, and the relative content of organic waste incinerated is relatively high (63% of the carbon is of biogenic origin). This scenario is expected to cover a situation where the LHV of the waste is 9.3 GJ tonne<sup>-1</sup> ww. The second scenario (WC2) represents the baseline scenario, where the composition of the incinerated waste reflects the current segregation rates for recyclables and organics in the Copenhagen area. This composition is compliant to CO<sub>2</sub> emissions and LHV observed at Amager Bakke for residual MSW (61% biogenic and 39% fossil, with an LHV of 10.8 GJ tonne<sup>-1</sup> ww). The third scenario (WC3) represents the case where most of the recyclables and organics are separated from the RMSW, either by source segregation schemes or MRF. In this scenario, the waste has a lower water content and a higher energy content (12.7 GJ tonne<sup>-1</sup> ww) and the share of



**Table 3.** Material fraction composition and key physico-chemical characteristics per tonne of residual MSW received at the MSWI plant. Details provided in the Supplemental Material, Section 3.

Waste composition scenario	WC1	WC2 (baseline)	WC3
Material fraction composition (% ww)			
Kitchen organics	44	34	8
Garden and yard waste	5	4	1
Paper and paper products	10	9	11
Cardboard	3	4	2
Milk and juice cartons	2	3	2
Plastic	23	18	6
Glass	3	4	1
Metals	3	3	5
Other, combustible	17	25	52
Other, non-combustible	4	4	12
Physico-chemical characteristics			
Total solids (kg)	548	586	728
Water (kg)	452	414	272
Volatile solids (kg)	419	455	512
Ash (kg)	128	131	215
Carbon, biogenic (kg)	160	169	175
Carbon, fossil (kg)	93	110	141
Carbon, total (kg)	253	280	316
Carbon, biogenic (% of total carbon)	63	61	55
Carbon, fossil (% of total carbon)	37	39	45
Energy content (LHV, GJ)	9.3	10.8	12.7

biogenic carbon is relatively lower (55%). Details on the waste compositions are presented in the Supplemental Material.

### Energy system scenarios

The use and recovery of energy in Amager Bakke with and without CCS amendment, presented in the previous sections and Table 2, affect the LCA results depending on the energy sources substituted in the energy market. Production of electricity and heat from different sources (e.g. coal, natural gas and wind) is associated with different environmental impacts depending on the energy source (e.g. high or low climate change impacts per unit energy provided), thus affecting the substitutional value of the net energy recovered at Amager Bakke. The recovered energy is assumed to affect energy production technologies outside the life cycle system boundary, that is, the marginal energy technologies in the market that are likely to react to changes in demand or supply in the lifetime of the CCS amendment (30 years). According to the approach of Weidema et al. (1999), long-term marginal energy technologies are those technologies whose future installed capacity is planned to change within the temporal scope of the study.

However, precise determination of capacity changes in the energy system of Copenhagen during the lifetime of the CCS amendment (2025–2055) is a complex task. While the electricity market is national and connected to neighbouring countries, heat

**Table 4.** Energy system scenarios. Details are provided in the Supplemental Material.

Energy technology	Energy scenarios				
	ES1	ES2	ES3 baseline	ES4	ES5
Electricity					
Natural gas	100%	50%	34%		
Wind onshore		25%	29%		
Wind offshore		25%	31%		100%
Solar (photovoltaics)			6%	100%	
kg CO <sub>2</sub> -eq per kWh	0.43	0.25	0.17	0.09	0.02
Heat					
Natural gas	100%				
Biomass with LUC		100%	27%		
Electricity in HPs			73%	100%	100%
kg CO <sub>2</sub> -eq per MJ	0.07	0.05	0.02	0.001	0.001

LUC: land use change.

cannot be transported far and made available nationally, and determination of the heat marginal needs to comply with local conditions and foreseen changes locally. The heat market is the current DH systems (one with a higher temperature used for process heat and one with a lower temperature used for space heating). Additional markets may develop if households and businesses not currently using DH, can be supplied by DH. Amager Bakke is connected to two DH systems, which supply heat to the Greater Copenhagen area: CTR/VEKS and of Amagerland. The two grids are connected and in terms of marginal can be seen as one grid. The Danish energy system is transitioning towards non-fossil and renewable energy with the purpose of reducing climate change impacts, with political targets aiming to reach fossil-free electricity and heat within 2050 (Danish Government, 2020b).

For this study, we follow two approaches. The first is to identify the marginal technologies for electricity and heat generation for the lifetime of the CCS amendment based on future energy scenarios for Denmark and the Nordic countries (International Energy Agency, 2016) following the approach of Weidema et al. (1999) and available reports on the current and foreseen developments for the Danish energy system (Danish Energy Agency, 2020; Fjernvarme Miljønetværk Hovedstaden, 2021). The second approach is based on scenario analysis. The purpose of the scenarios obtained is to cover potential alternative options for the energy system (and the environmental impact connected to the energy production technologies) to test the robustness of the LCA results. For this reason, and the focus on climate change impacts, the energy scenarios were chosen in order to span from fossil fuel-based energy sources to non-fossil based energy sources.

The scenarios utilized for the present study are presented in Table 4. The baseline scenario (ES3) is composed by the relative share of technologies foreseen to increase in capacity during the lifetime of the CCS amendment. The climate change impacts in the baseline energy scenario are 0.17 kg CO<sub>2</sub>-eq kWh<sup>-1</sup> for electricity and 0.02 kg CO<sub>2</sub>-eq per MJ for heat. The findings are in accordance to foreseen changes up to 2030 of electricity and heat provision in Denmark (Danish Energy Agency, 2020; Danish Government, 2020b). Further

**Table 5.** Carbon and energy balance for the baseline waste composition scenario (WC2). The results provided are independent of the ES. The numbers marked R1–R3 refer to identically numbered icons in Figure 1.

Amager Bakke configuration	Baseline		CCS	
	Baseline	HP	Net zero	Net zero, lower T
<b>Carbon balance</b>				
CO <sub>2</sub> in the flue gas (kg tonne <sup>-1</sup> ww)	1023	1023	1023	1023
CO <sub>2</sub> emitted, total, stack (kg tonne <sup>-1</sup> ww)	1023	1023	102	102
CO <sub>2</sub> emitted, fossil, stack (kg tonne <sup>-1</sup> ww)	404	404	40	40
CO <sub>2</sub> emitted, biogenic, stack (kg tonne <sup>-1</sup> ww)	619	619	62	62
CO <sub>2</sub> captured, total (kg tonne <sup>-1</sup> ww) (R3)	–	–	920	920
CO <sub>2</sub> captured, fossil (kg tonne <sup>-1</sup> ww)	–	–	363	363
CO <sub>2</sub> captured, biogenic (kg tonne <sup>-1</sup> ww)	–	–	557	557
CO <sub>2</sub> emitted, total, transportation and storage (kg tonne <sup>-1</sup> ww)	–	–	41	41
CO <sub>2</sub> emitted, fossil, transportation and storage (kg tonne <sup>-1</sup> ww)	–	–	16	16
CO <sub>2</sub> emitted, biogenic, transportation and storage (kg tonne <sup>-1</sup> ww)	–	–	25	25
CO <sub>2</sub> stored, total (kg tonne <sup>-1</sup> ww)	–	–	879	879
CO <sub>2</sub> stored, fossil (kg tonne <sup>-1</sup> ww)	–	–	347	347
CO <sub>2</sub> stored, biogenic (kg tonne <sup>-1</sup> ww)	–	–	532	532
<b>Energy balance</b>				
Electricity recovery, net (kWh tonne <sup>-1</sup> ww) (R1)	693	615	307	314
Heat recovery, net (GJ tonne <sup>-1</sup> ww) (R2)	7.8	9.1	9.6	10.0
Net energy efficiency (% of LHV)	95	105	99	104

four ES presented in Table 4 were defined in order to span from fossil fuel-based energy systems (e.g. the highest impacts arise from 0.43 kg CO<sub>2</sub>-eq per kWh electricity and 0.07 kg CO<sub>2</sub>-eq per MJ heat based on natural gas) to non-fossil based energy systems (e.g. the ‘greenest’ scenario presents 0.02 kg CO<sub>2</sub>-eq per kWh electricity based on off-shore wind power; 0.001 kg CO<sub>2</sub>-eq per MJ heat based on electricity-driven HPs). Details on ES are provided in the Supplemental Material.

## Results and discussions

### Carbon and energy balance

The carbon and energy balance results for the baseline waste composition scenario (WC2, Table 3) are shown in Table 5. The baseline waste composition yields approximately 1 tonne of CO<sub>2</sub> per tonne of combusted waste, of which 39% is of fossil origin. Therefore, in its baseline configuration without CCS, Amager Bakke emits around 400 kg of fossil CO<sub>2</sub> from combustion of 1 tonne of waste. The energy recovery without CCS varies depending on the flue gas condensation stages. In the baseline configuration (Table 2, ‘baseline’), with an LHV of the treated waste of 10.8 GJ tonne<sup>-1</sup> ww, the net electricity and heat recovery amount to 690 kWh tonne<sup>-1</sup> ww and 7.8 GJ tonne<sup>-1</sup> ww, respectively, thereby reaching an overall net energy efficiency of 95% of the LHV of the treated waste. In the baseline configuration with steam-driven HP (Table 2, ‘baseline HP’), a lower net electricity recovery of 615 kWh tonne<sup>-1</sup> ww allows higher net heat recovery of 9.1 GJ tonne<sup>-1</sup> ww, for an overall net efficiency of 105% of the LHV of the treated waste.

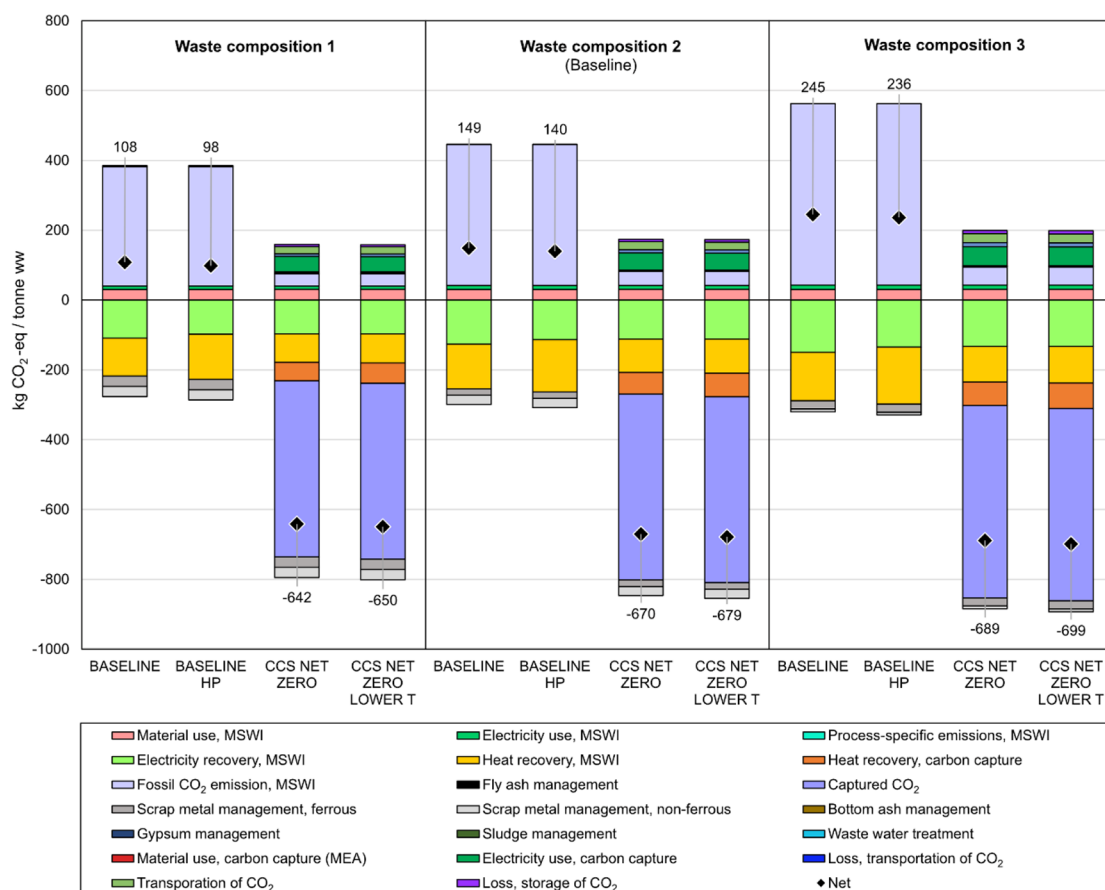
With the CCS amendment, Amager Bakke lowers its fossil CO<sub>2</sub> emissions in the flue gas to 40 kg CO<sub>2</sub> per tonne of incinerated waste. The captured CO<sub>2</sub> at Amager Bakke amounts to around 920 kg of CO<sub>2</sub> per tonne of incinerated waste. Of these,

16 kg of fossil CO<sub>2</sub> are emitted to atmosphere due to 2.5% of the CO<sub>2</sub> lost to atmosphere during transportation and with further 2% loss due to storage site injection and off-site migration. The captured and long-term stored amount of CO<sub>2</sub> is around 880 kg, of which 532 kg are of biogenic origin.

The energy recovery and overall efficiency with CCS amendment depend on the chosen operative mode. In ‘CCS net zero’, the net electricity recovery decreases by 56% with respect to ‘baseline’ without CCS due to the internal energy use for capture, compression and electricity-driven HP flue gas condensation post-capture. With CCS the net electricity recovery is 307 kWh tonne<sup>-1</sup> ww. However, the net heat recovery increases by 23% with respect to ‘baseline’. The post-capture flue gas condensation allows recovering 3.8 GJ tonne<sup>-1</sup> ww, for a net heat recovery of 9.6 GJ tonne<sup>-1</sup> ww and an overall net energy efficiency of 99%. In the configuration with a lower DH return temperature ‘CCS net zero, lower T’, the net electricity recovery of 314 kWh tonne<sup>-1</sup> ww is also 55% lower than ‘baseline’. However, the lower DH return temperature allows higher post-capture energy recovery (4.1 GJ tonne<sup>-1</sup> ww), higher net heat recovery of 10 GJ tonne<sup>-1</sup> (an increase of 28% with respect to ‘baseline’) and an overall energy efficiency of 104% of the LHV of the treated waste.

### LCA results

*Climate change results.* The LCA results for the climate change impact category for Amager Bakke with and without CCS amendment are illustrated in Figure 2, central section, and provided in detail in the Supplemental Material, section S5. Electricity use and electricity recovery are illustrated separately in Figure 2 in order to highlight the contribution of electricity use for the capture process on the results.



**Figure 2.** LCA results and climate change impact category, for the three waste composition scenarios (WC1, WC2 and WC3, Table 3) and baseline ES (ES3, Table 4). Results are provided in kg CO<sub>2</sub>-eq per tonne ww of incinerated waste and subdivided according to the processes contributing to the results. The Amager Bakke configurations with and without CCS correspond to those reported in Tables 1 and 2. The characterization factors for fossil and biogenic CO<sub>2</sub> are provided in 2.1.2.

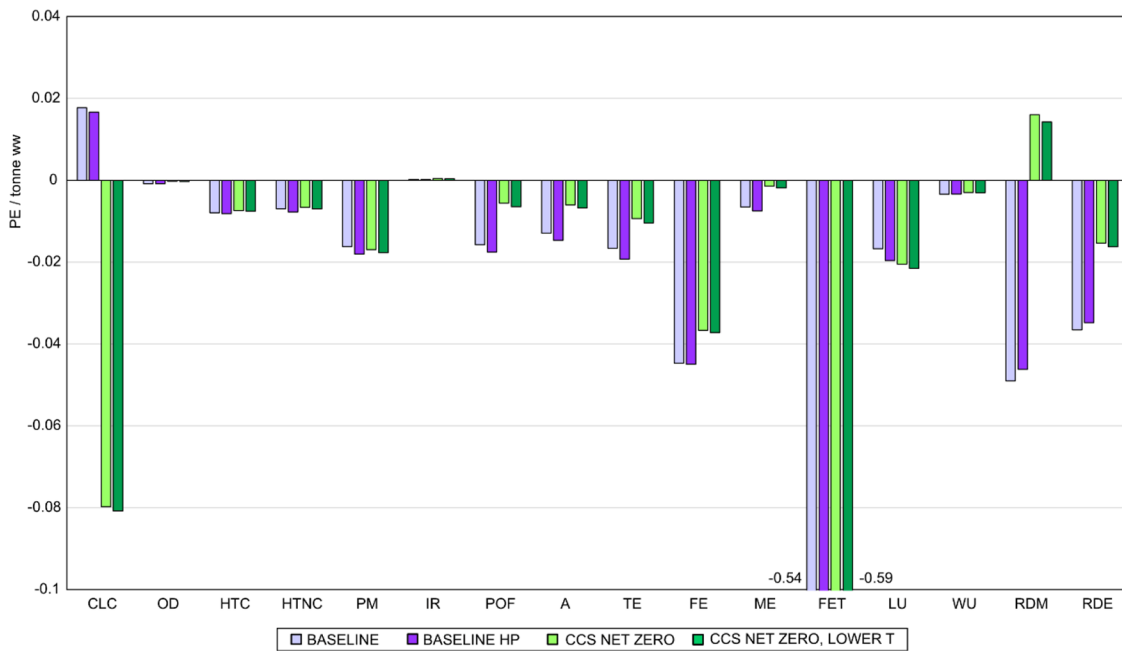
Without CCS amendment, in the ‘baseline’ configuration Amager Bakke results in a net climate change impact of about 150 kg CO<sub>2</sub>-eq per tonne ww. Fossil CO<sub>2</sub> emission to atmosphere as a result of waste incineration contributes with a climate change impact of 400 kg CO<sub>2</sub>-eq per tonne ww, while energy recovery in terms of electricity and heat in the baseline ES (0.17 kg CO<sub>2</sub>-eq per kWh, 0.02 kg CO<sub>2</sub>-eq per MJ, cf. ES3 baseline in Table 4) contributes with climate change savings of –125 kg CO<sub>2</sub>-eq per tonne ww for electricity and –130 kg CO<sub>2</sub>-eq per tonne ww for heat. Climate change impacts from material and energy use in the MSWI and disposal of residues are compensated by the climate change benefits of scrap metal recovery. In the configuration with steam-driven HPs for flue gas condensation ‘baseline HP’, the climate change impact is only slightly lower with respect to ‘baseline’ (140 kg CO<sub>2</sub>-eq per tonne ww).

With CCS amendment, Amager Bakke ‘CCS net zero’ shows net climate change benefits of –670 kg CO<sub>2</sub>-eq per tonne ww. The largest benefit derives from storage of captured biogenic CO<sub>2</sub>, which provides a climate change benefit of –530 kg CO<sub>2</sub>-eq per tonne ww. CC also lowers the fossil CO<sub>2</sub> emitted to atmosphere, thus lowering the climate change impact from emitted flue gas to 40 kg CO<sub>2</sub>-eq per tonne ww. Operation with CCS shows burdens due to additional electricity use, and

transportation and loss of CO<sub>2</sub>. The net benefit from electricity recovery reduces to –60 kg CO<sub>2</sub>-eq per tonne ww (half with respect to the baseline MSWI configuration without CCS). Transportation and loss of captured CO<sub>2</sub> cause a climate change impact of around 30 kg CO<sub>2</sub>-eq per tonne ww. Additional benefits are obtained from post-capture heat recovery, with –60 kg CO<sub>2</sub>-eq per tonne ww, which allows obtaining an overall net benefit from heat recovery of –160 kg CO<sub>2</sub>-eq per tonne ww. The MEA consumption for the capture process adds only 4 kg CO<sub>2</sub>-eq per tonne ww to the climate change impacts of CCS amended configurations.

The configuration with CCS and lower DH return temperature ‘CCS net zero, lower T’ allows for higher heat recovery and lower electricity consumption for capture. The overall net benefit from heat recovery is –165 kg CO<sub>2</sub>-eq per tonne ww and the overall climate change benefits of this configuration are about –680 kg CO<sub>2</sub>-eq per tonne ww.

Overall, introducing CCS at Amager Bakke is estimated to improve the climate change impacts by about 820 kg CO<sub>2</sub>-eq per tonne ww with respect to the ‘baseline’ configuration and by 810 kg CO<sub>2</sub>-eq per tonne ww with respect to ‘baseline HP’. With lower DH return temperature, the benefits increase to almost 830 kg CO<sub>2</sub>-eq per tonne ww with respect to the ‘baseline’



**Figure 3.** Normalized impact results in PE per tonne ww. Details are provided in the Supplemental Material. CLC: climate change; OD: ozone depletion; human toxicity (HTC, cancer and HTNC, non-cancer effects); PM: particulate matter, IR: ionizing radiation; POF: photochemical ozone formation; A: acidification; eutrophication (TE: terrestrial, FE: aquatic freshwater and ME: marine); FET: freshwater ecotoxicity; LU: land use; WU: water use; and resource use (RDM: minerals and metals and RDE: energy carriers).

configuration and to 820 kg CO<sub>2</sub>-eq per tonne ww with respect to 'baseline HP'.

*Other impact categories.* The normalized results for all impact categories assessed in this LCA study are presented in Figure 3 in PE per tonne ww of incinerated waste, for the baseline waste composition (WC2, Table 3) and energy system (ES3, Table 4). The results are reported in the Supplemental Material, including the analysis of the processes contributing to the results.

Almost all impact categories show environmental benefits, with and without CCS. Climate change is the impact category showing the largest difference in results due to CCS amendment, which change from impacts to benefits with more than -500%. The largest normalized benefits are obtained for the freshwater ecotoxicity impact category due to the recovered heat that partially substitutes heat production from biomass (ES3, Table 4). The benefits for freshwater ecotoxicity slightly increase with CCS, for the higher heat recovery. Slightly increased benefits for recovered heat with respect to 'baseline' are obtained also for the impact categories particulate matter and land use.

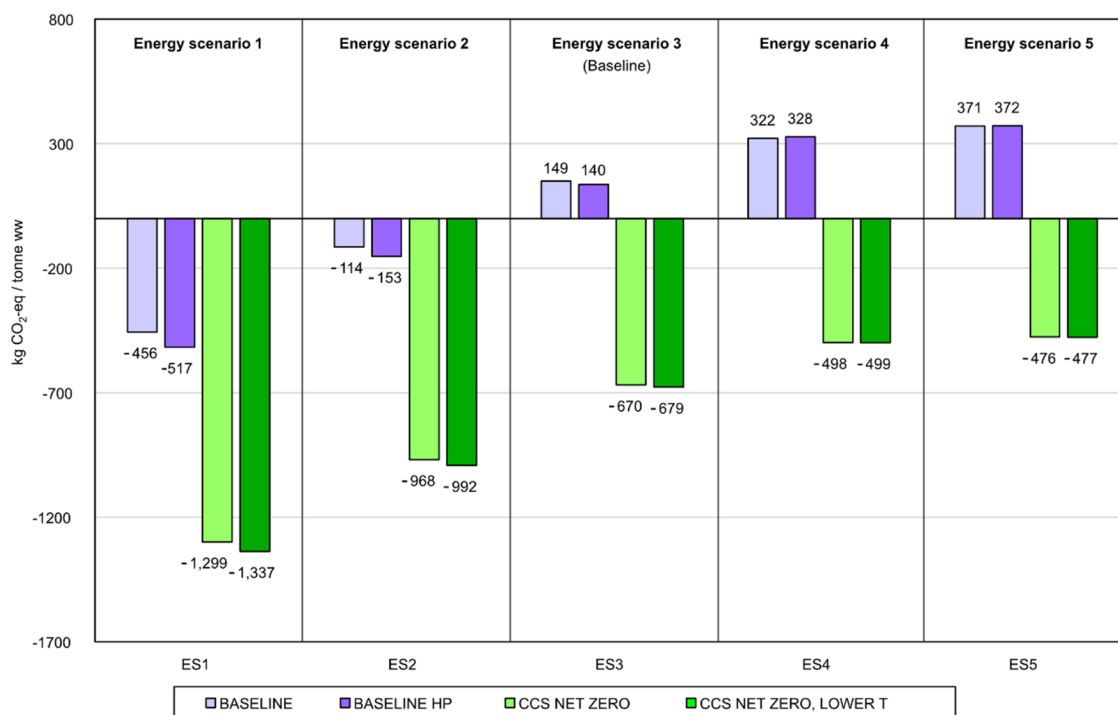
The benefits connected to the remaining impact categories decrease with amendment with CCS. The benefits decrease in the order of 10% for the impact categories: human toxicity, cancer and non-cancer effects, freshwater eutrophication and water use. Larger variations were observed for the impact categories ozone depletion, ionizing radiation, photochemical ozone formation, acidification, terrestrial, freshwater and marine eutrophication and resource depletion, both for minerals and energy. The largest increase in impacts occurs for resource depletion, minerals,

which changes from benefit to burden. In all cases, the decrease in environmental benefits with CCS amendment is due to lower electricity recovery, additional electricity use for capture, and transport fuel use for the sea carrier (see process contribution analysis, Supplemental Material, Section 5). In particular, the increase in the resource depletion impact category is due to use of mineral resources connected to the provision of transport fuel. Overall, relative variations in other impact categories are lower than the benefit gained in the climate change impact category. This suggest that in the future focus must also be on the fuel use of the ships carrying the captured CO<sub>2</sub> to the injection site.

### Waste composition scenarios

The LCA results for the climate change impact category with scenario analysis on the waste composition are shown in Figure 2. The results are based on the baseline energy scenario (ES3), and change with respect to waste composition scenarios (WC1, WC2 and WC3). The results for WC2 correspond to the net climate change results illustrated in 3.2.1. Results for all impact categories are provided in the Supplemental Material.

Without CCS amendment, the emission of fossil CO<sub>2</sub> with WC1 is lower than in the baseline waste composition scenario WC2 (340 kg CO<sub>2</sub> per tonne ww), but increases with WC3 to 516 kg CO<sub>2</sub> per tonne ww, due to the higher amount of carbon and higher relative share of fossil carbon in WC3. Due to the different LHV of the incinerated waste, WC1 and WC3 provide different net energy recovery than in the baseline waste composition scenario. 'baseline' WC1 yields 595 kWh tonne<sup>-1</sup> ww and 6.9 GJ



**Figure 4.** LCA results, climate change impact category, for the baseline waste composition scenario (WC2, Table 3) and the five ESs (ES1–ES5, Table 4). Results are provided in kg CO<sub>2</sub>-eq per tonne of incinerated waste. The Amager Bakke configurations with and without CCS correspond to those reported in Tables 1 and 2.

tonne<sup>-1</sup> ww, while WC3 yields 820 kWh tonne<sup>-1</sup> ww and 8.8 GJ tonne<sup>-1</sup> ww. In ‘baseline HP’ the heat recovery is higher, with 530 kWh tonne<sup>-1</sup> ww and 8.2 GJ tonne<sup>-1</sup> ww for WC1 and 731 kWh tonne<sup>-1</sup> ww and 10.4 GJ tonne<sup>-1</sup> ww for WC3.

With CCS amendment, the fossil CO<sub>2</sub> emission reduces to 34 kg CO<sub>2</sub> per tonne ww for WC1 and to 52 kg CO<sub>2</sub> per tonne ww for WC3. After transportation and storage losses, the stored CO<sub>2</sub> is around 810 kg CO<sub>2</sub> per tonne ww for WC1 and 1015 kg CO<sub>2</sub> per tonne ww for WC3. However, the amount of stored biogenic CO<sub>2</sub> is relatively higher for WC1 than WC3 (514 and 560 kg CO<sub>2</sub> per tonne ww, respectively). CCS amendment reduces net electricity recovery. In ‘CCS net zero’, WC1 yields 212 kWh tonne<sup>-1</sup> ww and 9.0 GJ tonne<sup>-1</sup> ww, while WC3 yields 411 kWh tonne<sup>-1</sup> ww and 10.2 GJ tonne<sup>-1</sup> ww. In the configuration with lower DH return temperature ‘CCS net zero, lower T’ the heat recovery is higher, with 261 kWh tonne<sup>-1</sup> ww and 8.2 GJ tonne<sup>-1</sup> ww for WC1 and 387 kWh tonne<sup>-1</sup> ww and 11.2 GJ tonne<sup>-1</sup> ww for WC3.

The climate change results for WC1 and WC3 show small variations with respect to the baseline waste composition scenario, especially in comparison to the change in result induced by the introduction of the CCS amendment. The variations in climate change results with WC1 and WC3 with respect to the baseline waste composition WC2 are larger (in the order of 30%–50%) without CCS amendment, due to the fossil CO<sub>2</sub> emissions. The variation in climate change results with CCS amendment is negligible with changes in the waste composition scenarios (3%–4% variation with respect to the baseline waste composition scenario). The difference in climate change impacts with and without CCS

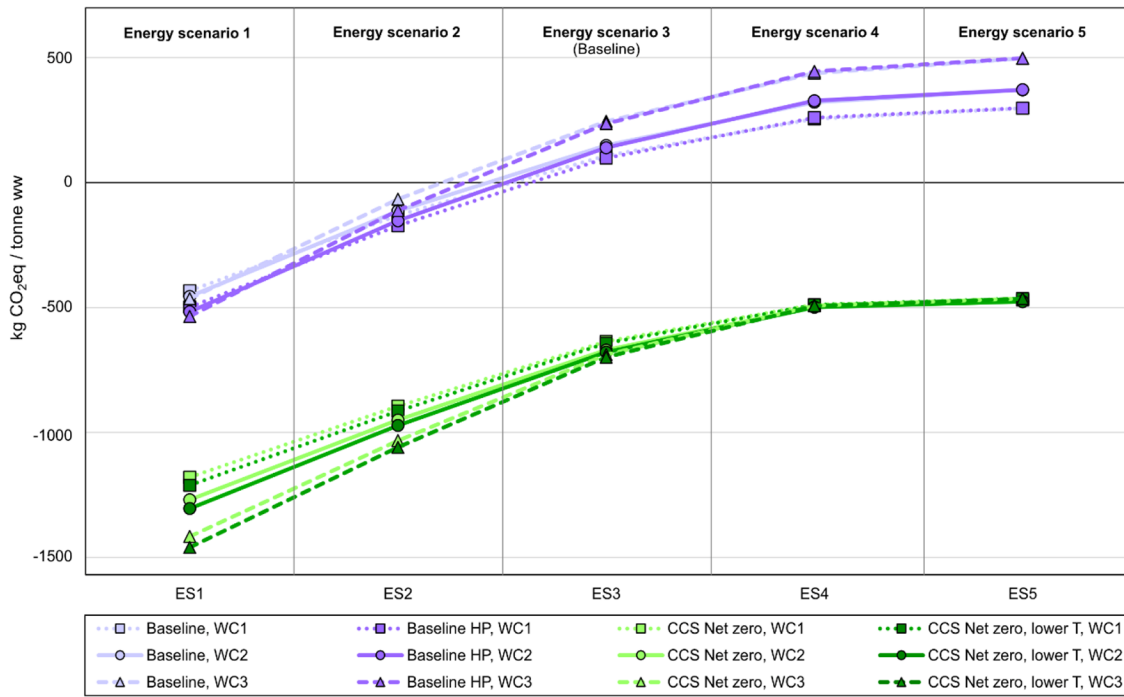
amendment is largest for WC3 (around 940 kg CO<sub>2</sub>-eq per tonne ww), due to the largest share and emissions of fossil CO<sub>2</sub>.

The LCA results for the other impact categories are also affected by the change of waste composition. However, the effects are due mostly to the change in LHV, which affects the energy recovery and the benefits from substituting production of energy from other energy sources. The impact categories affected the most are those already listed in 3.2.2. The variation in results between MSWI with and without CCS amendment is due to is due to lower electricity recovery, additional electricity use for capture and transport fuel use for the captured CO<sub>2</sub>. The variation in results with CCS amendment is largest with WC3, due to the higher sensitivity of energy recovery with higher LHV of the waste.

### Energy system scenarios

The climate change results for the ES analysis for the baseline waste composition (WC2) are shown in Figure 4. The results for ES3 correspond to the net climate change results illustrated in 3.2.1. The results for all impact categories are provided in the Supplemental Material.

The ESs influence the LCA results more than the waste composition scenarios. With a fixed waste composition, the variation in the results is strongly connected to the environmental profile of the utilized and recovered electricity and heat (see Table 4). In more fossil-based energy systems such as ES1 and MSWI without CCS provides environmental savings (–456 kg CO<sub>2</sub>-eq per tonne ww for ‘baseline’, ES1), since the



**Figure 5.** Summary of climate change results for each ES and waste composition scenario for Amager Bakke configurations with and without CCS.

fossil CO<sub>2</sub> emissions are outbalanced by climate change savings from recovered electricity and heat. However, already in the baseline energy system (ES3) and in completely ‘green’ energy systems (ES5), MSWI without CCS is a net burden for climate change (around 370 kg CO<sub>2</sub>-eq per tonne ww for ‘baseline’, ES5), when the climate change savings connected to the recovered energy do not outbalance the fossil CO<sub>2</sub> emissions. With CCS, MSWI provides environmental benefits in all the assessed ESs, ranging from around -1300 kg CO<sub>2</sub>-eq per tonne ww for ‘CCS Net zero’, ES1, to around -475 kg CO<sub>2</sub>-eq per tonne ww for ‘CCS net zero’, ES5.

The difference in climate change results between configurations with and without CCS is more sensitive with respect to the energy system choice in fossil-based energy systems, where energy recovery has a relatively higher contribution to the overall results. In ES1, the difference between ‘baseline’ and ‘CCS net zero’ is around 850 kg CO<sub>2</sub>-eq per tonne ww, and 880 kg CO<sub>2</sub>-eq per tonne ww between ‘baseline’ and ‘CCS net zero, lower T’. Considering the configuration with HP use, ‘baseline HP’ varies from ‘CCS net zero’ at 780 kg CO<sub>2</sub>-eq per tonne ww and at 820 kg CO<sub>2</sub>-eq per tonne ww from ‘CCS net zero, lower T’. In ‘greener’ energy systems, such as ES4 and ES5, the relative contribution to the results of energy recovery is negligible and the results are mainly governed by the emitted fossil CO<sub>2</sub> and captured and stored biogenic CO<sub>2</sub>. This can be seen in ES5, where the difference between configurations without CCS and configurations with CCS stabilizes to 850 kg CO<sub>2</sub>-eq per tonne ww.

In other impact categories, results differ with respect to ES3 when changing the energy system. However, the difference in

results with respect to ES3 is governed by the different substitutional value of the recovered energy rather than introduction of CCS. The environmental impacts connected to the ESs do not necessarily decrease from fossil-based to ‘green’ energy systems, and differ according to the specific characteristics of the energy technologies composing the scenarios and the impact categories considered (e.g. heat production from biomass is characterized by higher acidification and eutrophication impacts than in other heat production technologies). However, in ES4 and ES5 the environmental impacts for utilized and recovered electricity and heat decrease with respect to ES1–ES3 across most impact categories. With a decreased substitutional value for energy recovery, the benefits of MSWI with and without CCS decrease and become environmental impacts for ozone depletion, ionizing radiation, photochemical ozone formation, acidification, terrestrial and marine eutrophication, freshwater ecotoxicity, land use and resource depletion, minerals and energy. With lower savings and lower contribution from energy recovery in most impact categories, the difference between MSWI with and without CCS is ascribable to material use in the MSWI and transportation fuel utilized to transport the captured CO<sub>2</sub> to the storage site. The contribution of fuel consumption is more significant for ionizing radiation and for resource depletion, minerals.

*Sensitivity analysis and robustness*

Figure 5 summarizes the results of scenario analysis on the waste composition and on the energy system, illustrating the climate change results for MSWI configurations with and without CCS,

for each ES and waste composition scenario. The analysis of the results illustrated in Figure 5 is supplemented with sensitivity analysis. The normalized SRs associated to model parameters for the baseline waste composition and each ES are reported in the Supplemental Material (Tables S27–S28).

In fossil-based energy systems (ES1 and ES2), energy recovery parameters (e.g. electricity and heat recovery, Table 2) have the highest sensitivity and the substitutional value for recovered electricity and heat is governing the results. MSWI is a net climate benefit, with or without CCS. Without CCS, the results show negligible variation, due to the lower sensitivity of the fossil carbon content and the fossil CO<sub>2</sub> emissions in comparison to energy recovery parameters. For the same reason, results for Amager Bakke with CCS show larger variation, due to the high sensitivity of increased energy recovery and due to the higher LHV of WC3.

In ‘greener’ energy systems (ES4 and ES5), the sensitivity of the energy recovery parameters is negligible. The results depend almost exclusively on the CC efficiency and on the carbon content of the waste. Here configurations without CCS are a net climate change burden, and only configurations with CCS provide a net climate change saving. Without CCS, results are very sensitive with respect to the fossil carbon content of the waste. Variation in the climate change impact for the configuration with CCS is negligible. Both in fossil-based and greener energy systems, the loss of CO<sub>2</sub> from transportation and storage shows negligible sensitivity compared to the CC efficiency.

Overall, the results of scenario analysis on waste composition and energy system show that, moving towards a fossil-free energy system, Amager Bakke without CCS is becoming an environmental burden for climate change. The extent of the environmental burden is very sensitive to changes in the fossil carbon content in the waste, potentially spanning from 260 to 500 kg CO<sub>2</sub>-eq per tonne ww. On the other hand, Amager Bakke with CCS shows consistently climate change benefits. While the climate change results for configurations with CCS are very sensitive to the LHV of the waste and energy scenario in fossil-based energy systems, the results stabilize towards fossil-free energy systems to –500 kg CO<sub>2</sub>-eq per tonne ww and depend exclusively on the CC efficiency and biogenic carbon content of the waste. The higher the capture efficiency and the higher the biogenic content of the waste, the lower the overall net climate change impact of the incinerator with CCS. In ES5, the difference in climate change impacts between Amager Bakke with and without CCS is proportional to the carbon content of the incinerated waste and the capture efficiency, as previously observed in Bisinella et al. (2021b). The average difference in climate change results between configurations with and without CCS is 850 kg CO<sub>2</sub>-eq per tonne ww, ranging from 820 in ES1 to 860 in ES5. Figure 5 provides a valuable ‘operative envelope’ for climate change impacts of Amager Bakke depending on the substitutional value of the energy recovered and on possible developments in waste composition.

The process modelling of Amager Bakke, based on ARC data and carried out in collaboration with Ramboll Group, is

considered representative for the environmental performance of Amager Bakke in the time scope of the study. The transport via sea carrier considered in this study was assumed similar to transport of liquefied natural gas, and it is expected that the transport fuel will improve its environmental performance in the future, therefore reducing its contribution to impacts across impact categories. The results are also considered stable with respect to additional needs of energy for further compression of CO<sub>2</sub> prior to injection in the storage site. If the energy consumption is as high as the one utilized in Amager Bakke, further compression will require 30 kg CO<sub>2</sub>-eq per tonne ww, therefore not really affecting the benefits of CCS.

The baseline ES utilized is considered relevant for Denmark in the temporal scope of the study. Greener energy systems show a situation where the substitutional value (climate change impact) for electricity and heat is negligible, a condition that will hopefully be reached in the future. More fossil-based energy systems, other than allowing to understand the environmental performance of MSWI transitioning from fossil-based to green energy system, may also represent a transition situation where electricity is exported to neighbouring countries that rely more on fossil fuels (this is expected to change in the future as well, as more countries will transition to renewables (Danish Energy Agency, 2020)), and a situation where DH expands at the expense of small natural gas plants or individual oil based heating.

The CC efficiency is assumed to slightly increase throughout the lifetime of the amendment due to technological improvements. The amount of captured and stored carbon depends on the carbon content in the incinerated waste. The waste compositions utilized in the scenario analysis were based on recent data from ARC’s catchment area. The waste composition scenario WC3 was obtained assuming drastic source segregation and collection rates (or MRF prior to incineration), where more than 80% of the recyclables and organic waste in the residual MSW were separated from the waste stream. The aim of WC3 was to analyse effects of dramatic changes in the incinerated waste on the LCA results of the CCS amendment, while actual future changes to the incinerated waste at Amager Bakke are expected to be less dramatic.

## Conclusion

The recently built Amager Bakke MSWI in Copenhagen (Capacity: 600,000 tonnes per year) delivers to society around 615 kWh electricity and 9.1 GJ heat per tonne ww of MSW incinerated. However, the plant is a net burden with respect to climate change corresponding to 140 kg CO<sub>2</sub>-eq per tonne ww waste incinerated. As the Danish energy system becomes even greener, the burden to climate change will increase to 370 kg CO<sub>2</sub>-eq per tonne ww.

Amending the Amager Bakke MSWI with CCS as post-combustion technology affects the energy balance of the plant reducing the electricity delivery to 310 kWh but increasing the heat

delivery to 9.5 GJ heat per tonne ww. However, depending of the use of HPs and the temperature level in the DH systems, the overall net energy efficiency may not change dramatically by introducing CCS: 95%–105% without CCS and 99%–104% with CCS calculated on LHV.

With an assumed CC efficiency of 90%, around 900 kg CO<sub>2</sub> per tonne of incinerated waste will be captured. Accounting for the operational penalties, the transport and storage of the captured CO<sub>2</sub>, this improves the climate change impacts of the Amager Bakke MSWI by 820 kg CO<sub>2</sub>-eq per tonne ww (from 140 to –680 kg CO<sub>2</sub>-eq per tonne ww).

Scenario analyses considering possible developments in residual waste composition as well as in the Danish energy system, which the Amager Bakke MSWI interacts with, show that benefits of introducing CCS are significant and the climate change benefits are likely to increase slightly as the energy system becomes green. In a green energy system, the energy recovery of the MSWI is of less importance and the dominant parameter is the CC efficiency.

The robust results obtained suggest that fully implementing CCS at Amager Bakke could save around 500,000 tonnes CO<sub>2</sub> annually independent of likely developments in waste composition and in the surrounding energy system. While Amager Bakke today is a net burden in terms of climate change in spite of significant recovery of energy, introducing CCS converts Amager Bakke to a net saver in climate change with a continued high delivery of energy.

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### Supplemental material

Supplemental material for this article is available online.

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