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Environmental Assessment of Amending the Amager Bakke Incineration Plant in Copenhagen with Carbon Capture and Storage (CCS)

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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/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 (LCA). 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 CO₂ emissions to 40 kg CO₂ per tonne of incinerated waste and stores 530 kg biogenic CO₂ 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 CO₂-eq 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

Abbreviations

APC	Air pollution control
ARC	Amager Ressource Center
Bar(a)	Bar absolute pressure
CC	Carbon capture
CCS	Carbon capture and storage
DH	District heating
ES	Energy system scenario
ESP	Electrostatic precipitator
FU	Functional unit
HP	Heat pump
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value
LUC	Land use change
MRF	Material recovery facility
MSW	Municipal solid waste
MSWI	Municipal solid waste incineration
MVR	Mechanical vapor recompression
NO _x	Nitrogen oxides (i.e. NO and NO ₂)
PE	Person equivalent
PSA	Pressure swing operation
SCR	Selective catalytic reduction
SM	Supplementary material
WC	Waste composition scenario
ww	Wet weight

1. 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 three million 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 Ressource 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 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, synthetic textiles), MSWI is a net fossil CO₂ emitter. The carbon in the waste is almost completely combusted into CO₂, resulting in emissions close to one tonne of CO₂ per tonne of residual MSW. The fossil carbon content in the flue gas of Danish incinerators is around one-third of the emitted CO₂ (Larsen et al., 2013). Considering the principles of CO₂-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 CO₂-equivalents per tonne of incinerated MSW.

The climate change benefit of energy recovery from MSWI outbalances the climate change impacts of the emitted fossil CO₂ 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 CO₂ 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 CO₂ from high concentration sources (e.g. ammonia production, fermentation; IPCC (2005)). CC applied to MSWI with subsequent storage of the captured CO₂ reduces climate change impacts by reducing fossil CO₂ emissions to the atmosphere, but also provides a climate change benefit by capturing the biogenic CO₂ from the flue gas and removing it from the carbon cycle (Christensen et al., 2009). The captured CO₂ 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 CO₂ 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 reduced considerably, 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 CO₂ 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 CO₂ emissions to atmosphere, but also provides net climate change savings for the captured and stored biogenic CO₂. The difference in climate change impacts of MSWI and MSWI amended with CCS, without significant changes in the MSWI configuration, were 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, limit 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 CO₂. 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 the energy systems with which the plant interacts. Only few scientific reports exist on the amendment of CCS to actual waste incinerators (Lausselet 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 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), and in the energy system interacting with the MSWI plant (e.g. fossil-free energy system scenarios) throughout the lifetime of the technology.

2. MATERIALS AND METHODS

The environmental assessment of amending Amager Bakke with CCS is carried out with LCA (section 2.1). The LCA (section 2.1.1) compares two configurations of the MSWI plant (section 2.2) without CCS to two configurations with CCS (section 2.3), with specific attention to differences of the MSWI energy balance and their effects on the LCA results. Moreover, the interpretation of the LCA results (section 2.1.2) makes use of sensitivity analysis and scenario analysis 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 (section 2.4) and developments in the energy system that Amager Bakke interacts with (section 2.5).

2.1 LCA methodology

2.1.1 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 analyzes one configuration at a time. The functional unit (FU) of the study is the treatment of residual Danish municipal solid waste 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 one tonne (1000 kg) wet weight (ww) of residual municipal solid waste. The composition of the waste is presented in section 2.4 and in the Supplementary Material (SM).

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, i.e. 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. Specific details on energy recovery are presented in sections 2.2 and 2.3. The configurations where MSWI is amended with CCS include emissions related to CO₂ 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 (2.2. and 2.3) and in the SM. The LCI modelling approach is consequential, since the aim of the LCA is to analyze 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, glass) and physico-chemical properties (e.g. energy content, 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 section 2.2 and 2.3. 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® thermodynamic modelling software developed by Thermoflow Inc. (Thermoflow, 2021). The composition of the waste treated and the energy system scenarios in which Amager Bakke operates are studied with scenario analysis and are considered representative of the conditions in the years 2025-2055 (sections 2.4 and 2.5).

2.1.2 LCA results interpretation

The study assumes the following characterization factors for the contribution of CO₂ to climate change (Bisinella et al., 2021b; Christensen et al., 2009): (i) emission of biogenic CO₂ from waste bio-products (e.g. food waste): 0 kg CO₂-eq/kg biogenic CO₂; (ii) emission of fossil CO₂ from materials based on fossil carbon (e.g. plastic): 1 kg CO₂-eq/kg fossil CO₂; (iii) storage of biogenic CO₂ permanently (>1000 years): -1 kg CO₂-eq/kg biogenic CO₂; (iv) storage of fossil CO₂ permanently (>1000 years): 0 kg CO₂-eq/kg fossil CO₂.

The life cycle impact assessment (LCIA) phase utilizes the European Commission's recommended Environmental Footprint life cycle impact assessment methods (EF.3), including 16 midpoint impact categories (Fazio et al., 2018; Saouter et al., 2020). 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, ionising 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 SM and discussed in the results section.

The LCA results for two Amager Bakke configurations without CCS (section 2.2) and for two Amager Bakke configurations with CCS (section 2.3) were calculated with a baseline waste composition (WC2, section 2.4) and within a baseline energy system scenario (ES3, section 2.5). 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 analyzed 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 (section 2.4) and energy system (section 2.5) (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 analyzed with sensitivity analysis. This involved calculating normalized sensitivity ratios 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.

2.2 Amager Bakke MSWI

The Amager Bakke plant includes two identical lines each with a furnace with a moving grate that is 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 HP”). After particle removal in an electrostatic precipitator (ESP), the flue gas is treated with selective catalytic reduction (SCR) that reduces nitrogen oxides (NO_x) 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 sulfur dioxide (SO₂) 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 district heating (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 heat pump (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 lower heating value (LHV) of input waste. This definition implies that the water vapor released 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 of treated waste, for electricity use in the furnace, air pollution control (APC) and flue gas condensation.

The residues from Amager Bakke are APC residues (APCr; 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 sulfur 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 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 SM.

Table 1. Inventory of Amager Bakke plant with and without carbon capture and storage (CCS) amendment. The table includes main technical features of the APC system, material use and air emissions. Water emissions are reported in the SM.

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

¹ 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.

² Conservatively estimated not to change after amendment with carbon capture. 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 break-down products of MEA.

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

⁴ Changes after amendment with carbon capture. Ramboll's own calculations based on MEA capture process with a 90% capture efficiency (section 2.3.1). The MEA consumption is estimated in accordance with The Danish Energy Agency and Energinet, (2020).

* 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, cf. section 2.3.2 – which does not affect material use or air emissions.

Figure 1. Energy flows in Amager Bakke with the modeled CC-system. The values corresponding to the numbered flows 1-16 are reported in Table 2. R1: electricity grid; R2: DH network; R3: CO₂ storage.

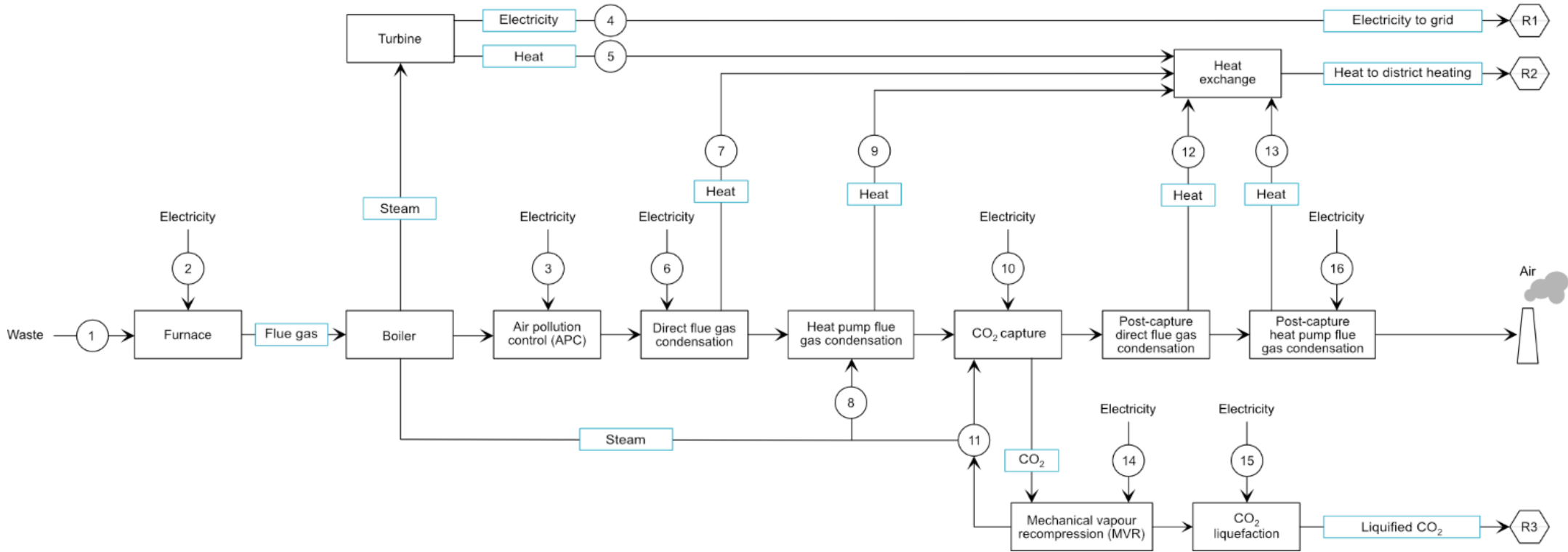


Table 2. Technical features of energy production in Amager Bakke and technical energy flows, for configurations with and without carbon capture and storage (CCS). The energy flows correspond to numbered flows 1-16 illustrated in Figure 1. Data derived from calculations performed by Ramboll Group, own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

Amager Bakke configuration	Baseline		Carbon capture and storage (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 heat pump flue gas condensation	No	Yes	No	Yes
Post-CC direct flue gas condensation	No	No	Yes	Yes
Post-CC electricity driven heat pump	No	No	Yes	Yes
Technical energy flows				
1. Waste input, LHV, GJ/tonne ww	10.8	10.8	10.8	10.8
2. Electricity use, furnace, kWh/tonne ww	34	34	34	34
3. Electricity use, APC, kWh/tonne 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 ww	7	7	7	7
7. Heat recovery, direct flue gas condensation, % of LHV	9	9	9	10
8. Steam use, heat pump flue gas condensation (GJ/tonne ww)	-	1.63	-	-
9. Heat recovery, heat pump flue gas condensation (% of LHV)*	-	26.0	-	-
10. Electricity use, CO ₂ capture kWh/tonne ww	-	-	42	44
11. Steam use, CO ₂ capture GJ/tonne CO ₂	-	-	2.49	2.49
12. Heat recovery, CO ₂ capture, heat exchange GJ/tonne CO ₂	-	-	2.03	2.55
13. Heat recovery, CO ₂ capture, compression heat pump GJ/tonne CO ₂	-	-	2.06	1.92
14. Electricity use, mechanical vapour recompression (MVR) kWh/tonne ww	-	-	105	104
15. Electricity use, CO ₂ liquefaction, kWh/tonne ww	-	-	42	42
16. Electricity use, electricity driven heat pump of CC-system, kWh/tonne ww	-	-	109	101
Total gross thermal efficiency, % of LHV	98	107	111	115
*: including driving energy (steam)				

2.3 Amager Bakke MSWI with CCS

2.3.1 CC at Amager Bakke

CC is a flue gas treatment technology for post-combustion separation and capture of CO₂. Several CC technologies exist: monoethanolamine scrubbing (MEA), pressure swing operation (PSA), 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 CO₂ absorber containing a 30% MEA solution, which absorbs around 90% of the CO₂ in the flue gas at 1

bar. After the CO₂ 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 CO₂-rich MEA-solution from the CO₂ absorber is heated to 104°C and fed into a CO₂ 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 CO₂ desorbs from the MEA and leaves saturated with water vapor. The CO₂-rich water vapor is then fed into a mechanical vapor recompression (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 vaporises 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 CO₂/water vapor mixture when cooling. After the MVR system the CO₂-pressure is 15 bar(a) at which pressure the CO₂ is cooled and liquefied in a conditioning stage, and leaves the system at -30°C and 14 bar(a) as liquid CO₂ 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 CO₂ absorption. However, part of the MEA degrades during the process (releasing 0.1 kg NH₃ per tonne CO₂ captured, which is separated in the post-absorber flue gas condensation stages), or is lost due to formation of heat-stable salts or as vapor and aerosols during stripping. This study considers a MEA use of around 1 kg per tonne of CO₂. This value is lower than the 4 kg per tonne of CO₂ 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 CO₂ 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.

2.3.2 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 CO₂ 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 heat pumps), 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 heat pump driven condensation stage – in this case cooled by an electricity-driven heat pump. This two-stage post-capture flue gas condensation allows recovering 4 GJ per tonne of captured CO₂, for a total gross thermal efficiency of 111%. The total electricity use in this configuration is 367 kWh per tonne of incinerated waste, due to use in the CO₂ capture and MVR-system and liquefaction, but also for the second post-combustion flue gas condensation via electricity-driven vapor compression heat pump.

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 heat pumps for the recovery. The lower DH temperature level increases the heat recovery from the CC-system to 4.5 GJ per tonne of captured CO₂ (or 38% of thermal input to the MSWI-plant) and slightly lowers the internal electricity use to 360 kWh per tonne of incinerated waste due to less energy required for energy reclamation via electricity-driven vapor compression heat pump. The total gross thermal efficiency of this operating mode is 115%.

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

2.3.3 Transport and storage of CO₂

After compression to 14 bar and cooling to -30°C, liquid CO₂ can be transported to a suitable storage site where it is injected and permanently stored. In general, the transportation of CO₂ 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 CO₂, the lifetime of the transportation scheme, the destination, transport logistics (e.g. harbors, railroads, roads) and, ultimately, the costs involved. Pipeline transport is usually possible within the supercritical envelope of CO₂ – the typical range is between 85 and 150 bar, and between 13°C 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 (-22°C to -28°C) and moderate pressures (15-18 bar), according to (Haugen et al., 2017) Haugen et al. (2017). IPCC (2005) suggests that the physical CO₂-loss by transportation by pipeline amounts to 1-2% of the transported CO₂ per 1000 km, and approximately 2.5% by ship. (Pour et al., 2018) Pour et al. (2018)

calculated that CO₂ transportation from an MSWI plant, although details were not specified, amounted to a net climate change load of 30 kg CO₂ 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 CO₂ is injected about one kilometer below the Earth's surface (European Parliament, 2009).

The liquid CO₂ captured at Amager Bakke is assumed transported by means of a 1.5 km concrete-covered steel DN125 pipeline to the nearby harbor of Prøvestenen. Here it can be stored for short term before transportation by sea carrier: 12 cylindrical tanks of 760 m³ each, allow short-term storage for a maximum of 5 days. CO₂ is then transported in tanks by dedicated ships to the storage site from existing harbor 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 CO₂ in geological structures off the coast of Norway. The CO₂ is transported by ship to a receiving station on the coast. From the coast, a 110 km pipeline transports CO₂ to storage site, which stores CO₂ 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. CO₂ 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 CO₂-eq per metric tonne transported per km (Ecoivent 3.7.1, sea carrier transportation with cooling). With 931 kg CO₂ captured/tonne ww waste, this amounts to around 20 kg CO₂-eq/tonne ww. Moreover, we assume that the transportation process causes a loss of 2.5% of the transported CO₂. 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 CO₂ confined for more than 1,000 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 CO₂ will be lost due to injection and off-site migration.

2.4 Waste composition scenarios

The composition of the incinerated waste material in terms of material fractions (e.g. paper, glass) and physico-chemical composition associated to each waste material fraction (e.g. water content, 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, 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 material recovery facility, 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 SM). 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, 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 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 carbon dioxide emissions and LHV observed at Amager Bakke for residual MSW (61% biogenic and 39% fossil, with an LHV of 10.8 GJ/tonne 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 (material recovery facility). In this scenario, the waste has a lower water content and a higher energy content (12.7 GJ/tonne ww) and the share of biogenic carbon is relatively lower (55%). Details on the waste compositions are presented in the SM.

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

Waste composition scenario	WC1	WC2 (Baseline)	WC3
Material fraction composition (% wet weight)			
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

2.5 Energy system scenarios

The use and recovery of energy in Amager Bakke with and without CCS amendment, presented in section 2.2, 2.3 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, 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, i.e. 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 neighboring countries, heat 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, become 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 CO₂-eq/kWh for electricity and 0.02 kg CO₂-eq/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 4 energy system scenarios 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 CO₂-eq/kWh electricity and 0.07 kg CO₂-eq/MJ heat based on natural gas) to non-fossil based energy systems (e.g. the “greenest” scenario presents 0.02 kg CO₂-eq/kWh electricity based on off-shore wind power; 0.001 kg CO₂-eq/MJ heat based on electricity-driven heat pumps). Details on energy system scenarios are provided in the SM.

Table 4. Energy system scenarios. Details are provided in the SM.

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 PV			6%	100%	
kg CO ₂ -eq/kWh	0.43	0.25	0.17	0.09	0.02
Heat					
Natural gas	100%				
Biomass with LUC		100%	27%		
Electricity in heat pumps			73%	100%	100%
kg CO ₂ -eq/MJ	0.07	0.05	0.02	0.001	0.001

3. RESULTS AND DISCUSSIONS

3.1 Carbon and energy balance

The carbon and energy balance results for the baseline waste composition scenario (WC2, Table3) are shown in Table 5. The baseline waste composition yields approximately 1 tonne of CO₂ 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 CO₂ from combustion of one 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 ww (see section 2.4), the net electricity and heat recovery amount to 690 kWh/tonne ww and 7.8 GJ/tonne 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 heat pump (Table 2, “Baseline HP”), a lower net electricity recovery of 615 kWh/tonne ww allows higher net heat recovery of 9.1 GJ/tonne ww, for an overall net efficiency of 105% of the LHV of the treated waste.

With the CCS amendment, Amager Bakke lowers its fossil CO₂ emissions in the flue gas to 40 kg CO₂ per tonne of incinerated waste. The captured CO₂ at Amager Bakke amounts to around 920 kg of CO₂ per tonne of incinerated waste. Of these, 16 kg of fossil CO₂ are emitted to atmosphere due to 2.5% of the CO₂ 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 CO₂ 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 heat pump flue gas condensation post capture. With CCS the net electricity recovery is 307 kWh/tonne 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 ww, for a net heat recovery of 9.6 GJ/tonne 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 ww is also 55% lower than “Baseline”. However, the lower DH return temperature allows higher post-capture energy recovery (4.1 GJ/tonne ww), higher net heat recovery of 10 GJ/tonne (an increase of 28% with respect to “Baseline”) and an overall energy efficiency of 104% of the LHV of the treated waste.

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

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

3.2 LCA results

3.2.1 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 SM, 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.

Without CCS amendment, in the “Baseline” configuration Amager Bakke results in a net climate change impact of about 150 kg CO₂-eq/tonne ww. Fossil CO₂ emission to atmosphere as a result of waste incineration contributes with a climate change impact of 400 kg CO₂-eq/tonne ww, while energy recovery in terms of electricity and heat in the baseline energy system scenario (0.17 kg CO₂-eq/kWh, 0.02 kg CO₂-eq/MJ, cf. ES3 baseline in Table 4) contributes with climate change savings of -125 kg CO₂-eq/tonne ww for electricity and -130 kg CO₂-eq/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 heat pumps for flue gas condensation “Baseline HP”, the climate change impact is only slightly lower with respect to “Baseline” (140 kg CO₂-eq/tonne ww).

With CCS amendment, Amager Bakke “CCS Net zero” shows net climate change benefits of -670 kg CO₂-eq/tonne ww. The largest benefit derives from storage of captured biogenic CO₂, which provides a climate change benefit of -530 kg CO₂-eq/tonne ww. CC also lowers the fossil CO₂ emitted to

atmosphere, thus lowering the climate change impact from emitted flue gas to 40 kg CO₂-eq/tonne ww. Operation with CCS shows burdens due to additional electricity use, and transportation and loss of CO₂. The net benefit from electricity recovery reduces to -60 kg CO₂-eq/tonne ww (half with respect to the baseline MSWI configuration without CCS). Transportation and loss of captured CO₂ cause a climate change impact of around 30 kg CO₂-eq/tonne ww. Additional benefits are obtained from post-capture heat recovery, with -60 kg CO₂-eq/tonne ww, which allows obtaining an overall net benefit from heat recovery of -160 kg CO₂-eq/tonne ww. The MEA consumption for the capture process adds only 4 kg CO₂-eq/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 CO₂-eq/tonne ww and the overall climate change benefits of this configuration are about -680 kg CO₂-eq/tonne ww.

Overall, introducing CCS at Amager Bakke is estimated to improve the climate change impacts by about 820 kg CO₂-eq/tonne ww with respect to the “Baseline” configuration and by 810 kg CO₂-eq/tonne ww with respect to “Baseline HP”. With lower DH return temperature, the benefits increase to almost 830 kg CO₂-eq/tonne ww with respect to the “Baseline” configuration and to 820 kg CO₂-eq/tonne ww with respect to “Baseline HP”.

3.2.2 Other impact categories

The normalized results for all impact categories assessed in this LCA study are presented in Figure 3 in person equivalents (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 SM, 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.

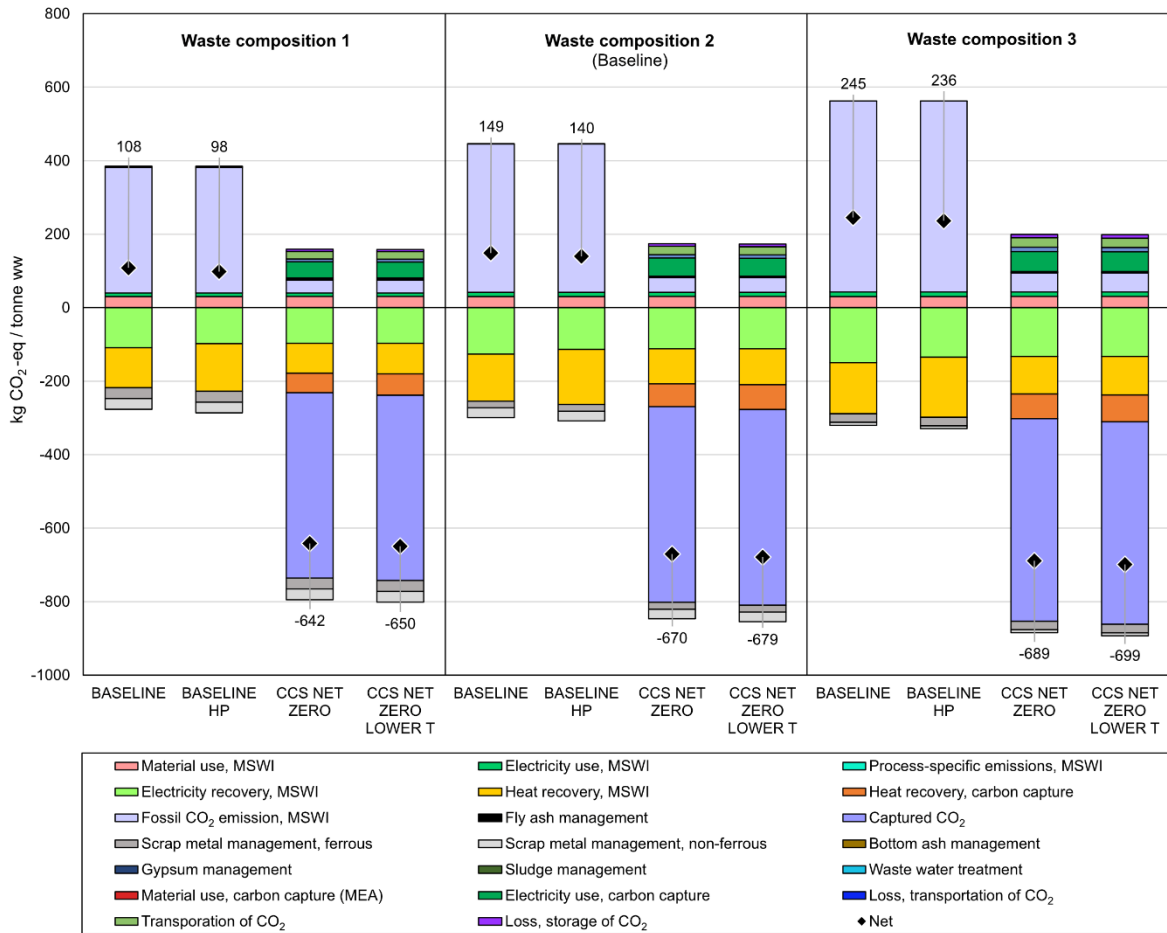


Figure 2. LCA results, climate change impact category, for the three waste composition scenarios (WC1, WC2, and WC3, Table 3) and baseline energy system scenario (ES3, Table 4). Results are provided in kg CO₂-eq per tonne ww of incinerated waste, and subdivided according to the processes contributing 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 CO₂ are provided in 2.1.2.

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, SM, 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 CO₂ to the injection site.

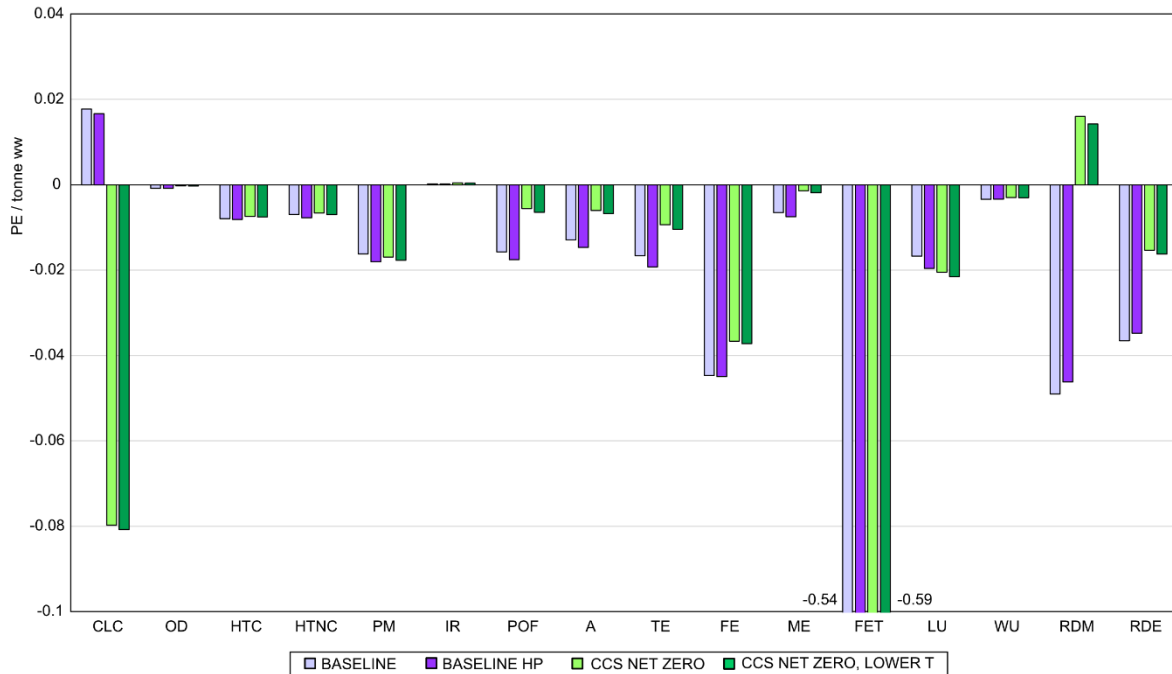


Figure 3. Normalized impact results in PE/tonne ww. Details are provided in the SM. CLC: climate change; OD: ozone depletion; human toxicity (HTC, cancer and HTNC, non-cancer effects); PM: particulate matter, IR: ionising radiation; POF: photochemical ozone formation; A: acidification; eutrophication (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).

3.3 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 SM.

Without CCS amendment, the emission of fossil CO₂ with WC1 is lower than in the baseline waste composition scenario WC2 (340 kg CO₂/tonne ww), but increases with WC3 to 516 kg CO₂/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 ww and 6.9 GJ/tonne ww, while WC3 yields 820 kWh/tonne ww and 8.8 GJ/tonne ww. In “Baseline HP” the heat

recovery is higher, with 530 kWh/tonne ww and 8.2 GJ/tonne ww for WC1 and 731 kWh/tonne ww and 10.4 GJ/tonne ww for WC3.

With CCS amendment, the fossil CO₂ emission reduces to 34 kg CO₂/tonne ww for WC1 and to 52 kg CO₂/tonne ww for WC3. After transportation and storage losses, the stored CO₂ is around 810 kg CO₂/tonne ww for WC1 and 1015 kg CO₂/tonne ww for WC3. However, the amount of stored biogenic CO₂ is relatively higher for WC1 than WC3 (514 and 560 kg CO₂/tonne ww, respectively). CCS amendment reduces net electricity recovery. In “CCS Net zero”, WC1 yields 212 kWh/tonne ww and 9.0 GJ/tonne ww, while WC3 yields 411 kWh/tonne ww and 10.2 GJ/tonne ww. In the configuration with lower district heating return temperature “CCS Net zero, Lower T” the heat recovery is higher, with 261 kWh/tonne ww and 8.2 GJ/tonne ww for WC1 and 387 kWh/tonne ww and 11.2 GJ/tonne 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 CO₂ 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 CO₂-eq/tonne ww), due to the largest share and emissions of fossil CO₂.

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 lower electricity recovery, additional electricity use for capture, and transport fuel use for the captured CO₂. 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.

3.4 Energy system scenarios

The climate change results for the energy system scenario 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 SM.

The energy system scenarios 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, MSWI without CCS provides environmental savings (-456 kg CO₂-eq/tonne ww for “Baseline”, ES1), since the fossil CO₂ 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 CO₂-eq/tonne ww for “Baseline”, ES5), when the climate change savings connected to the recovered energy do not outbalance the fossil CO₂ emissions. With CCS, MSWI provides environmental benefits in all the assessed energy system scenarios, ranging from around -1300 kg CO₂-eq/tonne ww for “CCS Net zero”, ES1, to around -475 kg CO₂-eq/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 CO₂-eq/tonne ww, and 880 kg CO₂-eq/tonne ww between “Baseline” and “CCS Net zero, Lower T”. Considering the configuration with heat pump use, “Baseline HP” varies from “CCS Net zero” at 780 kg CO₂-eq/tonne ww and at 820 kg CO₂-eq/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 CO₂ and captured and stored biogenic CO₂. This can be seen in ES5, where the difference between configurations without CCS and configurations with CCS stabilizes to 850 kg CO₂-eq/tonne ww.

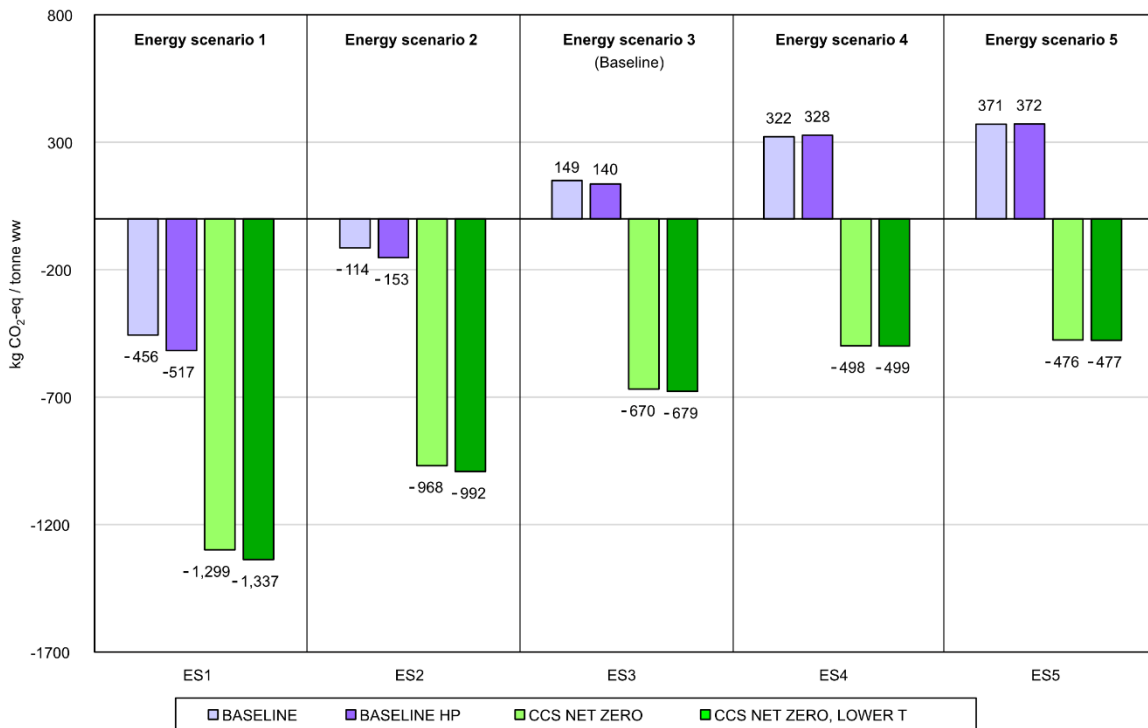


Figure 4. LCA results, climate change impact category, for the baseline waste composition scenario

(WC2, Table 3) and the five energy system scenarios (ES1-ES5, Table 4). Results are provided in kg CO₂-eq per tonne of incinerated waste. The Amager Bakke configurations with and without CCS correspond to those reported in Tables 1 and 2.

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 energy system scenarios 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 CO₂ to the storage site. The contribution of fuel consumption is more significant for ionizing radiation and for resource depletion, minerals.

3.5 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 energy system scenario and waste composition scenario. The analysis of the results illustrated in Figure 5 is supplemented with sensitivity analysis. The normalized sensitivity ratios (SRs) associated to model parameters for the baseline waste composition and each energy system scenario are reported in the SM (Tables S27-S28).

In fossil-based energy systems (ES1, 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 CO₂ 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, ES5), the sensitivity of the energy recovery parameters is negligible. The results depend almost exclusively on the carbon capture 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 CO₂ from transportation and storage shows negligible sensitivity compared to the carbon capture 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 CO₂-eq/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 CO₂-eq/tonne ww and depend exclusively on the carbon capture 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 CO₂-eq/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.

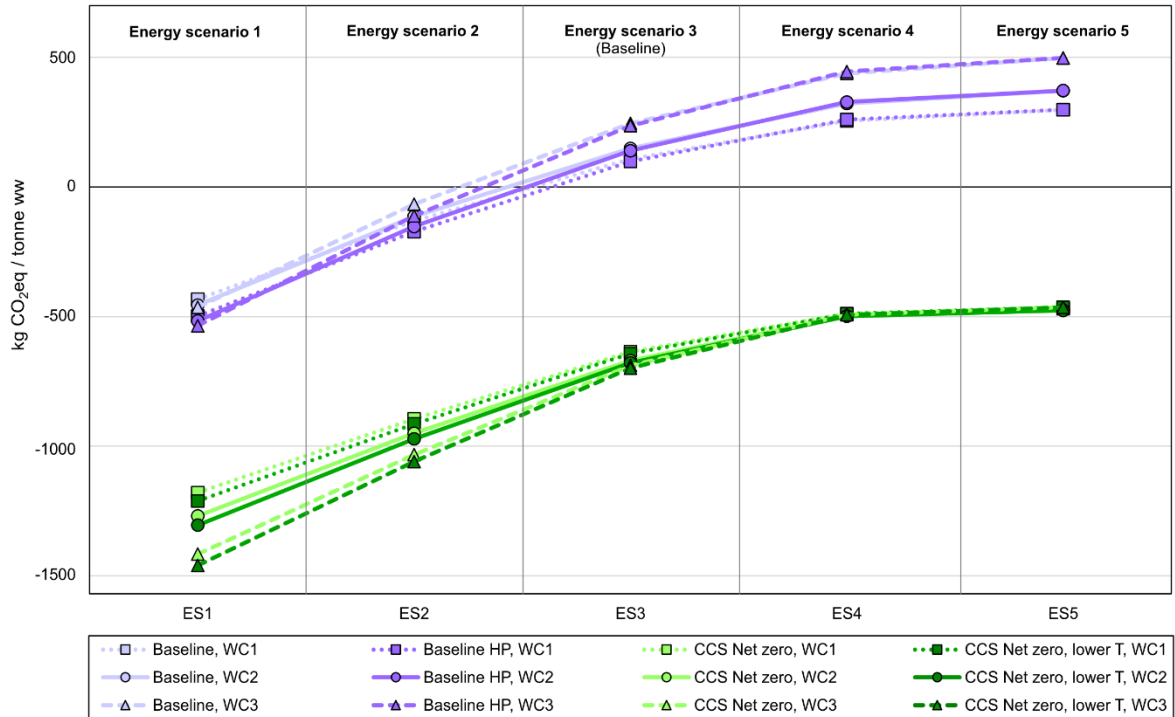


Figure 5. Summary of climate change results for each energy system scenario and waste composition scenario for Amager Bakke configurations with and without CCS.

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 CO₂ 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 CO₂-eq/tonne ww, therefore not really affecting the benefits of CCS.

The baseline energy system scenario utilized are 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 district heating expands at the expense of small natural gas plants or individual oil based heating.

The carbon capture 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.

4. 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 wet weight (ww) of MSW incinerated. However, the plant is a net burden with respect to climate change corresponding to 140 kg CO₂-eq. per tonne ww waste incinerated. As the Danish energy system becomes even greener, the burden to climate change will increase to 370 kg CO₂-eq per tonne ww.

Amending the Amager Bakke MSWI with carbon capture and storage (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 heat pumps and the temperature level in the district heating 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 (lower heating value).

With an assumed carbon capture efficiency of 90%, around 900 kg CO₂ per tonne of incinerated waste will be captured. Accounting for the operational penalties, the transport and storage of the captured CO₂, this improves the climate change impacts of the Amager Bakke MSWI by 820 kg CO₂-eq per tonne ww (from 140 to -680 kg CO₂-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 carbon capture efficiency.

The robust results obtained suggest that fully implementing CCS at Amager Bakke could save around 500,000 tons CO₂ 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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