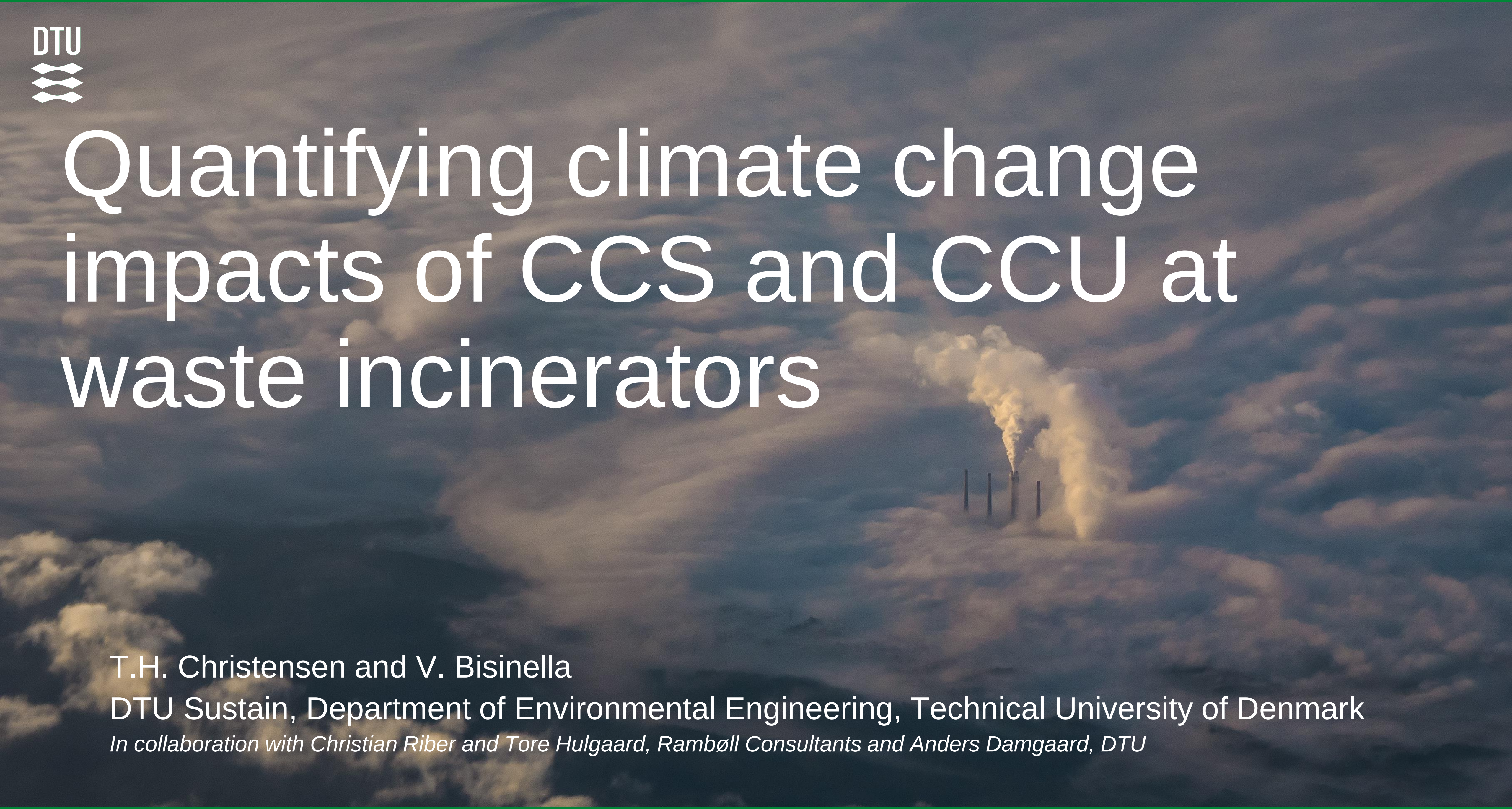
DTU



Quantifying climate change impacts of CCS and CCU at waste incinerators

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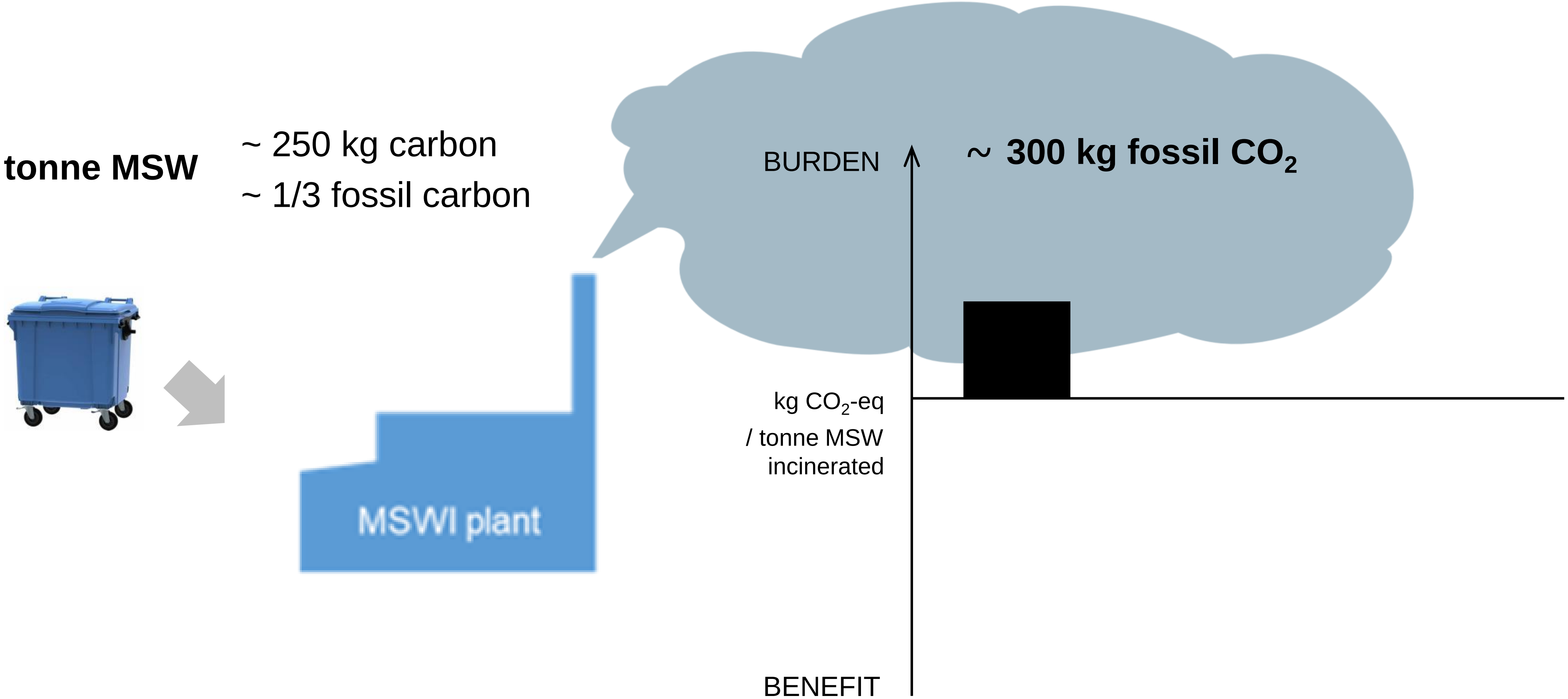
In collaboration with Christian Riber and Tore Hulgaard, Rambøll Consultants and Anders Damgaard, DTU

Waste incineration is a contributor to climate change



1 tonne MSW

~ 250 kg carbon

~ 1/3 fossil carbon

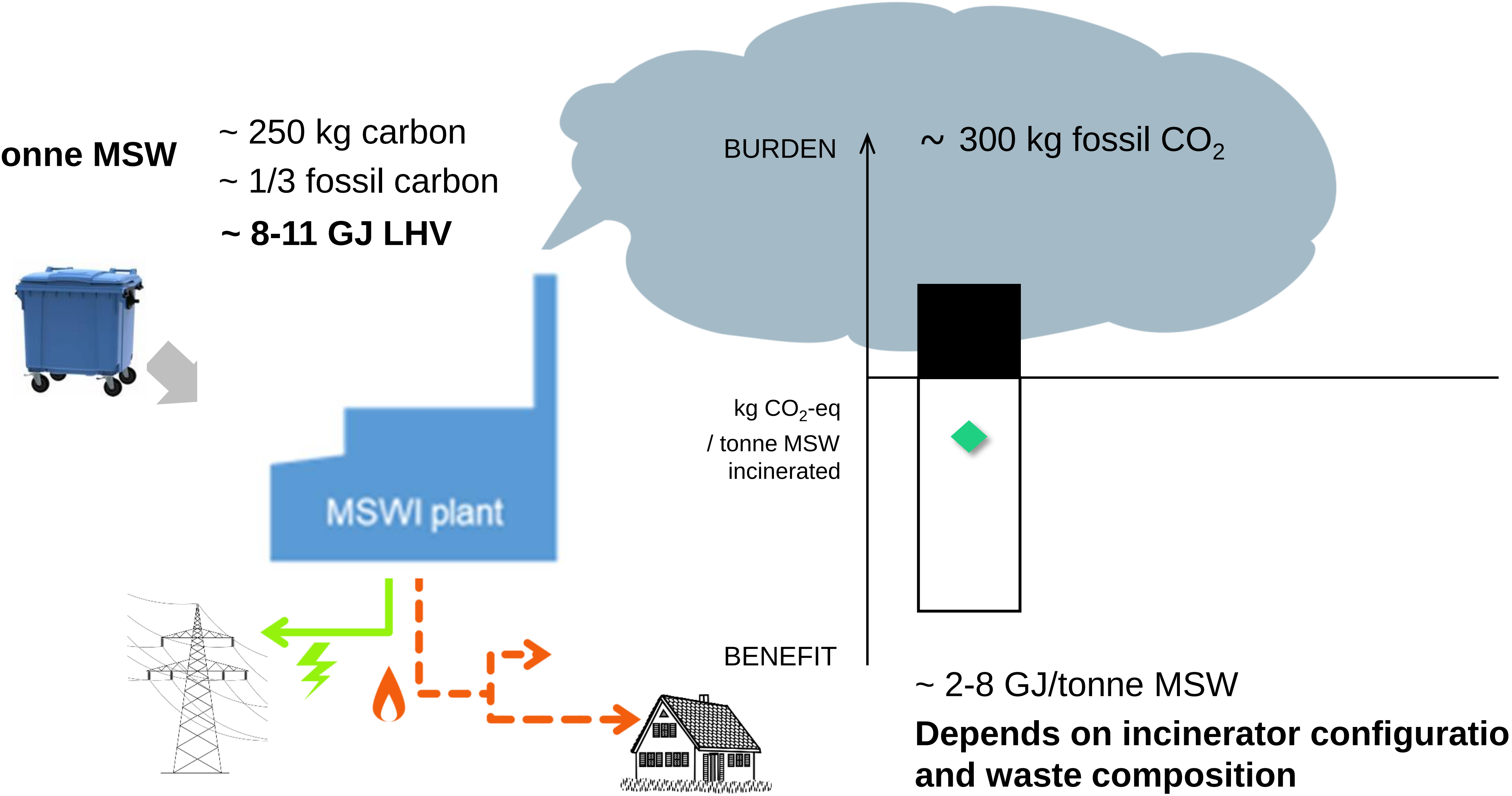
Climate change impacts and energy recovery

1 tonne MSW

~ 250 kg carbon

~ 1/3 fossil carbon

~ 8-11 GJ LHV

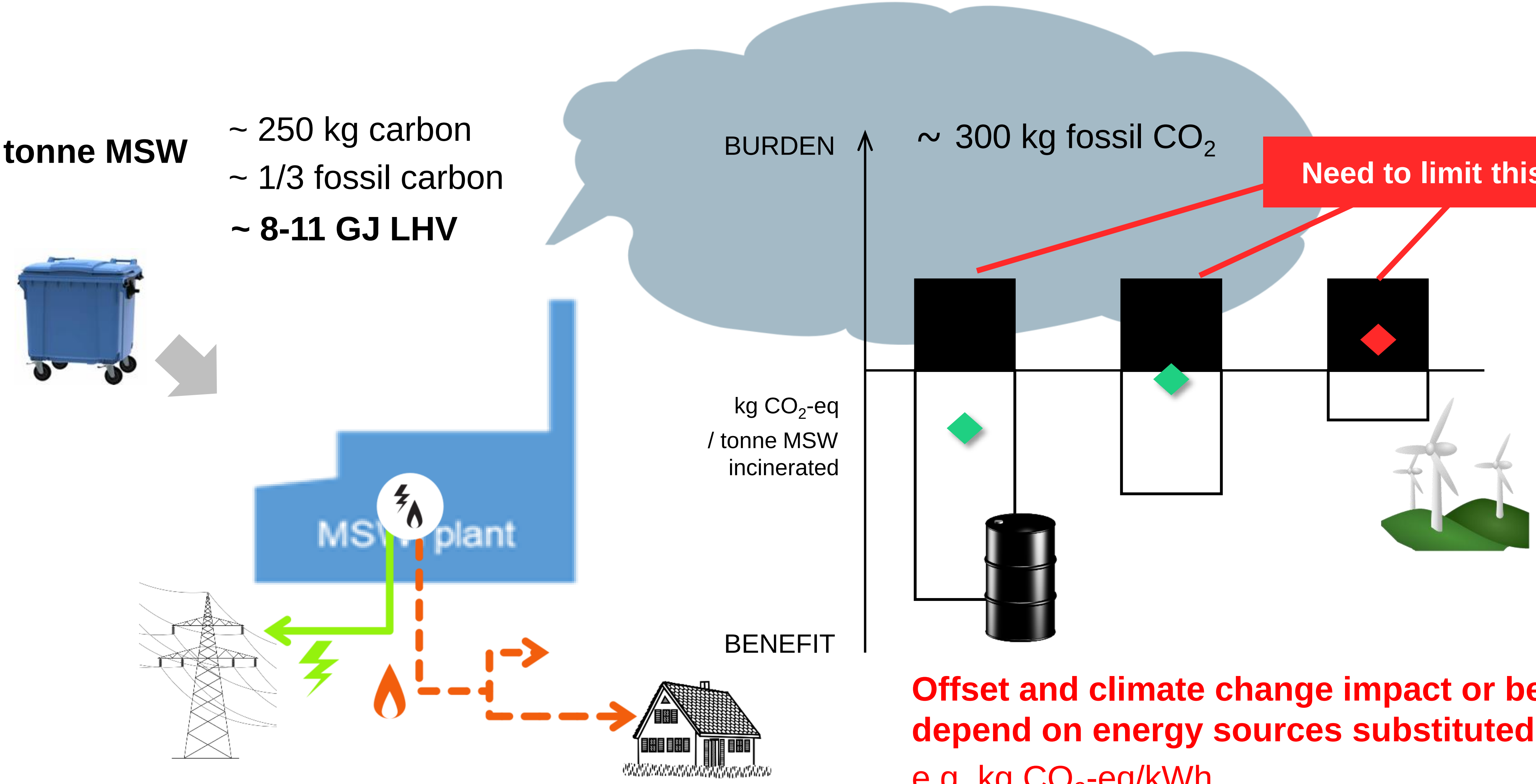


~ 300 kg fossil CO_2

~ 2-8 GJ/tonne MSW

Depends on incinerator configuration and waste composition

Net climate change contribution in the future



1 tonne MSW

~ 250 kg carbon
~ 1/3 fossil carbon
~ 8-11 GJ LHV

~ 300 kg fossil CO_2

Need to limit this impact

BURDEN

kg CO_2-eq
/ tonne MSW
incinerated

BENEFIT

Offset and climate change impact or benefit depend on energy sources substituted

e.g. kg CO_2-eq/kWh

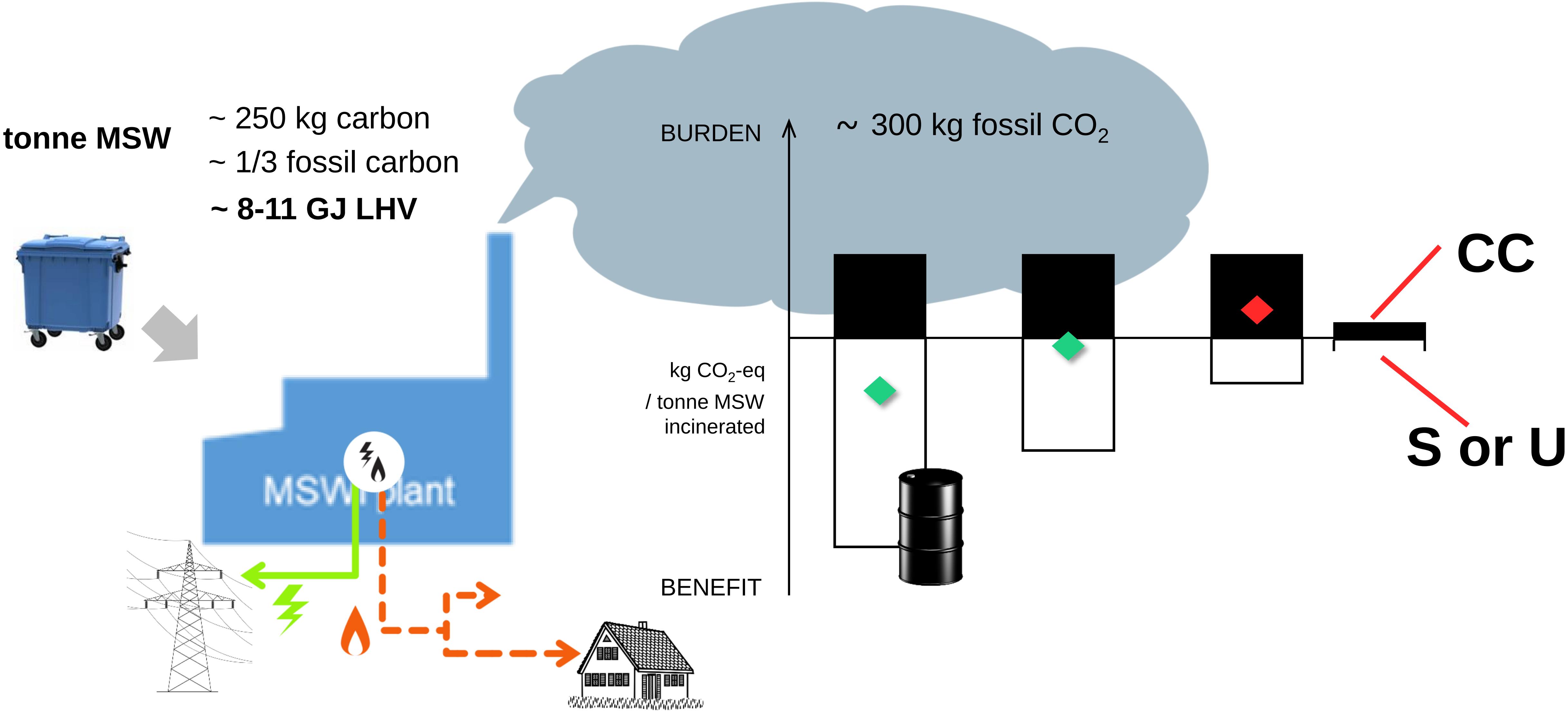
Net climate change contribution in the future

1 tonne MSW

~ 250 kg carbon

~ 1/3 fossil carbon

~ 8-11 GJ LHV



Net climate change contribution in the future

1 tonne MSW

~ 250 kg carbon

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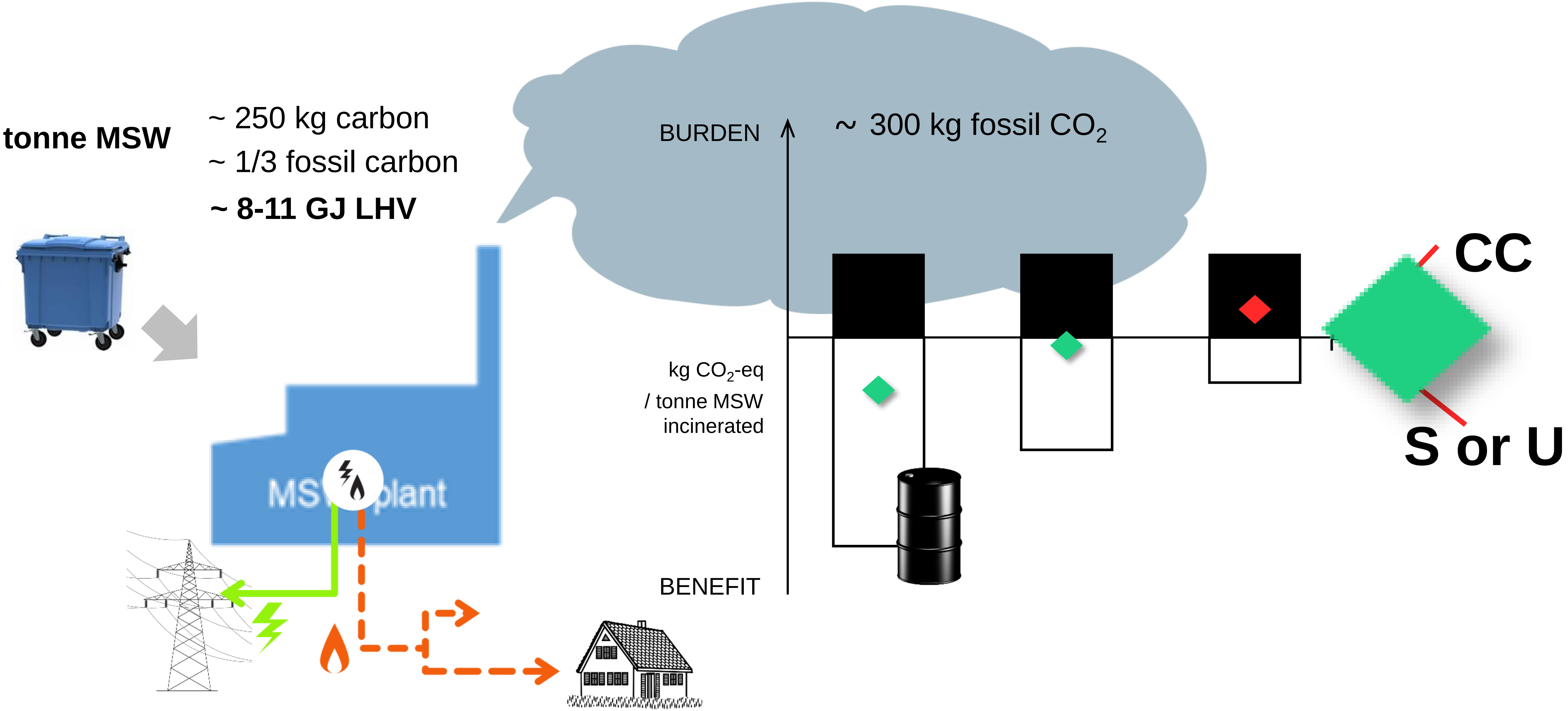

Net climate change contribution in the future

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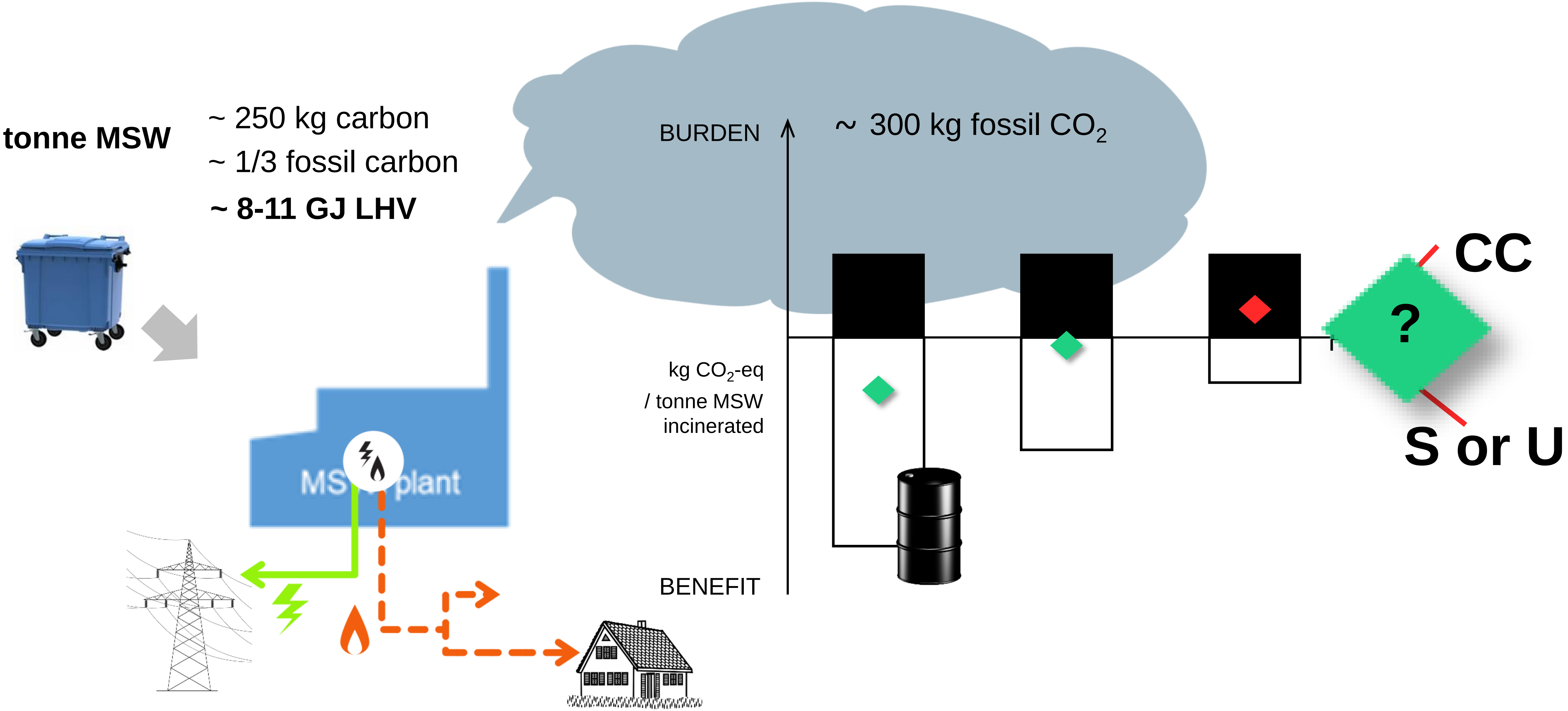


Aim: Climate change impacts

Assess the impacts of amending MSWI with CC

How can CC apply to MSWI? What are the implications in terms of energy recovery for different MSWI configurations?

Assess the impacts of management options for the captured CO_2

- Storage
- Utilization:

Effects of the exchange with the energy system being in transition

How does the climate change impacts CCS and CCU change in different energy systems in which the technology operates?

Methods

- Life Cycle Assessment carried out in EASETECH
- Foreground system modelling: new MSWI with/without CC processes (9 configurations)
- Background data from Ecoinvent 3.6 (ancillary materials and energy)

- Waste composition varied
- Energy flows modelled

- Analysis of results:
  - CO_2 balance
  - Energy recovery in terms of electricty and heat
  - Process contribution analysis
  - Scenario analysis (energy system, utilization options)
  - Sensitivity analysis (perturbation)

Methodological assumptions: Carbon

39% of the carbon in the waste is fossil

61% of the carbon in the waste is biogenic

Climate change impacts are quantified according to the following characterization factors:

- 0 kg CO_2-eq/kg CO_2 for biogenic CO_2 emissions (e.g. from food waste)
- 1 kg CO_2-eq/kg CO_2 for fossil CO_2 emissions (e.g. non-recyclable plastic and synthetic textiles)
- -1 kg CO_2-eq/kg CO_2 for avoided emission of biogenic CO_2
- 0 kg CO_2-eq/kg CO_2 for avoided emissions of fossil CO_2

Similarly for chemicals and fuels substituted

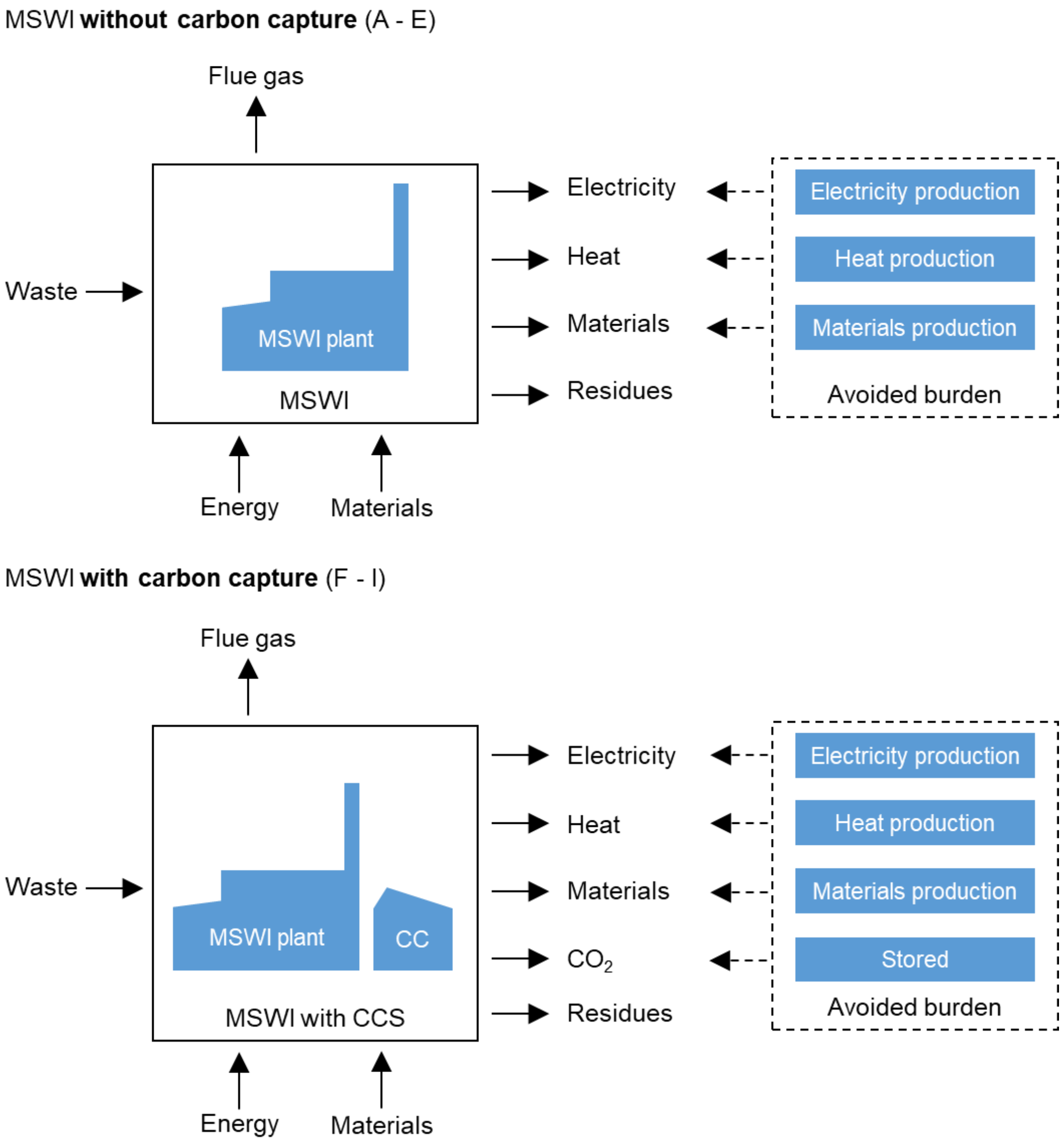
We keep track of the fossil/biogenic content of emissions, products and fuels

MSWI configurations

MSW varied 9.3 -11.3 GJ/Tonne

MSWI technology varied:

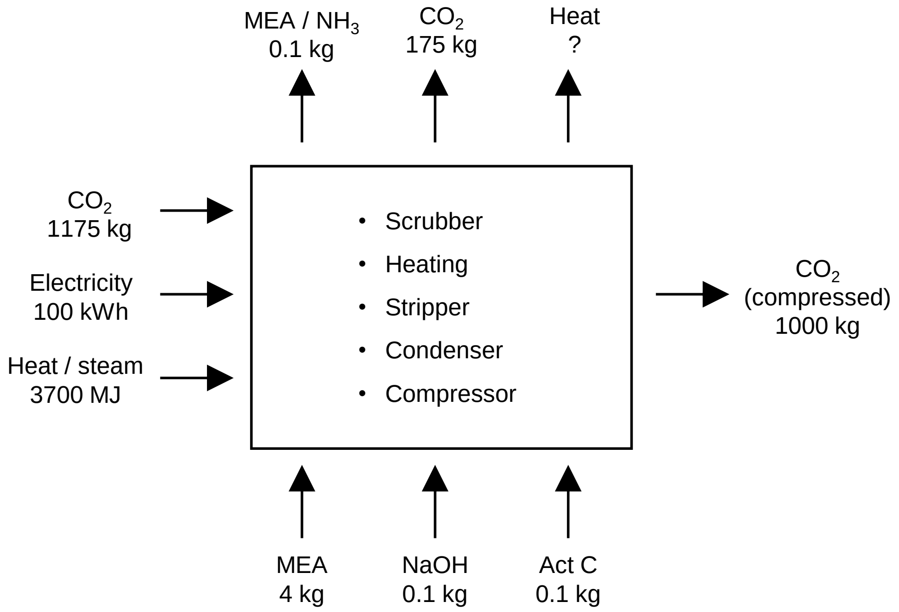
- Flue gas condensation
- Heat/ no heat recovery
- w/wo CC
- w/wo heat recovery from CC unit



Carbon capture (CC) technology

- **MEA:**

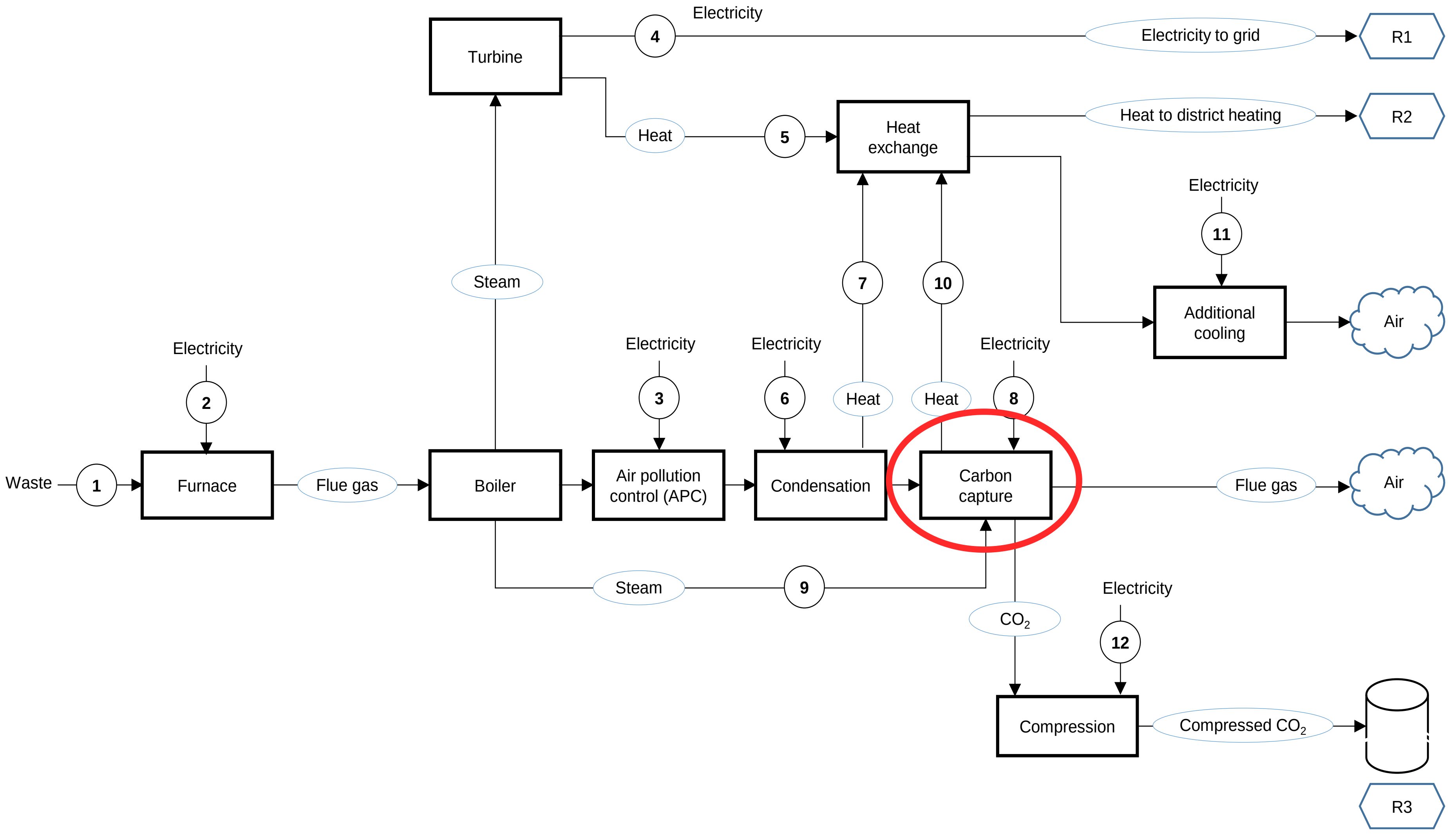
CO_2 is exposed to a monoethanolamine (MEA) solution forming a water soluble salt. After stripping at 100 - 140 °C and condensing of water, the >99% purity CO_2 is compressed. About 85-90% of the CO_2 is captured. The MEA is recovered and recycled, but some losses must be compensated. The electricity consumption is low, but the steam use for the MEA recovery is high **(3700 MJ per tonne CO_2)** after Reiter and Lindorfer (2017). The technology is well established.



Other:

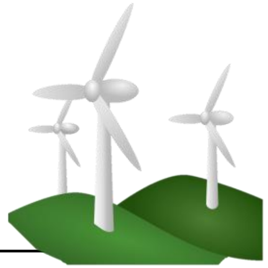
- PSA (pressure-swing operation)
- Hydrate-based
- Cryogenic distillation
- Membrane filtration

CC amended to MSWI



Energy system scenarios

What if the energy system changes?



SCENARIO No.	**1**	**2**	**3**	**4**	**5**	**6 BASELINE**	**7**	**8**	**9**	**10**	**11**	**12**
Notes	Hypothetical	Hypothetical	Hypothetical	NETP 6DS single 2020-2030	NETP 6DS mix 2020-2030	NETP 4DS mix 2020-2030	Hypothetical	NETP 2DS mix 2020-2030	NETP 4DS single 2020-2030	Hypothetical	Hypothetical	Hypothetical
ELECTRICITY												
Share	%	%	%	%	%	%	%	%	%	%	%	%
Oil	100											
Hard coal		100			17							
Natural gas			100	100	51	23		17				
Biomass with LUC							100					
Solar panels						45		29	100			
Wind onshore					23	19		15		100		
Wind offshore					9	13		39			100	100
kg CO2-eq/kWh	**1.20**	**1.04**	**0.70**	**0.70**	**0.54**	**0.21**	**0.21**	**0.16**	**0.09**	**0.02**	**0.02**	**0.02**
HEAT												
Share	%	%	%	%	%	%	%	%	%	%	%	
Hard coal	100											
Oil		100										
Natural gas			100									
Biomass with LUC				100	100	54	100	42	100	100	100	
Heat pumps						46		58				100
kg CO2-eq/MJ	**0.13**	**0.09**	**0.07**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.01**

50-60 times reduction

10-13 times reduction

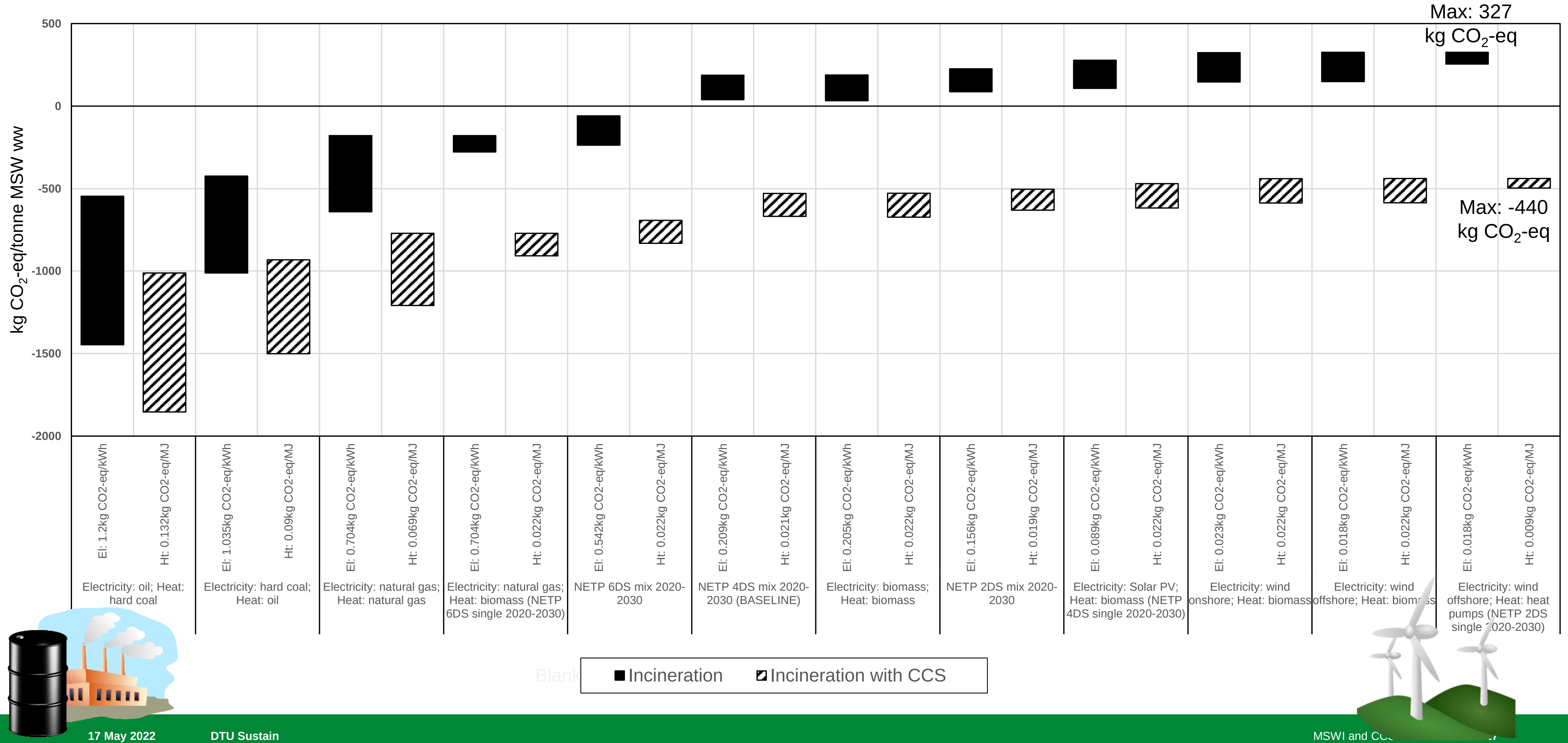
Storage

- Captured CO_2 is transported and stored

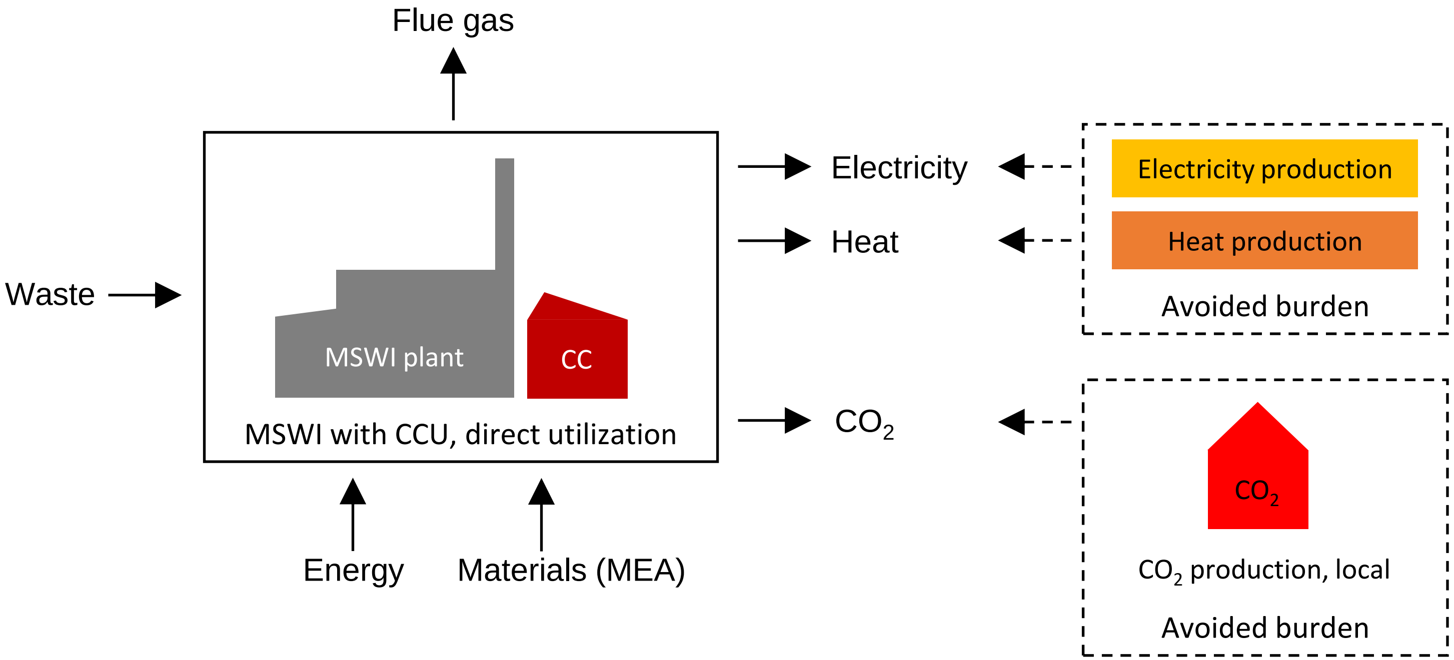
- Transportation:
  - Different options (road tankers, railroad tankers, sea carriers, pipeline)
  - Environmental impacts: energy used for compression, emissions of CO_2 during loading/unloading and transport
  - Data from industries document losses of CO_2 1-2% per 1000 km transported
  - We assumed 1000 km distance and 1% loss

- Storage:
  - Geological formations
  - We assume that CO_2 is stored indefinitely (> 1000 years)
  - Loss 2% CO_2

CCS: Climate change impacts: different energy systems

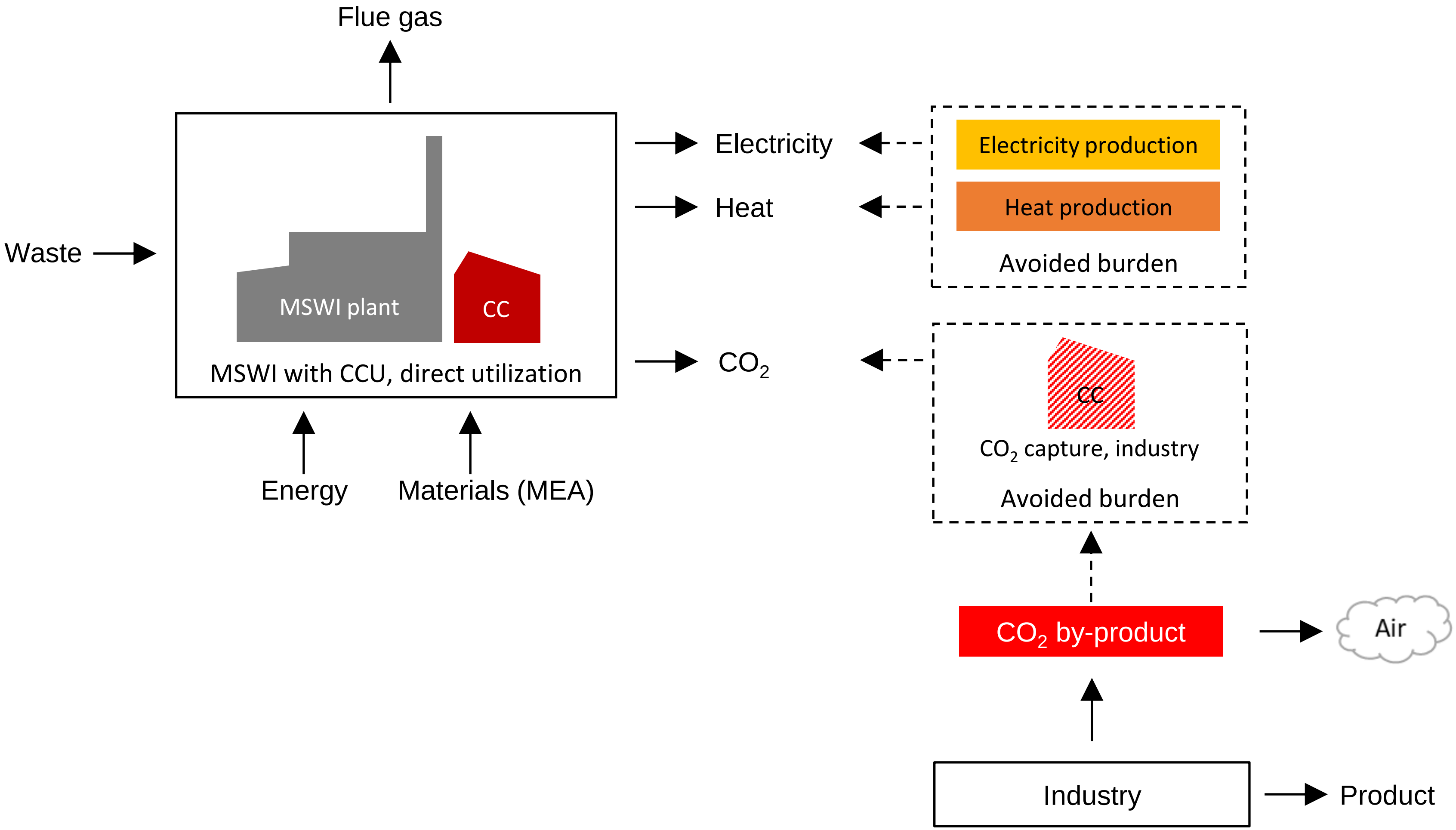


Direct utilization: local use



PAPER 2

Direct utilization: market use

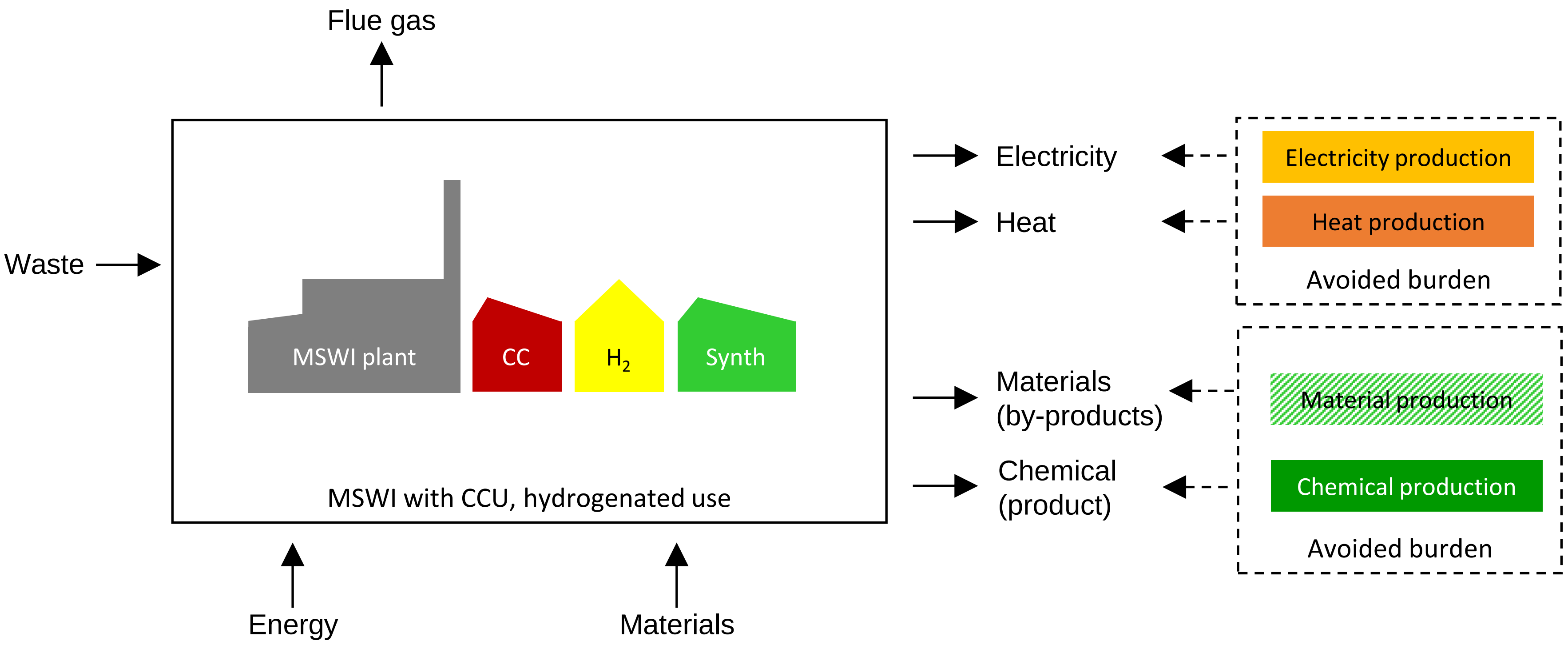


Hydrogenated utilization

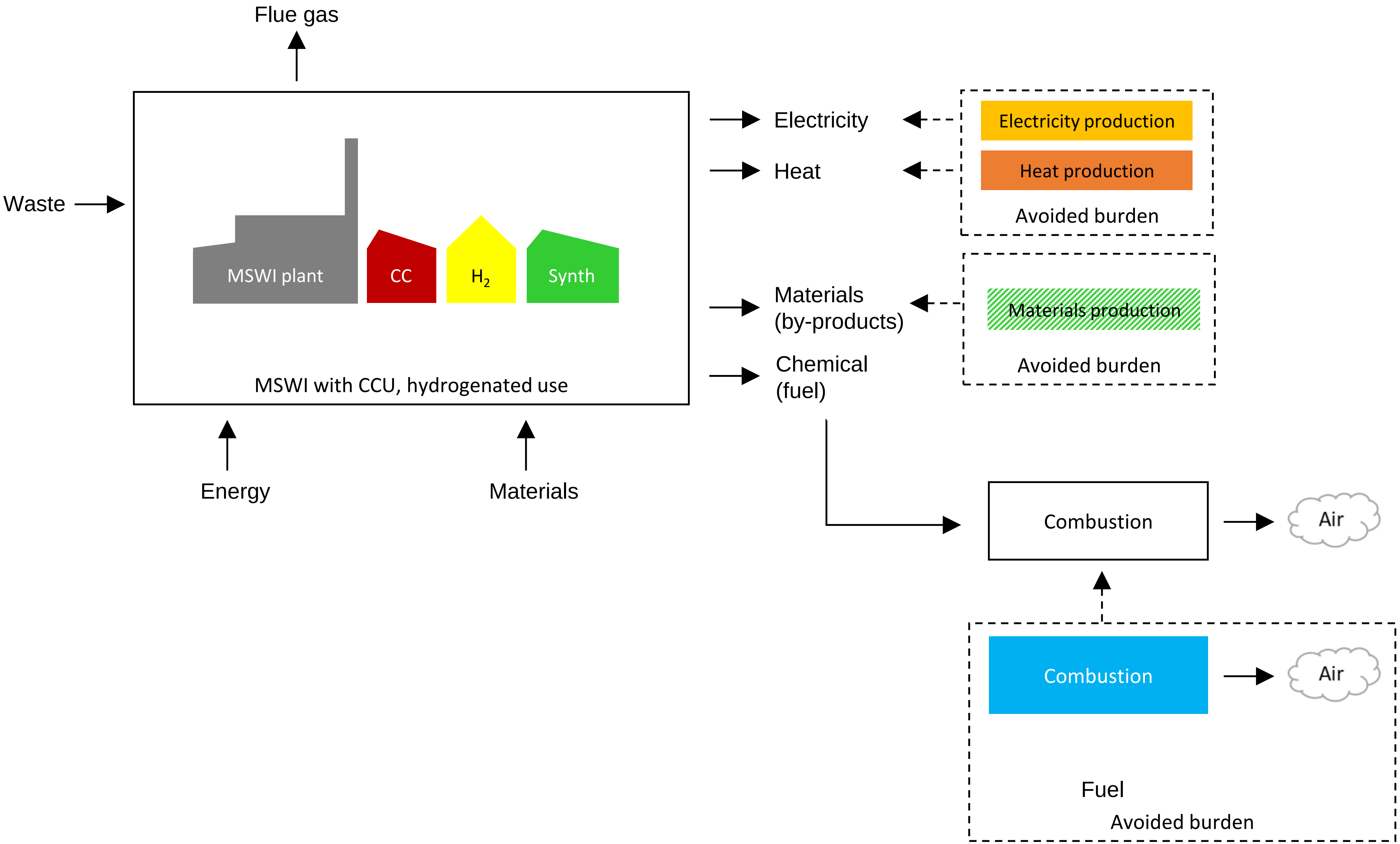
Simple, single, versatile uses

	CH_4	CH_3OH	DME	HCOOH
Names	Methane Methyl Hydride	Methanol Methylalcohol	Dimethyl Ether Methoxymethane	Formic Acid Methanoic Acid
Chemical composition	CH_4	CH_3OH CH_4O	CH_3OCH_3 C_2H_6O	HCOOH CH_2O_2
H/C ratio in production process including H_2O formation	8	6	6	4
Molar mass, g/mol	16.04	32.04	46.07	46.03
Heat of combustion, kJ/mol	890	726	1455	255
Heat of combustion, kJ/g	55.5	22.7	31.6	5.5
Boiling point, °C	-164	65	-24	101
Melting point, °C	-182	-98	-141	8
Density (liquid), kg/l	0.42	0.73	1.97	1.22
Liquefaction	Liquid below -150°C at pressures above 46 bar	Liquid at ambient temperature and pressure	Liquid at ambient temperature at pressures above 6 bar	Liquid at ambient temperature and pressure
Storage and transport	Like natural gas	Like alcohol	Like propane gas	Like weak acid
Used as baseline chemical	Yes	Yes	Yes	Yes
Used as fuel	Yes, in combustion	Yes	Yes	Yes, in fuel cells
Other uses		Anti-freeze		Leather industry Dyeing Rubber industry Food and fodder
Climate change characterisation factor if released into the atmosphere, kg CO_2-eq/ kg product	28	None	None	None
Carbon footprint of common production method, kg CO_2-eq/ kg product	0.5	1.1	2.1	4.3

Hydrogenated utilization: chemicals



Hydrogenated utilization: fuels



Production of chemicals

1000 kg product	Methane	Methanol	DME	Formic acid
Inputs				
CO_2 (kg)	3000	1450	2000	1000
H_2 (kg)	500	190	260	0
H_2O (kg)	0	0	0	1410
Electricity (kWh)	60[a]	20[a]	30[a]	12000
Steam/heat (GJ)	0	0	0	26
Outputs				
Product (kg)	1000	1000	1000	1000
H_2O (kg) -reusable	2500	570	1175	180
H_2 (kg) – byproduct	0	0	0	92
O_2 (kg) - byproduct	0	0	0	1090
CO_2 (kg) - loss	250	75	85	40
Heat/steam (GJ)	9.0[b]	1.4[c]	2.5[d]	0

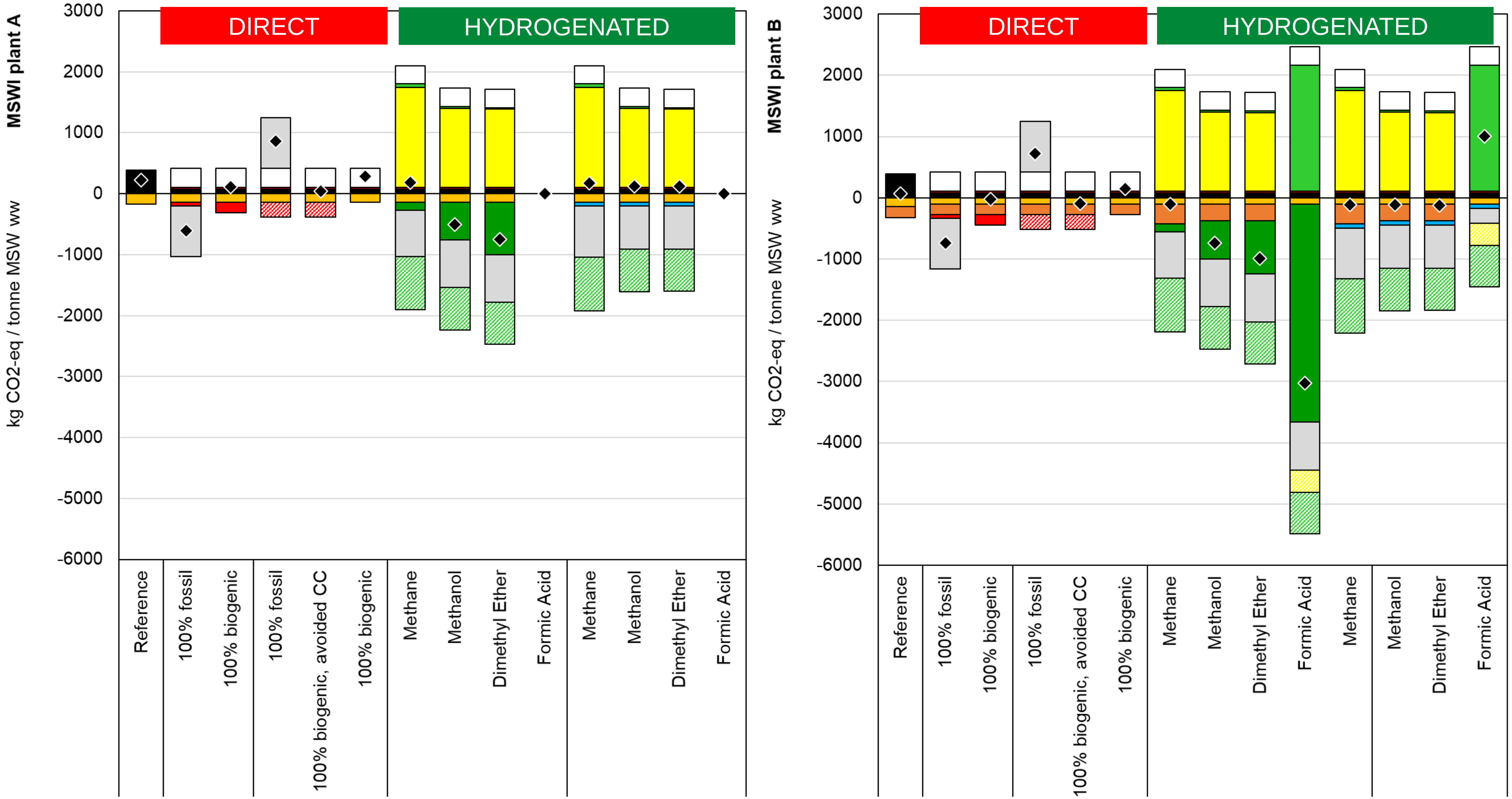
Production of hydrogen

Flows for production of 1000 kg of H_2	Hydrogen production (AEC electrolysis)
Inputs	
H_2O k(g)	16800
Electricity (kWh)	58000
Outputs	
H_2 (kg)	1000
H_2O (kg)	7200
O_2 (kg)	8400
Heat/steam (GJ)	62.4

Technical outcome per ton of waste

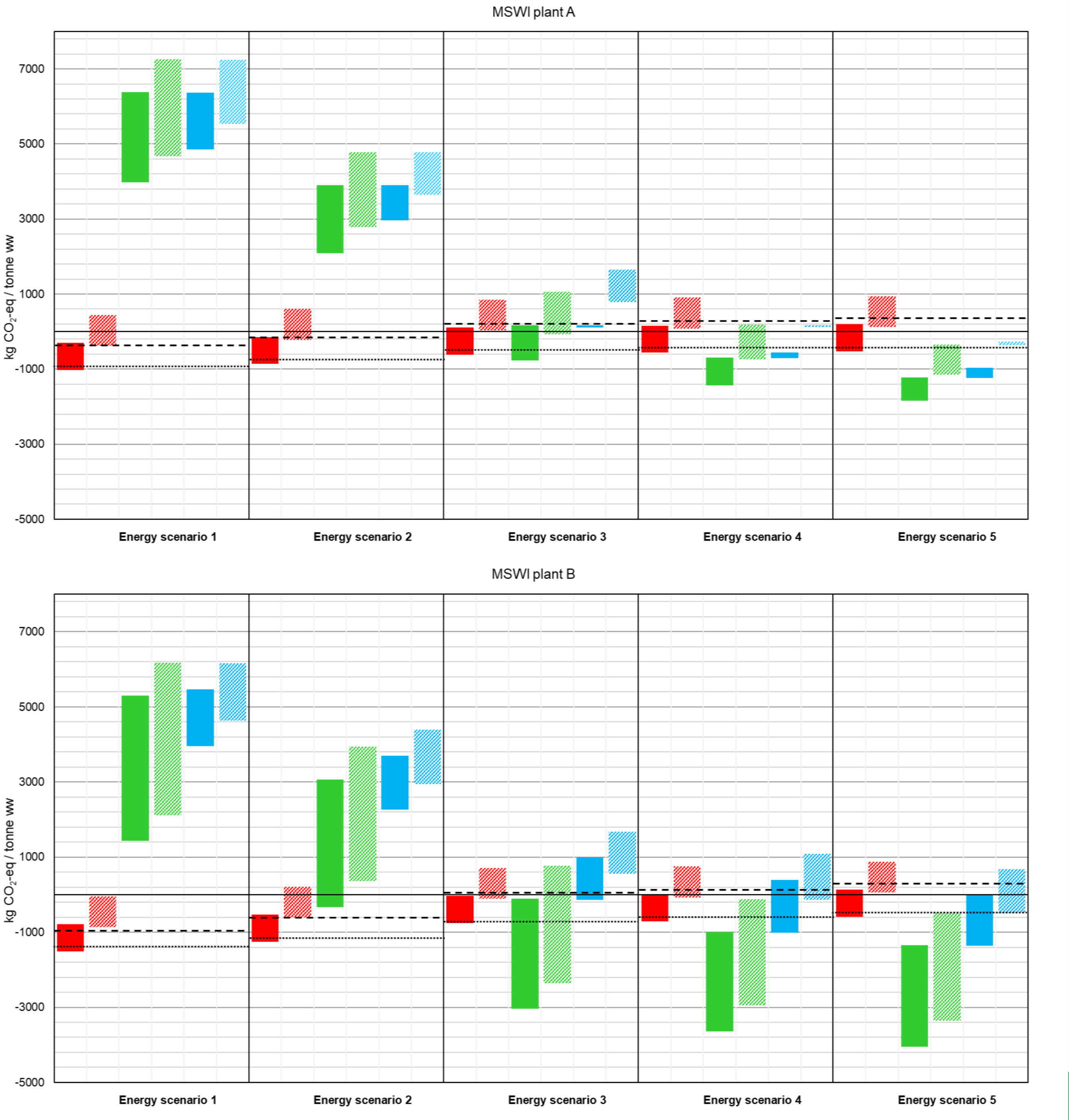
MSWIB	Unit	Ref	Methane	Methanol	DME	Formic Acid
MSWI, net electricity	kWh/tonne ww	618	-7650	-5945	-5897	-9553
MSWI, net heat	GJ/tonne ww	8	14	12	12	0
MSWI, CO_2 air emissions, fossil	kg CO_2/tonne ww	373	82	72	69	69
MSWI, CO_2 air emissions, biogenic	kg CO_2/tonne ww	595	131	115	111	109
CC, ancillary material use (MEA)	kg MEA/tonne ww	0	4	4	4	4
H_2 production, water use (ultrapure)	kg H_2O/tonne ww	0	-2303	-1811	-1796	0
H_2 production, oxygen by-product	kg O_2/tonne ww	0	1152	905	898	897
H_2 production and synthesis, water by-product	kg H_2O/tonne ww	0	1673	1099	1253	148
Synthesis, hydrogen by-product	kg H_2/tonne ww	0	0	0	0	76
Synthesis, product	kg product/tonne ww	0	274	567	411	823
Synthesis, CO_2 loss, fossil	kg CO_2/tonne ww	0	26	16	13	13
Synthesis, CO_2 loss, biogenic	kg CO_2/tonne ww	0	42	26	21	20
Industry, product	kg product/tonne ww	0	-274	-567	-411	-823
Industry, oxygen	kg O_2/tonne ww	0	-1152	-905	-898	-897
Industry, hydrogen	kg H_2/tonne ww	0	0	0	0	-76
Industry, water	kg H_2O/tonne ww	0	-1673	-1099	-1253	-148

Climate change impacts



Climate change impacts
Varying energy scenarios

With 5000 kWh/tonne MSW of electricity pulled from the grid for CCU, an incinerator treating 500,000 tonnes of waste per year import about 2500 GWh electricity per year. In Denmark, a good land-based wind turbine delivers about 10 GWh electricity per year, corresponding to the annual consumption of about 2500 family houses. This suggests that the CCU at a large incinerator may need electricity from 250 wind turbines, corresponding to the electricity used by 600,000 family houses. If we assume an average of three persons per family home, and 270 kg per person of waste incinerated annually, the MSWI plant will use the same amount of electricity as the amount of electricity used domestically by the number of people it services with waste management.



🟥 Direct utilization, local
▨ Direct utilization, market
🟩 Hydrogenated utilization, chemicals, with market for oxygen byproducts
▨ Hydrogenated utilization, chemicals, without market for oxygen by-product
🟦 Hydrogenated utilization, fuels, with market for oxygen byproducts
▨ Hydrogenated utilization, fuels, without market for oxygen by-product
--- Reference MSWI
······ MSWI with CC and storage

Conclusion/ Discussion

Our results suggest:

- From a climate perspective it does make sense to CC at MSWI: Early phases as CCS evt as CCU if direct local uses can be identified, later when power is fully wind turbine based production of chemicals looks attractive
- Methanol and DME looks most promissing

However do our assumtrions stay relevant in the long term?:

- What are the substitution wrt chemicals in the non-fossil future?
- Maybe the long term reference will be alternative fuels and even further in the future what is the cheapest cost of CC in any industry

MSWI image wise:

- Plastic becomes less impotent for the MSWI image because impacts will be savings
- But the less fossil content, the larger the saving

Read more!

CCS

Bisinella, V., Hulgaard, T., Riber, C., Damgaard, A., Christensen, T.H. (2021)

Environmental assessment of carbon capture and storage (CCS) as post-treatment technology in waste incineration.

Waste Management, 128, 99-113.

CCU

Christensen, T.H. and Bisinella, V. (2021)

Climate change impacts of introducing carbon capture and utilization (CCU) in waste incineration.

Waste Management, 126, 754-770.

CCS
applied

Bisinella, V., Nedenskov, J., Riber, C., Hulgaard, T., Christensen, T.H. (2021)

Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage (CCS).

Waste Management & Research, .40, 79-95