Biological recycling and treatment processes - Climate impacts

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teach4waste
International E-Learning Platform
Waste and Resource Management

Virtual Network Brazil-Germany

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COOPERAÇÃO PARA A PROTEÇÃO DO CLIMA
NA GESTÃO DE RESÍDUOS SÓLIDOS URBANOS

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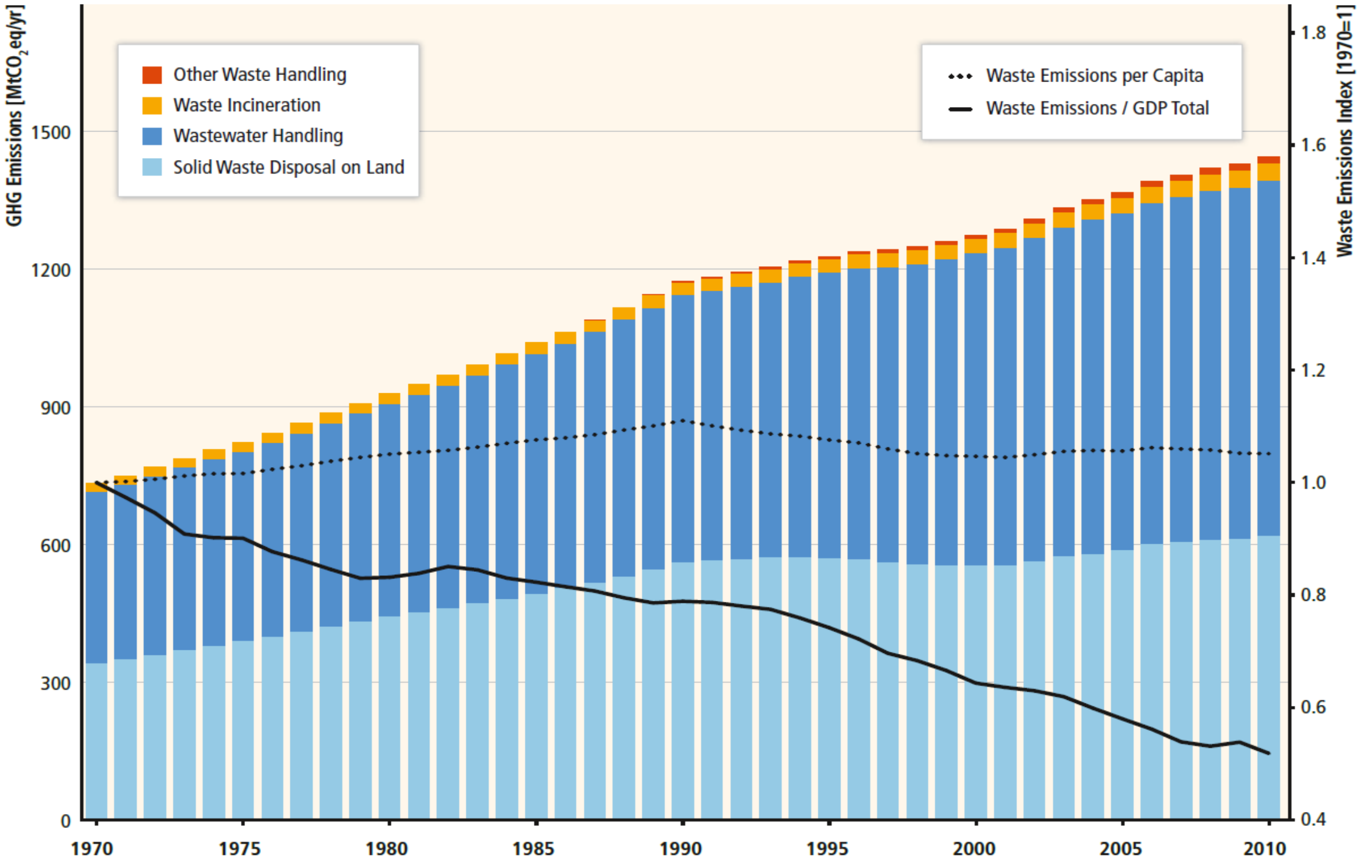
Climate impacts of waste management sector - Learning objectives

- Students should acquire basic knowledge of the climate impact of the various waste management measures and be able to use this knowledge to carry out weak-point analyses
- With the options for action learned, they should be able to develop climate-friendly measures

Climate impacts of waste management sector - Subareas of waste management

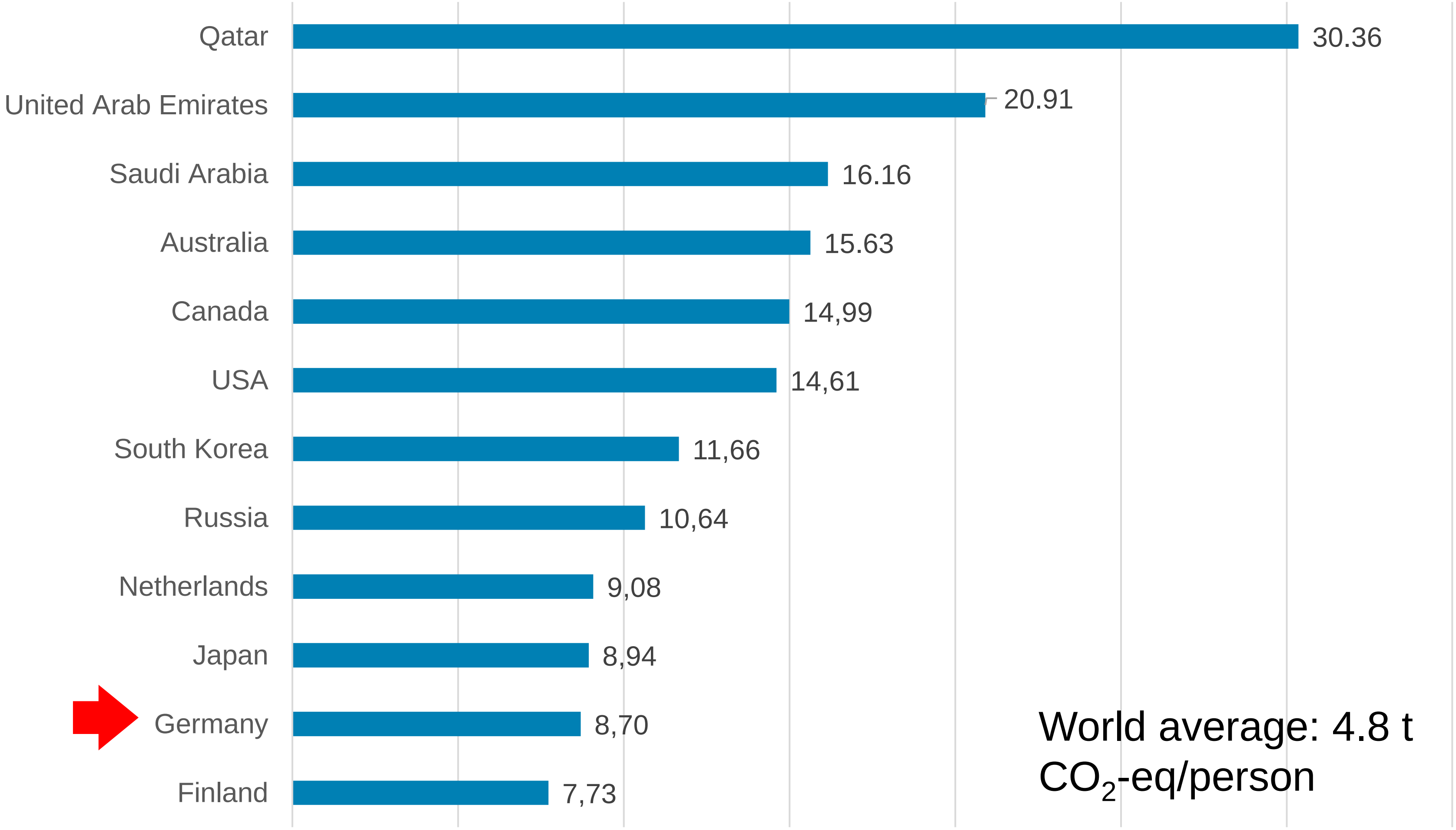
Global waste GHG emissions
Mt CO_2-eq per year and GDP per capita, referred to 1970



Source: IPCC, 2014

Up to 12 % of total GHG emissions in developing countries and emerging markets originate from the waste sector

GHG emissions in t CO_2-eq per citizen in selected countries (status 2018)

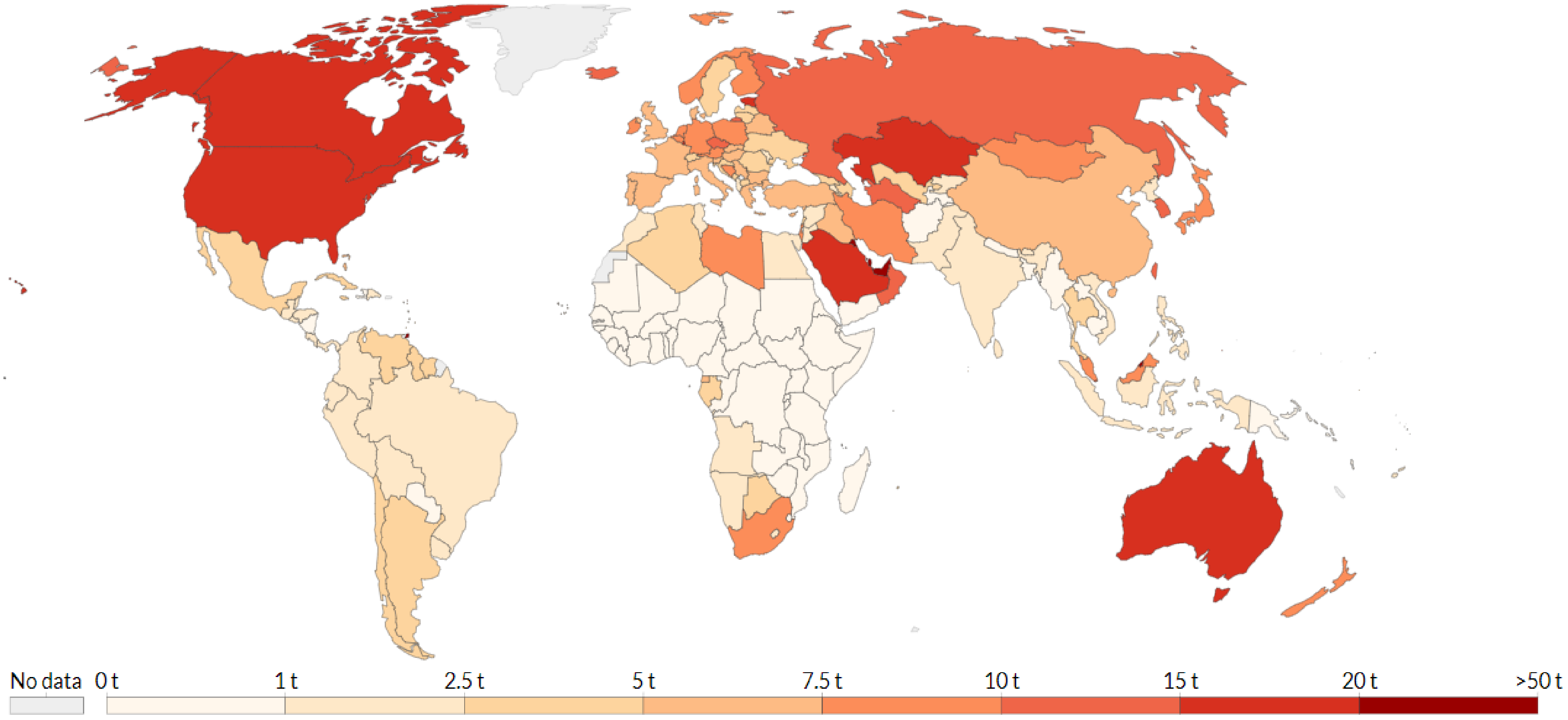


World average: 4.8 t CO_2-eq/person

Source: Statista, 2020: https://de.statista.com/statistik/daten/studie/167877/umfrage/co-emissionen-nach-laendern-je-einwohner/

Global GHG emissions - per citizen (status 2017)

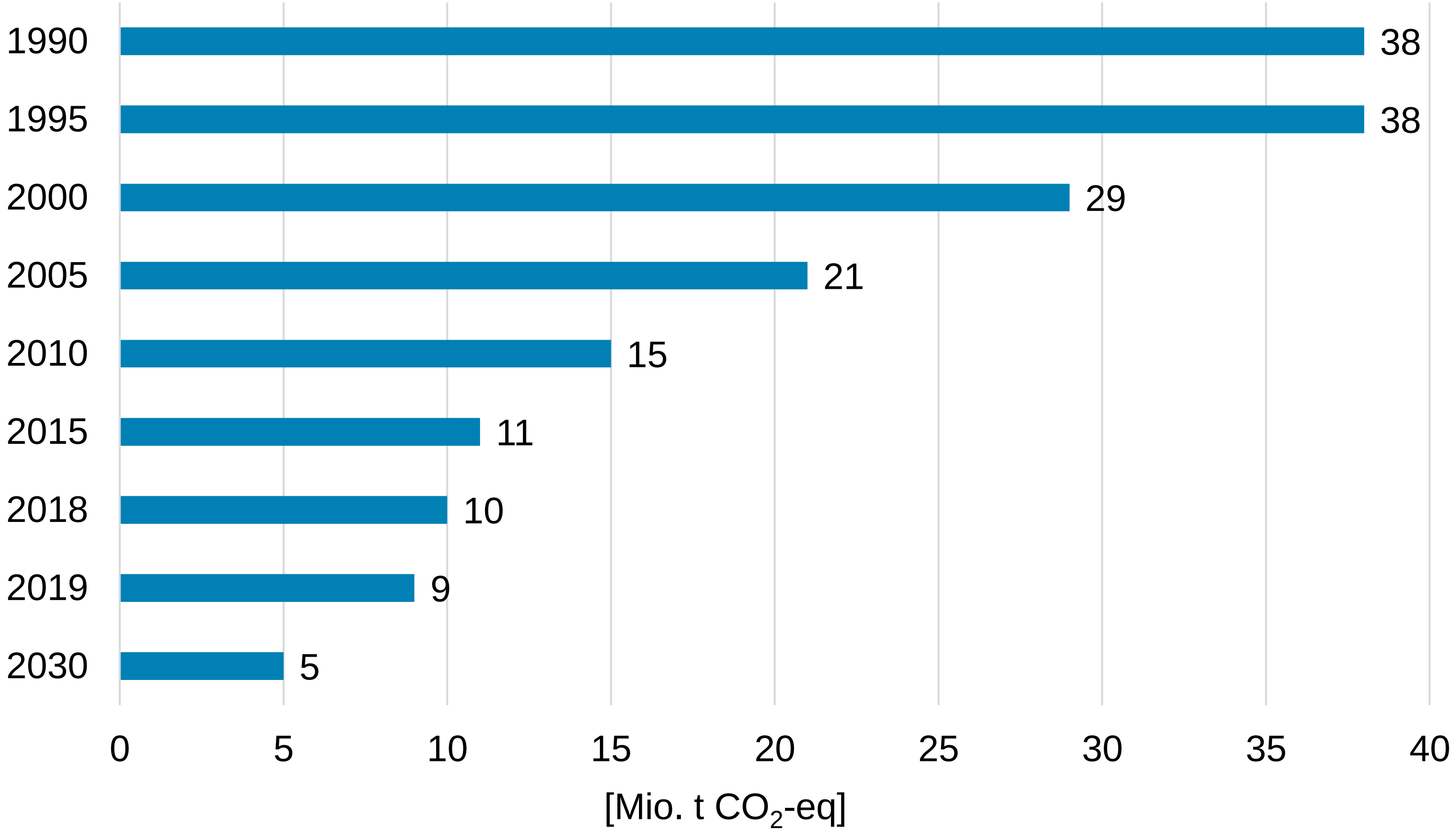
CO_2 emissions per capita in 2017



Source: OWID based on the Global Carbon Project; Carbon Dioxide Information Analysis Centre (CDIAC); Gapminder and UN population estimates

GHG emissions in Germany in the waste sector - GHG reduction

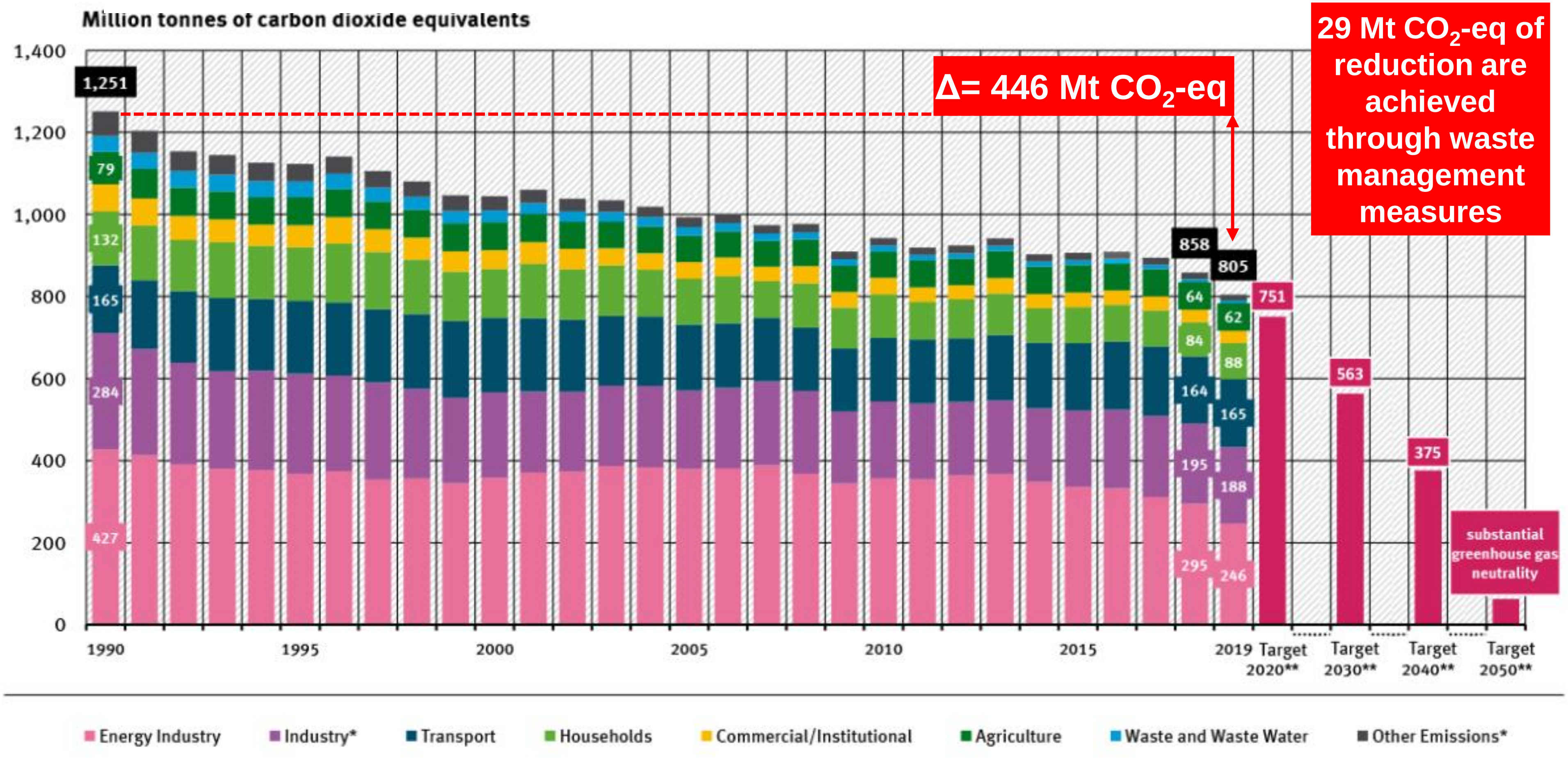
Development of GHG emissions from the waste sector in Germany, 1990 - 2019 – without credits



Source: UBA, 2020a (modified)

Mitigation of GHG emissions in Germany - Sector waste management

Development GHG emissions in Germany 1990 - 2019



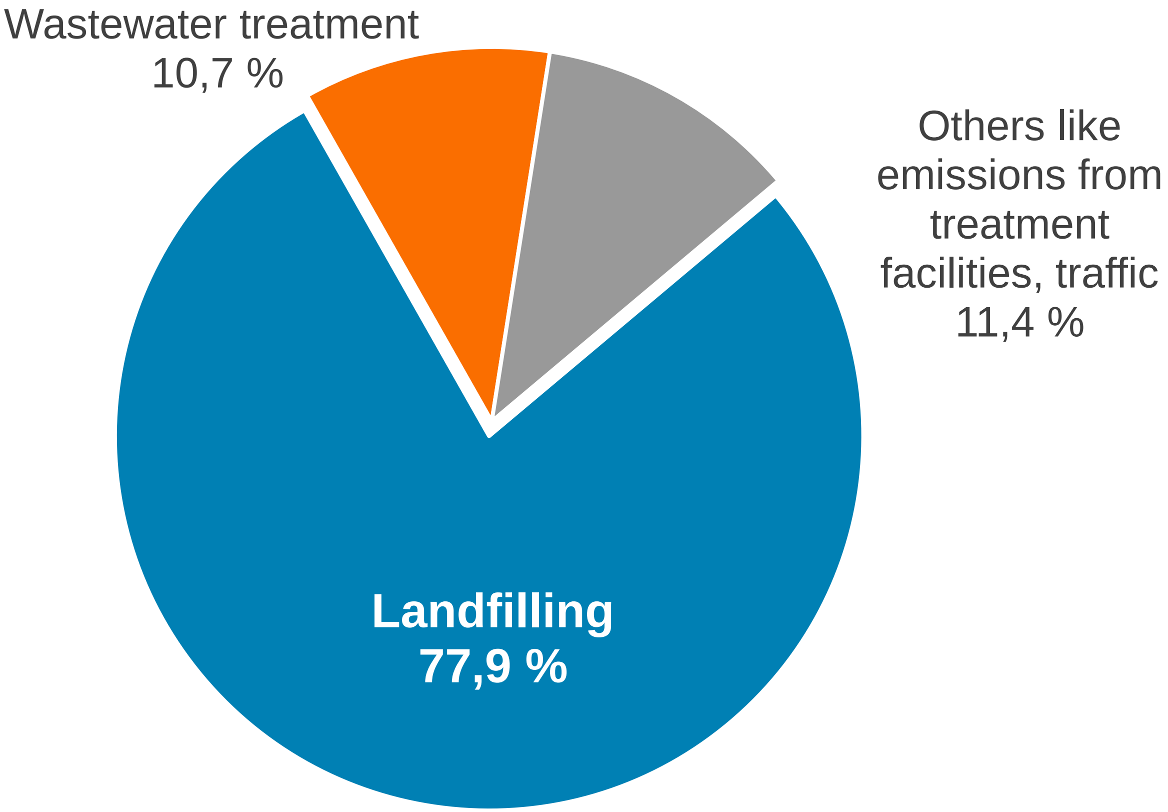
Δ= 446 Mt CO_2-eq

29 Mt CO_2-eq of reduction are achieved through waste management measures

Source: UBA, 2020

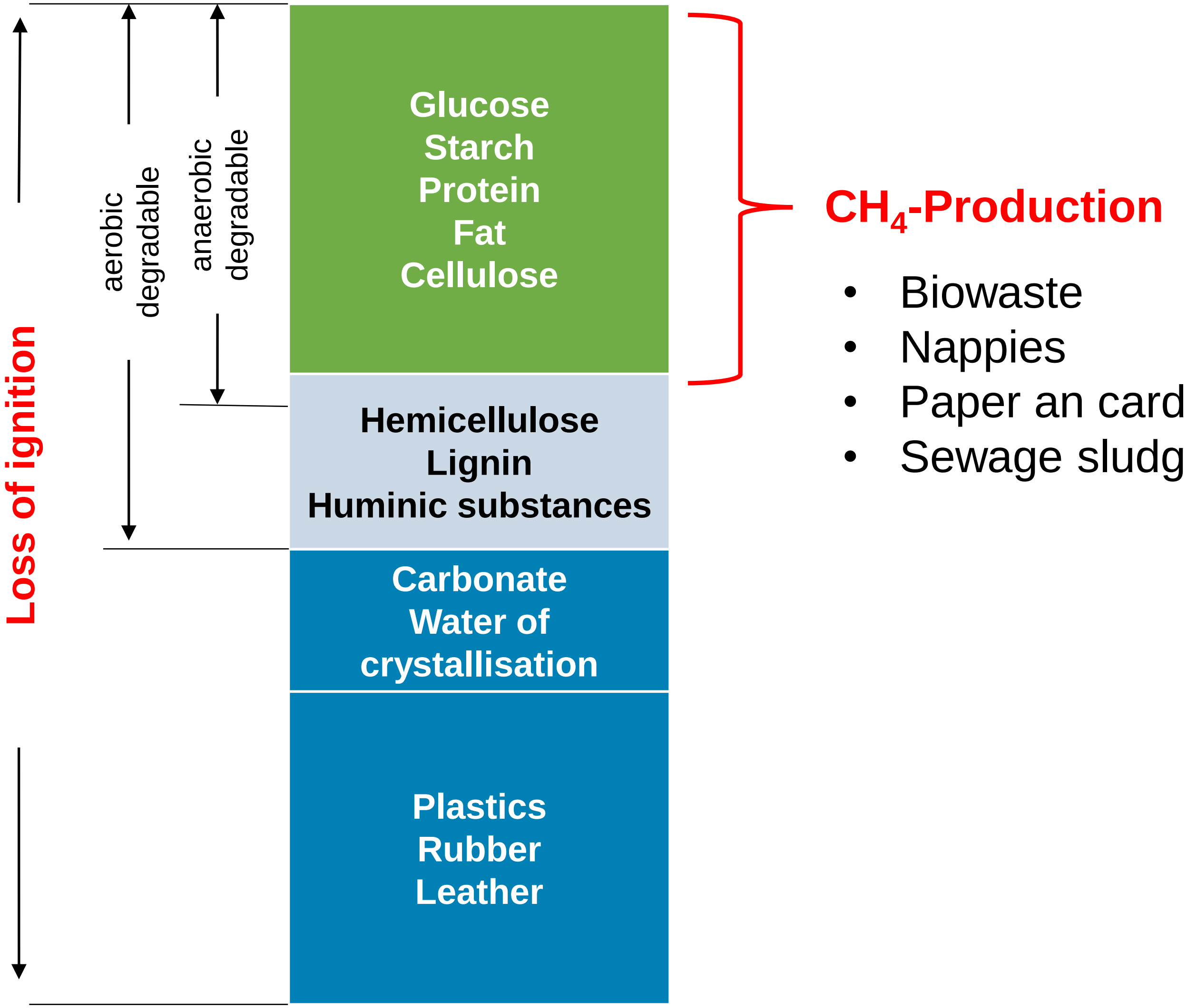
GHG emissions in Germany - Waste and wastewater treatment

GHG sources from the sector waste and wastewater treatment in 2018 - without CO_2 from biomass use



Source: BMU, 2020

GHG emissions from landfills - Relevant raw materials



Glucose
Starch
Protein
Fat
Cellulose

Hemicellulose
Lignin
Huminic substances

Carbonate
Water of crystallisation

Plastics
Rubber
Leather

CH_4-Production

- Biowaste
- Nappies
- Paper an cardboard
- Sewage sludge

Mitigation of GHG emissions in Germany - CO_2 emissions and credits

The total effect of waste management measures results from the sum of GHG credits and GHG emissions:

$$CO_{2,eq,total} = \sum_{i=1}^{n} Emissions_i - \sum_{k=1}^{n} Emissions\ Credits_k$$

GHG mitigation in Germany from the sector of waste management from 1990 up to 2018:

By GHG emissions	29 Mio. t CO_2-eq/a
By GHG credits through recycling and energy recovery	20 Mio. t CO_2-eq/a

- GHG avoidance through waste management measures **0.61 t CO_2-eq/person*a**

Source: UBA 2018 (modified)

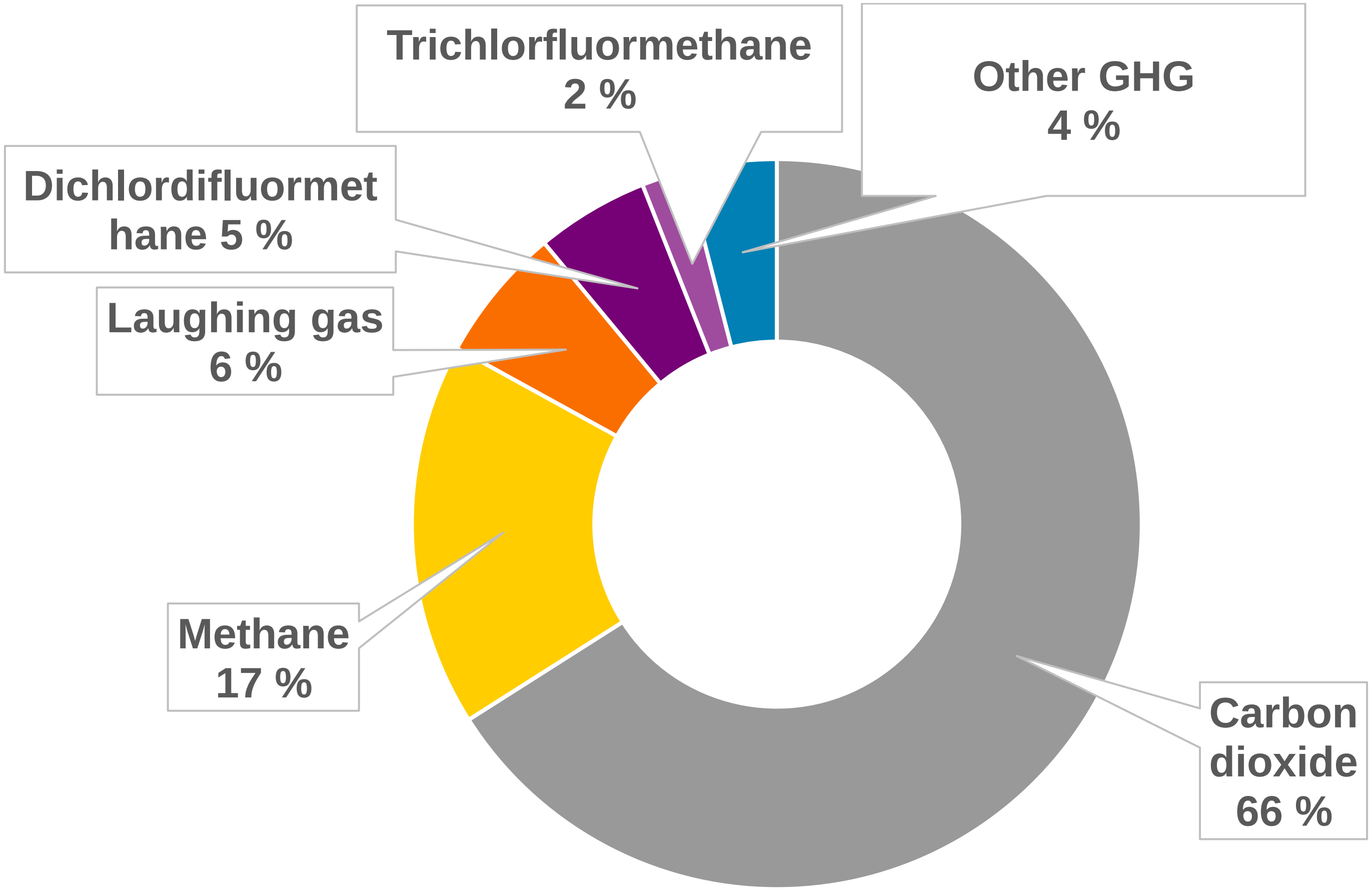
GHG credits of individual waste management measures as of 2011 and projected for 2030

Waste management measures	2011 Satus quo	2030 Status quo	2030 optimised
	[1,000 t CO_2-eq/a]		
Landfill	163	0	0
Waste incineration	-1,691	-14	-2
MBT	-951	-1,246	-5,473
Recycling			
• Biowaste	-180*	-180*	2,600*
• Greenwaste	-14	61	-183
• Paper and cardboard	-6,120	-7,457	-9,290
• Glass	-1,232	-1,155	-1,155
• Light packages	-2,100	-2,840	-5,301
• Metals	-1,781	-1,842	-1,842
• Electronic waste	-764	-764	1,076
Wood (biomass power plants)	-5.060	-3,108	-5,624
Total	**-19.731**	**-18,188**	**-32,546**

(Ökoinstitut, 2014, * Own data)

Global GHG emissions
- Contribution of different greenhouse gases

Contribution of different greenhouse gases to the greenhouse gas effect



Source: UBA 2018 (modified)

Specifications of GHG
- Global warming potential (GWP)

⬇

GHG	**Concentration today**	**Average lifespan**	**GWP**	**Global share greenhouse effect**	**Share greenhouse effect in GER**
Units	[ppm]*	[a]	[weight unit over 100 a]	[%]	[%]
Carbon dioxide (CO_2)	407.38	120	**1**	66	88.2
Methane (CH_4)	1.92	15	**25**	17	6
Nitrous oxide (N_2O)	0.33	114	**298**	6	4.2

* Except water vapour

Source: UBA, 2017

GHG emissions
- Credits by energy saving or providing

Credits for saving or providing electricity and heat

- Calorific value of waste
- Electric und thermal efficiency (η) of the incineration plant
- **Emission factors** for substituted electricity and heat

Calculation:

- Emissions from incineration = m (waste) * C_{fos} * 44/12
- Credit for electricity from incineration = m (waste) * Hu (waste) * η_{el} * EF Electricity
- Credit for heat from incineration = m (waste) * Hu (waste) * η_{th} * EF Heat

GHG credits
- Calculation of the energy intensity

$$\mathit{Emissions\ intensity}\left[\frac{g\ CO_2}{kWh}\right] = \frac{\mathit{direct}\ CO_2\,\mathit{emissions}}{\mathit{Electricity\ consumption}}$$

Relevance for calculation:

- Energy saving through avoidance, reuse and recycling
- Energy generation using fuels produced from waste
- Energy generation using biomass fuels produced from waste

GHG emissions - Credits by energy saving or providing

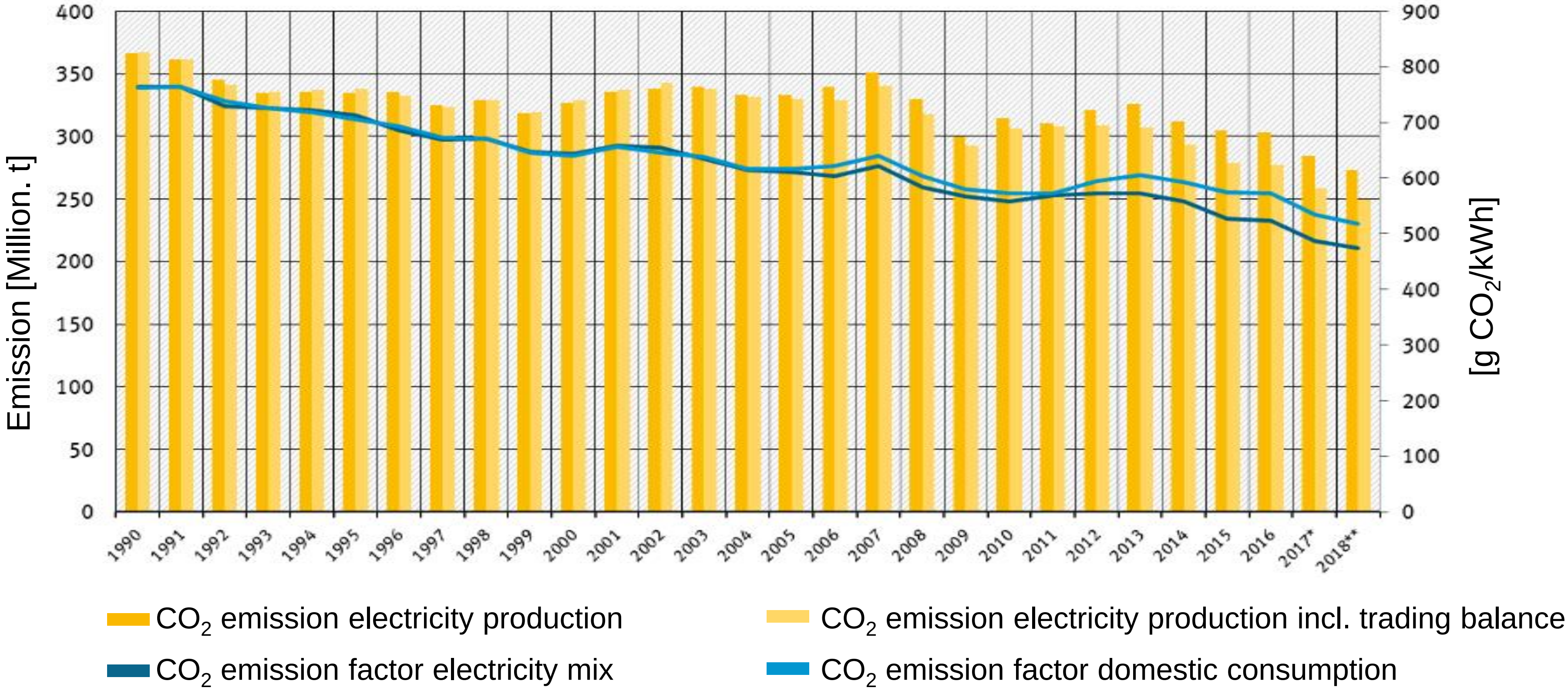
Dependency of credits from the reference system:

- Depending on which electricity (heat) is substituted, different credits result.
- The lower the emissions from substituted electricity (heat), the lower the credits for electricity (heat) from incineration.
- That means for a decarbonized world, in which the most of the electricity (heat) comes from regenerative energy: Incineration gains less and less credits for electricity (heat)

Electricity	**Credits for 1 kWh**
Unit	[kg CO_2-eq]
German electricity mix	0.40
French electricity mix	0.06
Brazilian electricity mix	0.29
Lignite-based electricity	1.22

Source: ecoinvent V 3.4 2017; UBA 2020

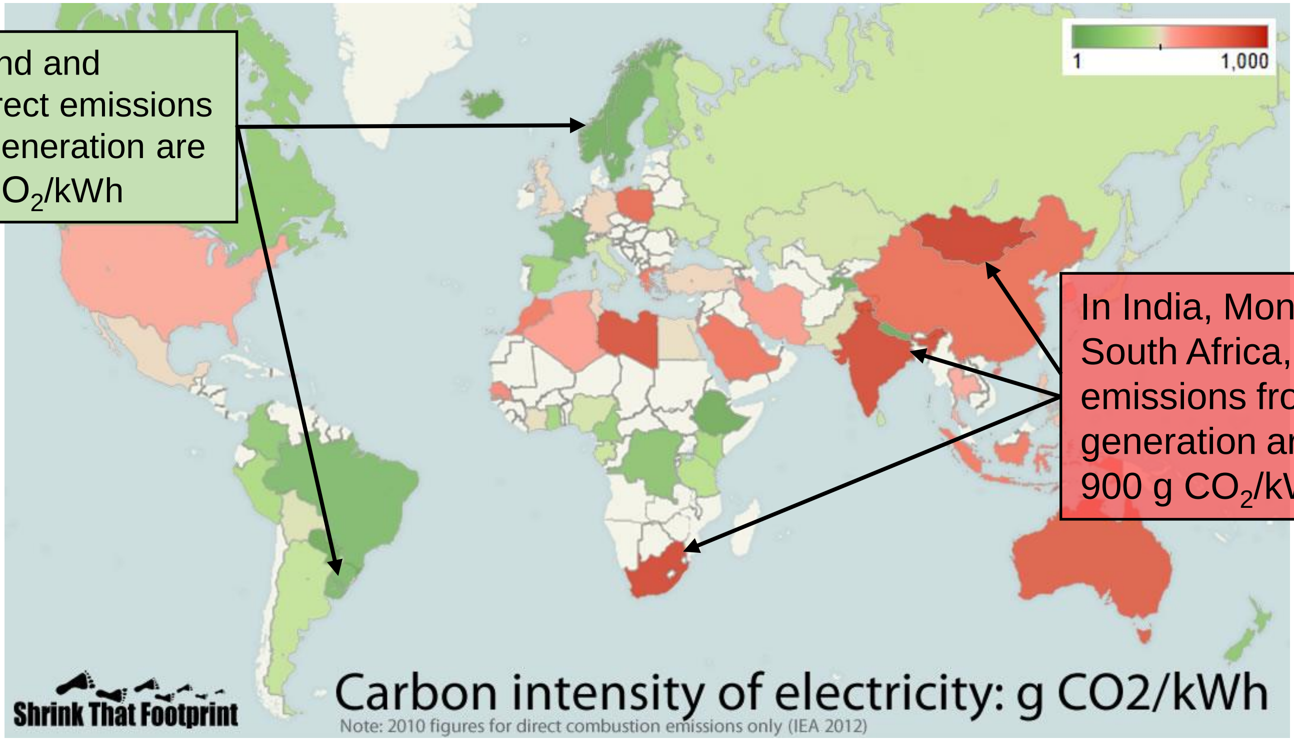
GHG credits by energy saving - CO_2 emissions intensity in GER



$$\textit{Emissions intensity}\left[\frac{g\,CO_2}{kWh}\right] = \frac{\textit{direct } CO_2\textit{ emissions}}{\textit{Electricity consumption}}$$

Source: UBA, 2019

GHG credits by energy saving - CO_2 emissions intensity worldwide



Carbon intensity of electricity: g CO2/kWh

Note: 2010 figures for direct combustion emissions only (IEA 2012)

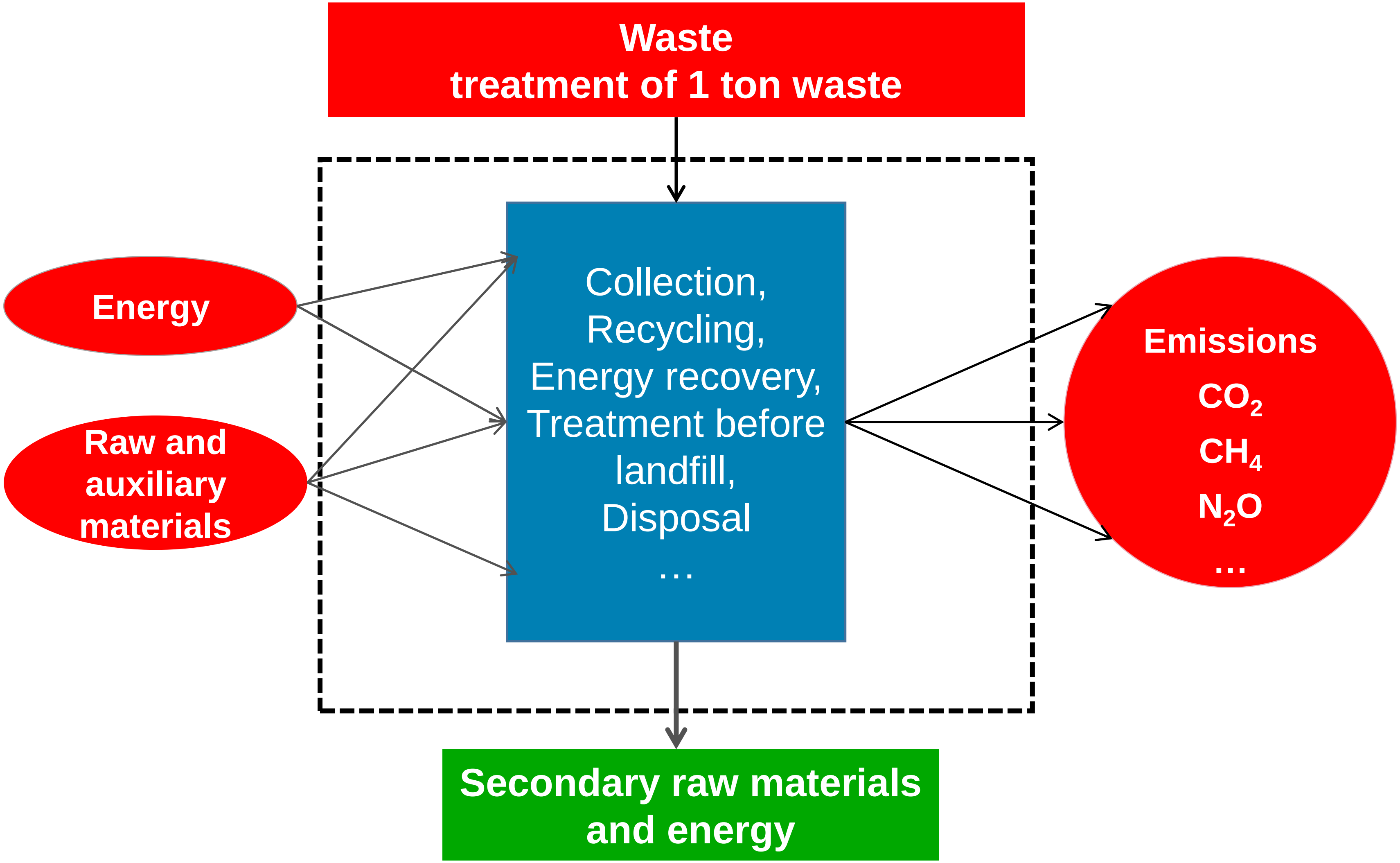
In Norway, Iceland and Paraguay the direct emissions from electricity generation are less than 20 g CO_2/kWh

In India, Mongolia and South Africa, the direct emissions from electricity generation are more than 900 g CO_2/kWh

CO_2 emissions intensity for the electricity around the world in 2010 [g/kWh]

Source: shrinkthatfootprint.com

LCA in waste management



Waste
treatment of 1 ton waste

Energy

Raw and auxiliary materials

Collection,
Recycling,
Energy recovery,
Treatment before landfill,
Disposal
…

Emissions
CO_2
CH_4
N_2O
…

Secondary raw materials and energy

GHG emissions and credits

GHG emission reduction

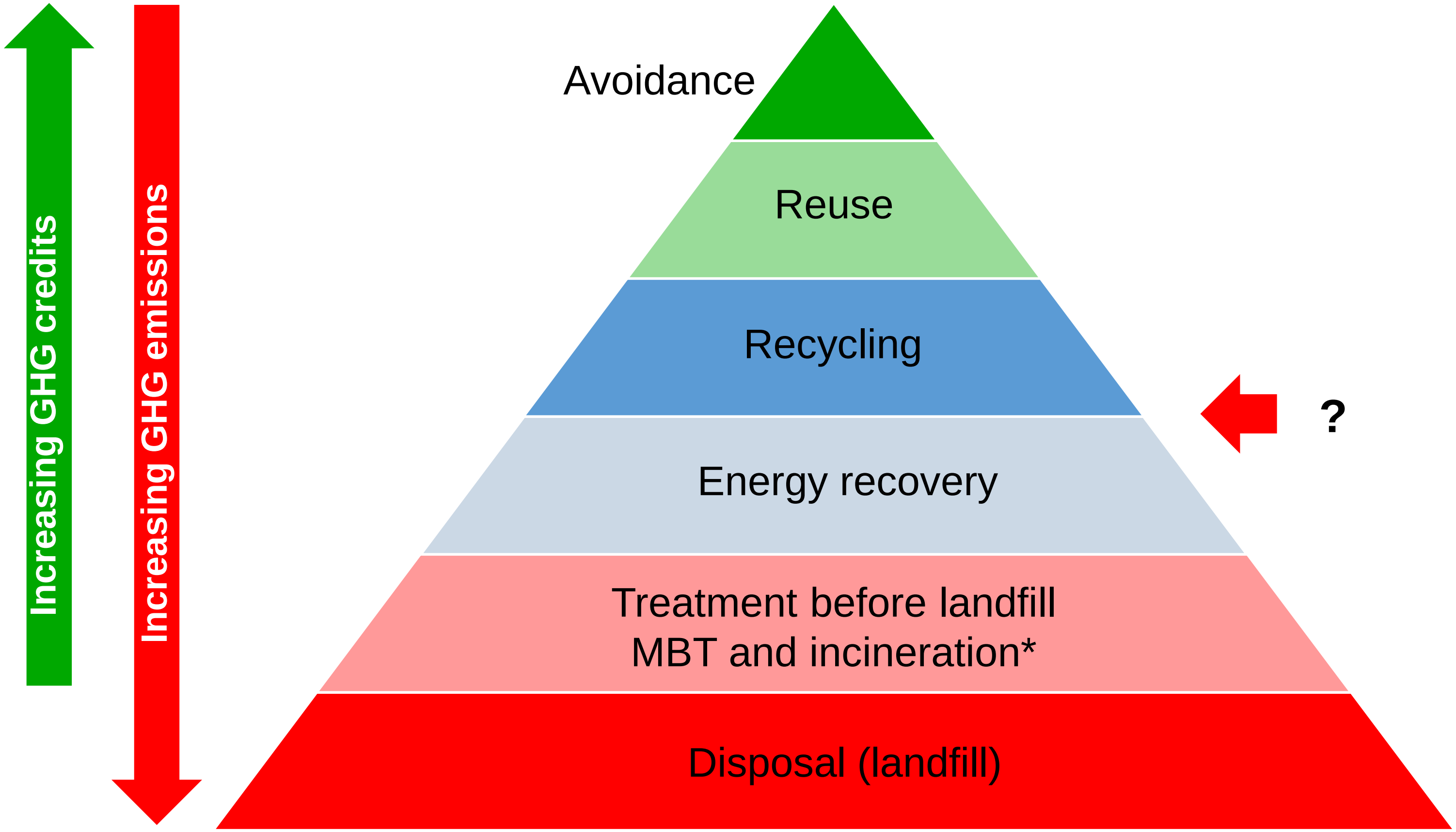
- Collection and transportation
- Processing e.g.
  - Sorting, composting, digestion, incineration
- Using secondary resources
- Landfilling

GHG credits

- Prevention
- Reuse
- Recycling
- Energy recovery
- Landfill gas utilisation

Sustainable waste management

Waste hierarchy - climate protection



*Not included in the official waste hierarchy of Germany and the EU as a separate level

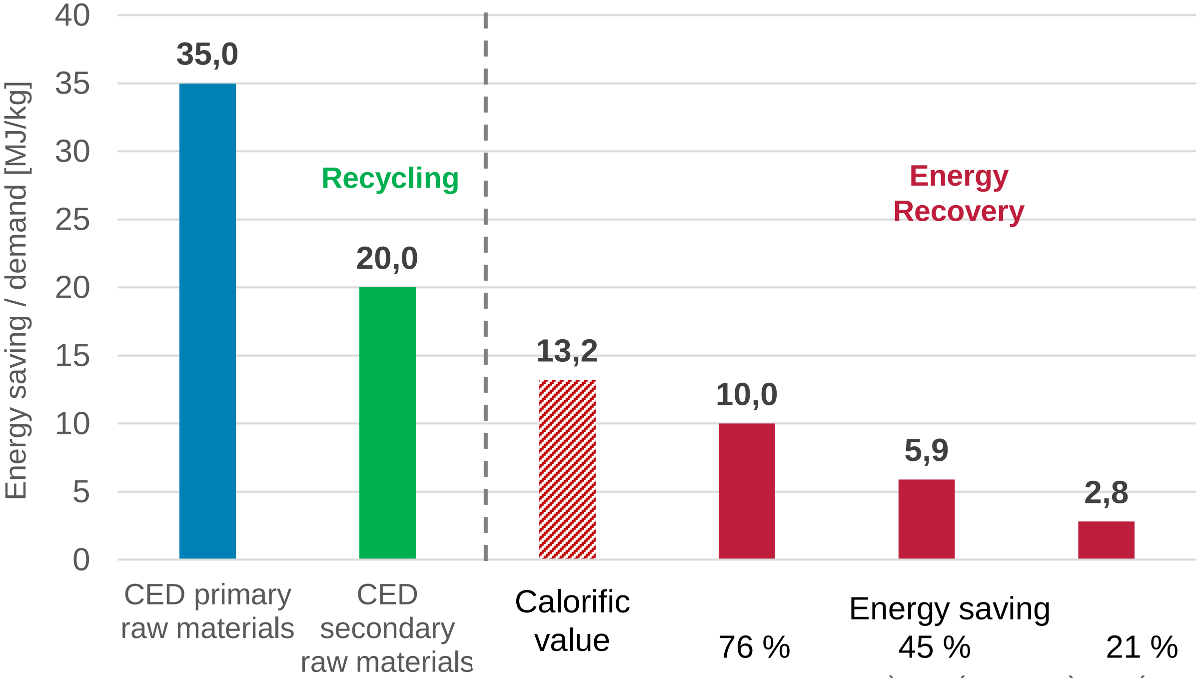
Material recycling vs. energy recovery - What is the most sustainable strategy?

- **Material recycling vs. energy recovery**
- What is the most sustainable strategy in terms of:
  - Resource efficiency?
  - Environmental protection, i.e. mitigation of **GHG emissions?**

Material recycling vs. energy recovery - Energy saving, example paper

Example paper fibre:

- 35 MJ/kg: Cumulated energy demand (CED) of primary raw materials
- 15 MJ/kg CED of equivalent paper made from wastepaper
- 20 MJ/kg energy saving by recycling
- Lower calorific value (LCV) 13.2 MJ/kg calorific value of paper
- Max. 10 MJ/kg energy saving by energy recovery
- Energy efficiency in German waste incineration plants 21 % up to 76 %

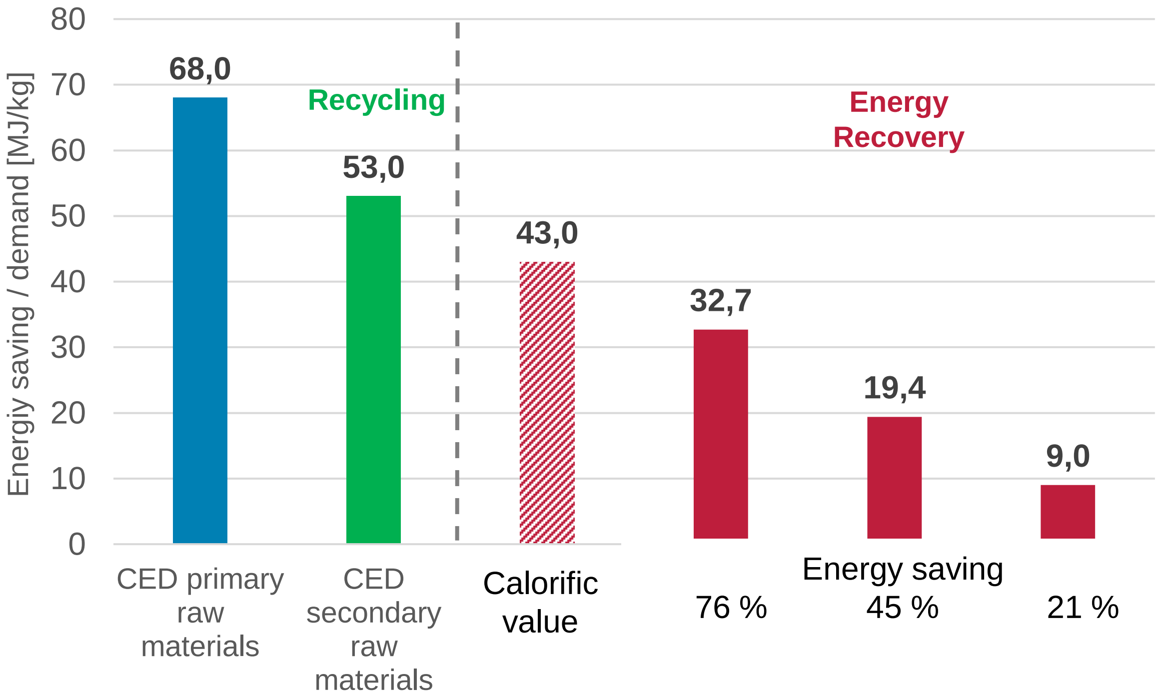


Source: Fricke et al. 2011

Material recycling vs. energy recovery - Energy saving, example LDPE

Example LDPE polymer:

- 68 MJ/kg: CED of primary raw materials
- 15 MJ/kg CED of equivalent LDPE made from waste LDPE
- 53 MJ/kg energy saving by recycling
- LCV 43 MJ/kg calorific value of waste LDPE
- Max. 32.7 MJ/kg energy saving by energy recovery



Source: Fricke et al. 2011

Material recycling vs. energy recovery - Energy saving by various polymeres

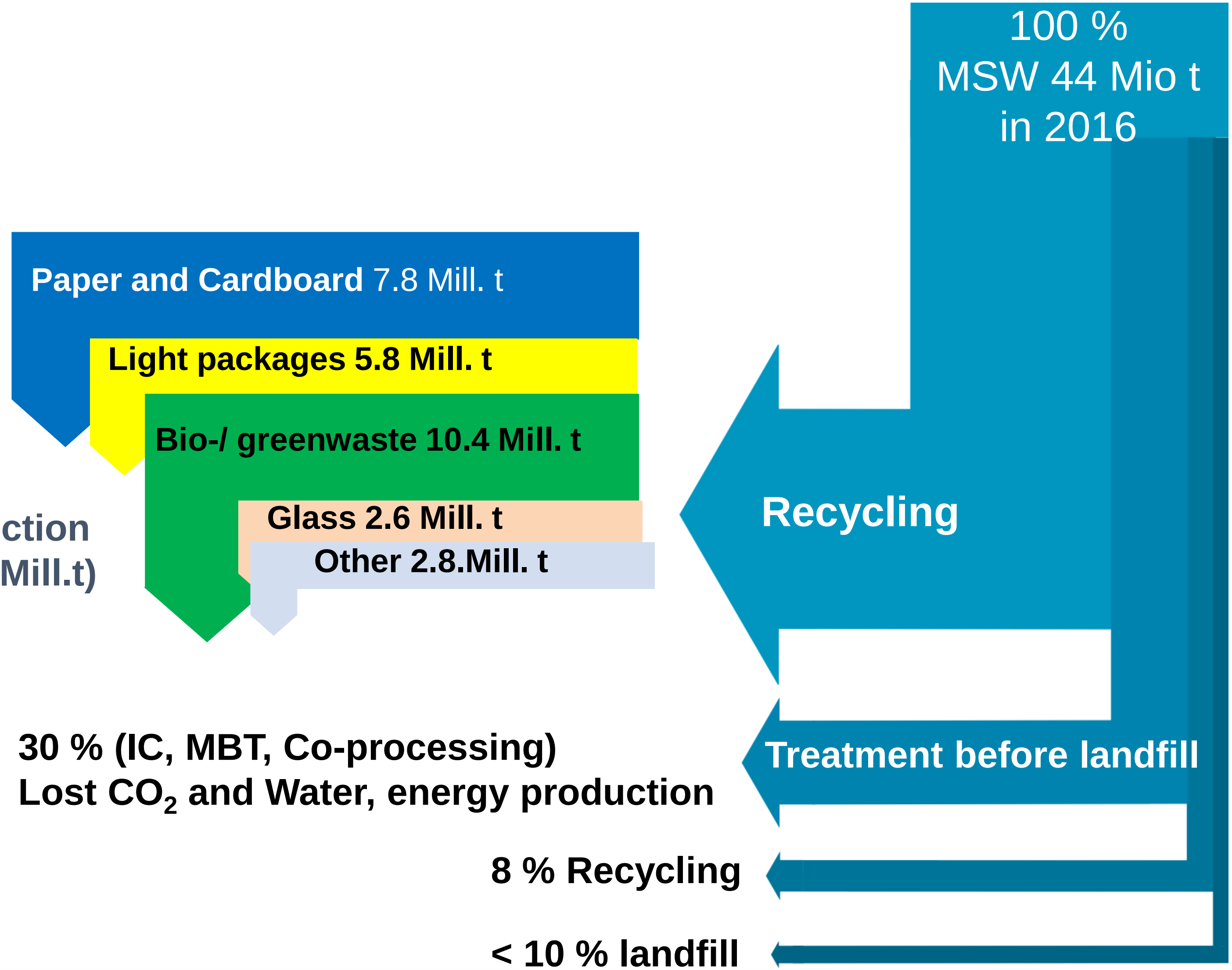
Cumulated energy demand and lower calorific values for different polymers

Polymers	**Cumulated energy demand (CED)**	**Lower calorific value (LCV)**
Units	[MJ/kg]	[MJ/kg]
LD-PE	68	43
Polystyrol	79	40
Polyamid-6	166	28
PP	72	43
PVC	51	18

➡ The higher the difference between CED and LCV, the higher the energy saving factor by (material) recycling!!!

Sources: Kindler and Nikles, 1979 HTP and IFEU, 2001

Mass flow MSW Germany - Separate collection



100 %
MSW 44 Mio t
in 2016

Paper and Cardboard 7.8 Mill. t

Light packages 5.8 Mill. t

Bio-/ greenwaste 10.4 Mill. t

Glass 2.6 Mill. t

Other 2.8.Mill. t

Recycling

66 % Separate collection
60 % Recycling (29 Mill.t)

Treatment before landfill

30 % (IC, MBT, Co-processing)
Lost CO_2 and Water, energy production

8 % Recycling

< 10 % landfill

Recycling
- GHG emissions, losses and credits

	Emissions of recycling process	**Recycling losses**	**Substituted raw materials**	**Credits**
Units	[kg CO_2-eq/kg] Input into recycling	[%]		[kg CO_2-eq/kg] raw material
HDPE	0.37	25	HDPE	2.03
LDPE	0.69	30	LDPE	2.18
PP	0.37	25	PP	2.06
PET	0.43	30	PET, amorphous	3.13
PS	0.32	15	PS	3.60
Paper	0.37	32	Fiber (chemical/mechanical pulp)	1.11
Glass	0.02	10	Glass fragments	0.46
Metal	0.42	5	Steel, low alloy	1.91
Aluminum	0.57	5	Aluminum, wrought alloy	9.55

Source: Öko Institut, 2018, eigene Daten

Recycling
- Example calculation

Simplified example calculation (PET)

Input recycling		**Recycling**		**Output recycling**	
PET-waste	1 kg	Loss	30 %	Secondary PET	0.70 kg
Electricity	0.7 kWh			Emissions-Electricity	0.40 kg CO_2-eq/kWh

Emissions for 1 kg primary PET
3.13 kg CO_2-eq

Overall results PET recycling.

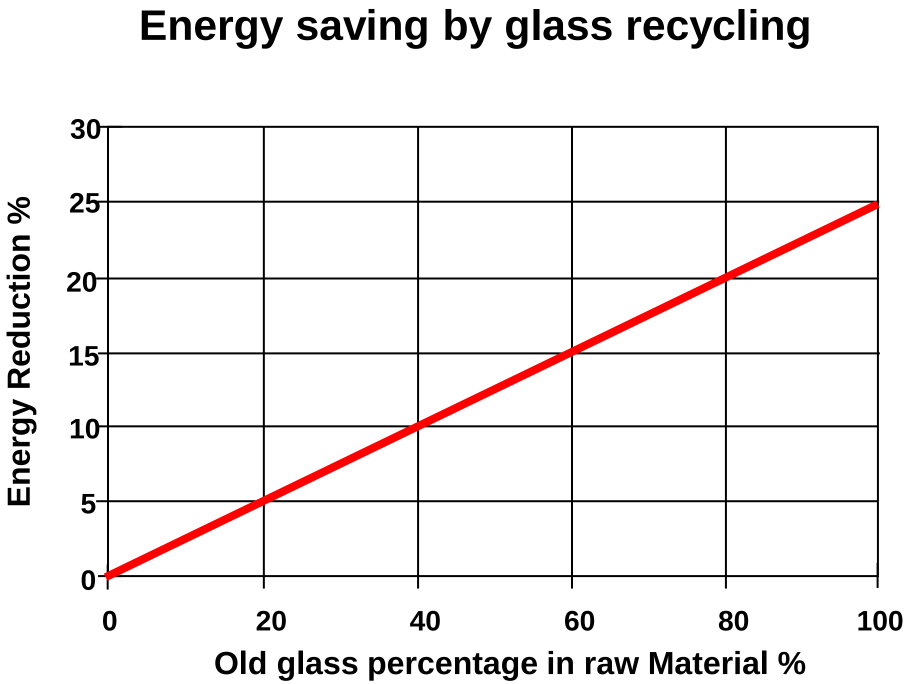
- Emissions for recycling: 0.7 kWh * 0.40 kg CO_2-eq/kWh = 0.28 kg CO_2-eq
- Avoided emission production: 0.7 * 3.13 kg CO_2-eq = 2.19 kg CO_2-eq
- **Total balance:** **= - 1.91 kg CO_2-eq**

Material recycling vs. energy recovery - Conclusion

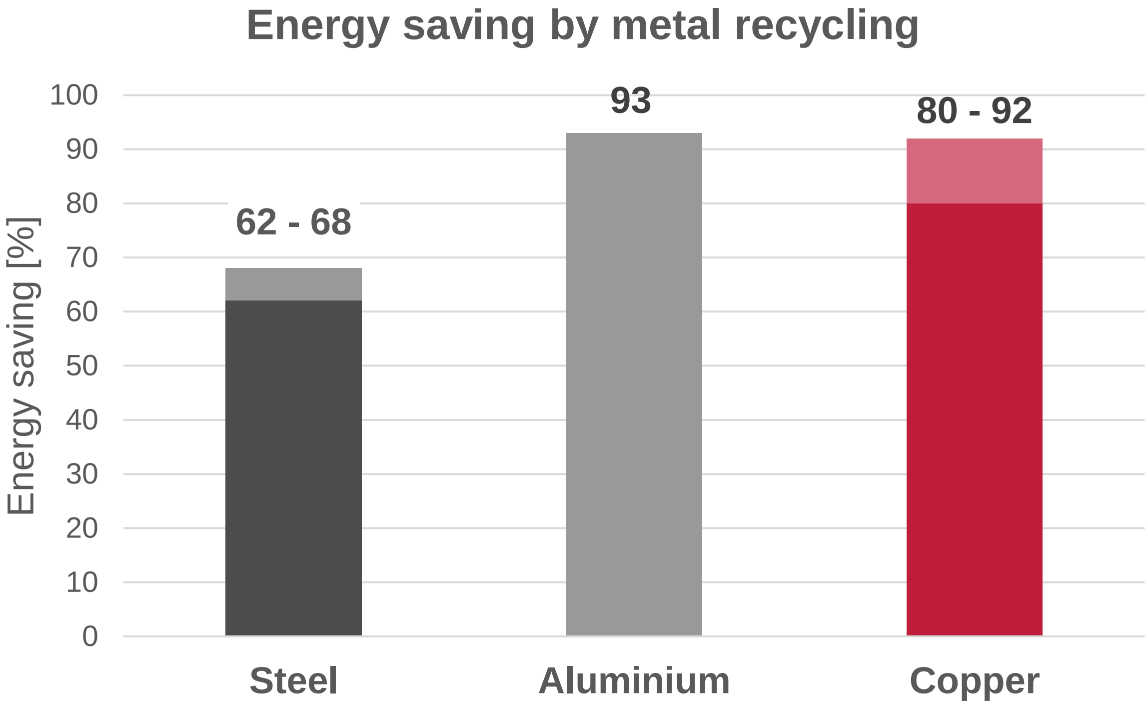
- Regarding resource efficiency, material recycling shows **significant advantages** compared to energy recovery and disposal for paper and plastics
- **Biowaste** recycling is more sustainable if cascade use takes place, this means biogas utilization **and** compost use
- **Metals** (except aluminum) and **glass** can be used only for recycling, as they are not suitable for incineration
- **Higher energy efficiency** corresponds to **lower climate effects**

Recycling - Glass

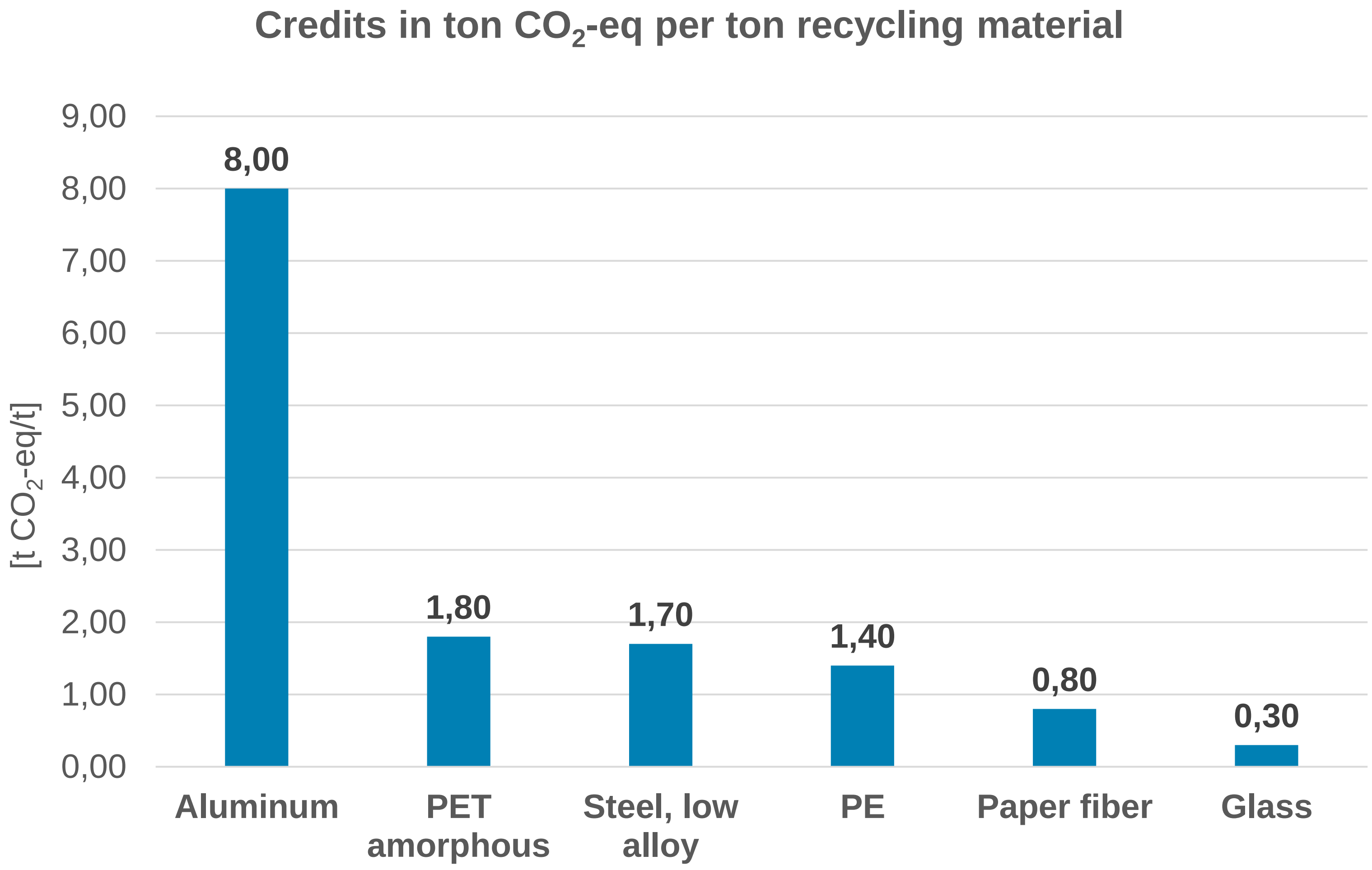
- With increased use of old glass, the melting point is lowered
- Resource saving:
  - Energy
  - Quartz sand
  - Soda
  - Lime



Recycling
- Metals



GHG emissions
- Reduction performance through recycling

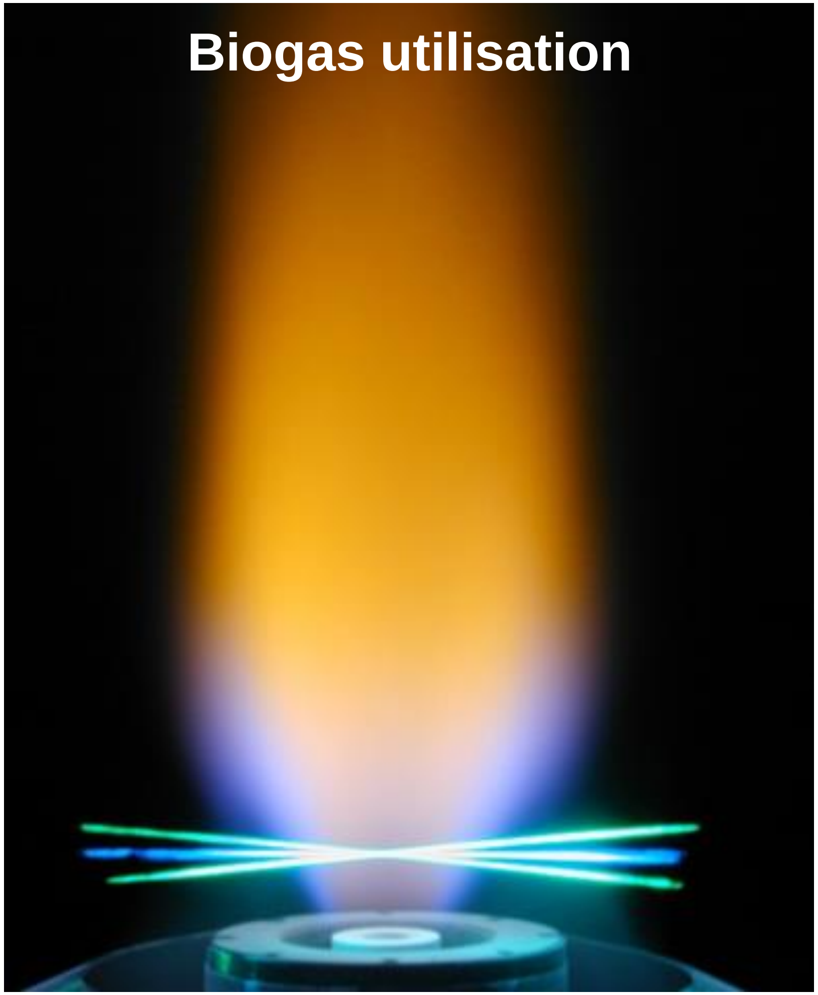


Source: regarding to Öko Institut, 2018

Recycling
GHG credits ranges

Material	**Credits**
Unit	[t CO_2-eq/t recycling]
Paper and cardboard	0.6 - 2.5
Glass	0.4 - 0.5
Plastics	1.0 - 2.0
Ferrous metals	1.8 - 2.0
Aluminium	9 - 10
Biowaste	0.13 - 0.39

Recycling of biowaste - Example calculation


Biogas utilisation

+


Compost use

Recycling of biowaste
- Example calculation methodology

$$\boldsymbol{CO_{2,eq,total} = \sum_{i=1}^{n} Emissions_i - \sum_{k=1}^{n} Emission\ Credits_k}$$

$$\sum_{i=1}^{n} E_i = E_{Collection} + E_{Transport} + E_{Compost\ process} + E_{Composting\ energy\ consum.} + E_{Compost\ transport} + E_{Compost\ application}$$

$$\sum_{k=1}^{n} E\ Credits_k = E\ Credits_{EnergY\ Supply} + E\ Credits_{Nutrients} + E\ Credits_{Humus\ C}$$

Where:
E Emissions
i Index
k Index
n Final value

Recycling of biowaste
- Example calculation methodology

GHG emissions	GHG credits
Collection: CH_4 in the collecting bin, not considered because of same emission in MSW collection and no data available	Energy supply
Transport of biowaste, not considered because of alternating collection	Nutrients supply
Biological treatment process (CH_4 and N_2O)	Humus C supply
Energy consumption of treatment process	Indirect: Mitigation of landfill GHG emissions through recycling measures for biowaste and greenwaste
Transport of compost products, not considered because of comparison with organic fertilizers	
Compost application	

Recycling of biowaste
- Emissions through energy consumption

GHG emissions through energy consumption of biowaste composting process

	Energy consumption	**Energy types**	**Spec. GHG emissions**	**GHG emissions**
Units	[MJ/t]	[MJ/t]	[kg CO_2-eq/MJ]	[kg CO_2-eq/t bio waste]
Energy expenditure - **extensive composting**, rotting degree IV	170	90 % diesel	0.093	16.81
		10 % electricity	0.152	
Energy expenditure - **intensive composting**, rotting degree IV	300	30 % diesel	0.093	40.29
		70 % electricity	0.152	

Recycling of biowaste
- Emissions through energy consumption

GHG emissions through energy consumption of biowaste fermentation and composting process

Expenditures and credits	Energy consumption	Energy types	Spec. GHG emissions	GHG emissions
Units	[MJ/t]	[MJ/t]	[kg CO_2-eq/MJ]	[kg CO_2-eq/t biowaste]
Energy expenditure-intensive **fermentation and composting,** rotting degree IV	300	20 % diesel	0.093	42.60
		80 % electricity	0.152	

Recycling of biowaste
- Emissions of biological processes

GHG emissions from composting and fermentation process

Methane	Units	**Composting**	**Fermentation**
Spec. load	kg CH_4/t biowaste	1.4	2.8
GWP	kg CO_2/kg CH_4	25	25
CO_2-eq	kg CO_2-eq/t biowaste	35	70
Laughing gas			
Spec. load	kg N_2O/t biowaste	0.05	0.05
GWP	kg CO_2/kg N_2O	298	298
CO_2-eq	kg CO_2-eq/t biowaste	14.9	14.9
Sum	**kg CO_2-eq/t biowaste**	**49,9**	**84.9**

Source: UBA, 2015

Recycling of biowaste
- Emissions through compost application

GHG emissions by compost application

Methane	Unit	**Composting**	**Biowaste***
Spec. load	g CH_4/t	<< 1	
GWP	kg CO_2/kg CH_4	25	
CO_2-eq	kg CO_2-eq/t	<< 1	<< 1
Laughing gas plus 10 % of 76.2 g NH_3			
Spec. load	g N_2O/t	39,3 + 7,6 = 46.9	
GWP	kg CO_2-eq/kg N_2O	298	
CO_2-eq	kg CO_2-eq/t	14	
Sum	**kg CO_2-eq/t**		**5.39**

*Conversion factor of nutrient content in compost relative to compost raw material = 0.385

Recycling of biowaste
- Credits by energy supply

GHG credits by energy recovery of residuals from biowaste processing

	Mass residues	**LCV***	**Energy/t biowaste**	**Efficiency ratio**	**Energy production**	**Spec. GHG credits**	**GHG credits**
Units	[kg/t] biowaste	[MJ/kg]	[MJ/t]	[%]	[MJ/t]	[kg CO_2-eq/ MJ]	[kg CO_2-eq/t biowaste]
Credits heat	80	10.2	816	33.5 1)	273	0.0645	17.65
Credits electricity				11.3 1)	92	0.152	14.00
Sum							**31.65**

*Lower calorific value, 1) Quicker et al. (2018)

Recycling of biowaste
- Credits by energy supply

GHG credits through biogas utilisation

Energy supply	Energy production	Spec. GHG credits	GHG credits
Units	[kWh/t biowaste]	[kg CO_2-eq/MJ]	[kg CO_2-eq/t biowaste]
Energy production - electricity	235 (846)*	0.15182	128.44
Energy production - heat	321 (1,156)*	0.06456	74.61
Sum			**203.05**

*kWh = 3.6 MJ

Recycling of biowaste
- Credits by fertilizer supply

GHG credits by using nutrients in the compost

Nutrients	**Biowaste**	**Spec. GHG credits**	**GHG credits**
Units	[kg/t FM]	[kg CO_2-eq/kg nutrients]	[kg CO_2-eq/t biowaste]
Nitrogen ($N_{ges.}$)	3.88	8.85	34.03
Phosphorus (P_2O_5)	1.95	2.30	4.48
Potassium (K_2O)	3.30	2.26	7.47
Magnesium (MgO)	1.85	1.20	2.21
Calcium (CaO)	12.64	0.028	0.35
Sum			**45.66**

Recycling of biowaste - Credits by fertilizer supply

GHG credits by using humus C in the compost

Humus C	**Biowaste**	**Spec. THG credits**	**THG credits**
Units	[kg/t]FM]	[kg CO_2-eq/kg humus C]	[kg CO_2-eq/t biowaste]
Humus C[4)	37.44		
Intercropping cultivation		1.60	8.98
Under sawing		0.35	0.66
Peat substitute		3.74	42
Straw utilisation		5.59	104.6
Sum			**156.23**

Recycling of biowaste
- Balance extensive composting

Emissions	[kg CO_2-eq/t biowaste]	**Credits**	[kg CO_2-eq/t biowaste]
Energy consumption - extensive composting	16.81	Energy supply - Energy recovery of residuals from pre processing	31.65
Biological treatment process (CH_4 and N_2O)	55,29	Nutrients supply	45.66
		Humus C supply	156.23
Balance			**- 161.44**

*Transport and application are not considered

Recycling of biowaste
- Balance intensive composting

Emissions	[kg CO_2-eq/t biowaste]	**Credits**	[kg CO_2-eq/t biowaste]
Energy consumption - intensive composting	40.29	Nutrients supply	45.66
Biological treatment process (CH_4/N_2O)	55,29	Humus C supply	156.23
		Energy supply - Energy recovery of residuals from pre processing	31.56
Balance			**- 137.96**

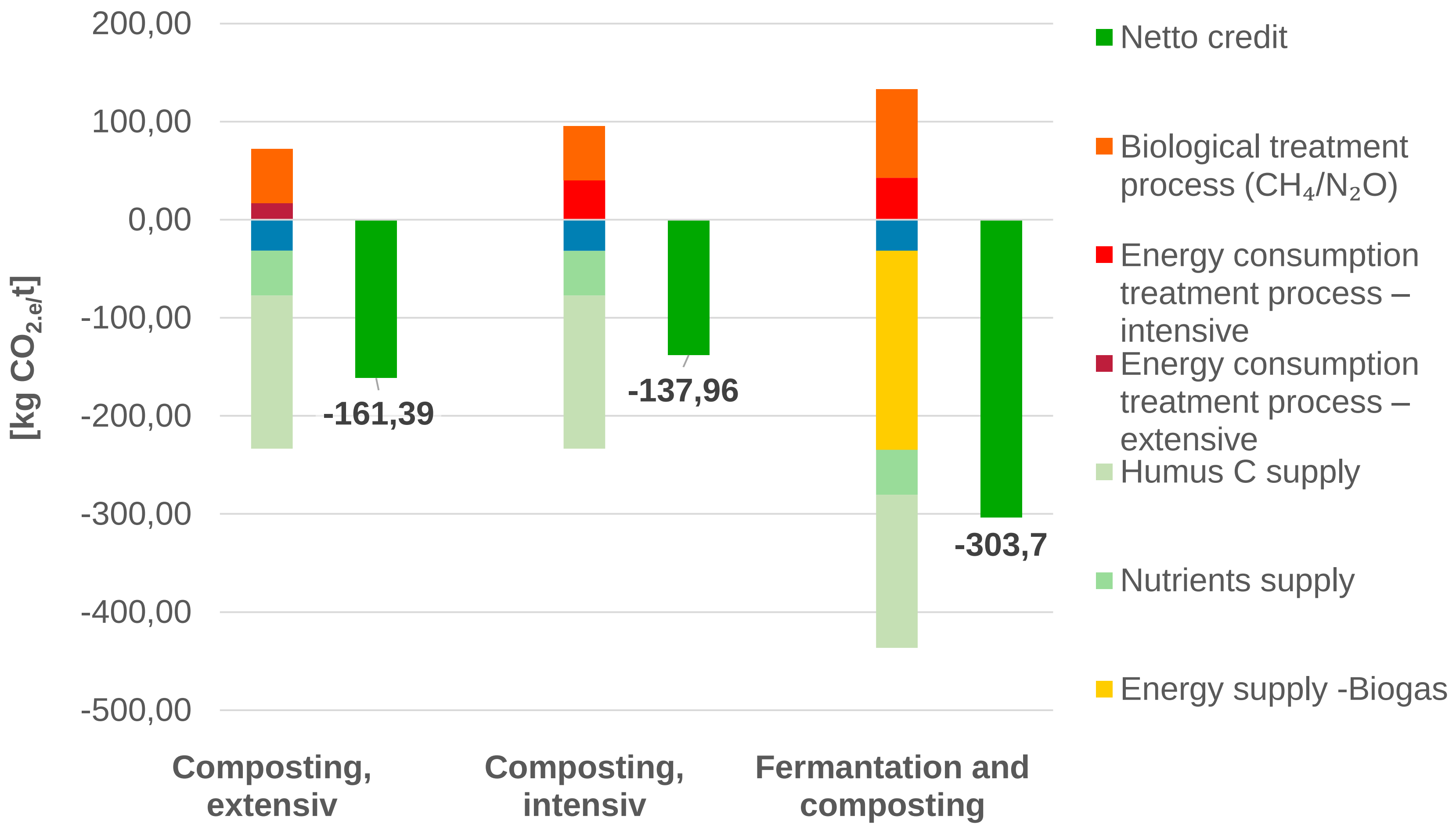
*Transport and application are not considered

Recycling of biowaste
- Balance fermentation and composting

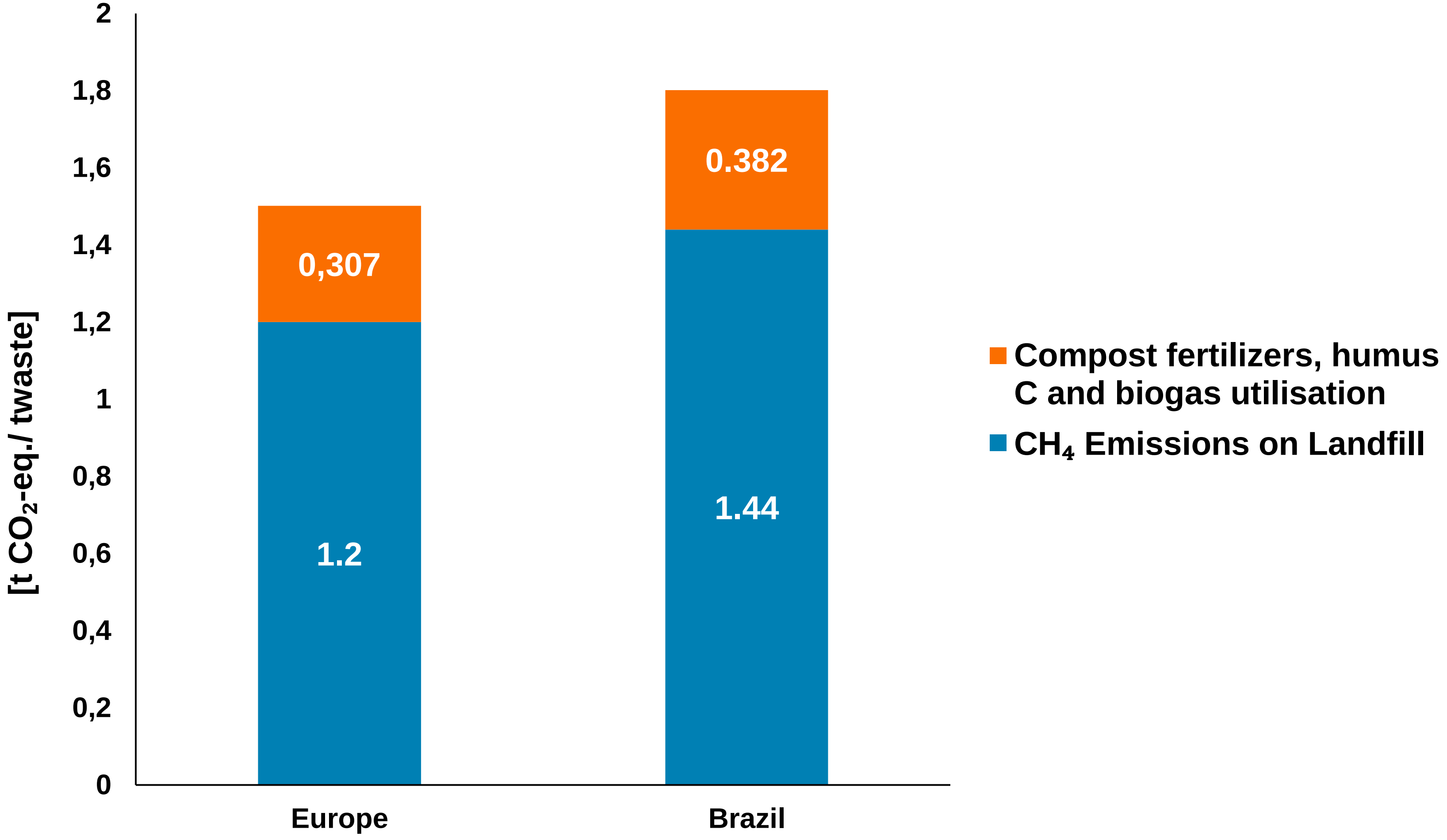
Emissions	[kg CO_2-eq/t biowaste]	**Credits**	[kg CO_2-eq/t biowaste]
Energy consumption treatment process – intensive	42.6	Nutrients supply	45.66
Biological treatment process (CH_4/N_2O)	90,29	Humus C supply	156.23
		Energy supply - Energy recovery of residuals from pre processing - Biogas	31.65 203,05
Balance			**- 303,70**

*Transport and application are not considered

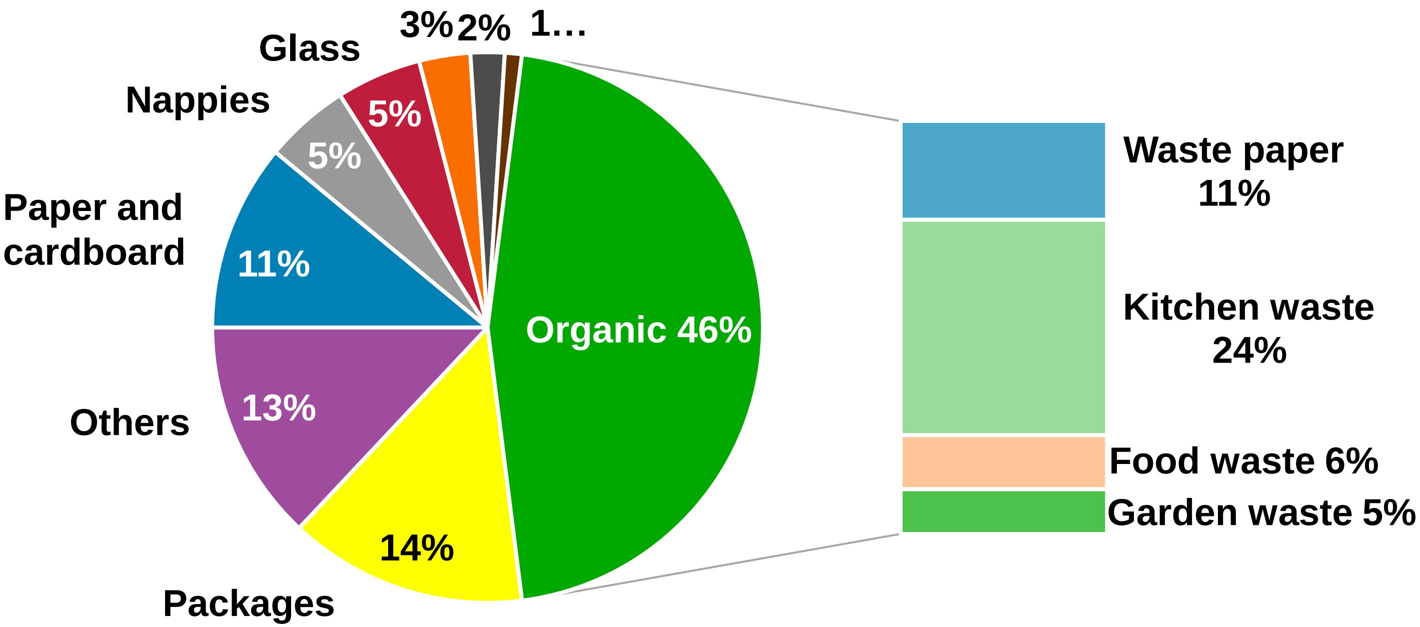
Recycling of biowaste - Balance of losses and credits



Recycling of biowaste
- GHG mitigation of biowaste recycling and landfill



Waste composition in Braunschweig (GER)



- 11 Mio. t/a food waste in Germany, value approx.16,6 up to 21,6 billion €/a
- 210 up to 280 €/a per capita in MSW, biowaste and wastewater
- GHG mitigation potential?

Measures climate protection - Biowaste

Prevention by reducing food waste:

- Better labelling
- Better management in retail
- Conscious shopping
- Better kitchen management

Photo: dpa/Arno Burgi

Further measures:

- Climate-friendly production and reduction of transport efforts for food
- Conscious shopping - regional products

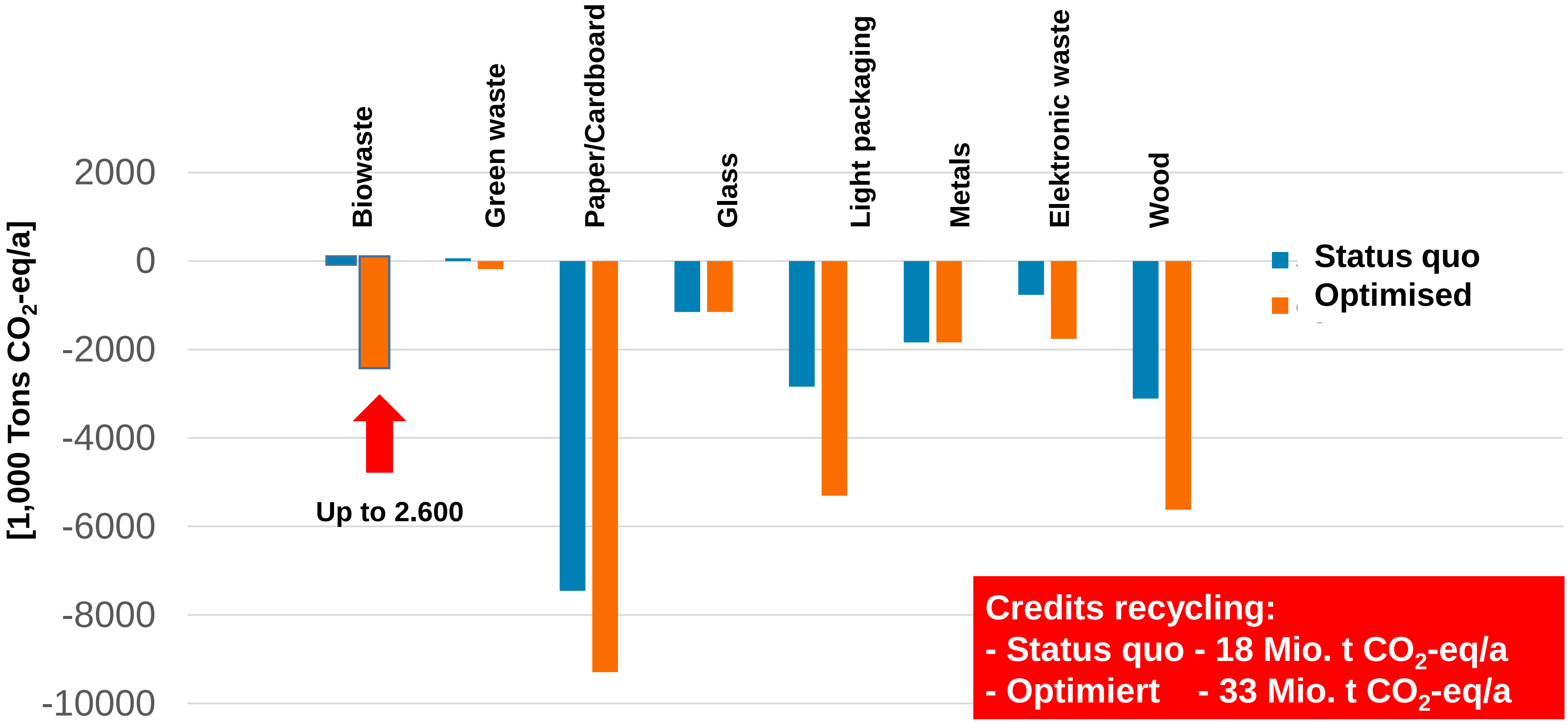
© iStock

Measures climate protection - Biowaste

Increase in separate collection:

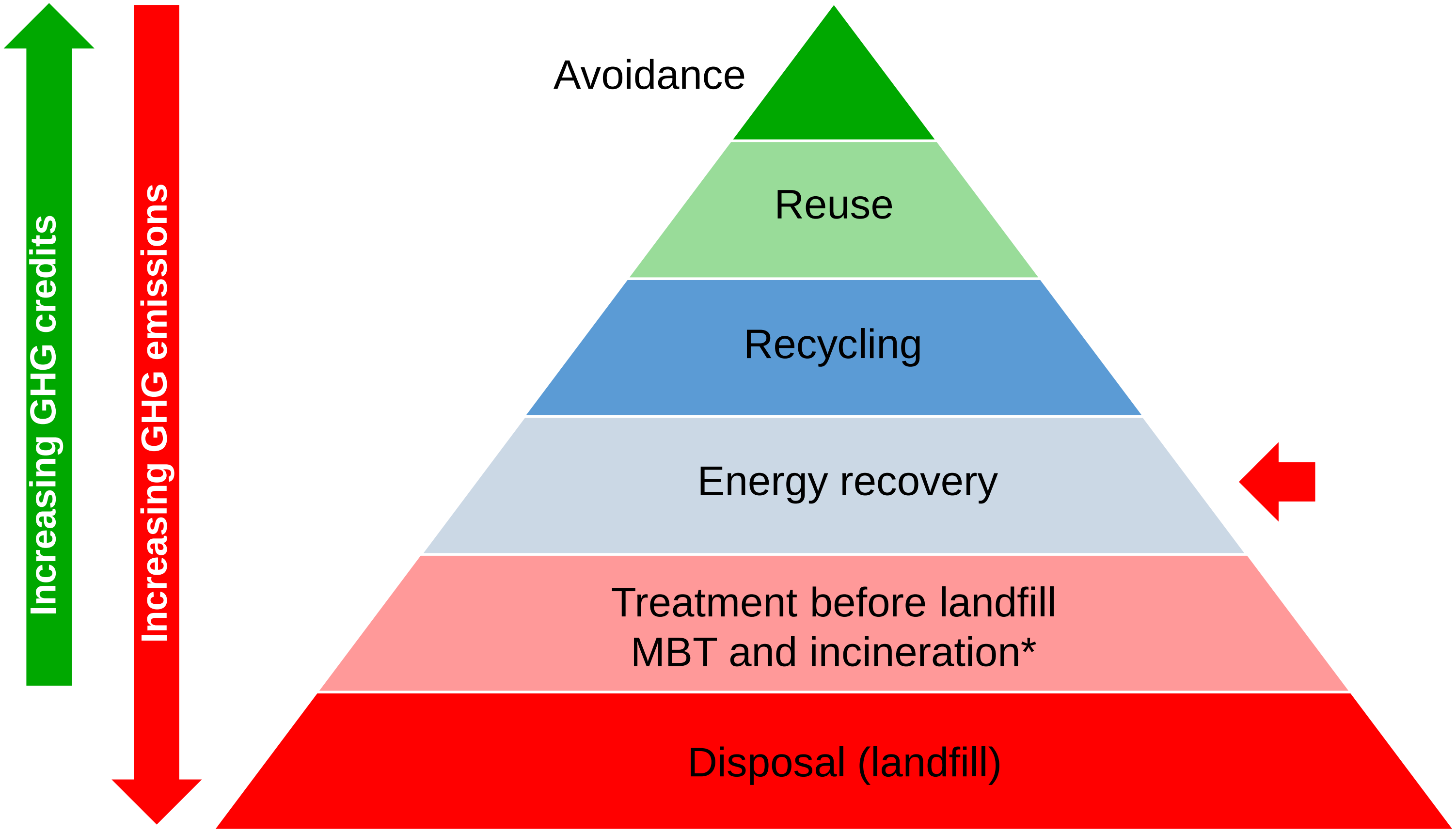
- Increase of home composting
- Increasing separate collection of kitchen waste
- Cascade utilisation of valuable components of biowaste through fermentation **and** composting
- Reduction of GHG emissions from composting and fermentation
- Increasing energy efficiency in composting and fermentation processes

GHG-Credits in Germany - Recycling



Credits recycling:
- **Status quo - 18 Mio. t CO_2-eq/a**
- **Optimiert - 33 Mio. t CO_2-eq/a**

Waste hierarchy
- climate protection



*Not included in the official waste hierarchy of Germany and EU as a separate level

Energy recovery technologies - Overview

Equipment and processes for utilization of fuels from waste (AF)			
Waste incineration (untreated waste)	Pyrolysis (untreated / pre-treated waste)	Power plants (pretreated waste)	Production facilities (pretreated waste)
Grate technologies	Gasification technologies	Lignite and hard coal power stations	**Cement manufacturing**
Fluidized technologies	Degasification technologies	Biomass power stations	Blast furnace (use as reducing agent)

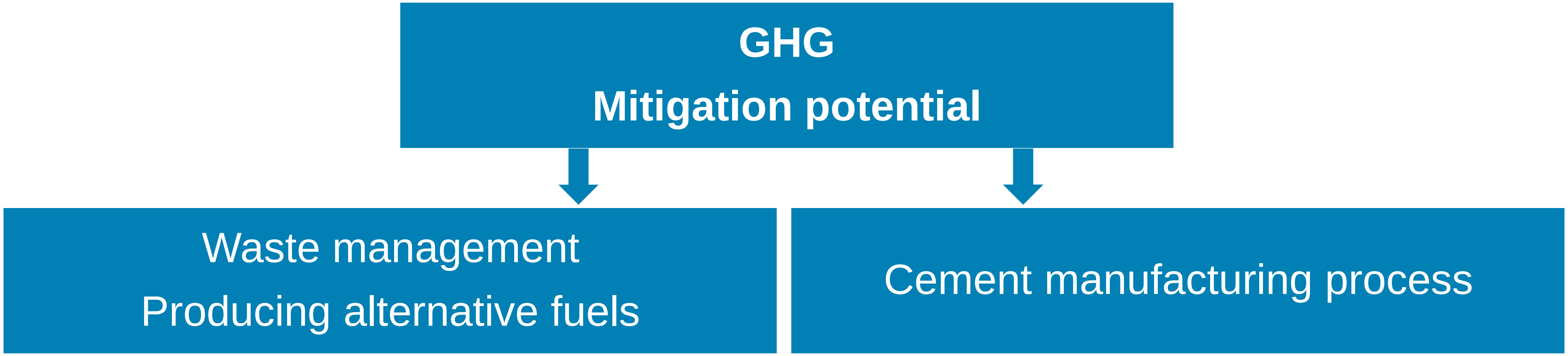
Energy recovery
- Cement manufacturing

Annual cement production volumes and their CO_2 emissions

	Germany	World
Annual cement production	33.7 Million t[1)]	4,100 Million t[2)]
Annual CO_2 emission	19.2 Million t	app. 2,800 Million t
Spec. CO_2 emission per t_{Cement}	**0.57 t**	**0.57 - 0.95 t**
Share of the cement production in annual global GHG emission	2.2 %	app. 5 - 8 %

Sources: [1)] VDZ, 2019 (in 2018); [2)] Statista 2019 in (2018)

Cement manufacturing
- Example calculation energy recovery



GHG

Mitigation potential

Waste management

Producing alternative fuels

Cement manufacturing process

Cement manufacturing
- Waste management sector

Producing and using AF in cement manufacturing process

GHG emission reduction

- Collection
- Processing
    - Composting, digestion, **MBT**
    - Incineration
- Recycling
- **Landfilling**

Reduction of GHG emissions from **landfills**:

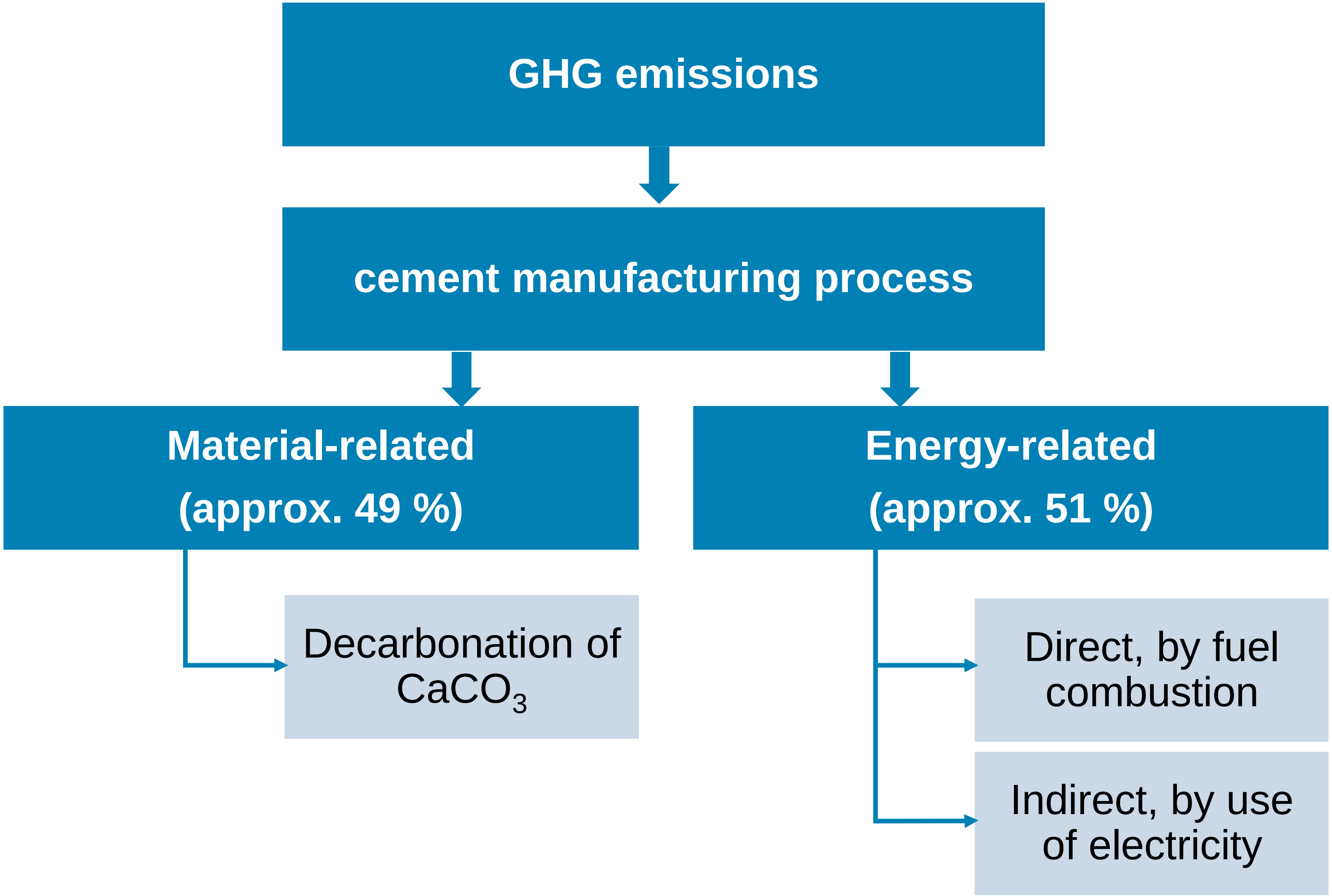
- The lower the deposited biomass, the higher the GHG mitigation rate

GHG credits

- Prevention
- Reuse
- **Recycling**
- **Energy recovery**

- Credits for **recycling** of metals, PVC, paper, minerals etc. out of MBT
- Credits for **energy recovery**: The higher the biomass proportion in the AF, the higher the amount of credits

Cement manufacturing - GHG emissions areas of origin



GHG emissions

cement manufacturing process

Material-related (approx. 49 %)

Decarbonation of $CaCO_3$

Energy-related (approx. 51 %)

Direct, by fuel combustion

Indirect, by use of electricity

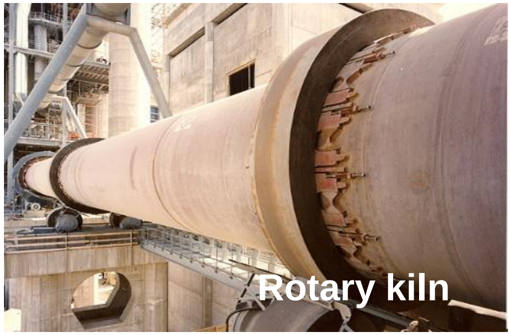
GHG mitigation areas
- Cement production sector

Decarbonisation of limestones
49 %

Fuels
35 %

Milling
12 %

Transport 4 %


Rotary kiln


Main burner


Ballmill

Measures GHG mitigation - Alternative fuels

Measures for the production of alternative fuels in MBT plants:

- **Reduction of the C_{fos} content** by increasing the biomass fraction by introducing a drying step in MBT - the higher the biomass fraction, the higher the GHG mitigation
- **Improving energy efficiency:** Deploying existing state-of-the-art technologies in new cement plants and retrofitting existing facilities

Cement manufacturing
- Measures GHG mitigation

CO_2 mitigation by	Measures
Reduction of CO_2 release from decarbonization process	• Reduction of clinker-cement ratio, e.g. by using de-carbonated additives in the clinker by using pozzolan, granulated blast furnace slag (the suitability of waste incineration slags is also currently being tested)
Reduction of energy demand	• Reduction of clinker-cement ratio, e.g. by using de-carbonated additives (see above) • Technical process optimization, e.g. heat recovery
Use low fossil-C fuels	• Use of low fossil carbon fuels like biomass-rich alternativ fuels e.g. RDF or biomass fuels
CO_2 capture and storage **CO_2 utilisation**	• Currently various methods for CO_2 storage (Carbon Capture and Storage, CCS) and CO_2 utilisation (Carbon Capture and Utilization, CCU) are being developed and tested. • This technologies currently are not state of the art

Cement manufacturing
- CO_2 emission factors of fuels

Energy resources	**Emission factors**
Unit	[t CO_2/TJ]
Brown coal (Rhineland, GER)	113
Lignite (GER)	98
Scrap tyres	88
Heavy oil	81
Natural gas	56
Plastics	61
MSW	**45**
Alternative fuel (biomass-rich RDF)	**10 - 25***
Solid biomass	**4**
Sewage sludge	**3**

Sources: UBA, 2016: Auszug der Liste der CO2-Emissionsfaktoren für Brennstoffbezogene Emissionsfaktoren aus nationalen Inventarbericht (NIR)M; * own data

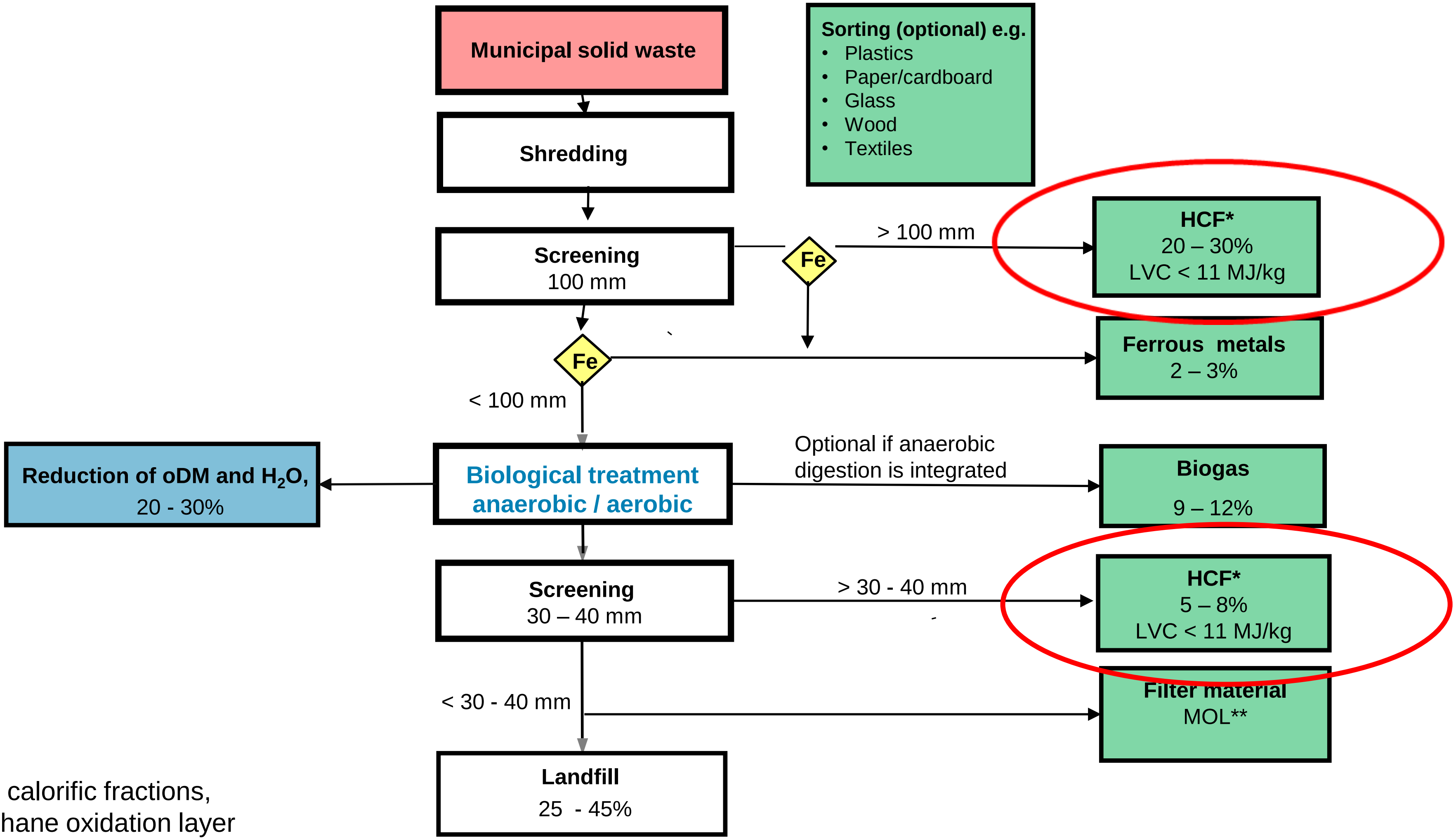
Cement manufacturing
- Used alternative fuels (AF) in GER

AF used in German cement manufacturing in 2016	Quantity	Proportion of biomass
Units	[t/a]	[%]
Waste tires (tires consist of 40 % rubber, app. 70 % of which are made of synthetic rubber)	201,000	12
Waste oil	66,000	0
Pre-processed waste fractions: Pulp, paper, cardboard	81,000	100*
- Plastics and packaging	640,000	app. 10
- Textiles	7,000	40
- Others	116,300	?
Meat and bone meal, fat	145,000	100
HCF and its derived RDF or SRF	283,000	50
Waste wood	< 1,000	100
Solvents	126,000	0
Dried sewage sludge	463,000	100
Others e.g. oil sludge, distillation residues	58,000	0
Sum	**2,187,300**	**app. 42**

Source: VDZ 2017

* 5 - 8 % filling materials, non biomass

Cement manufacturing
- MBT process to produce HCF (simplified)



Municipal solid waste

Shredding

Sorting (optional) e.g.
- Plastics
- Paper/cardboard
- Glass
- Wood
- Textiles

Screening
100 mm

> 100 mm

Fe

HCF*
20 – 30%
LVC < 11 MJ/kg

Fe

Ferrous metals
2 – 3%

< 100 mm

Reduction of oDM and H_2O,
20 - 30%

Biological treatment anaerobic / aerobic

Optional if anaerobic digestion is integrated

Biogas
9 – 12%

Screening
30 – 40 mm

> 30 - 40 mm

HCF*
5 – 8%
LVC < 11 MJ/kg

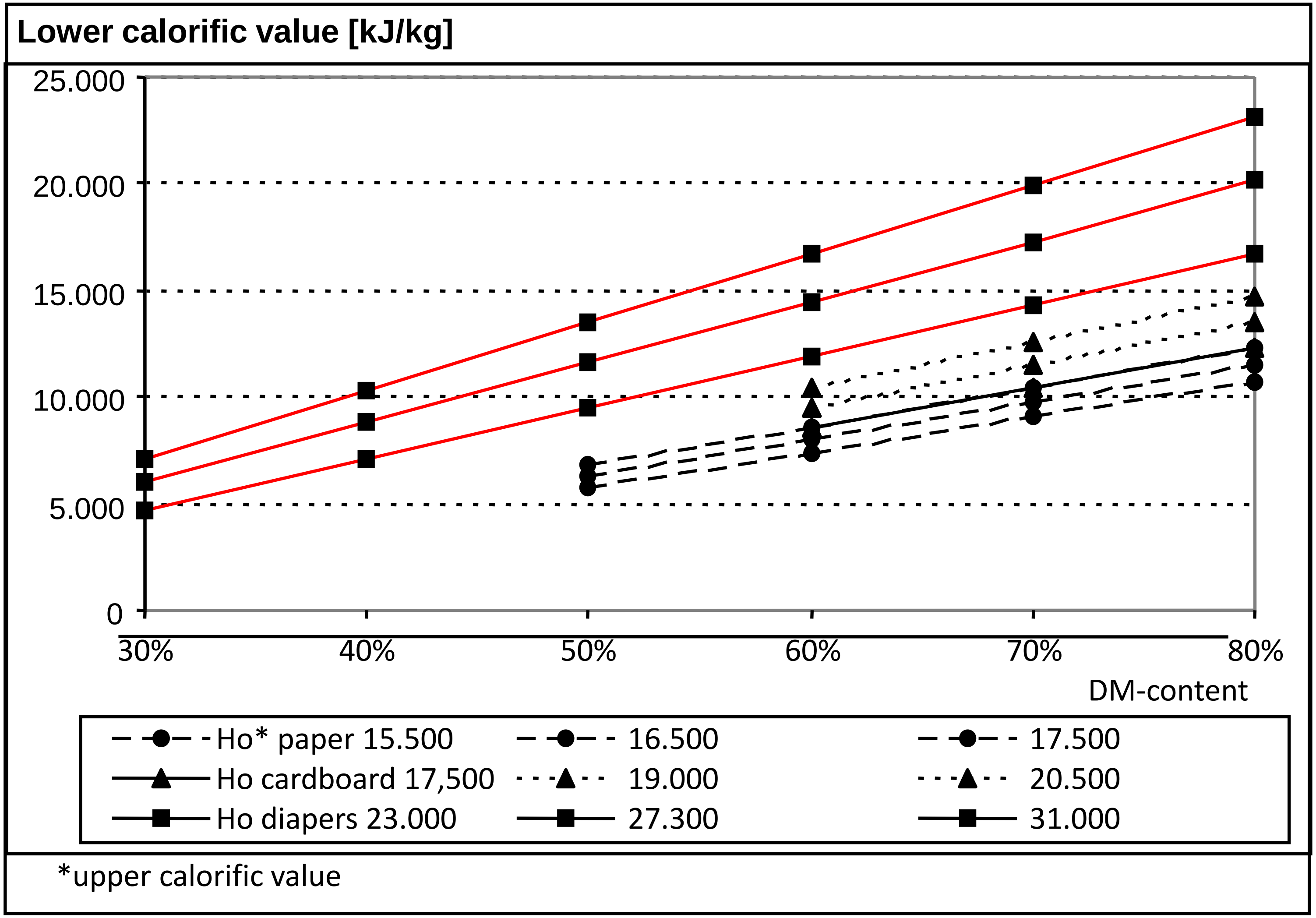
< 30 - 40 mm

Filter material
MOL**

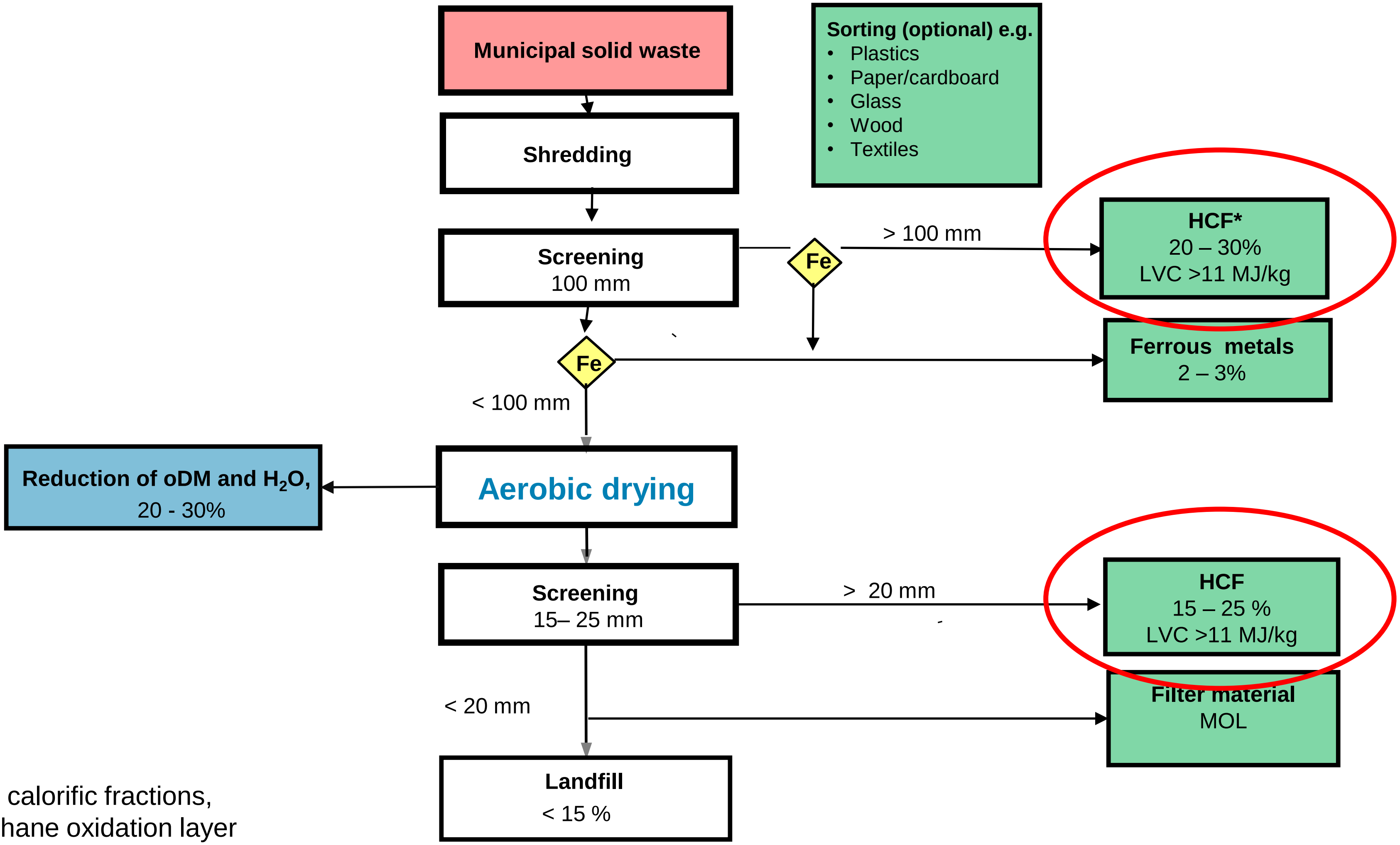
Landfill
25 - 45%

*High calorific fractions,
**Methane oxidation layer

Cement manufacturing
- Increasing the calorific value through drying



Cement manufacturing
- MBT process to produce HCF/RDF (simplified)



*High calorific fractions,
**Methane oxidation layer

Cement manufacturing
- Calculation example energy recovery

The credits include the emissions avoided by substituting the fossil primary fuels otherwise used in the cement plant. Substitution is based on a calorific value equivalent substitution factor of 1

The mass of the substituted coal is calculated according to the following formula:

$$m(Primary\ fuel) = \frac{m * LCV\ (RDF)}{LCV\ (Lignite)}$$

where

m	*Primary fuel (lignite)*	*[kg]*
LCV	*spec. energy content (LCV)*	*[MJ/kg]*

- 1,000 kg RDF with a LCV of 14 MJ/kg deliver 14,000 MJ of energy in total with a fossil C-content of the RDF ➡ **0.09 kg C_{fos}/kg**
- This RDF may susbtitute lignite with a LCV of 21 MJ/kg with a fossil C content of the lignite ➡ **0.66 kg C_{fos}/kg**

Cement manufacturing
- Calculation example energy recovery

1. GHG emissions by using alternative fuels like RDF:

$$\mathrm{m}\ \mathrm{CO}_2 - missions = 1{,}000\,kg\ *\ 0.09\,\frac{kg\,C_{fos}}{kg}\ *\ \frac{44}{12} = \boldsymbol{330\ kg\ CO_2}$$

2. Mass replacement of primary fuels (lignite) based on energy quantity:

$$m\ (subst.primary\ fuels) = \frac{1{,}000\ kg * 14\ MJ/kg}{21\ MJ/kg} = \boldsymbol{667kg\ primary\ fuel}$$

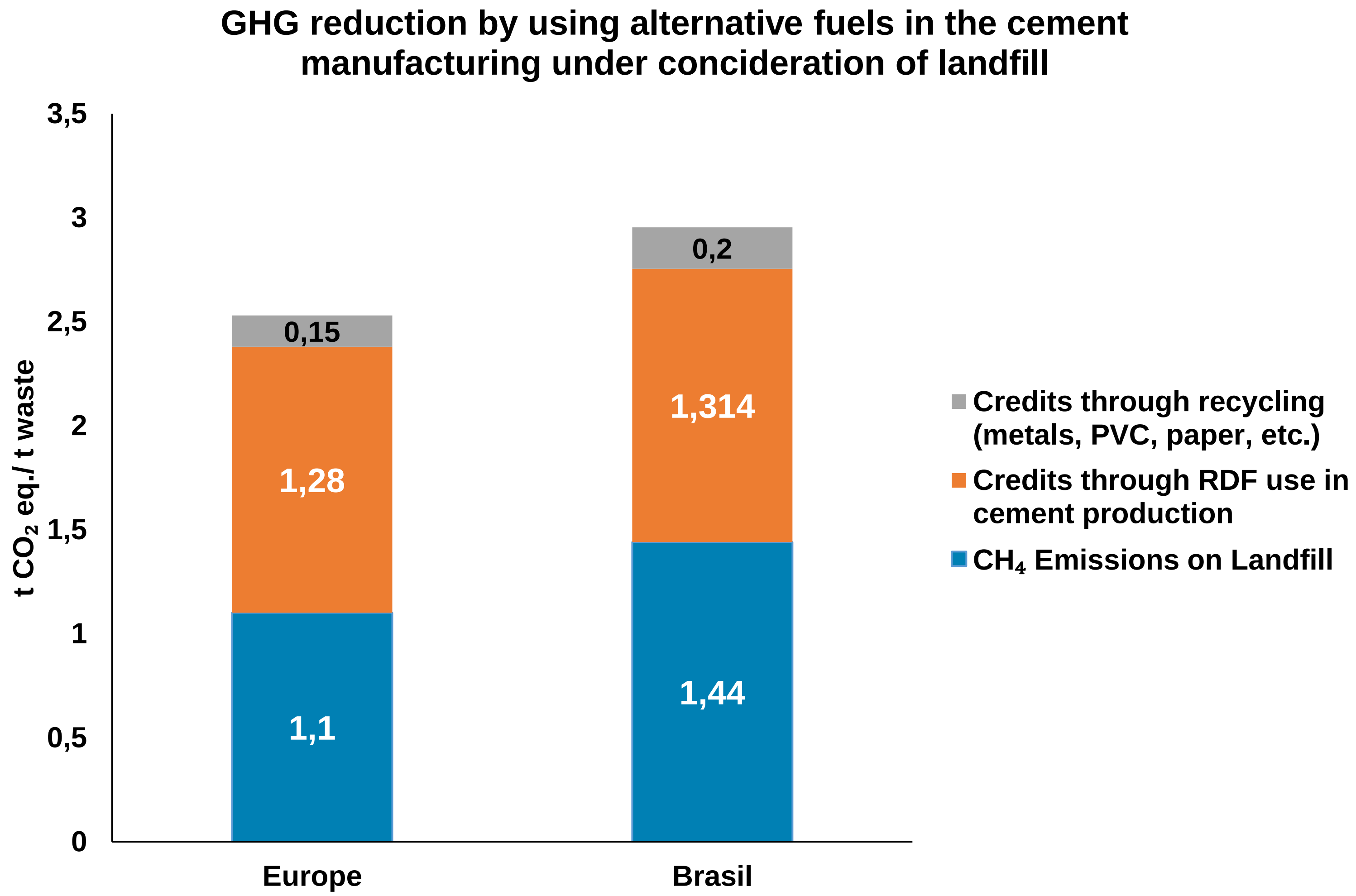
3. CO_2 emissions not used lignite:

$$m\ (CO_2 - emissions) = 667\ kg\ *\ 0.66\,\frac{kg\ C_{fos}}{kg\ lignite}\ *\ \frac{44}{12} = \boldsymbol{1,614\ kg\ CO_2}$$

4. Net credits:

➡ $m\ (Net - credits) = 330\ kg\ CO_2 - 1{,}614\ kg\ CO_2 = \boldsymbol{-1,284kg\ CO_2}$

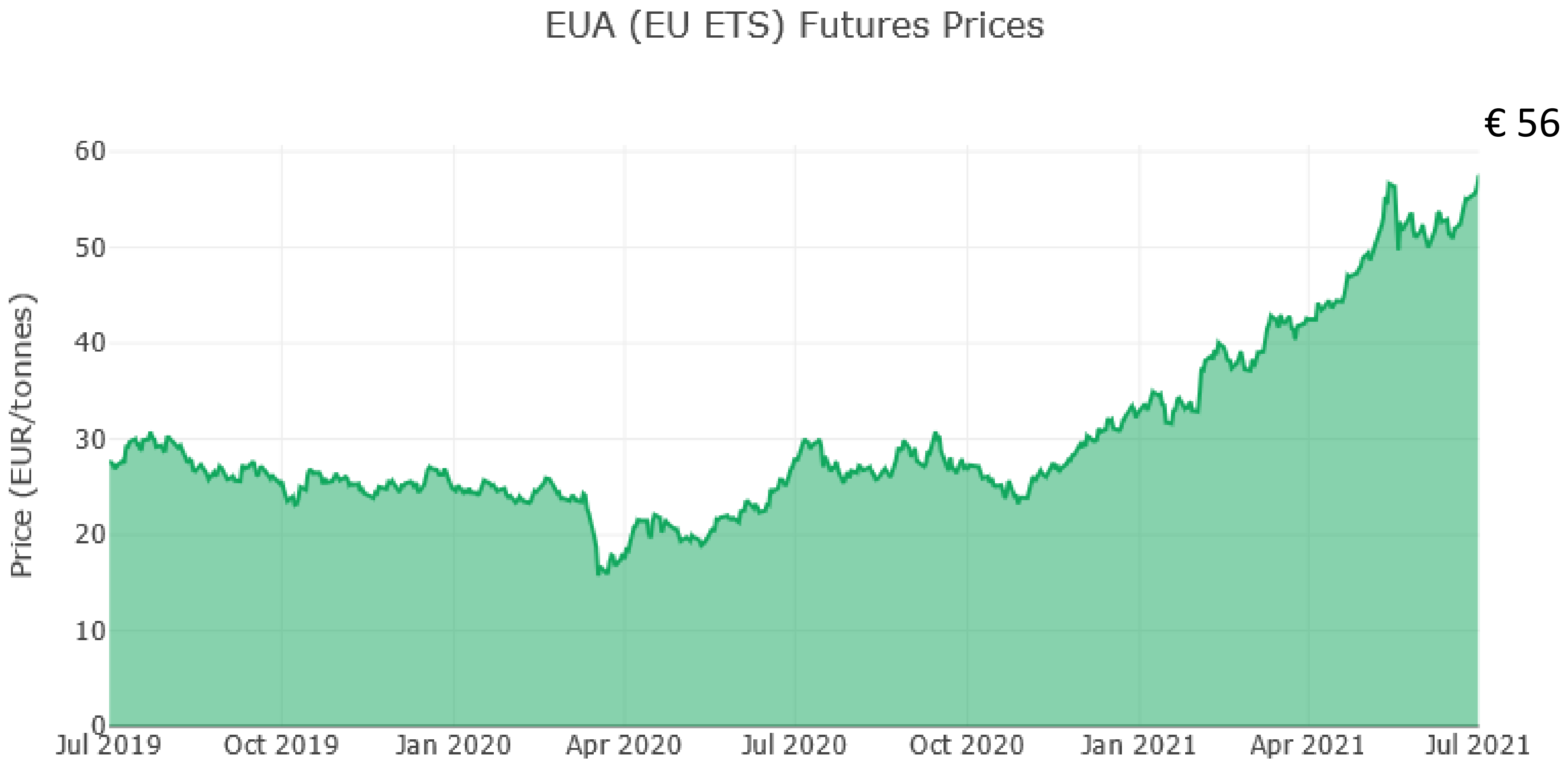
Cement manufacturing
- Using AF in the cement manufacturing



Cement manufacturing
- GHG mitigation political measures

- Simplified **approval procedures** for the use of quality-assured waste-based substitute fuels with a high biomass content in accordance with RAL quality mark
- Increased **public acceptance** in the implementation of the measures
- Simplified standardization of CO_2-friendly cement products (binders), especially recycled concrete
- Establishing of **legal certainty** for carbon capture and storage (CCS) and carbon capture and utilisation (CCU)
- Application of climate protection criteria in award of **public works contracts** The public sector accounts for approximately 23 % of German cement consumption (BBSR, 2018)
- **Effective CO_2 pricing** (taxation or emissions trading) - (see also German government's climate package of December 2019)

Economic framework - GHG trading system



Regarding source and purpose, the composition of blend waste-derived fuels can vary between 0 % (polymers) and 100 % (biomass) of CO_2 neutral compounds.

Source:EMBER

Cement manufacturing
- Short and medium mitigation potential

- The short- and medium-term CO_2 mitigation potential of the cement industry in **Germany** is estimated to be about **20 to 30 %** **-** without carbon capture and utilization
- **Worldwide,** due to pent-up demand, the mitigation potential is rated **significantly higher**

Climate Protection Programme 2030 (GER) - CO_2 pricing

CO_2 emission pricing with effect on cement production costs

	Germany	World
Spec. CO_2-production per t cement	**0.57 t**	**0.57 - 0.95 t**
Production costs cement	35 - 75 €/t	
55 € CO_2 pricing	+ 31 €/t	

Level of the CO_2 tax in GER:

- From January 2021 25 €/Mg
- Increase to 55 €/Mg by 2025
- From 2026, between 55 and max. 65 €/Mg

➡ CO_2 pricing resp. tax strongly favours the use of biomass fuels!

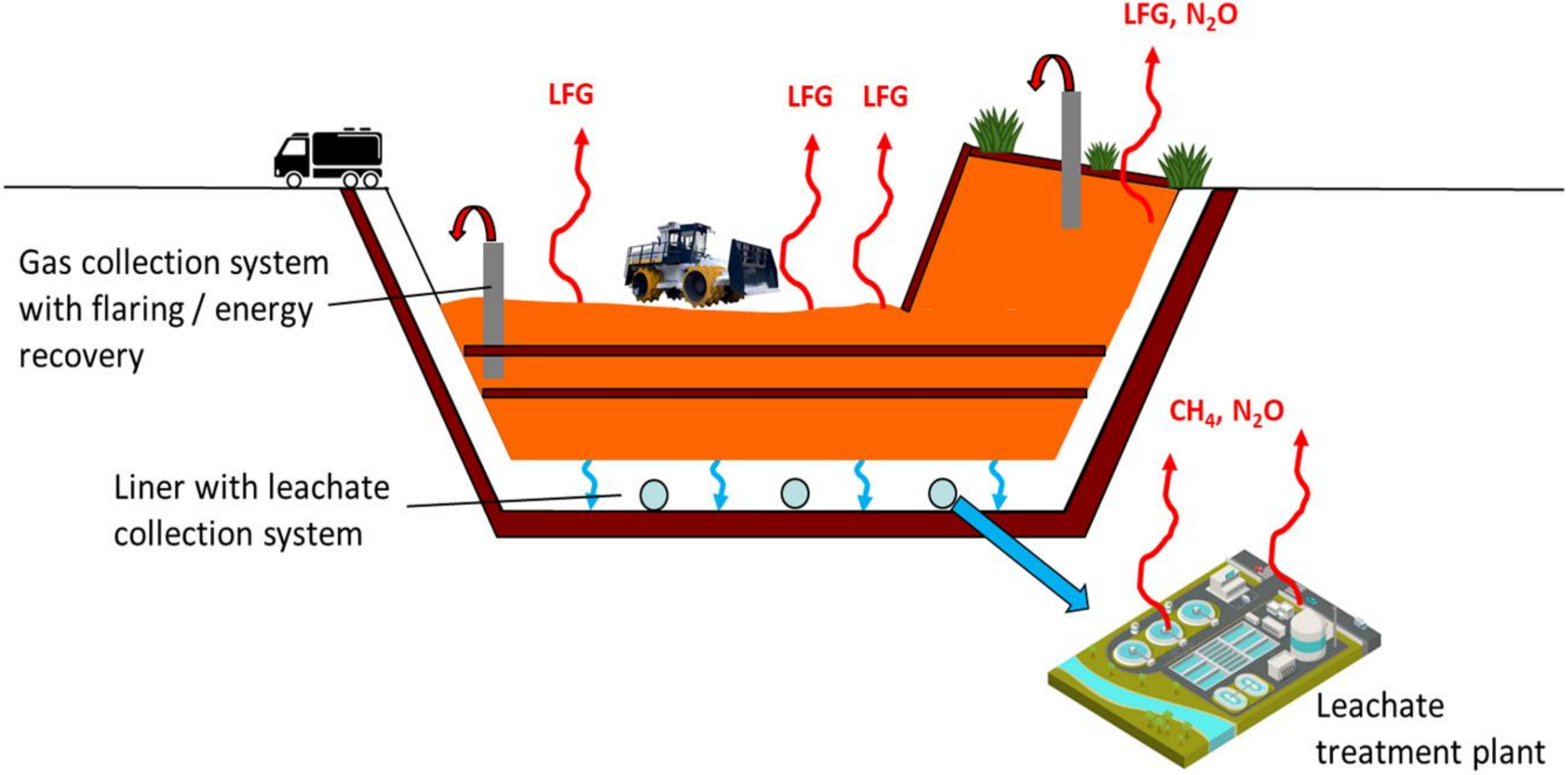
Treatment before landfill
- Legal framework GER and EU

Ban of landfilling of untreated waste **since 2005** in Germany, Switzerland and Austria

Ban of landfilling of untreated waste in the **EU from 2022**

GHG emissions from landfills - Sources

Landfill in operation

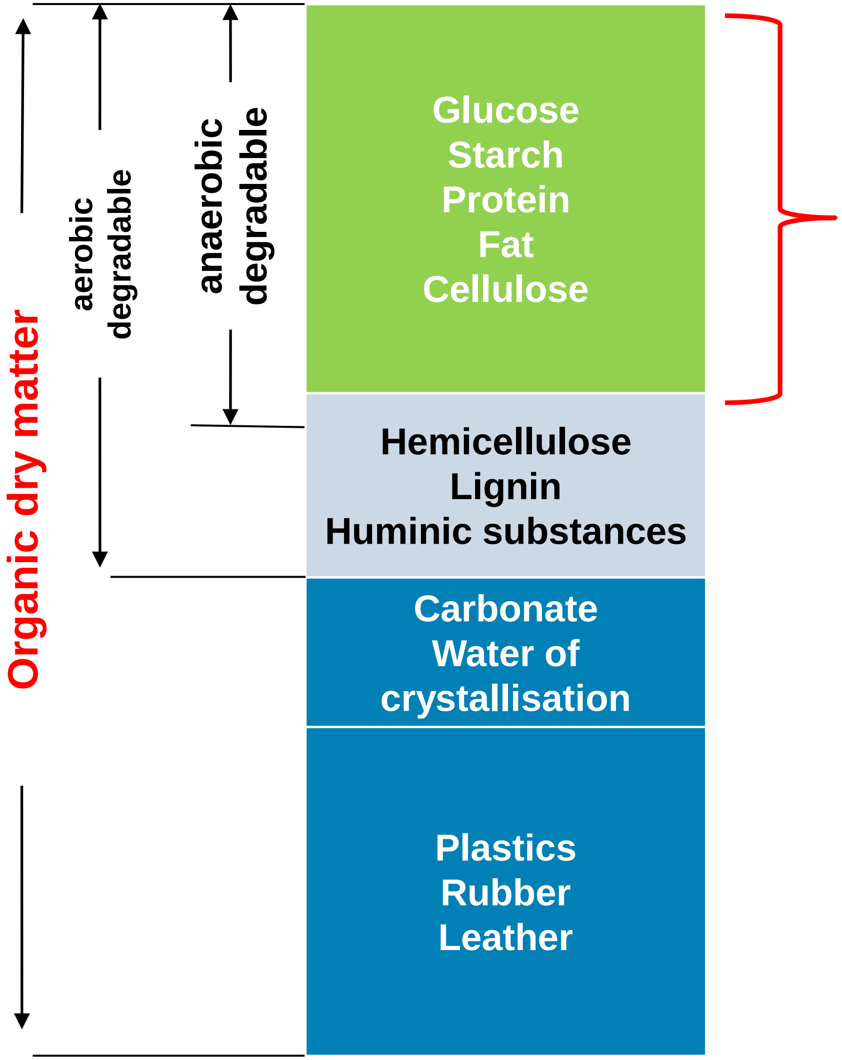


Gas collection system with flaring / energy recovery

Liner with leachate collection system

Leachate treatment plant

GHG emissions from landfills - Relevant raw materials



CH_4-Production

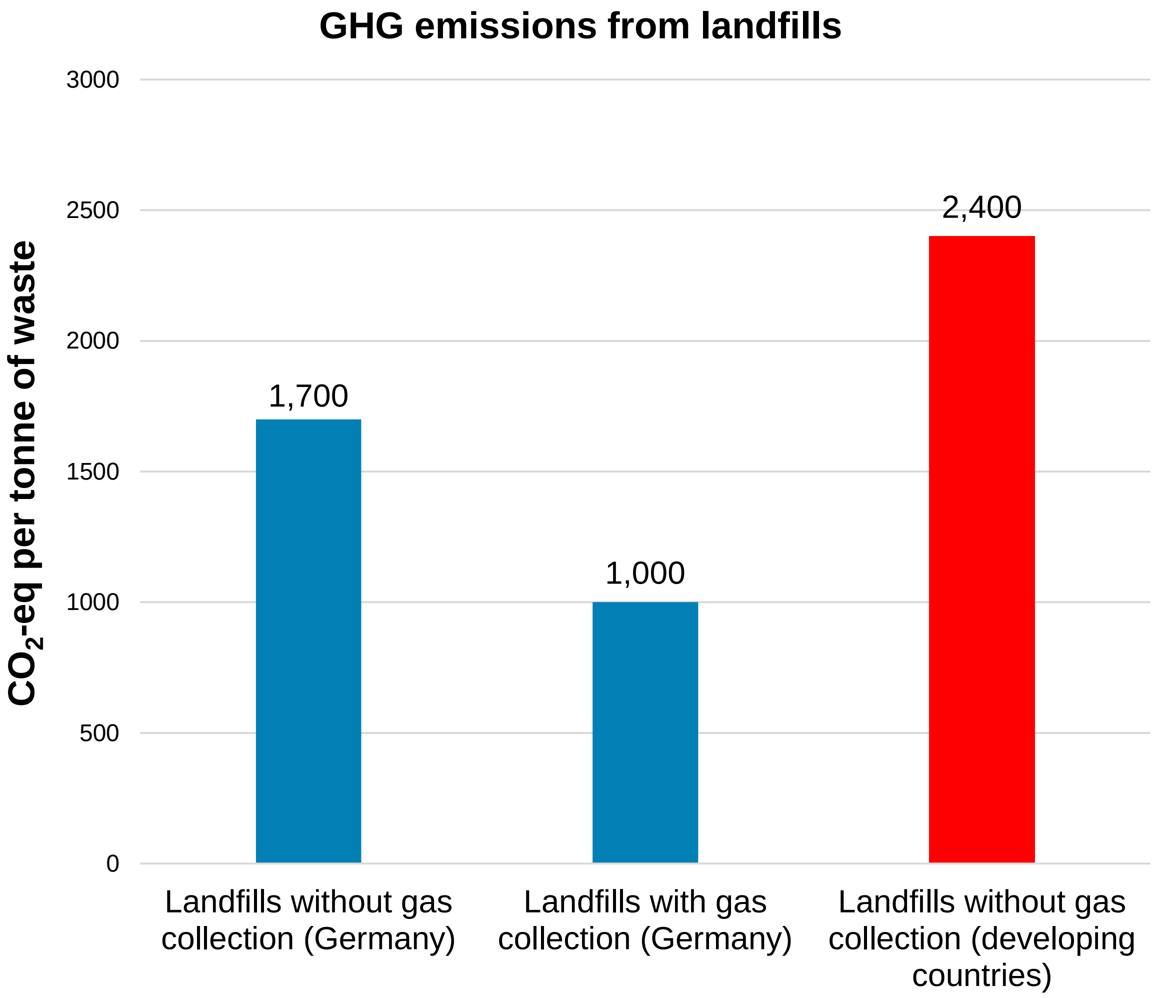
- Biowaste
- Nappies
- Paper
- Sewage sludge

GHG emissions from landfills - Relevant raw materials

Waste fraction	Germany	China	Brazil	Thailand	India	Java
Paper/cardboard [%]	5.2	15.0	13.1	7.7	1.5	3.5
Glass [%]	4.6	2.0	2.4	2.0	0.2	1.7
Organic [%]	**39.3**	**63.9**	**51.4**	**62.0**	**75.2**	**78.5**
Plastics [%]	6.7	16.9	13.5	12.0	0.9	2.6
Textiles [%]	3.5	1.4			3.1	1,0
Metals [%]	2.0	0.7	2.9	0,5	0.1	
Hygiene products [%]	13.5					
Rests [%]	25.2	3.2	16.7	16,0	19.0	13.7
Water content [%]	35 - 45	42 - 60	42 - 55	41 - 53	42 - 60	49 - 63
Calorific value [kJ/kg]	8 - 9,000	4 - 7,300	6 - 8,200	4 - 7,500	< 4,000	< 4,000
GHG-Emissions [-]	**very low***	**very high**	**high**	**very high**	**very high**	**very high**

*Since 2005, only pre-treated waste may be landfilled

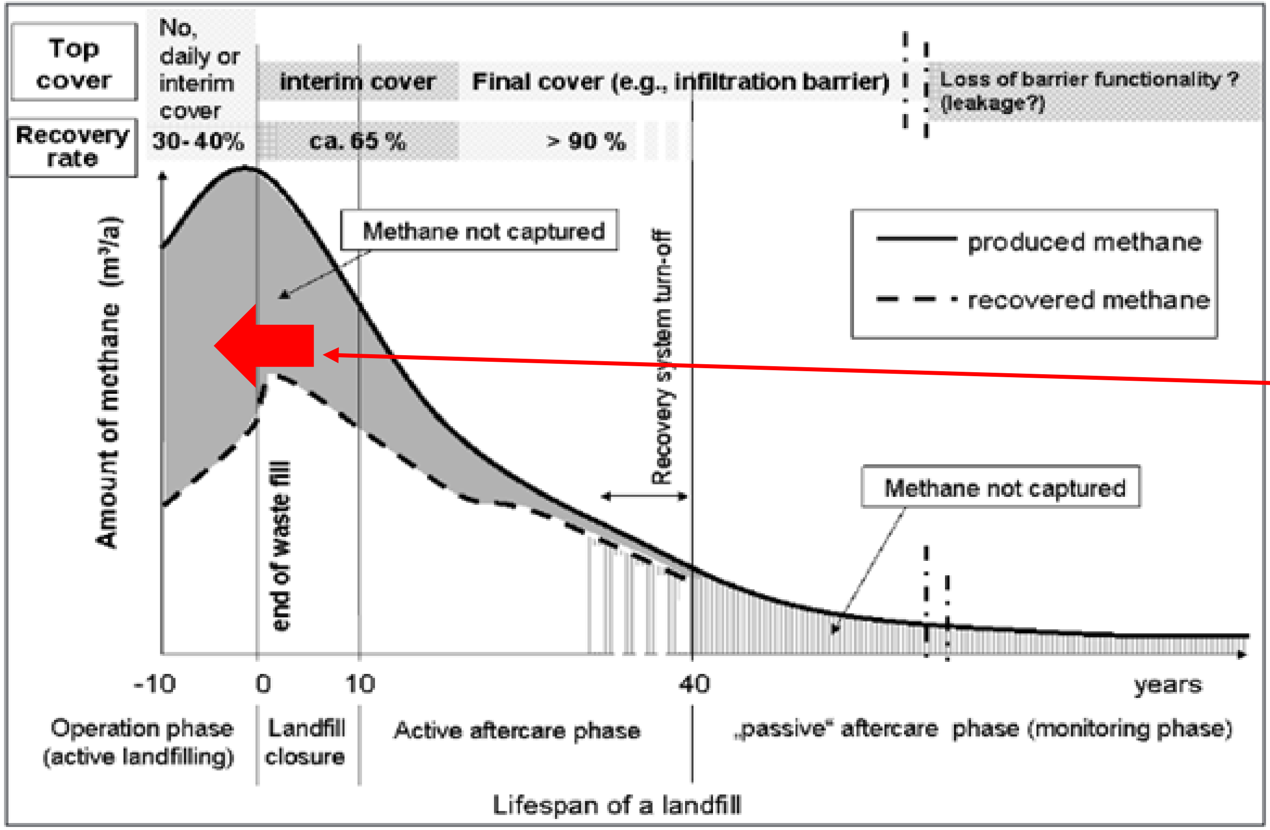
GHG emissions from landfills - Germany and the developing countries



In developing countries, GHG emissions from landfills are 1.4 - 1.7 times higher, due to the higher proportion of readily degradable organic substances

➡ **8 - 12 % of GHG emissions in developing and emerging countries come from the waste sector!**

GHG emissions from landfills
- Methane production and collection



Half-life Gas formation

- Climate in Central Europe: 7 years
- Tropical wet climate: 3-5 years, this leads to a shift to the operating phase, in which no gas is usually collected from landfill

Gas collection rates in Germany: << 45 % !!!

Treatment before landfilling - Goals

- Minimizing volume and mass of waste delivered to the landfill
- Inactivation of biological and chemical processes

➡ to **prevent landfill gas production** and settlement

- Immobilizing contaminants within waste, in order to reduce leachate emissions
- Separation of recyclable materials, Fe- and Non-Fe-Metals, alternative fuels (RDF) etc.

GHG emissions from landfills
- GHG modelling methodologies (incomplete)

- **Zero order model (default model):** LFG formation is constant over time, so there is no effect of waste age
- **Constant rate model:** After a lag phase LFG formation rises instantly to a constant value until all organics are degraded, and decreases than to zero
- **First-order model (FOD):** Effect of waste age is incorporated by an exponentially decline of LFG generation. With modifications, this model is mostly used (e.g. **IPCC model**)
- **Multiphase model:** FOD model which distinguishes different waste fractions with different degradation rates
- **Scholl Canyon model:** Most commonly used FOD model. The model doesn´t consider a lag phase or limiting factors like moisture
- **Stoichiometric model:** Based on a stoichiometric reaction, in which the waste is represented by an empirical chemical formula. It only estimates the total amount of LFG but gives no information in view of the generation rate. Requires knowledge of the chemical composition of waste

GHG emissions from landfills - IPCC Model

IPCC model (2006)

- FOD model for estimating methane emissions from landfills
- National greenhouse gas inventories must be compiled according to this model

Choose the right level:

- **Stage 1:** IPCC FOD method using mainly standard activity data and standard parameters
- **Level 2:** IPCC FOD method and some standard parameters but requires good quality country-specific activity data on current and historical landfill waste disposal, historical waste disposal data for 10 years or more should be based on country-specific statistics, surveys or other similar sources. Data on the quantities disposed of in landfills are required
- **Level 3:** Level 2 plus use of either the FOD method with nationally developed key parameters or country-specific parameters derived from the measurement Key parameters should include the half-life and either the methane formation potential or the DOC content in the waste and the percentage of decomposing DOC (DOCf)

GHG emissions from landfills - IPCC Model

IPCC model (1)

$$CH_{4,emissions} = \left[\sum CH_{4,generated,x,T} - R_T \right] * (1 - OX_T)$$

$CH_{4,Emission}$	CH_4 emitted in year T	[Gg]
T	Inventory year	[a]
x	Waste category or type/material	
R_T	CH_4 recovered in year T	[Gg]
OX_T	Oxidation factor per year (per fraction)	[-]

$$CH_{4,generated,T} = DDOCm\ decomp_T * F * \frac{16}{12}$$

$DDOCm\ decomp_T$	DDOCm decomposes in the year T	[Gg]
$DDOC_m$	degradable under landfill conditions organic carbon	[Gg]
F	Volume fraction of CH4 in the produced LFG (fraction)	
$\frac{16}{12}$	Molecular weight ratio between CH4 and C	[-]

GHG emissions from landfills - IPCC model

IPCC model (2)

For each year, the mass of anaerobically degradable carbon at the beginning of the year and out of this the mass of anaerobically degraded carbon is calculated:

$$DDOCm\ decomp_T = DDOCma_{T-1} * (1 - e^{-k})$$

$$DDOCma_T = DDOCmd_T + DDOCma_{T-1} * e^{-k}$$

$DDOCma_T$	DDOCm accumulated in landfill at the end of the year T	[Gg]
$DDOCma_{T-1}$	DDOCm accumulated in landfill at the end of the year T-1	[Gg]
$DDOCmd_T$	DDOCm deposited in the landfill in year T	[Gg]
k	degradation constant = $\frac{\ln(2)}{t_{1/2}}$	[1/a]
$t_{1/2}$	half time	[a]

$$DDOCm = W * DOC * DOC_f * MCF$$

W	mass of waste deposited	[Gg]
DOC	degradable organic carbon in the year of deposition (fraction	[Gg-C/Gg-waste]
DOC_f	fraction of DOC that can decompose (fraction)	
MCF	CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)	

GHG emissions from landfills - IPCC Model

IPCC model (3)

$$CH_{4,emission} = MWS_T * MWS_F * MCF * DOC * DOC_F * F * \left(\frac{16}{12} - R\right) * (1 - OX)$$

MWS_T	Total municipal waste produced	[Gg/a]
MWS_F	fraction of municipal solid waste going to landfill	[Gg/a]
MCF	Methane correction factor (fraction)	[-]
DOC	Degradable organic carbon (fraction)	
DOC_F	fraction of DOC that is biodegradable under real landfill conditions	
F	fraction of methane in LFG	
R	recovered methane	[Gg/a]
OX	oxidation factor	[-]

In the meantime, the model has been adapted to many country-specific conditions (waste composition, climate conditions, landfill technologies, etc.)

Source: www,ipcc-nggip,iges,or,jp/public/2006gl/pdf/5_Volume5/IPCC_Waste_Model,xls

GHG emissions from landfills - IPCC Model

IPCC model (4)

Default values:

- Deviations are possible, but must be well justified
- If possible, use validated country-specific values
- DOCf: 0.5
- MCF: aerobic degradation in the year of deposition

Categories of landfills:

- Managed site - anaerobic: 1,0
- Managed website - semi-aerobic: 0.5
- Non-managed site - deep (> 5 m waste) and/or high groundwater level: 0.8
- Non-managed landfill - flat (< 5 m waste): 0.4
- If categorization is not possible: 0.6
- F: Methane concentration 50 % by volume 0,5
- Half-life and degradation constant, To take into account the influence of the moisture content in the waste and the ambient temperature, the table is divided into two climate zones
  - MAT = average annual temperature
  - MAP = mean annual precipitation
  - PET = potential evapotranspiration

GHG emissions from landfills - IPCC Model

IPCC model (5) Standard values for the half-life [a]

Type of waste		Climate zone							
		Boreal and moderate (MAT = 20 °C)				Tropical (MAT > 20 °C)			
		Dry (MAP/PET < 1)		Wet (MAP/PET > 1)		Dry (MAP < 1000 mm)		Wet and humid (MAP = 100)	
		By default	Area	By default	Area	By default	Area	By default	Area
Slowly degradable	Paper/textiles	17	14 - 23	12	10 - 14	15	12 - 17	10	8 - 12
	Wood/straw	35	23 - 69	23	17 - 35	28	17 - 35	20	14 - 23
Moderately degradable	Other (non-food) organics, garden/park	14	12 - 17	7	6 - 9	11	9 - 14	4	3 - 5
Rapidly degradable	Food waste/sewage sludge	12	9 - 14	4	3 - 6	8	6 - 10	2	1 - 4
Municipal or industrial waste		44	12 - 17	7	6 - 9	11	9 - 14	4	3 - 5

GHG emissions from landfills - IPCC Model

IPCC model (6)

Standard values for the degradation constant [1/a]

Type of waste		**Climate zone**							
		Boreal and moderate (MAT = 20 °C)				Tropical (MAT > 20 °C)			
		Dry (MAP/PET < 1)		Wet (MAP/PET > 1)		Dry (MAP < 1000 mm)		Wet and humid (MAP = 100)	
		By default	Area	By default	Area	By default	Area	By default	Area
Slowly degradable	Paper/ textile	0.04	0.03 - 0.05	0.06	0.05 - 0.07	0.045	0.04 - 0.06	0.07	0.06 - 0.085
	Wood/straw	0.02	0.01 - 0.03	0.03	0.02 - 0.04	0.025	0.02 - 0.04	0.035	0.03 - 0.05
Moderately degradable	Other non-food organics, garden/park	0.05	0.04 - 0.06	0.1	0.06 - 0.1	0.065	0.05 - 0.08	0.17	0.15 - 0.2
Rapidly degrading	Food, sewage sludge	0.06	0.05 - 0.08	0.185	0.1 - 0.2	0.085	0.07 - 0.1	0.4	0.17 - 0.7
Municipal or industrial		0.05	0.04 - 0.06	0.09	0.08 - 0.1	0.065	0.05 - 0.08	0.17	0.15 - 0.2

GHG emissions from landfills - IPCC model

IPCC model (7)

Delay time:

- After disposal, it takes 7 months up to 1 year until methane is generated
- Delay time depends on waste composition and climate conditions
- Default value is 6 months, but changes to values from 0 - 6 months are allowed

	DOC (Degradable org. carbon), weight fraction (FM)	
Type of waste	Range	Default
Food waste	0.08 - 0.20	0.15
Garden	0.18 - 0.22	0.2
Paper	0.36 - 0.45	0.4
Wood and straw	0.39 - 0.46	0.43
Textiles	0.20 - 0.40	0.24
Disposable nappies	0.18 - 0.32	0.24
Sewage sludge	0.04 - 0.05	0.05
Industrial waste	0 - 0.54	0.15

GHG emissions from landfills - Uncertainties

Uncertainties with regard to the results of the modelling:

- The FOD method is a very simple method to describe very complex processes during waste degradation, but errors cannot be excluded
- The physico-chemical composition of the waste is assumed to be homogeneous
- Relevant errors may arise in modelling if significant changes occur in the mass of the deposited waste and/or in the composition of the waste
- DOC values often too high
- Only one DOCf value for different wastes
- Three subdivisions in only two climate regions cannot reflect the influence of humidity on the degradation constant
- Insufficient or inaccurate input data

➡ Predicted methane emissions vary between 38 and 492 % of actual emissions !

GHG emissions from landfills - Mitigation measures

- Intensify avoidance, reuse, recycling and energy recovery
- Treatment before Landfill
- Landfill gas collection already during the disposal period
- Intensify of an efficient gas utilisation
- Application of an methane oxidation layer
- Landfill mining

Treatment before landfilling
- Limit values for MBT and incineration in GER

Parameters (selection)	Unit	MBT Germany
TOC in solid matter	% of DM*	≤ 18
TOC in eluate	mg/l eluate	≤ 300
Respiration activity in 4 days (AT_4)	mg O_2/g DM*	≤ 5
Gas formation in 21 days (GB_{21})	**l/kg DM***	**≤ 20**
Upper heating value (HCV)	kJ/kg DM*	≤ 6,000

		Incineration Germany
TOC in solid matter	% of DM*	≤ 5
TOC in eluate	mg/l eluate	≤100
Loss of ignition	% of DM*	≤ 3

* DM = Dry matter

Source: German Landfill Ordinance, 2001 and 2009

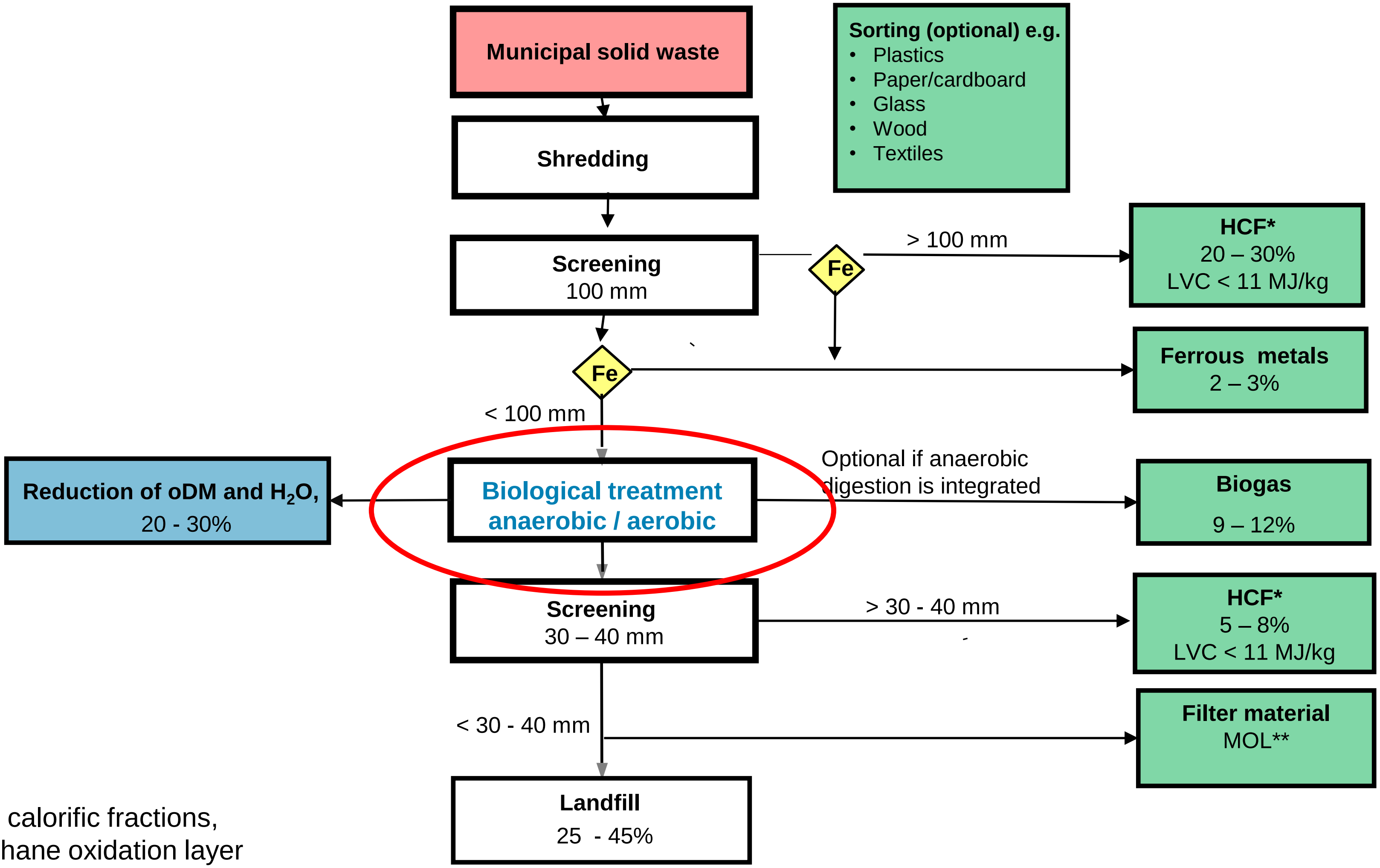
Treatment before landfilling
- Treatment technologies

- Thermal treatment (waste incineration, energy recovery)
- Mechanical biological treatment (MBT)

Treatment before landfill
- Incineration and energy recovery

- Waste incineration slags do **not emit relevant quantities of GHG**
- The quantities of slag result from the inert content of the input and an average of 1.5 % unburned material in the slag (Öko-Institut, 2002)
- Only the federal state of Bavaria has waste incineration plant slags landfilled

Treatment before landfill
- MBT flow chart (simplified)



Municipal solid waste

Shredding

Sorting (optional) e.g.
- Plastics
- Paper/cardboard
- Glass
- Wood
- Textiles

Screening
100 mm

HCF*
20 – 30%
LVC < 11 MJ/kg

Ferrous metals
2 – 3%

Reduction of oDM and H_2O,
20 - 30%

Biological treatment anaerobic / aerobic

Optional if anaerobic digestion is integrated

Biogas
9 – 12%

Screening
30 – 40 mm

HCF*
5 – 8%
LVC < 11 MJ/kg

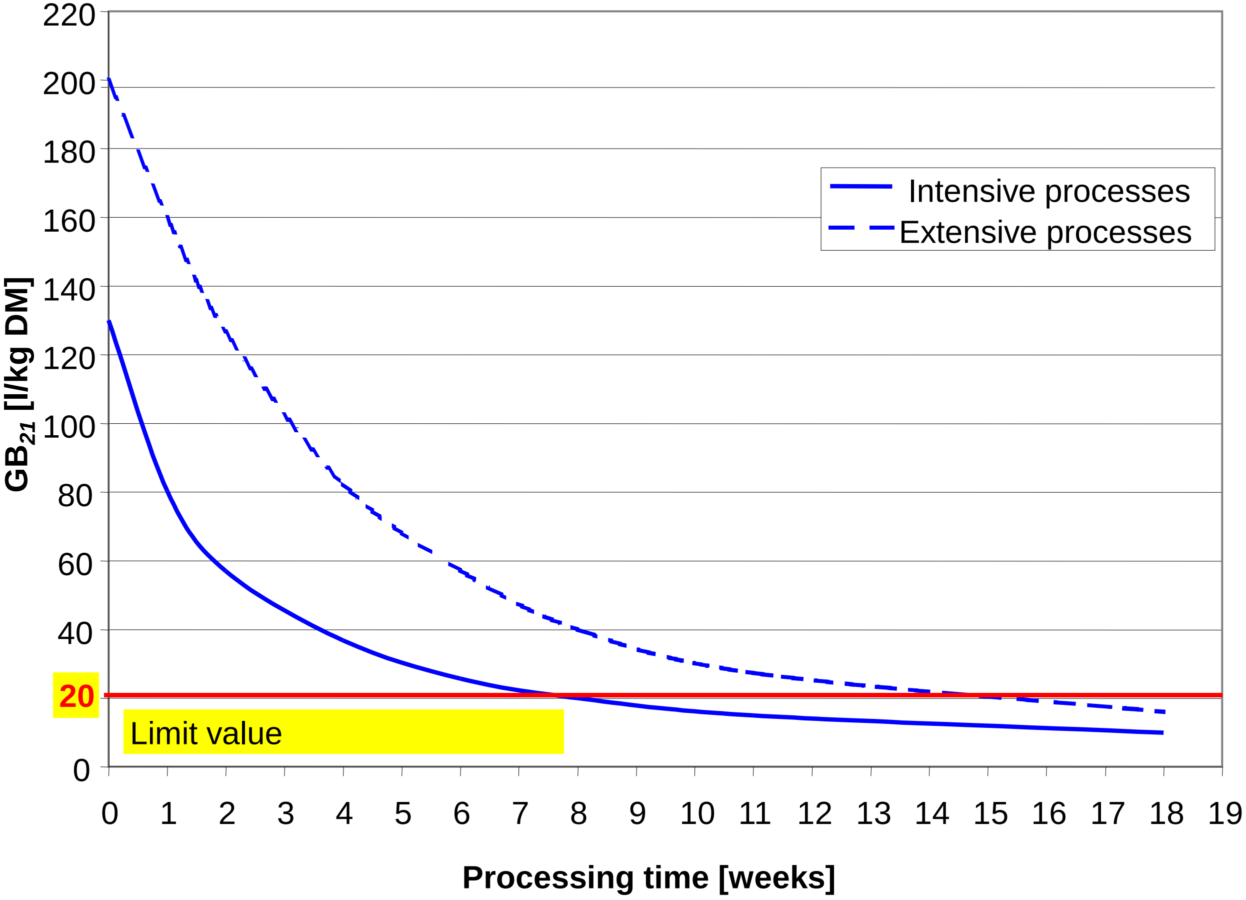
Filter material
MOL**

Landfill
25 - 45%

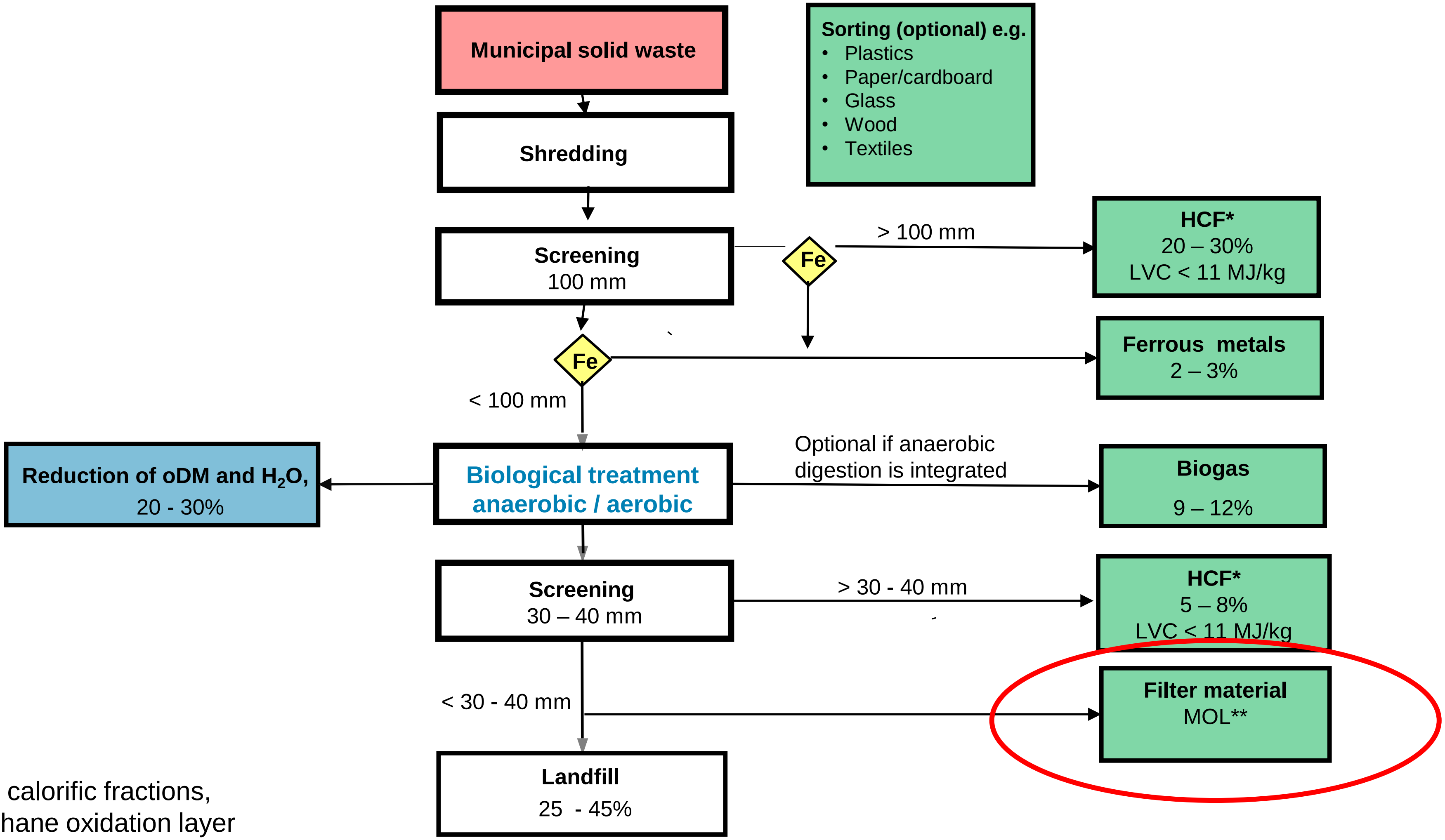
*High calorific fractions,
**Methane oxidation layer

GHG mitigation from landfills
- Mecanical-biological pre-treatment

Reduction of landfill gas formation through aerobic treatment in MBT



Treatment before landfill
- MBT flow chart (simplified)



Municipal solid waste

Shredding

Sorting (optional) e.g.
- Plastics
- Paper/cardboard
- Glass
- Wood
- Textiles

Screening
100 mm

Fe

> 100 mm

HCF*
20 – 30%
LVC < 11 MJ/kg

Fe

Ferrous metals
2 – 3%

< 100 mm

Reduction of oDM and H_2O,
20 - 30%

Biological treatment anaerobic / aerobic

Optional if anaerobic digestion is integrated

Biogas
9 – 12%

Screening
30 – 40 mm

> 30 - 40 mm

HCF*
5 – 8%
LVC < 11 MJ/kg

< 30 - 40 mm

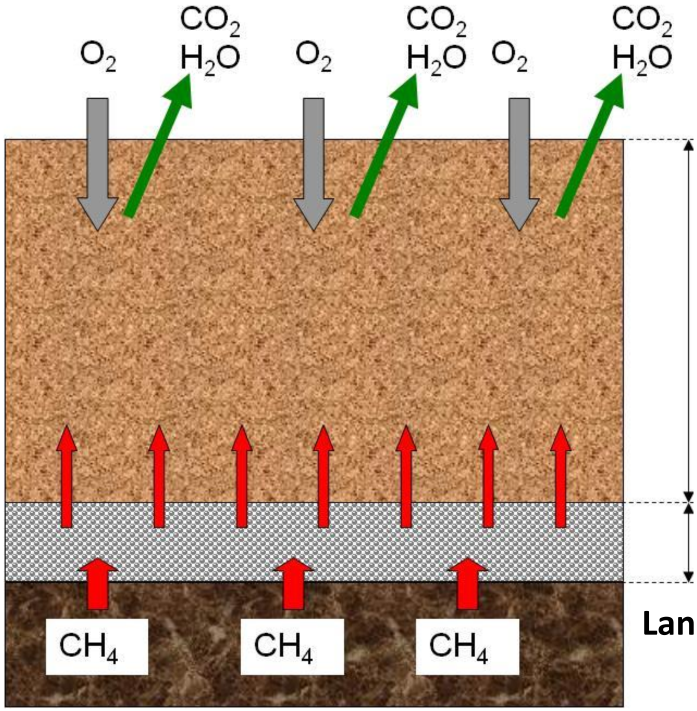
Filter material
MOL**

Landfill
25 - 45%

*High calorific fractions,
**Methane oxidation layer

Landfill gas collection
- Passive systems (MOL)

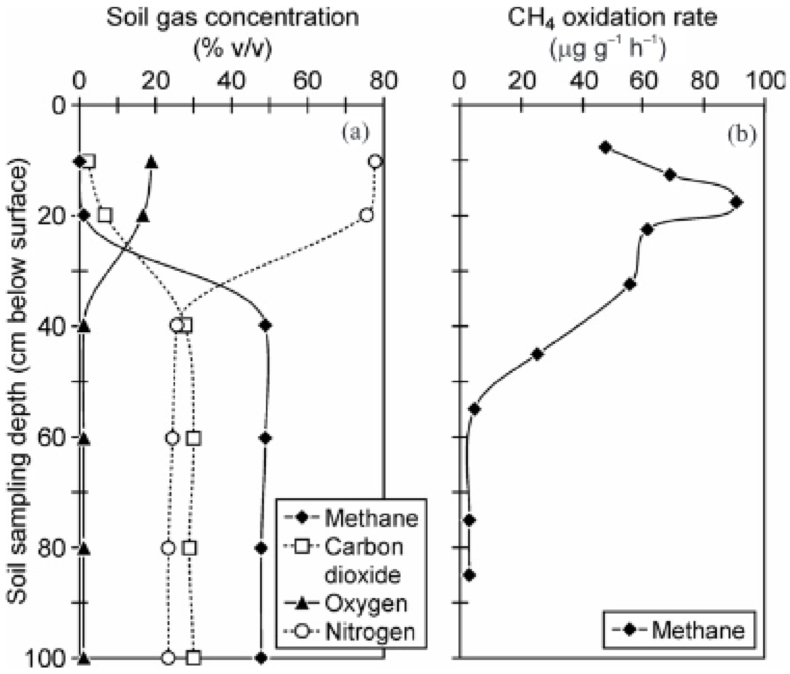
Methane oxidation layer (MOL)



Methane oxidation layer > 120 cm

Gas diffusion layer

Landfill body, top layer preferably uncompressed



$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + 883\ \text{kJ/mol}$$

Source: Scheutz et al., 2009, modified

Landfill gas collection
- Passive systems (MOL)

Methane oxidation layer:

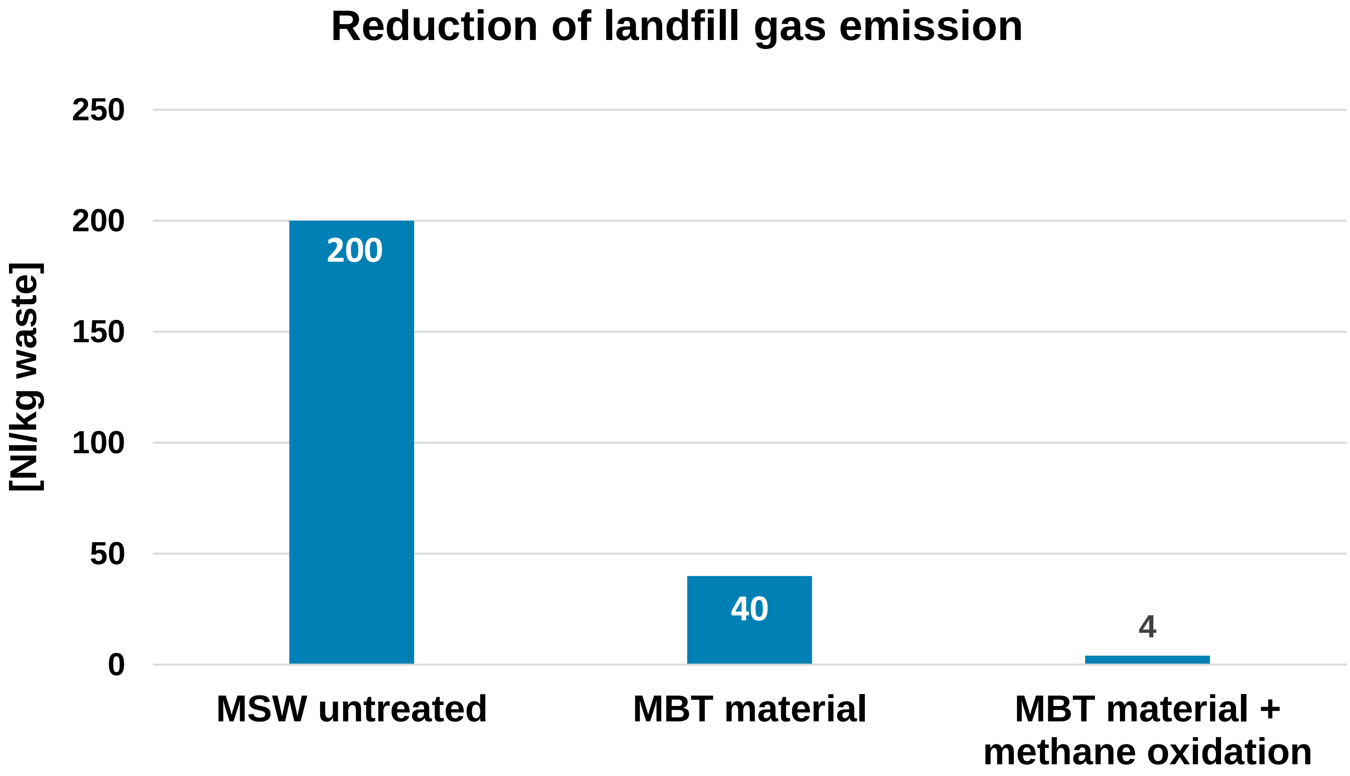
- Suitable for low LFG fluxes and low CH_4 concentrations

➡ Optimal methane input flux to methane oxidation layer: 12 - 96 [l/m²d]

Only system for MBT landfills or old landfills, where these values are met and where permeabilities are very low

- CH_4 is in the presence of O_2 degraded by special micro organisms (methanotrophic bacteria) to water, CO_2 and microbial biomass
- The process is exothermal

Treatment before landfill
- Reduction of landfill gas generation



➡ **Gas reduction rate through MBT and MOL > 90 %**

Lessons learned

- Explanation of the waste hierarchy with regard to climate impact
- Define GWP and give examples for the calculation of the CO_2 equivalent (CO_2-eq)
- What is the emission factor?
- Emission intensity electricity (emission factor) and credits
- Define CO_2-eq emissions and credits by given examples
- Which emissions and credits must be taken into account in the various waste management measures?
- What is the function of carbon pricing and trading?