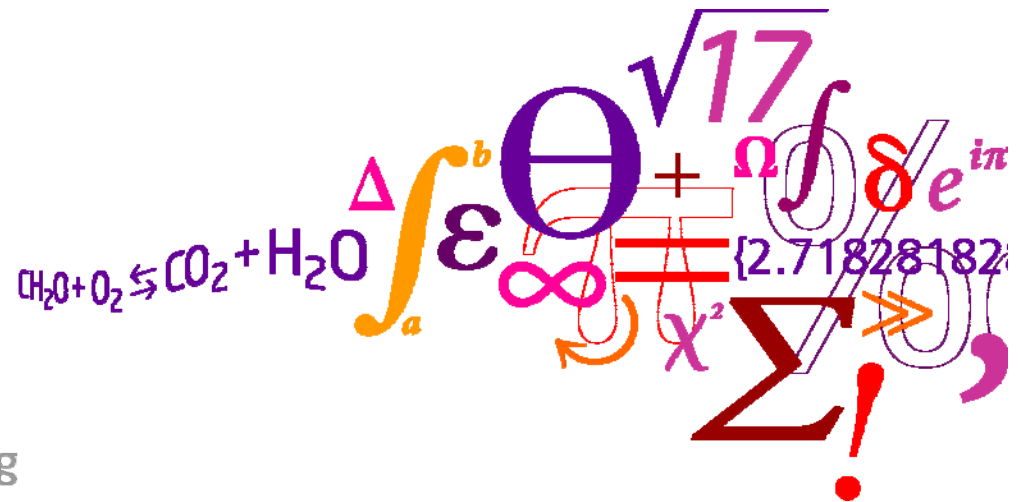


Waste management technologies and Greenhouse gas (GHG) emissions – a European comparison

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Introduction:

Greenhouse gas (GHG) accounting

- Waste management must like any other sector determine its contribution to global warming by presenting its GHG-account – and contribute to the solution by improving its performance
- Many GHG emission-factors are being made available and published these years – using different approaches and different assumptions
- Very little consensus exist
- Most of the activities in waste management are GHG loads while the savings come from what we offer to other parts of society: recyclable paper, metal scrap, electricity, heat, compost etc.
- The lack of consensus is not beneficial to the sector if it shall convince society that we are contributing to reducing GHG emissions in society although most of the savings take place outside our sector

Introduction: Greenhouse gas (GHG) accounting

- The GHG-account of a waste management technology depends per tonne of waste on:
 - indirect up-stream: the use of electricity, materials and the provision of fuels
 - direct emissions from the facility: fuel combustion, process emissions etc.
 - indirect down-stream: the substitutional value of the out-puts
- In the special issue of Waste Management & Research (Vol. **27**, p.696-836, 2009), we described each technology:

| Indirect: Upstream | Direct: Operation/ Waste | Indirect: Downstream |
|--|---|--|
| GWF (kg CO ₂ -eq./tonne ww): | GWF (kg CO ₂ -eq./ton vv): | GWF (kg CO ₂ -eq./ tonne ww): |
| GWF (kg CO ₂ -eq./ tonne ww): •Xxx •Xxx •Xxx | GWF (kg CO ₂ -eq./ton vv): •Xxx •Xxx •Xxx | GWF (kg CO ₂ -eq./ tonne ww): • Xxx •Xxxx •Xxx |
| Accounted (unit/ tonne ww) : •Xxxxx • Xxxx • Xxxx | Accounted (unit tonne ww /): • Xxx • Xxxx • Xxxx | Accounted (unit/ tonne ww): •Xxx •Xxx •Xxx |
| Not accounted: Xxxx •Xxxx | Not accounted: • Xxxxx | Not accounted: • XXXXXXX |

Introduction: Greenhouse gas (GHG) accounting

- The GHG-account of each waste technology depends on the actual waste composition
- Recycling technologies, composting and digestion may handle part of the waste flow, but only incineration, MBT (mechanical-biological-treatment) and landfilling can handle residual waste or all MSW
- Thus comparison of waste management technologies wrt. GHG-contribution can take place only on a system level: integrated systems that manage the same type of waste
- To illustrate this we defined 40 different waste management scenarios as they could look like in Europe and modeled their GHG contribution by means of the LCA-waste model EASEWASTE (www.easewaste.dk)

Purpose of GHG-modeling

- To compare modern waste management systems in order to identify where GHG loads and savings take place within a system and to compare systems with different technological approaches, including recycling activities
- To assess the importance of waste composition
- To assess the importance of energy substitutions

Full paper:

Christensen, T.H., Simion, F., Tonini, D. & Møller, J. (2009): Global warming factors modelled for 40 generic municipal waste management scenarios.

Waste Management & Research, **28**, 871-884

Defining the system

- Waste composition: Average European MSW + variations
- Up-to-date modern technologies as they could be build in year 2010 and on
- Source-separation schemes are efficient where introduced
- A carbon-limited economy:
 - strong efforts to reduce fossil-C emission: coal burning is the electricity marginal + variations
 - biomass is a limited resource and saved biomass from paper recycling is as renewable fuel also substituting for hard coal
- GHG counting:
 - o C-fossil emitted as CO₂: GWP = 1 Kg CO₂-equivalents/ kg CO₂
 - o C-fossil bound: GWP = 0
 - o C-biogenic emitted as CO₂: GWP = 0
 - o C-biogenic bound: - 3.67 Kg CO₂-equivalents/ kg C bound

Waste composition

| % ww | Average European MSW (baseline) | “Northern European” Modified MSW (sensitivity analysis) | “Southern European” Modified MSW (sensitivity analysis) |
|----------------|--|--|--|
| Organic | 35 | | 47 |
| Paper | 22 | 33 | 20 |
| Textile | 3 | 4 | 3 |
| Plastic | 10 | 9 | 9 |
| Glass | 6 | 4 | 5 |
| Metal | 4 | 4 | 5 |
| Other | 20 | 16 | |

Electricity and heat substitution

| Resources (kg) | Energy production | | | | | Fuel/coal combustion | |
|---------------------------|-------------------------------------|--|---|-------------------------|-------------------------------|----------------------|---------------------|
| | 1 kWh marginal European electricity | 1 kWh average European electricity mix | 1 kWh European brown coal based electricity | 1 kWh European heat mix | 1 kWh European oil based heat | 1 l Diesel oil* | 1 kWh hard coal** |
| Resources (kg) | | | | | | | |
| Hard coal | 0.613 | 0.078 | 0.0014 | 0.105 | $1.9 \cdot 10^{-4}$ | 0.018 | 0.124 |
| Lignite | 0.0025 | 0.186 | 1.161 | $2.9 \cdot 10^{-4}$ | - | 0.012 | 0.001 |
| Nat.gas | 0.0015 | 0.033 | 0.0027 | 0.041 | 0.024 | 0.05 | 0.0002 |
| Oil | 0.015 | 0.017 | 0.001 | 0.011 | 0.041 | 0.911 | 0.001 |
| Biomass | $0.17 \cdot 10^{-3}$ | - | - | 0.035 | - | 0.001 | |
| Air emissions (kg) | | | | | | | |
| CO ₂ | 0.9 | 0.56 | 1.498 | 0.324 | 0.14 | 3.015 | 0.321 |
| CH ₄ | 0.0053 | 0.001 | $2.1 \cdot 10^{-5}$ | $3.6 \cdot 10^{-4}$ | - | 0.0036 | 0.0015 |
| N ₂ O | $8.9 \cdot 10^{-6}$ | $1.4 \cdot 10^{-5}$ | $4.4 \cdot 10^{-5}$ | $2.7 \cdot 10^{-6}$ | - | $9.8 \cdot 10^{-6}$ | $6.5 \cdot 10^{-6}$ |

Technologies:

- Source separation of paper (65%), glass (55%), plastic (50%), biowaste for composting(60%)/biowaste (50%) for anaerobic digestion
- Collection of recyclables and residual waste
- Transport of recyclables and residual waste
- Recycling of paper
- Recycling of glass
- Recycling of plastic
- Recycling of iron
- Recycling of aluminum
- Composting (tunnel composting plant)+ rational use of compost in agriculture (15% C left after 100 years, fertilizer saving)
- Anaerobic digestion (70% of methane potential collected and used producing electricity at 35% efficiency) + rational use of digestate on land (8% C left after 100 years, fertilizer saving)

Technologies (residual waste)

- Landfilling with gas collection and flaring/electricity production (35% efficiency). Gas collection over 100 years were 50% for conventional and 80% for bioreactor landfill
- Incineration (use of electricity, 21% (LHV) electricity delivered to grid, 40 % (LHV) heat delivered, recovery of iron scrap and aluminum) + landfilling of bottom ash
- MBT:
 - MBP: Mechanical removal of RDF fraction (14-15 GJ/tonne) to power plant directly substituting for coal+ metal scrap, followed by composting prior to landfilling
 - MBS: Bio-drying followed by mechanical separation of RDF fraction going to incinerator with energy recoveries as other incinerator + metal scrap + small fraction to inert waste landfill.

Mass flows

| Scenario – Landfill-based | Source separation of paper | Source separation of glass | Source separation of plastic | Source separation of organics | Compost (kg) | Anaerobic digestate | Landfill: conventional | Landfill: bioreactor | Energy from digester | Energy from landfill |
|---------------------------|----------------------------|----------------------------|------------------------------|-------------------------------|--------------|---------------------|------------------------|----------------------|----------------------|----------------------|
| 1000 kg | kg | kg | kg | kg | kg | kg | kg | kg | kWh | kWh |
| LAN1-0 | - | - | - | - | - | - | 1000 | - | - | - |
| LAN2-0 | - | - | - | - | - | - | 1000 | - | - | 99 |
| LAN3-0 | - | - | - | - | - | - | - | 1000 | - | 178 |
| LAN1-1 | 143 | 33 | - | - | - | - | 824 | - | - | - |
| LAN2-1 | 143 | 33 | - | - | - | - | 824 | - | - | 77 |
| LAN3-1 | 143 | 33 | - | - | - | - | - | 824 | - | 140 |
| LAN1-2 | 143 | 33 | 13 | - | - | - | 811 | - | - | - |
| LAN2-2 | 143 | 33 | 13 | - | - | - | 811 | - | - | 77 |
| LAN3-2 | 143 | 33 | 13 | - | - | - | - | 811 | - | 140 |
| LAN1-3 | 143 | 33 | 13 | 231 | 58 | - | 580 | - | - | - |
| LAN2-3 | 143 | 33 | 13 | 231 | 58 | - | 580 | - | - | 45 |
| LAN3-3 | 143 | 33 | 13 | 231 | 58 | - | - | 580 | - | 81 |
| LAN1-4 | 143 | 33 | 13 | 173 | - | 609* | 638 | - | 47 | - |
| LAN2-4 | 143 | 33 | 13 | 173 | - | 609* | 638 | - | 47 | 51 |
| LAN3-4 | 143 | 33 | 13 | 173 | - | 609* | - | 638 | 47 | 92 |

CO₂-eqv. (Kg per tonne)

| Scenario | Total | Collection | Transport | Recycling of paper | Recycling of glass | Recycling of plastic | Composting plant (total) | Use of compost | Digester (total) | Use of Digestate | Landfill: operation | Landfill: gas emissions | Landfill: energy recovery | Landfill: C-binding |
|----------|-------|------------|-----------|--------------------|--------------------|----------------------|--------------------------|----------------|------------------|------------------|---------------------|-------------------------|---------------------------|---------------------|
| LAN1-0 | 18 | 9 | 16 | - | - | - | - | - | - | - | 22 | 233 | - | -261 |
| LAN2-0 | -112 | 9 | 16 | - | - | - | - | - | - | - | 22 | 232 | -129 | -261 |
| LAN3-0 | -275 | 9 | 16 | - | - | - | - | - | - | - | 21 | 102 | -202 | -221 |
| LAN1-1 | -207 | 10 | 19 | -255 | -8 | - | - | - | - | - | 18 | 183 | - | -172 |
| LAN2-1 | -309 | 10 | 19 | -255 | -8 | - | - | - | - | - | 18 | 183 | -102 | -172 |
| LAN3-1 | -437 | 10 | 19 | -255 | -8 | - | - | - | - | - | 17 | 80 | -158 | -141 |
| LAN1-2 | -216 | 10 | 19 | -255 | -8 | -10 | - | - | - | - | 18 | 183 | - | -172 |
| LAN2-2 | -318 | 10 | 19 | -255 | -8 | -10 | - | - | - | - | 18 | 183 | -102 | -172 |
| LAN3-2 | -446 | 10 | 19 | -255 | -8 | -10 | - | - | - | - | 17 | 80 | -158 | -141 |
| LAN1-3 | -277 | 12 | 18 | -255 | -8 | -10 | 23 | -3 | - | - | 13 | 106 | - | -172 |
| LAN2-3 | -335 | 12 | 18 | -255 | -8 | -10 | 23 | -3 | - | - | 12 | 106 | -59 | -172 |
| LAN3-3 | -396 | 12 | 18 | -255 | -8 | -10 | 23 | -3 | - | - | 12 | 46 | -92 | -141 |
| LAN1-4 | -318 | 12 | 21 | -255 | -8 | -10 | - | - | -34 | -6 | 14 | 120 | - | -172 |
| LAN2-4 | -385 | 12 | 21 | -255 | -8 | -10 | - | - | -34 | -6 | 14 | 120 | -67 | -172 |
| LAN3-4 | -485 | 12 | 21 | -255 | -8 | -10 | - | - | -34 | -6 | 13 | 53 | -104 | -141 |



Mass flows

| Scenario – Incinerator-based | Source separation of paper | Source separation of glass | Source separation of plastic | Source separation of organics | Compost | Anaerobic digestate | Incineration | Recovery of iron scrap from bottom ash | Landfilling of bottom ash | Electricity from digester | Electricity from incinerator | Heat from incinerator |
|------------------------------|----------------------------|----------------------------|------------------------------|-------------------------------|---------|---------------------|--------------|--|---------------------------|---------------------------|------------------------------|-----------------------|
| 1000 kg | kg | kg | kg | kg | kg | kg | kg | kg | kg | kWh | kWh | kWh |
| INC1-0 | - | - | - | - | - | - | 1000 | 13 | 165 | - | 587 | |
| INC2-0 | - | - | - | - | - | - | 1000 | 13 | 165 | - | 587 | 1134 |
| INC1-1 | 143 | 33 | - | - | - | - | 824 | 13 | 110 | - | 477 | |
| INC2-1 | 143 | 33 | - | - | - | - | 824 | 13 | 110 | - | 477 | 921 |
| INC1-2 | 143 | 33 | 13 | - | - | - | 811 | 13 | 109 | - | 452 | |
| INC2-2 | 143 | 33 | 13 | - | - | - | 811 | 13 | 109 | - | 452 | 873 |
| INC1-3 | 143 | 33 | 13 | 231 | 58 | - | 580 | 13 | 98 | - | 396 | |
| INC2-3 | 143 | 33 | 13 | 231 | 58 | - | 580 | 13 | 98 | - | 396 | 765 |
| INC1-4 | 143 | 33 | 13 | 173 | - | 609* | 638 | 13 | 106 | 47 | 410 | |
| INC2-4 | 143 | 33 | 13 | 173 | - | 609* | 638 | 13 | 106 | 47 | 410 | 792 |

CO₂-eqv. (Kg per tonne)

| scenario | Total | Collection | Transport | Recycling of paper | Recycling of glass | Recycling of plastic | Composting plant (total) | Use of compost | Digester (total) | Use of Digestate | Incinerator (consumption) | Incinerator: air emissions | Incinerator: scrap iron recovery | Incinerator: bottom ash landfilling | Incinerator: electricity recovery | Incinerator: heat recovery |
|----------|-------|------------|-----------|--------------------|--------------------|----------------------|--------------------------|----------------|------------------|------------------|---------------------------|----------------------------|----------------------------------|-------------------------------------|-----------------------------------|----------------------------|
| NC1-0 | -239 | 9 | 8 | - | - | - | - | - | - | - | 72 | 297 | -22 | 2 | -606 | - |
| NC2-0 | -620 | 9 | 8 | - | - | - | - | - | - | - | 72 | 297 | -22 | 2 | -606 | -380 |
| NC1-1 | -398 | 10 | 12 | -255 | -8 | - | - | - | - | - | 59 | 296 | -22 | 1 | -492 | - |
| NC2-1 | -707 | 10 | 12 | -255 | -8 | - | - | - | - | - | 59 | 296 | -22 | 1 | -492 | -309 |
| NC1-2 | -416 | 10 | 13 | -255 | -8 | -10 | - | - | - | - | 58 | 263 | -22 | 1 | -466 | - |
| NC2-2 | -708 | 10 | 13 | -255 | -8 | -10 | - | - | - | - | 58 | 263 | -22 | 1 | -466 | -293 |
| NC1-3 | -352 | 12 | 15 | -255 | -8 | -10 | 23 | -3 | - | - | 42 | 262 | -22 | 1 | -408 | - |
| NC2-3 | -608 | 12 | 15 | -255 | -8 | -10 | 23 | -3 | - | - | 42 | 262 | -22 | 1 | -408 | -256 |
| NC1-4 | -419 | 12 | 17 | -255 | -8 | -10 | - | - | -34 | -6 | 46 | 262 | -22 | 1 | -423 | - |
| NC2-4 | -684 | 12 | 17 | -255 | -8 | -10 | - | - | -34 | -6 | 46 | 262 | -22 | 1 | -423 | -265 |



Mass flows

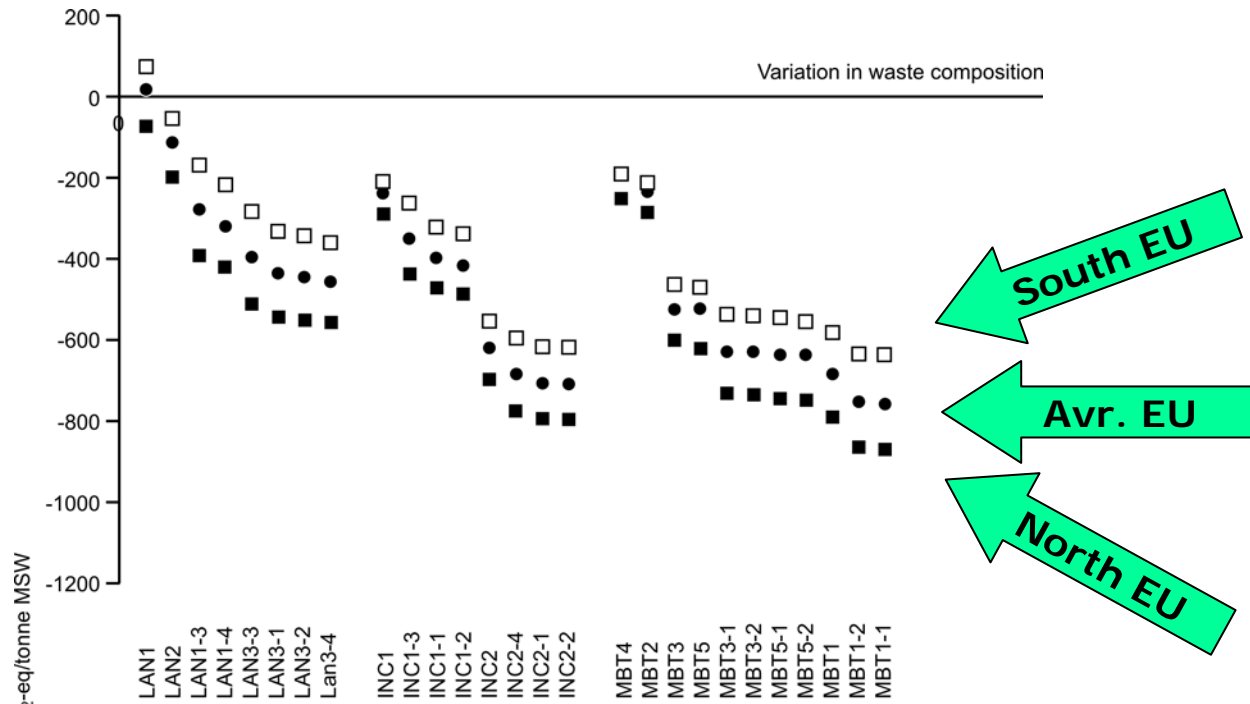
| Scenario – MBT-based | Source separation of paper | Source separation of glass | Source separation of plastic | MBP | MBS | Recovery of iron scrap from MBT | Landfilling of MBT waste | RDF to power plant | RDF to incinerator | Landfilling of bottom ash | Electricity from incinerator | Heat from incinerator |
|----------------------|----------------------------|----------------------------|------------------------------|------|------|---------------------------------|--------------------------|--------------------|--------------------|---------------------------|------------------------------|-----------------------|
| 1000 kg | kg | kg | kg | kg | kg | kg | kg | kg | kg | kg | kWh | kWh |
| MBT1-0 | - | - | - | 1000 | - | 40 | 188 | 530 | - | - | - | - |
| MBT2-0 | - | - | - | 1000 | - | 40 | 188 | - | 530 | 61 | 446 | - |
| MBT3-0 | - | - | - | 1000 | - | 40 | 188 | - | 530 | 61 | 446 | 863 |
| MBT4-0 | - | - | - | - | 1000 | 38 | - | - | 597 | 102 | 518 | - |
| MBT5-0 | - | - | - | - | 1000 | 38 | - | - | 597 | 102 | 518 | 1001 |
| MBT1-1 | 143 | 33 | - | 824 | - | 40 | 131 | 420 | - | - | - | - |
| MBT2-1 | 143 | 33 | - | 824 | - | 40 | 131 | - | 420 | 37 | 357 | - |
| MBT3-1 | 143 | 33 | - | 824 | - | 40 | 131 | - | 420 | 37 | 357 | 690 |
| MBT4-1 | 143 | 33 | - | - | 824 | 38 | - | - | 437 | 67 | 408 | - |
| MBT5-1 | 143 | 33 | - | - | 824 | 38 | - | - | 437 | 67 | 408 | 789 |
| MBT1-2 | 143 | 33 | 13 | 811 | - | 40 | 130 | 400 | - | - | - | - |
| MBT2-2 | 143 | 33 | 13 | 811 | - | 40 | 130 | - | 400 | 37 | 335 | - |
| MBT3-2 | 143 | 33 | 13 | 811 | - | 40 | 130 | - | 400 | 37 | 335 | 648 |
| MBT4-2 | 143 | 33 | 13 | - | 811 | 37 | - | - | 425 | 66 | 386 | - |
| MBT5-2 | 143 | 33 | 13 | - | 811 | 37 | - | - | 425 | 66 | 386 | 746 |

CO₂-eqv. (kg per tonne)

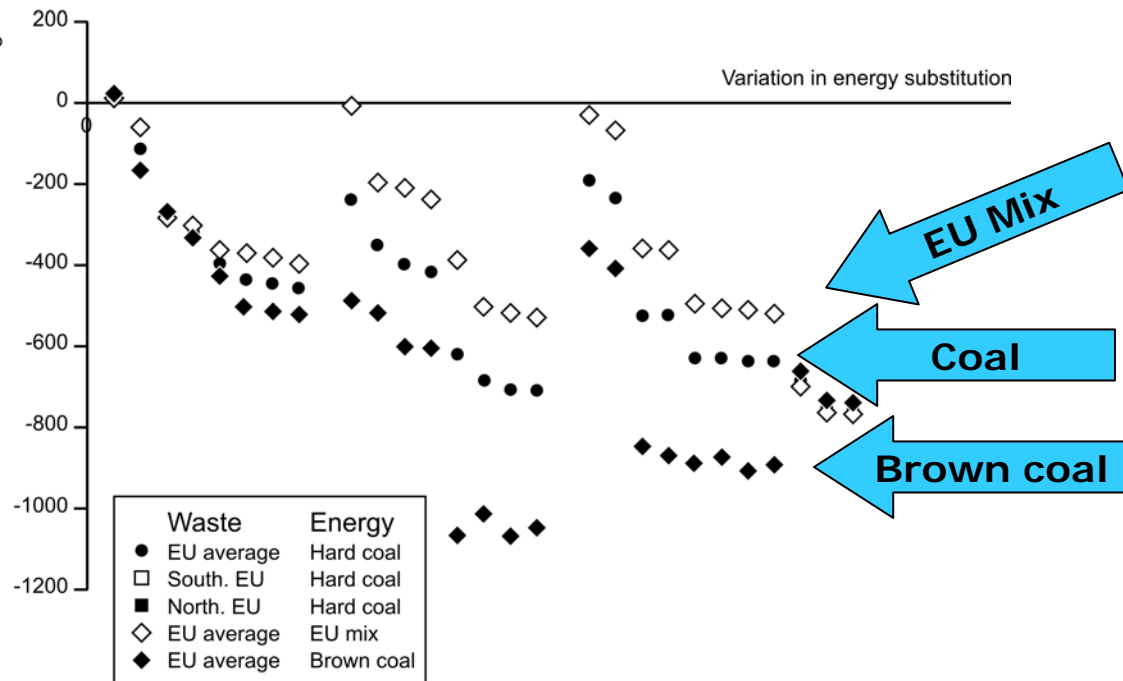
| Scenario | Total | Collection | Transport | Recycling of paper | Recycling of glass | Recycling of plastic | MBT plant (total) | MBT plant: Iron scrap recovery | Power plant: Emissions from RB | Power plant: Coal substitution | Incinerator (consumption) | Incinerator: Emissions | Incinerator: Electricity recovery | Incinerator : heat recovery | Landfilling: C-binding |
|----------|-------|------------|-----------|--------------------|--------------------|----------------------|-------------------|--------------------------------|--------------------------------|--------------------------------|---------------------------|------------------------|-----------------------------------|-----------------------------|------------------------|
| MBT1-0 | -684 | 9 | 34 | - | - | - | 51 | -60 | 270 | -892 | - | - | - | - | -101 |
| MBT2-0 | -234 | 9 | 20 | - | - | - | 51 | -60 | - | - | 39 | 261 | -460 | - | -101 |
| MBT3-0 | -523 | 9 | 20 | - | - | - | 51 | -60 | - | - | 39 | 261 | -460 | -289 | -101 |
| MBT4-0 | -190 | 9 | 19 | - | - | - | 125 | -118 | - | - | 43 | 268 | -534 | - | - |
| MBT5-0 | -525 | 9 | 19 | - | - | - | 125 | -118 | - | - | 43 | 268 | -534 | -335 | - |
| MBT1-1 | -757 | 10 | 33 | -255 | -8 | - | 42 | -60 | 267 | -715 | - | - | - | - | -74 |
| MBT2-1 | -397 | 10 | 23 | -255 | -8 | - | 42 | -60 | - | - | 30 | 260 | -369 | - | -74 |
| MBT3-1 | -628 | 10 | 23 | -255 | -8 | - | 42 | -60 | - | - | 30 | 260 | -369 | -231 | -74 |
| MBT4-1 | -372 | 10 | 21 | -255 | -8 | - | 103 | -118 | - | - | 31 | 267 | -421 | - | - |
| MBT5-1 | -636 | 10 | 21 | -255 | -8 | - | 103 | -118 | - | - | 31 | 267 | -421 | -264 | - |
| MBT1-2 | -752 | 10 | 33 | -255 | -8 | -10 | 41 | -60 | 237 | -671 | - | - | - | - | -74 |
| MBT2-2 | -414 | 10 | 23 | -255 | -8 | -10 | 41 | -60 | - | - | 29 | 231 | -346 | - | -74 |
| MBT3-2 | -631 | 10 | 23 | -255 | -8 | -10 | 41 | -60 | - | - | 29 | 231 | -346 | -217 | -74 |
| MBT4-2 | -388 | 10 | 21 | -255 | -8 | -10 | 101 | -118 | - | - | 31 | 238 | -399 | - | - |
| MBT5-2 | -638 | 10 | 21 | -255 | -8 | -10 | 101 | -118 | - | - | 31 | 238 | -399 | -250 | - |



Waste composition



Energy substitution



Conclusions

- For modern well managed waste management systems (Europe):
 - Scenarios with landfilling may have GHG savings in the range 0-400 kg CO₂-eqv. per tonne
(Technology factor: gas recovery and utilization)
 - Scenarios with incineration may have GHG savings in the range 200-700 kg CO₂-eqv. per tonne
(Technology factor: electricity and heat production (here 40%))
 - Scenarios with MBT may have GHG savings in the range 200-750 kg CO₂-eqv. per tonne
(Technology factor: direct substitution for coal burning)
- Major contributors to savings: paper recycling and use of excessive wood, energy recovery and storage of C in landfills
- Waste management activities as collection, transport, glass recycling, plastic recycling, anaerobic digestion and composting play only minor roles

Conclusions

- Waste composition matters: Different savings available in north and south Europe – but ranking of technological systems does not change
- The energy substitution is crucial to the results: the dirtier the better
- Significant savings can be obtained by a rational waste management system
- GHG accounting for decision making on future waste management systems must take place on a system level – not on a single technology level



Thank You