Appendix – LCA of Waste Strategy Options

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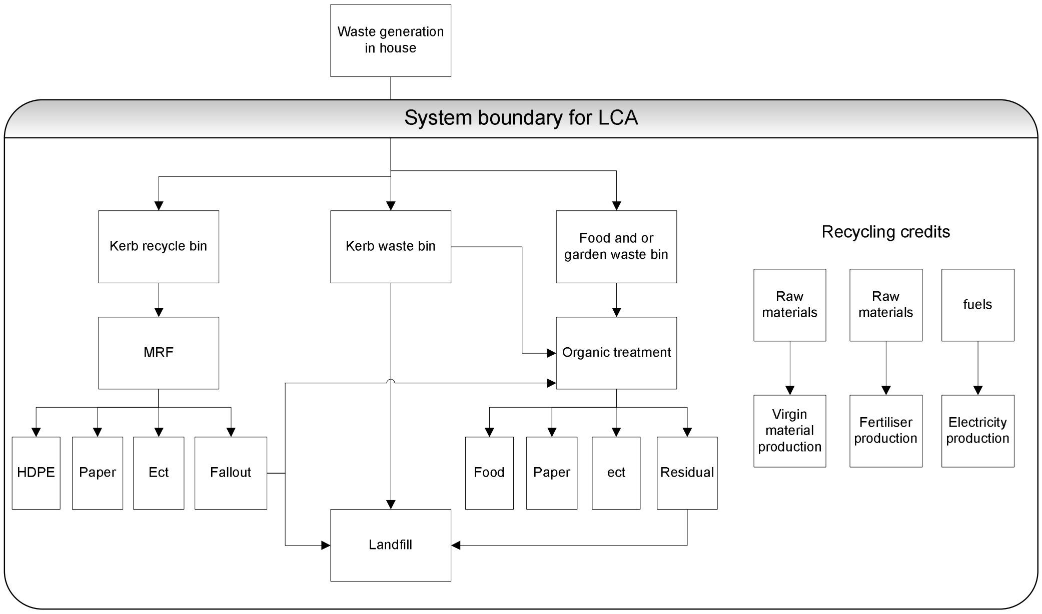
1. Introduction

The appendix provides details of the life cycle assessment (LCA) of waste options analysed for Sustainability Victoria's study. The LCA was streamlined through the use of the earlier LCA model developed for the Waste Management Options report published in 2003 (Grant, James *et al*. 2003). The earlier report included extensive documentation on assumptions for materials recycling and residual waste management technologies. It is not intended to reproduce that information here, but to note the information which has been updated.

2. LCA scope

This LCA includes all activities from the collection of waste materials from households, to the transport, sorting, processing and disposal of these materials, and the recovery of commodities. It also includes credits for the production of virgin materials, fertilisers and electricity which would be needed in the economy if the waste had not been recovered.



Waste collection and management system

3. Model structure

The LCA model is based on annual flows for inner and outer suburbs for collection of garbage, recyclables and green waste, or green and food waste. It includes data on collection and waste transfer on an annual basis for these areas. Each waste stream is processed through given waste and recycling technologies, based on the material composition of the waste stream. For aerobic and anaerobic treatments, only the biogas production is modelled per material component to account for the different organic contents of the waste stream fractions. Overall plant emissions (other than CO_2 and methane) and energy use of the plant are modelled on the basis of each tonne of waste processed through the plant. This means that the energy use from enclosed, composting, and anaerobic treatments is not sensitive to waste composition. However, different assumptions are made for green and food waste processing and mixed waste processing in both aerobic and anaerobic treatment technologies. Recycling and landfill processes are all modelled per material component to account for the different materials recovered from different fractions of the recycling mix. Transport of sorted recyclables to the reprocessing facilities is including in the model based on best estimates of where the reprocessing would occur.

4. Details of options

The recycling model used in the 2003 study has not been modified for this study, although the quantity of recyclables and their composition have been taken from updated waste data developed for this study. This data includes contamination rates which are specified in the recycling composition data, and it is assumed that contamination is processed by the same technologies used to process residual waste fractions. Therefore, recycling contamination will be sent to anaerobic treatment in option 1.

The anaerobic technology model is based largely on data from a UK study (Eunomia 2002) which was used in the 2003 study. The electricity use for the mixed waste processing (detailed in Table 1) is approximately the same as energy generation, which varies depending on the waste composition. Figure 1 shows the energy balance for anaerobic treatment of the waste composition in this study. The net electricity use is 10 MJ (2.8 kWh) per tonne of waste processed, and after accounting also for diesel energy use the anaerobic treatment consumes a small net amount of energy.

The anaerobic digestion of green and food waste produces significant net electricity for export. Figure 2 shows the electricity production and use in anaerobic digestion of green and food waste for one tonne of the material. The net electricity production is 759MJ (211 kWh) for one tonne of green and food waste.

The model for composting green and food waste is taken directly from the 2003 study and assumes that compost produced has substantial benefits, which are outlined in Table 1. Compost derived from mixed waste is only used in non-production situations, so the only benefit included is the increase in soil carbon.

The model for incineration was provided by Hannes Partl based on Stationary Fluidised Bed (FB) Incinerator from Vienna, Austria.

Figure 1: Process network showing electricity use (in MJ) and generation from anaerobic digestion of 1 tonne of mixed waste

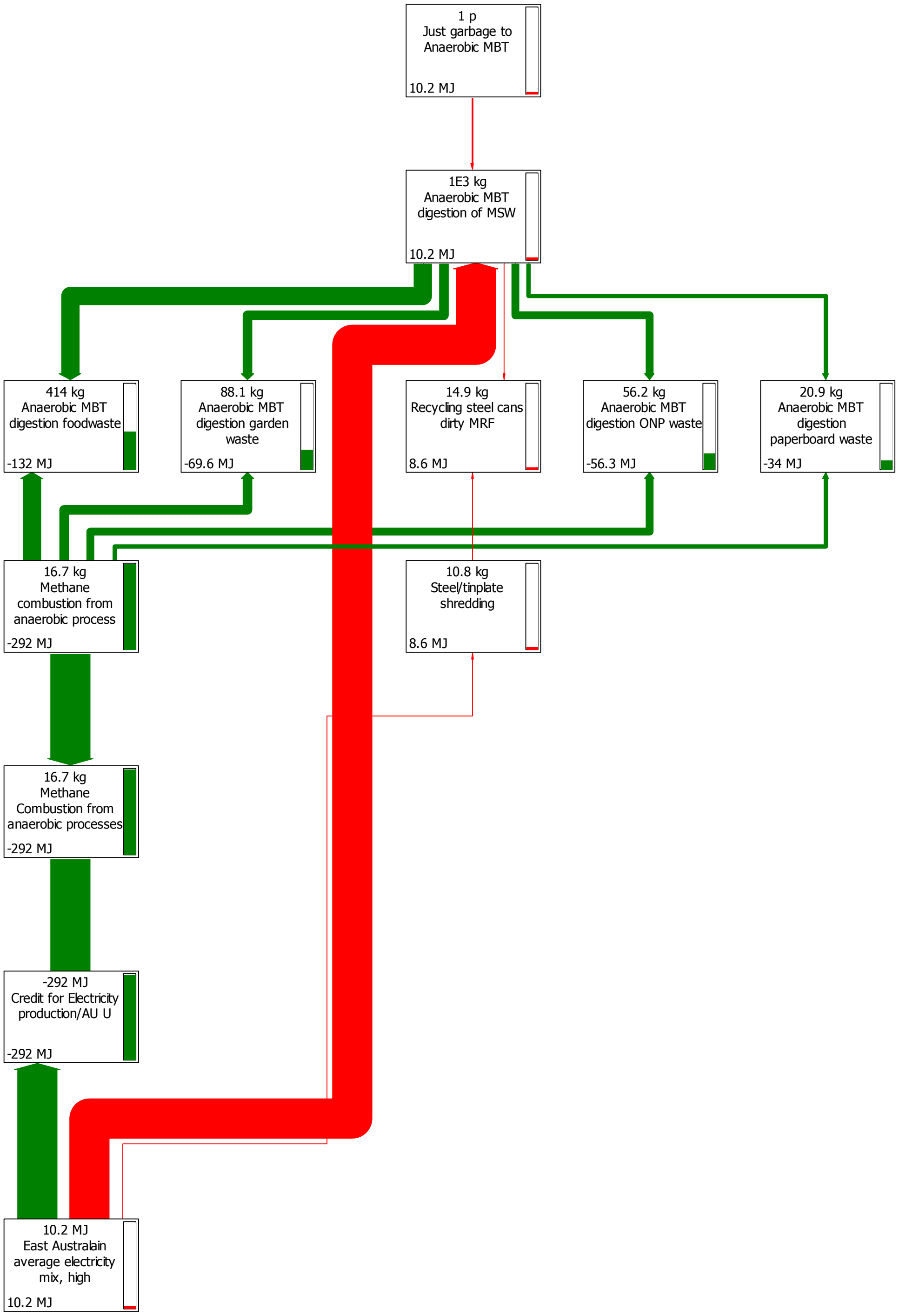
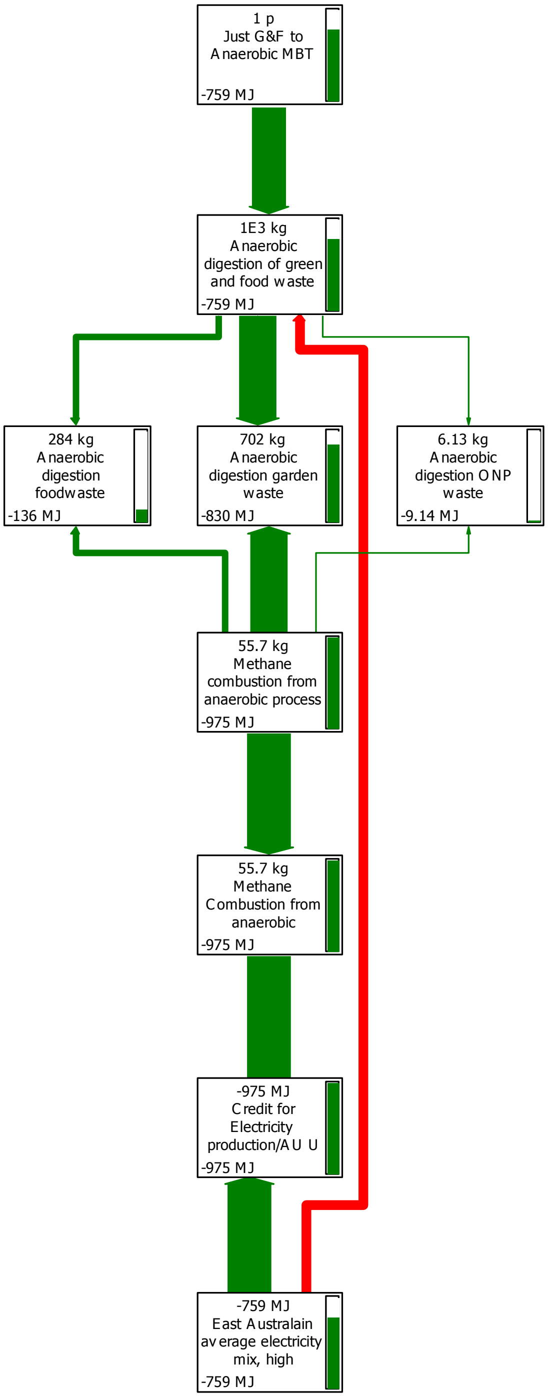


Figure 2: Process network showing electricity use (in MJ) and generation from anaerobic digestion of 1 tonne of mixed waste garden and food waste



A summary of key assumptions used in modelling the treatment technologies in the LCA is listed in Table 1.

Table 1: Key assumptions of the LCA

Process	**Key assumptions**
Dynamics at landfill (MSW)	• Values for methane generation from organic fractions taken from Smith (2001). • Assume landfill gas capture is 60% and all of this is used for electricity generation. Of the remaining 40% not captured, assume 10% (ie 4% of total methane) degrades through the landfill cap. • Assume that carbon remaining in the landfill is not counted as sequestration, but eventually emits as carbon dioxide. • Stabilised material reduces gas generation by 90%.
Open composting	• No energy use is included. • 3kg of fossil CO_2 emissions and 0.2kg of methane and 0.011g of nitrous oxide per tonne of material processed. • 45% of input to process is output as compost. 20% input is output to landfill.
Enclosed composting	• 1.186kWh electricity and 38 MJ of diesel used per tonne of material throughput. Emissions from compost pile are the same as emissions from open composting. • 45% of input to process is output as compost. 20% input is output to landfill.
Anaerobic digestion (green and food waste)	• Digestion is followed by aerobic compost production. • 35% of input to process is output compost. 20% input is output to landfill. • Energy use of 60kWh of electricity and 36 MJ of diesel are used per tonne of material throughput. • 80 – 100 kWh/t net electricity output.
Anaerobic digestion (MSW)	• Digestion is followed by aerobic curing. • 50% of input to process is output. Of this 28% is low-grade compost and 72% is stabilised residue sent to landfill. Automated ferrous metal recovery. • Energy use of 80kWh of electricity and 54MJ of diesel are used per tonne of material throughput. • 0-20 kWh/t input net electricity output.
Incineration	• Slag disposal kg 25 • Filter cake disposal kg 100 • Electricity 231 kWh per tonne waste • Heat 1867 kWh per tonne – but not credited as no use identified • Recycling steel cans 80% • Recycling aluminium 60% • Fly ash stabilisation with 0.5t of cement per tonne flyash.
Aerobic stabalisation (MSW)	• 62% of input to process is output. Of this 32% is low-grade compost and 68% is stabilised residue sent to landfill. Automated ferrous metal recovery. • Energy use of 3.85kWh of electricity and 38MJ of diesel are used per tonne of material throughput..
Recovery rates in front-end separation	• 50% for plastics and 75% for metals.
Benefits of using compost (from green and food waste)	• 2.5% increase in crop yield through increase in water-holding capacity (estimated on wheat crop) • Fertiliser replacement of 1.5% N and 0.25% for K and P • Reduction in nitrous oxide emissions • 20% reduction in pesticide use • 10% of carbon is sequestrated in the land.
Benefits of using compost (from MSW)	• 10% of carbon is sequestrated in the land.

Table 2 Emissions from incineration

Flow	Unit	Value	Comment
Products			
Generic emissions from incineration, per to nne waste	%	100	
Materials and Energy			
Emissions to air			
Carbon dioxide, fossil	kg	300	From synthetic materials combustion
Particulates, < 10 um	mg	510	
VOC, volatile organic compounds	mg	4590	
Hydrogen chloride	mg	510	
Sulfur dioxide	mg	5610	
Nitrogen dioxide	mg	196350	
Carbon monoxide	kg	41310	
Lead	mg	51	Provided as sum Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V+Sn entered as Pb
Ammonia	mg	6630	
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	ng	41.82	Listed as dioxin and furans 1-TEF□
Mercury	mg	5.1	
Emissions to water			
Chloride	kg	0.0023	Value from Eunomia (2002)□
Ammonia	kg	0.0023	Value from Eunomia (2002)□

5. Indicator description

Five indicators have been used in the study as outlined in Table 3.

Table 3 Description of Impact Categories

Indicator	Characterisation factors	Comments
Greenhouse impacts	IPCC factor for Kyoto accounting	Not updated from more recent factors as accounting is still being undertaken on orginal factor identified under Kyoto
Fossil energy use	Nett energy values of fossil fuels taken from ABARE definitions and Australian electricity data from ESAA.	Not only fossil energy and not full embodied energy is used. This focuses on the depletion of fossil fuel rather that total energy in the system.
Water use	Strait addition of total water uses through system	Take no account of local scarcities
Solid waste	Strait addition of waste sent to landfill – prior to degradation in landfill.	Waste redeposited on land such as mining tailing and overburden are not included.
Human toxicity potential	Characterisation factors taken from Huijbrechts and Lundie for Australian environment,	Include metals, organics and pesticides. HF and F excluded due to apparent over valuation in the model.

6. Results

Results are presented below for each of the four indicators and across the four time periods in the study. The greenhouse results are presented in Figure 3, and it can be seen that all options are better than the base case while option 1 and option 4 are the best performers.

The difference in greenhouse gas emissions between option 1and 2 and is principally caused by two factors:

- Reduced landfill in option 1 leads to lower methane emissions from landfill.
- Increased recycling results from increased front-end recycling in option 1, as all garbage streams are processed.

Option 2a has much lower benefits that option 2 as there is no electricity generation when the green and food waste from the outer suburbs is aerobically composted (rather than anaerobically digested to produce electricity in Option 2).

Option 4 is similar in benefits to option 1 but the transport in reduced due to commingling green and food waste with residual waste. Option 3 has the highest greenhouse benefits due to high electricity production and front end separation of metals.

Figure 3: Greenhouse results for three scenarios for four different time points.

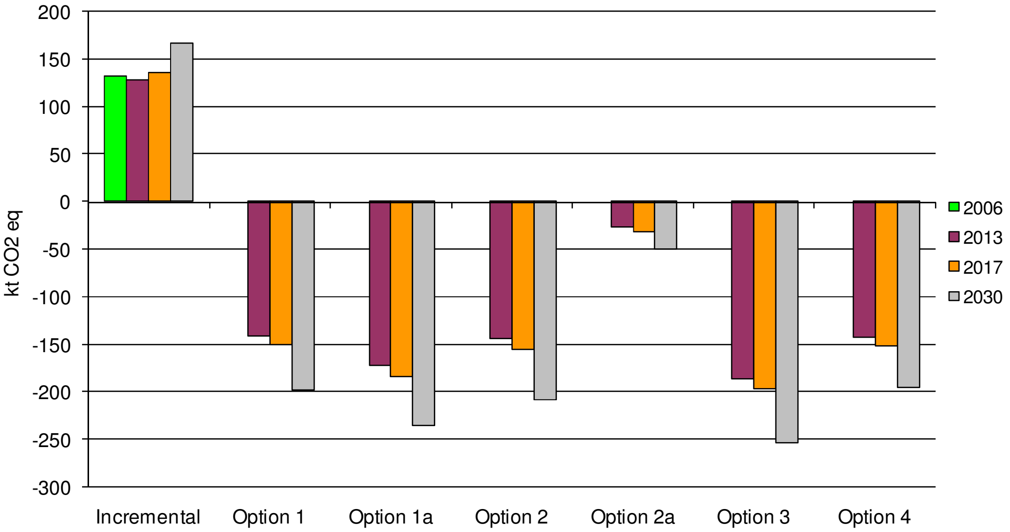


Figure 4 shows the results for fossil energy use. There is a positive outcome for all options, but fossil energy savings are highest for option 3, which generates the most electricity for export from incineration followed by anaerobic digestion of green and food waste. The base case shows marginally higher fossil energy savings than option 1, due to electricity production from landfill gas which is not available in option 1.

Figure 4: Fossil fuel use results for three scenarios for four different time points.

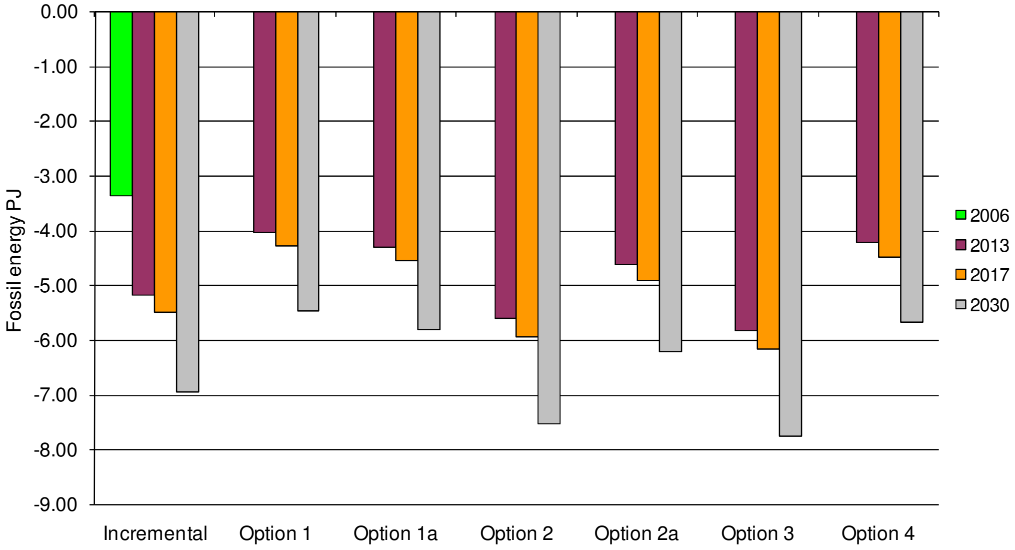


Figure 5 shows the results for water savings. Savings occur dominantly through recycling (newsprint, paperboard, glass, aluminium), which is common to all options. However, options 1 and 2 also save water through compost production (and consequent avoided fertiliser production) while option 3 reduce water use from electricity generation.

Figure 5: Water use results for three scenarios for four different time points.

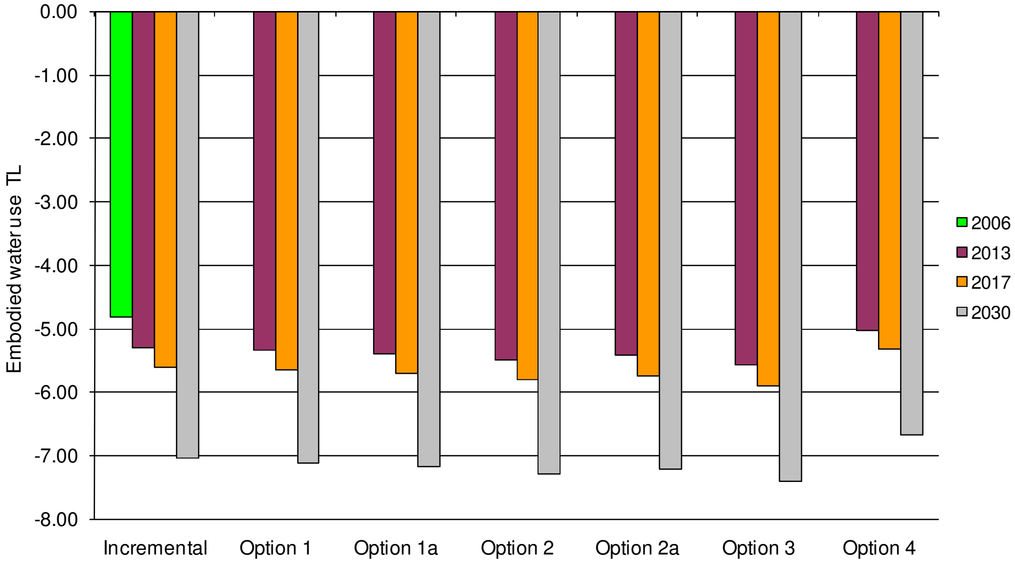


Figure 6 shows the impact of waste-to-landfill. Option 1 and 3 are the best option as all residual fractions are treated prior to landfilling of the residue. The base case is clearly the worst for waste-to-landfill.

Figure 6: Waste-to-landfill results for three scenarios for four different time points

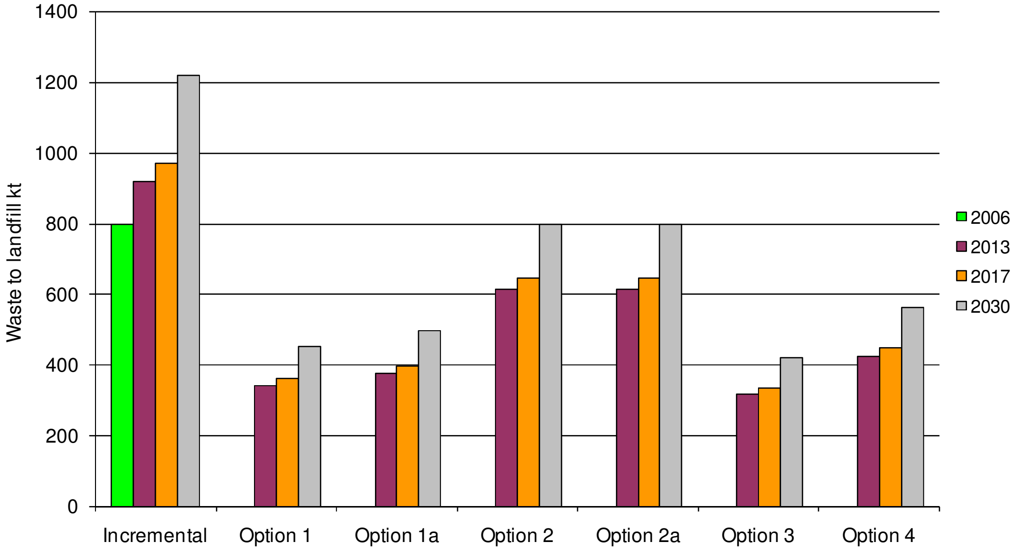


Figure 7 shows net reduction in human toxicity potential from all waste management option however the results don't vary substantially between options. The reasons for this are shown in Figure 11 and Figure 12. Figure 11 shows that kerbside recycling dominates the human toxicity savings and most options have roughly the same recycling result. Figure 12 shows the same results without the kerbside recycling savings and shows the major differences are the presence of front end recycling, and oddly enough the presence of landfill which can generate electricity which is cleaner that average Victorian grid electricity. This is also the reason that option 3 performs well with incineration having lower emissions than Victorian power generation. Figure 13 shows which substances are contributing to toxic results with the main one being polycyclic aromatic hydrocarbons (PAHs) which is due to savings in steel, aluminium and paper, and ethylene oxide which is saved though recycling of PET. The only significant impact from the composting in arsenic emission to soil from compost application.

Figure 7: Human toxicity potential results for three scenarios for four different time points

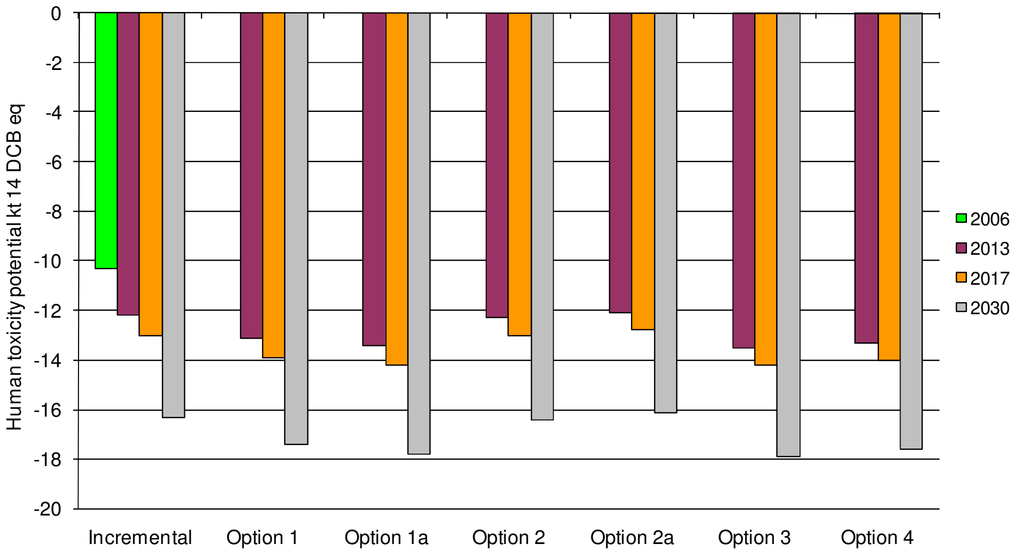


Table 4 and Table 5 show numerically the same data presented in the graphs above. In Table 5 the results are shown as an improvement on the base case.

Table 4: Results for three scenarios for four different time points for the four studied indicators

GHG kt	**Incremental**	**Option 1**	**Option 1a**	**Option 2**	**Option 2a**	**Option 3**	**Option 4**
2006	132	0	0	0	0	0	0
2013	128	-142	-172	-144	-27	-186	-143
2017	135	-151	-184	-156	-32	-197	-152
2030	166	-198	-236	-209	-50	-253	-196
Fossil energy TJ	Incremental	Option 1	Option 1a	Option 2	Option 2a	Option 3	Option 4
2006	-3.35	0.00	0.00	0.00	0.00	0.00	0.00
2013	-5.18	-4.03	-4.29	-5.59	-4.62	-5.81	-4.21
2017	-5.49	-4.28	-4.55	-5.94	-4.90	-6.15	-4.47
2030	-6.93	-5.46	-5.79	-7.52	-6.20	-7.74	-5.66
Water TL	Incremental	Option 1	Option 1a	Option 2	Option 2a	Option 3	Option 4
2006	-4.81	0.00	0.00	0.00	0.00	0.00	0.00
2013	-5.29	-5.33	-5.39	-5.48	-5.42	-5.57	-5.02
2017	-5.60	-5.65	-5.71	-5.80	-5.74	-5.90	-5.31
2030	-7.03	-7.11	-7.17	-7.29	-7.21	-7.41	-6.67
Solid waste to landfill Kt	Incremental	Option 1	Option 1a	Option 2	Option 2a	Option 3	Option 4
2006	800	0	0	0	0	0	0
2013	918	342	377	614	614	317	424
2017	972	362	399	647	647	336	449
2030	1220	452	497	799	798	420	563
Human toxics	Incremental	Option 1	Option 1a	Option 2	Option 2a	Option 3	Option 4
2006	-10	0	0	0	0	0	0
2013	-12	-13	-13	-12	-12	-14	-13
2017	-13	-14	-14	-13	-13	-14	-14
2030	-16	-17	-18	-16	-16	-18	-18

Table 5 Net improvement in indicator from base case

GHG Kt CO_2 e	**Option 1**	**Option 1a**	**Option 2**	**Option 2a**	**Option 3**	**Option 4**
2013	270	300	272	155	314	271
2017	286	319	291	167	332	287
2030	364	402	375	216	419	362
Fossil energy TJ	Option 1	Option 1a	Option 2	Option 2a	Option 2a	Option 2a
2013	-1.15	-0.89	0.41	-0.56	0.63	-0.97
2017	-1.21	-0.94	0.45	-0.59	0.66	-1.02
2030	-1.47	-1.14	0.59	-0.73	0.81	-1.27
Water TL	Option 1	Option 1a	Option 2	Option 2a	Option 2a	Option 2a
2013	0.040	0.100	0.190	0.130	0.280	-0.270
2017	0.050	0.110	0.200	0.140	0.300	-0.290
2030	0.080	0.140	0.260	0.180	0.380	-0.360
Solid waste to landfill Kt	Option 1	Option 1a	Option 2	Option 2a	Option 2a	Option 2a
2013	576	541	304	304	601	494
2017	610	573	325	325	636	523
2030	768	723	421	422	800	657
Human toxics	Option 1	Option 1a	Option 2	Option 2a	Option 2a	Option 2a
2013	-10	-10	-10	-10	-10	-10
2017	1	1	0	0	1	1
2030	1	1	0	0	1	1

6.1 Breakdown of greenhouse impacts for different options

Figure 8 shows the greenhouse gas emissions from different processes within each option studied. The results are absolute emissions or avoided emissions as a result of the management of the waste fractions. The impacts of waste management above the line consist of methane from landfill, transport emissions and anaerobic digestion of mixed waste in option 1. Kerbside recycling produces the largest benefit in the waste management system, but is consistent across all options. Front-end recycling produces a smaller benefit where is it available, and is particularly important in option 1 1a and 4. The anaerobic digestion of green and food waste is a major benefit of option 2. The baseline and option 2 and 2a have high impacts from methane emissions from landfill.

Figure 9 shows the fossil fuel use from different processes within each option studied. Kerbside recycling dominates the benefits from avoiding fossil fuel use in the materials sector, while the options with landfill option 1 1a and 4 also get some credit for electricity generation from landfill gas. Option 3 shows fossil saving from incineration electricity generation.

Figure 10 shows the water use from different processes within each option studied and again kerbside recycling dominates the benefits from avoiding water use in pulp and paper product, as well as metals production.

Figure 15 shows how individual materials recycling operations and processing of organic fractions contribute to different indicators. For greenhouse, the benefit of recycling derives largely from aluminium, newsprint and glass recycling. The other major benefit is the application and use of compost.

Figure 8:Breakdown of greenhouse emissions for different options in 2013

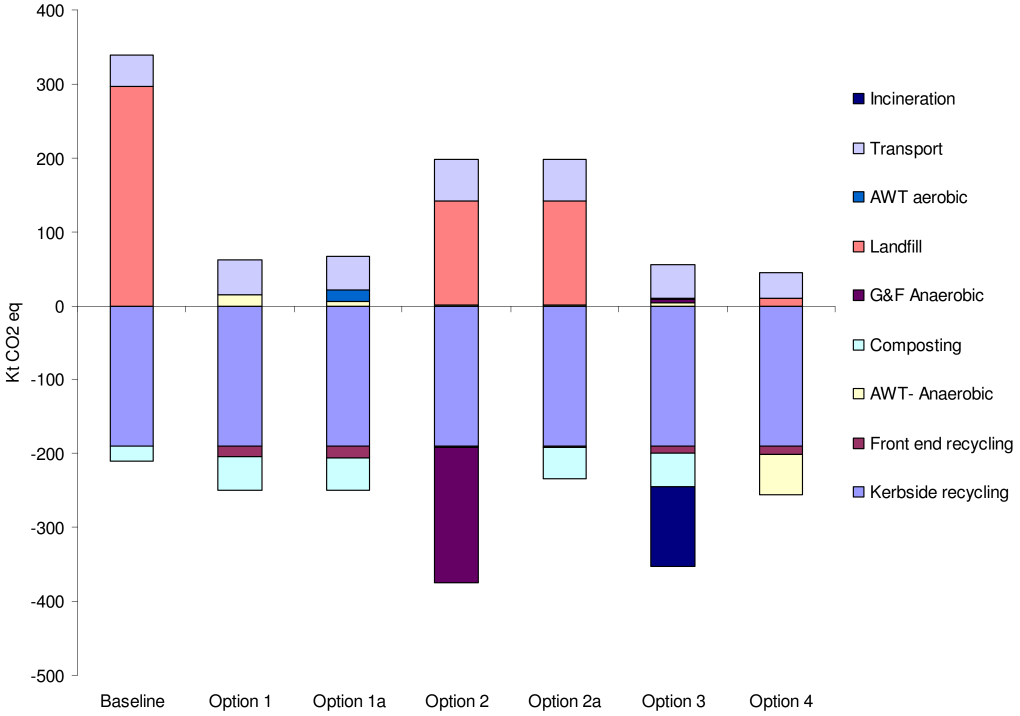


Figure 9:Breakdown of fossil energy use for different options in 2013

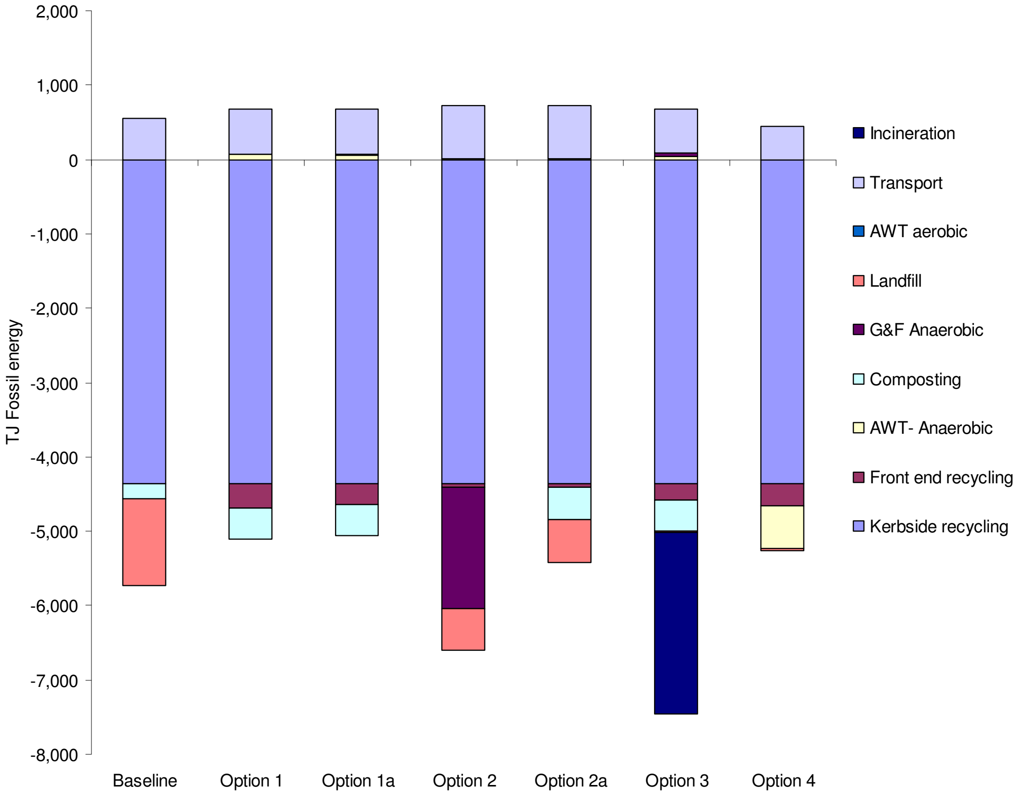


Figure 10:Breakdown of water use for different options in 2013

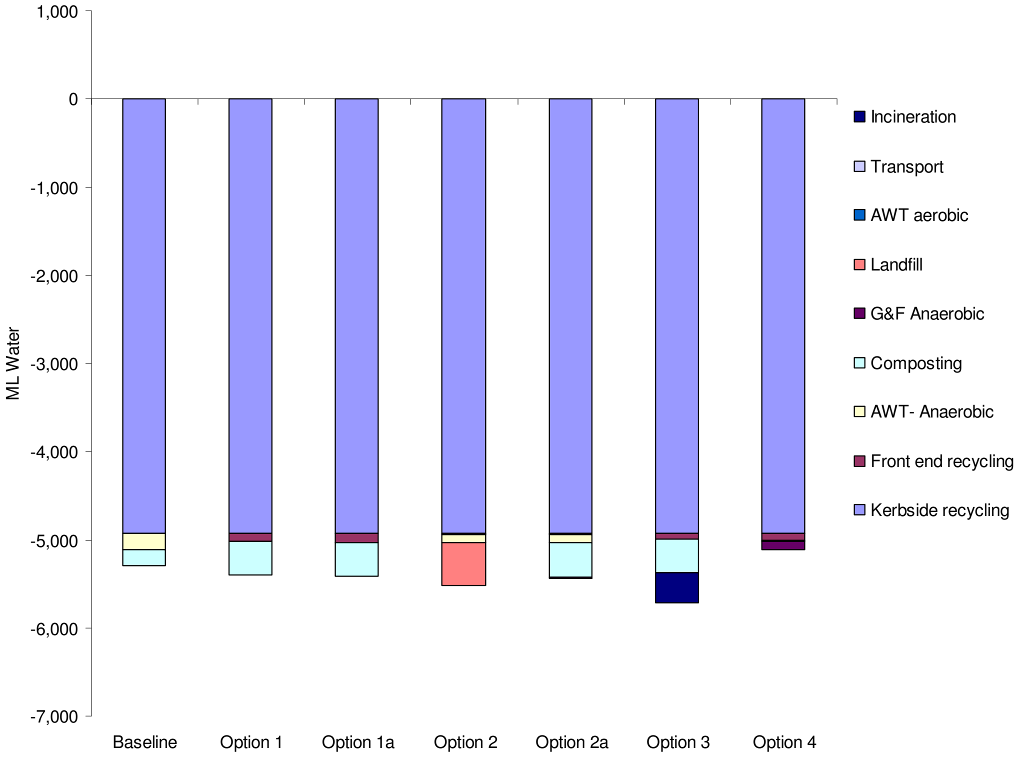


Figure 11:Breakdown of human toxicity potential for different options in 2013

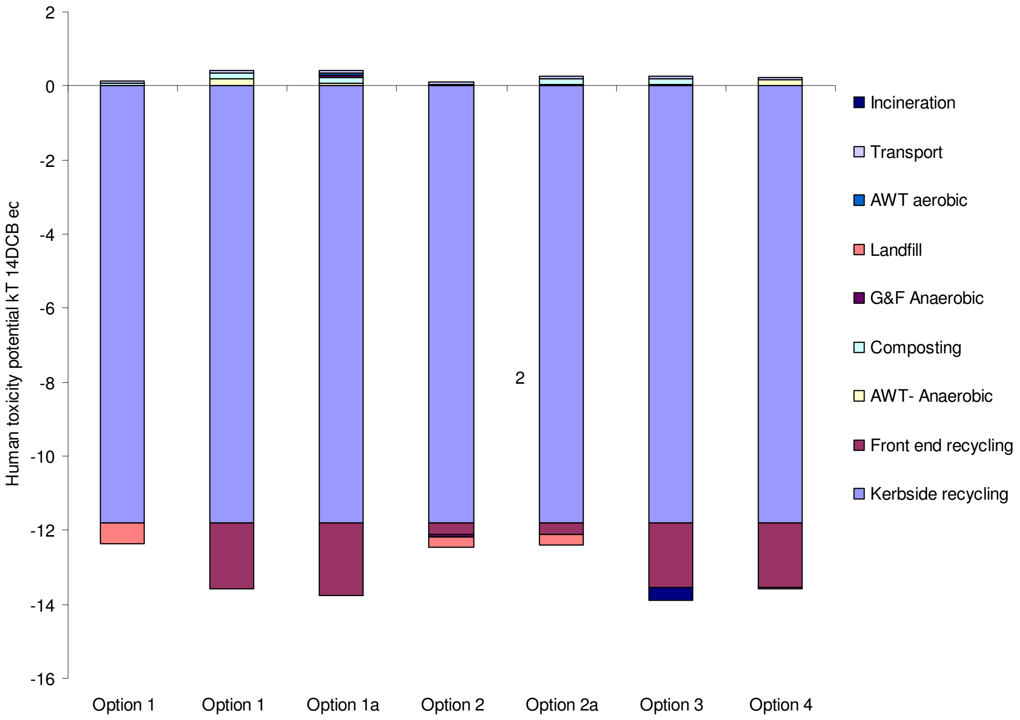


Figure 12:Breakdown of human toxicity potential for different options in 2013 without kerbside recycling saving shown.

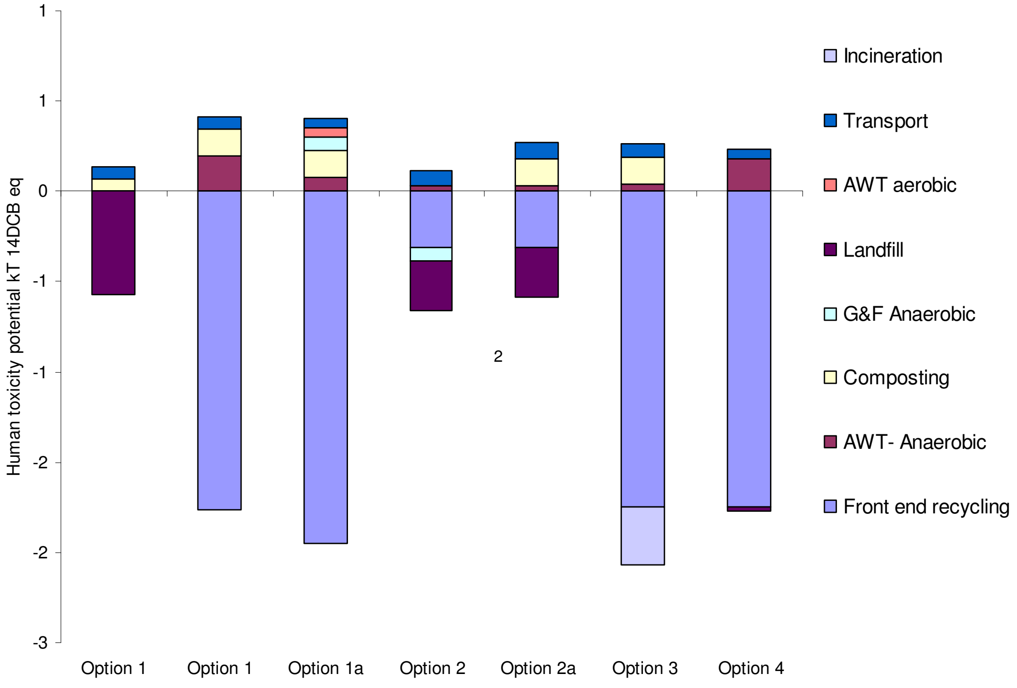


Figure 13:Breakdown of human toxicity potential for different options in 2013 without kerbside recycling saving shown.

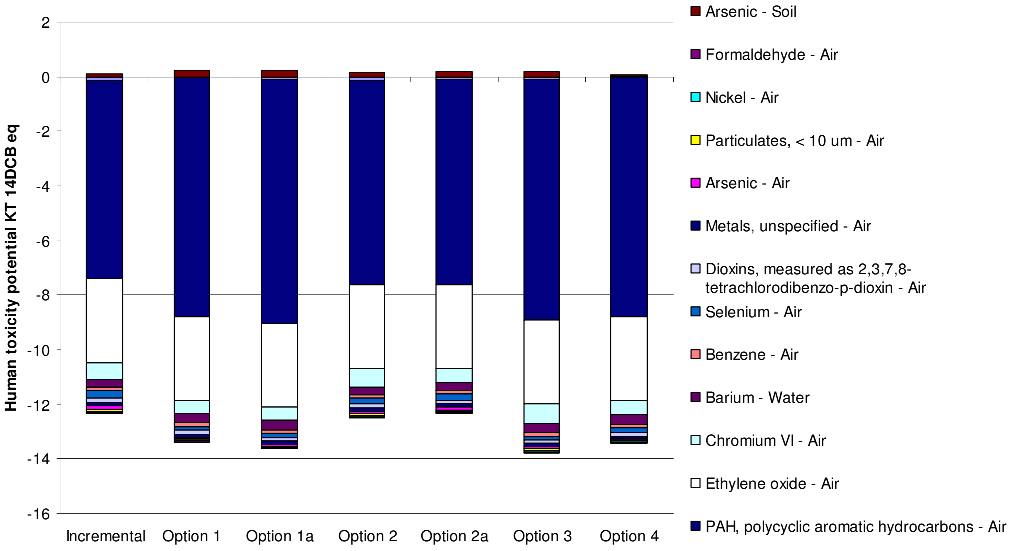


Figure 14:Breakdown of solid waste for different options in 2013

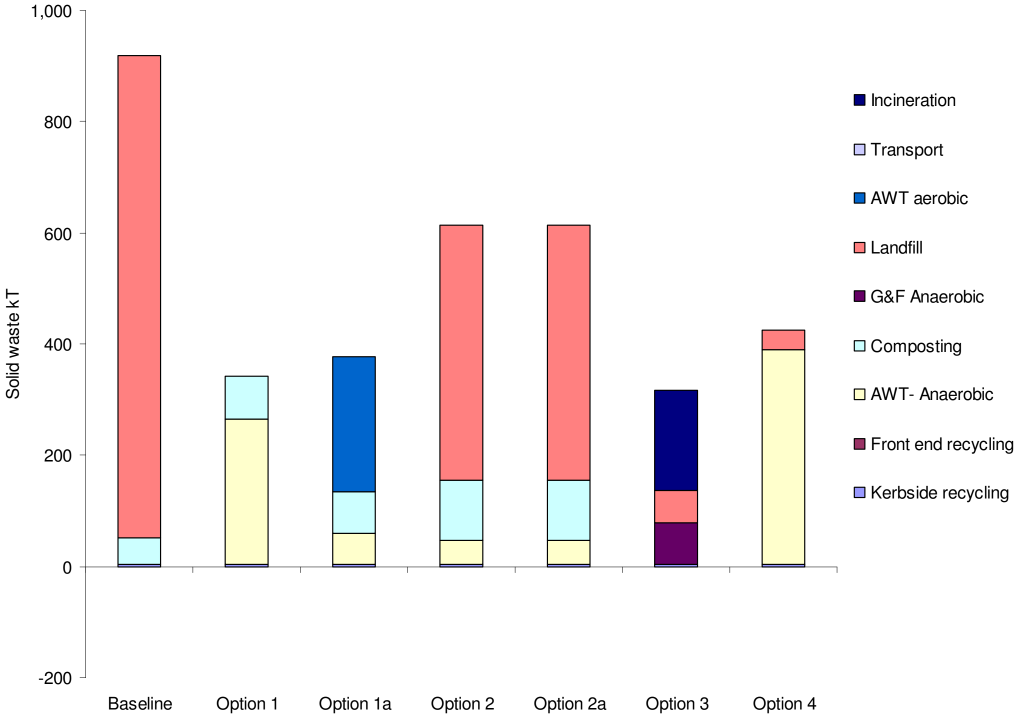
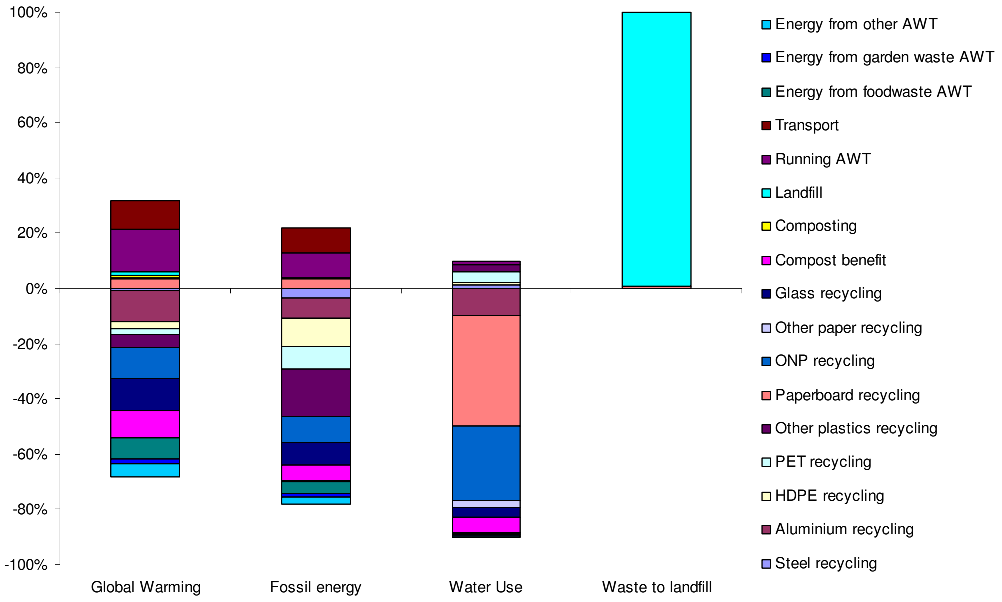


Figure 15: Detailed breakdown of indicator contribution for individual materials and waste treatment processes in option 1



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