HERU Life Cycle Assessment

Report for Manik Ventures Ltd

ED 11813 | Issue Number 2 | Date 01/03/2019

Customer:

Manik Ventures Ltd

Customer reference:

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01 March 2019

Ricardo Energy & Environment reference:

Ref: ED11813- Issue Number 2

Executive summary

The Home Energy Resources Unit (HERU) enables householders to generate hot water from everyday items that would otherwise be discarded as waste. As such, it presents a radically different approach to dealing with such materials, which are traditionally handled through extended waste collection, sorting, treatment and reprocessing supply chains.

The developers of the HERU, Manik Ventures Ltd, commissioned Ricardo Energy & Environment (Ricardo) to deliver a life cycle assessment (LCA) study comparing the HERU's environmental impacts with those from the traditional UK household waste management system.

The HERU uses pyrolysis to convert the materials into an oil phase (neutralised with detergent before being sent to sewer), a solid phase carbon-rich char, which is combusted in situ post pyrolysis, and a gas phase that is scrubbed with water before being combusted in the household boiler. The HERU is designed to operate such that non-combustible materials (notably metals and glass) emerge free from contamination and composites materials that might have previously been attached, making them suitable materials for recycling via bring banks.

Two traditional waste management systems were modelled as alternative approaches to the HERU; collecting co-mingled (COM) mixed dry recyclables for sorting at a materials recovery facility, and using a kerbside sort system (KSS) to separate them ready for onwards transport to reprocessors, in the UK and further afield. Organic materials were assumed to be composted, or anaerobically digested to produce heat and/or power. Residual waste was mostly incinerated with power recovery or simply landfilled.

Ricardo used the Waste and Resources Assessment Tool for the Environment (WRATE), originally developed for the Environment Agency, as its LCA platform for the study. The WRATE modelling system boundary starts at the point when materials are discarded, assuming they arise at no environmental cost, and follows those materials until they are recycled, composted, recovered, "lost" (such as gaseous emissions from a thermal process or water evaporation from a biological process) or disposed in landfill. Any process that creates (for example) recyclate or electricity or credited with offsetting the traditional production processes, so it is common for WRATE results to be net negative values (environmental benefits (green numbers below) rather than impacts (in red)), demonstrating the value inherent in the original waste.

The top-level results, associated with handling one year's waste capacity for the HERU (2.2t), are presented in the table below. We see that the HERU delivers the greatest carbon (GWP) benefit, offsetting about 300kg CO_2-eq. It also outperforms the collection scenarios for ARD, HTP and FAETP. In contrast, the collection scenarios fare better for AP and EP. The results for GWP, ARD and AP were found to be sensitive to the assumed grid electricity mix, with the HERU's relative performance increasing into the future, as more renewable energy comes on line. This is exemplified by the HERU result if using Norwegian (2012) grid electricity, presented in the "NO12" column below.

Impact Category	Units	HERU	COM	KSS	NO12
Global Warming Potential (GWP)	kg CO_2-eq	-285	-2	-52	-1,047
Acidification Potential (AP)	kg SO_2-eq	0.1	-0.9	-1.3	-1.13
Abiotic Resource Depletion (ARD)	kg antimony-eq	-6.9	-4.0	-4.3	-13.0
Eutrophication Potential (EP)	kg PO_4-eq	6.8	0.2	0.2	6.6
Human Toxicity Potential (HTP)	kg 1,4-DCB-eq	-1,605	-1,070	-1,127	-1,773
Freshwater Aquatic EcoToxicity Potential (FAETP)	kg 1,4-DCB-eq	-123	-83	-89	-142

The detailed WRATE results will help the HERU team to further finesse their technology during the pilot phase. In particular, it appears that nitrates in the effluent could be targeted to reduce the EP result, even though these nitrates would be removed at the wastewater treatment works. A bigger opportunity may exist if the carbon in the waste can be captured as a bio-char.

Glossary of abbreviations

Although each abbreviation is defined in full on its first use, the table below compiles all their definitions for ease of reference.

Table 1: Table of Abbreviations

Abbrev	Explanation
1,4-DCB	1,4-DiChloroBenzene
AD	Anaerobic Digestion
AP	Acidification Potential
APC(R)	Air Pollution Control (Residues)
ARD	Abiotic Resource Depletion
BEIS	UK Government Department for Business, Energy and Industrial Strategy
CH_4	Methane
CHP	Combined Heat and Power
CML	Centrum voor Milieuwetenschappen Leiden (Centre for Environmental Studies, University of Leiden, Holland)
CO_2	Carbon Dioxide
COM	Co-mingled waste collection
CV	Calorific Value
EP	Eutrophication Potential
EPE	European Person Equivalent
EU	European Union
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HDPE	High Density PolyEthylene
HERU	Home Energy Recovery Unit
HTP	Human Toxicity Potential
HWRC	Household Waste Recycling Centre
ISO	International Standards Organisation
IVC	In-Vessel Composting
KS(S)	KerbSide (Sort) waste collection
kW	kilo-Watt
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MBT	Mechanical-Biological Treatment
MDR	Mixed Dry Recyclables
MJ	Mega-Joule
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MW	Mega-Watt
MWh	Mega-Watt-hour
N, N_2	Nitrogen
NCV	Net Calorific Value
NH_3	Ammonia
NM	Nautical Miles
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
PAS	Publicly Available Standard
PO_4	Phosphate
PV	Photo-Voltaic
QA	Quality Assurance
RCV	Refuse Collection Vehicle
RDF	Refuse-Derived Fuel
Sb	Antimony ("*Stibium*")
SO_2	Sulphur Dioxide
SOx	Oxides of Sulphur
SRF	Secondary Recovered Fuel
UDP	Unitary Development Plan
UK	United Kingdom
WEEE	Waste Electrical and Electronic Equipment
WRAP	Waste and Resources Action Programme
WRATE	Waste and Resources Assessment Tool for the Environment
WTS	Waste Transfer Station

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1 Introduction

Manik Ventures Ltd commissioned Ricardo Energy & Environment (Ricardo) to deliver a life cycle assessment (LCA) study of the environmental impacts associated with the operation of its HERU technology, in comparison with the traditional methods by which UK households manage unwanted materials.

1.1 The Home Energy Resources Unit (HERU)

As its website[1] explains, *"the HERU is a world-first global solution that literally gives you the power of generating hot water for your home from everyday items you previously had little option but to discard as waste"*.

The HERU uses pyrolysis to convert the input items into:

- An oil phase, which is combined with a little detergent before being sent to sewer;
- A gas phase, consisting of varying degrees of steam and syngas (itself a mixture of mostly hydrogen and carbon monoxide), which is scrubbed with water before being fed to the household boiler for combustion; and
- A solid phase carbon-rich char, which is combusted in situ, post pyrolysis, to produce heat for household heating.

The HERU requires electricity, to drive its heater and compressor. It is designed to handle most unwanted household items, the main exception being those that are not easily pyrolysed, such as metals and glass. These should emerge from the HERU free from any contamination and composite materials that might have previously been attached, making them suitable materials for recycling via bring banks.

Figure 1: The HERU

1.2 The traditional alternative systems

The traditional alternative system for handling the above-described materials would be to consign them to the waste stream. Households in the UK are requested to separate their wastes into at least three and frequently many more material streams, and to present them at their kerbside in a stipulated combination of bins, boxes and sacks. The local authority (or its contractors) run multiple house-to-house services to collect the different materials. Typically, they are taken to a transfer station, where limited levels of sorting and processing take place, before the materials are transported on to treatment facilities. Dry recyclates are separated into their material streams, baled together and subsequently shipped to reprocessors, in the UK or further afield. Organic materials are composted, or anaerobically digested to produce heat and/or power. Residual waste is mostly incinerated with power recovery or simply landfilled.

1.3 This study

In this study, Ricardo performed an LCA comparing the HERU with the traditional waste collection services, to reveal their relative environmental impacts. The next section provides a brief introduction to LCA before explaining the decisions underlying the goal and scope that were agreed. Further

[1] www.myheru.com [accessed 27Jun2018 @ 16:21]

details are then provided about the scenarios that were developed to model the alternatives, also revealing the key assumptions underpinning the modelling. Section 2.3 presents the results and analyses what is driving the differences seen.

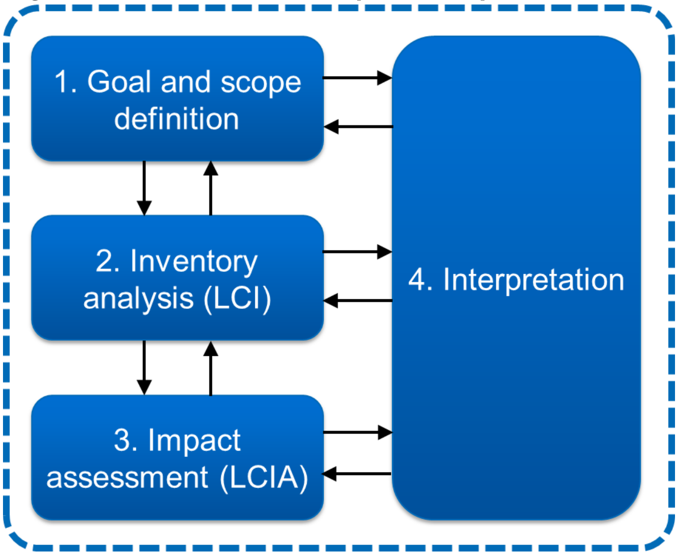
2 Life cycle assessment

Life cycle assessment (LCA) is an established method for assessing the environmental (and sometimes social) impacts of a product, service, business, policy or process. Covering multiple environmental indicators and looking from cradle to grave, a full LCA helps avoid adopting initially attractive changes that simply shift burdens to other life cycle stages or to other impact categories.

The LCA method has been standardised by the International Standards Organisation (ISO 14040 series), which sets out that LCA is a four-stage process. As depicted by the arrows in Figure 2, this process is expected to be an iterative one, in which results from one stage feed into the next and iterations are performed to arrive at sound final conclusions.

This LCA study followed the four-stage ISO approach, as outlined below.

Figure 2: The LCA Process (ISO14040)



2.1 Step 1: Goal and scope definition

The goal of the study was agreed to be as follows:

"To determine the life cycle impacts of handling unwanted household materials using the HERU technology, compared with using the traditional UK waste management system."

There are five principal considerations to agree under the scope. In this instance, the first to consider was the LCA platform to be used for the modelling.

2.1.1 LCA platform

In this study, the focus is on alternative methods of handled unwanted household materials. For over ten years, since its release by the England and Wales Environment Agency, the Waste and Resources Assessment Tool for the Environment (WRATE) has been the software of choice for UK waste managers. WRATE is a specialist LCA tool for the management of household waste. Although no longer owned by the Environment Agency (it is maintained by one of the original developers, Golder Associates), WRATE continues to enjoy a good level of acceptance amongst most waste professionals. More details about WRATE are provided in Appendix B.

2.1.2 Impact categories

The second scope consideration concerns which environmental impacts are of interest. WRATE features six key indicators, including global warming potential (GWP), that provide a broad coverage of environmental concerns and allow for an objective assessment of the various benefits and dis-benefits of technologies modelled.

2.1.3 System boundary

The third consideration is the system boundary, defining what will be included in and excluded from the scope of study. Once again, this is clearly defined by the use of the WRATE software. The model starts at the point when materials are discarded into a waste management system, and follows those materials until they are recycled, composted, recovered, "lost" (such as gaseous emissions from a thermal process or water evaporation from a biological process) or disposed in landfill. Waste arrives for "free" (with no environmental burden for its original generation), and is then credited the environmental burdens of any electricity, heat or recyclates that the waste's handling offsets. For this reason, many WRATE analyses produce negative results, as the scenarios yield a net environmental improvement, because of the value embedded in the original waste. This is not an issue, however, as all scenarios are evaluated on the same basis, so the investigation can still assess which options are better for each environmental criterion.

2.1.4 Functional unit

The fourth consideration is the definition of the declared or functional unit – the unit of study for the project. We chose the annual throughput of one HERU, taking 6kg per day, every day of the year, amounting to 2.2t.[2]

2.1.5 Data quality

The fifth and final consideration concerns what data will be used – primary or secondary. "Primary" data come from the actual operations under investigation, whereas "secondary" (or proxy) data come from literature and databases. We used as much primary data as possible on the HERU, using secondary data from the literature and from WRATE to supplement it where required, and for the alternative system.

2.2 Step 2: Inventory analysis

When using WRATE, the inventory analysis effectively becomes the design of the scenarios. These are described in turn below.

It is well known that there is significant variation across the country between the waste collection schemes offered by different local authorities. It is clearly not possible to model all the alternatives here, so it was decided to examine the systems that the Waste and Resources Action Programme (WRAP) is promoting. In its "framework for greater consistency in household recycling in England"[3], WRAP recommends that councils adopt one of three collection services:

- Multi-stream with separate food (kerbside-sort)
- Two-stream (fibres separate) with separate food
- Co-mingled with separate food

It was beyond the scope of this study to investigate the different diversion and contamination rates that might arise from these different collection regimes. Under this simplification, the difference between the two-stream and co-mingled collections becomes marginal, therefore it is appropriate to model the kerbside-sort and co-mingled alternatives only. More details of these regimes are provided in the dedicated sections below.

2.2.1 The waste arisings

The first thing to determine in the modelling is the composition of household waste to be used. WRATE has a default waste composition which was deemed a suitable data set for the modelling. In detail, the composition is defined across 80 waste fractions, but is usually summarised into the

[2] For context, this is roughly double the average UK household arisings. Factoring this into the assessment would have the effect of doubling the capital burdens of the HERU, which are found to be inconsequential, so this is not a significant factor.

[3] See www.wrap.org.uk/collections-and-reprocessing/consistency [accessed 13Sep2018]

fractions reported in Table 2. It can be seen that, from the composition and the internal data on the waste fractions in WRATE, we can also infer some important characteristics of the waste, as follows:

- Moisture content: 32.1%
- Net calorific value (NCV): 8.46MJ/kg
- Fossil:biogenic carbon ratio: 30:70

Table 2: The default WRATE waste composition

Waste Fraction	Share	Moisture	Net CV	%C (Bio)	%C (Fos)	%N	%S
Paper and card	24.0%	24.5%	10.8	31.6%	0.0%	0.3%	0.1%
Plastic film	3.8%	27.9%	21.3	0.0%	48.1%	0.5%	0.2%
Dense plastic	6.2%	10.5%	23.0	0.0%	52.2%	0.5%	0.1%
Textiles	2.8%	19.1%	14.3	19.7%	20.1%	2.6%	0.2%
Absorbent hygiene products	2.3%	62.9%	5.5	14.8%	3.7%	0.3%	0.0%
Wood	3.6%	9.6%	16.8	43.8%	0.0%	1.0%	0.1%
Combustibles	6.1%	15.6%	14.9	24.0%	16.0%	1.8%	0.2%
Non-combustibles	2.7%	5.6%	2.6	2.1%	4.9%	0.2%	0.5%
Glass	7.9%	1.8%	1.4	0.3%	0.0%	0.1%	0.0%
Organic – Garden	14.2%	60.9%	3.8	14.9%	0.0%	0.9%	0.1%
Organic – Food	17.4%	60.9%	3.8	14.9%	0.0%	0.9%	0.1%
Ferrous metal	3.1%	13.2%	0.0	0.0%	0.0%	0.0%	0.0%
Non-ferrous metal	1.3%	13.3%	0.0	0.0%	0.0%	0.0%	0.0%
Fine material <10mm	2.0%	41.0%	3.5	13.7%	0.0%	1.0%	0.2%
Waste electronics	2.2%	10.1%	7.1	0.0%	15.8%	0.3%	0.1%
Hazardous materials	0.5%	10.4%	0.0	0.0%	0.0%	0.0%	0.0%
Total	**100.0%**	**32.1%**	**8.46**	**16.6%**	**7.2%**	**0.7%**	**0.1%**

2.2.2 The HERU scenario

In the HERU scenario, all of the household waste is put into the HERU, and it is run overnight, producing hot water ready for the morning. The WRATE model handles the gas and liquid emissions from the HERU, leaving just the unburnt metals and glass.

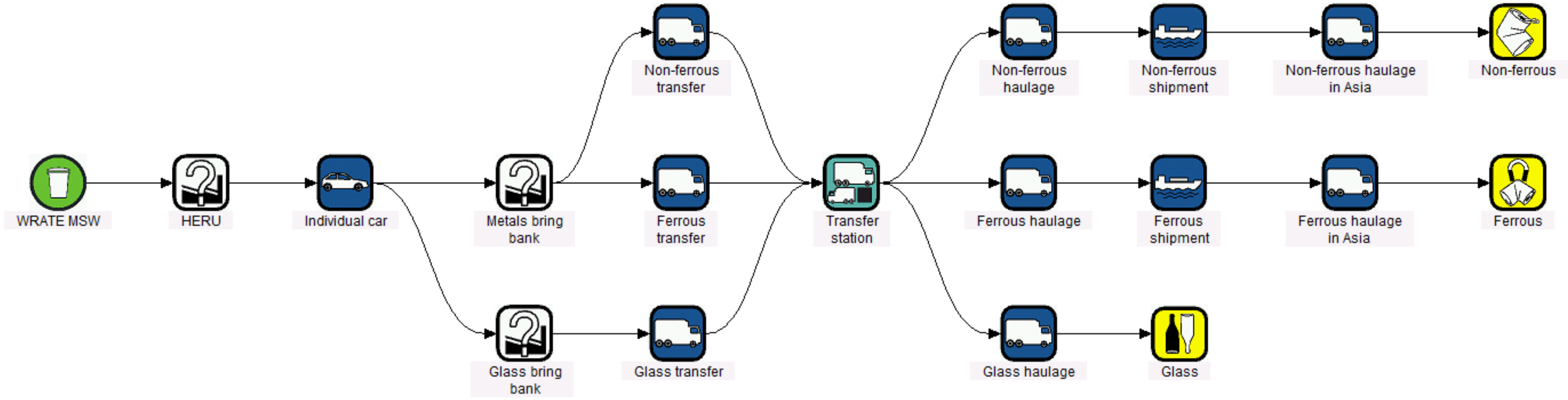
With no household waste collection service (and noting that legislation would need to be changed to permit authorities to stop providing such services), it is assumed that householders would have to take their waste metals and glass to local bring banks or alternatively household waste recycling centres. For modelling purposes, we have assumed bring sites as this is likely to be the larger environmental impact. From the bring sites, the materials would be hauled to a transfer station and thence to a UK glass recycling facility or Asian metals recycling facilities. The full HERU scenario is depicted in Figure 3.

2.2.2.1 The HERU UDP

At the heart of the HERU scenario is the user-defined process (UDP) that Ricardo developed to model the performance of the HERU itself. The HERU team's research is being supported by Brunel University, whose staff provided Ricardo with a detailed bill of materials and measured performance data on the HERU.

Ricardo carefully scrutinised the data, in particular adjusting some of the figures (using energy, carbon, sulphur and nitrogen balances) to estimate how the HERU would perform if fed the WRATE waste composition. The tables that comprise the final UDP are reproduced in Appendix A.

Figure 3: The HERU scenario in WRATE



2.2.2.2 The bring banks

In Figure 3, the bring bank icons (with their question marks) indicate that UDPs were also created to model these components. WRATE was originally designed for local authority waste managers looking to design their entire waste services, so it did not foresee the need to allow for fractions of a bring bank. However, in this scenario, the HERU processes 2.2t of waste across the whole year (and less than 200kg of glass and metal) whereas a large bring bank has a capacity of 2.5t.

If we assume that the bring banks are emptied on a weekly basis, we can deduce how many households can be supported by one metals bank and one glass bank. The default bring bank processes were accordingly downscaled by these numbers to model the amount of bank required for one household.

2.2.2.3 The transport distances

It would be possible to go into great detail modelling transport distances for the three scenarios. However, transport is not an especially significant contributor to the overall results, so it is sufficient to make a few simplifying assumptions on the transport calculations, including that vehicles will spend equal amounts of time on motorways, rural and urban roads.

As with the bring banks, a single vehicle could typically transport significantly more than one household’s materials on a given journey, so it was necessary to determine total annual distances, taking into account an assumed A-B distance and a payload capacity for each vehicle.

The entire fleet of transport vehicles required for the three scenarios, their payloads for each scenario and the resultant freight distance per year, are reported in Table 4. The A-B distance assumptions are cited in Table 3 below.

Table 3: Freight distance assumptions

Journey	Value	Unit	Source
Average UK journey distance to bring-bank (local supermarket)	1	km	Ricardo assumption (typical distance of 5km, but with 1 in 5 trips assumed to be specifically for taking the wastes)
Average RCV A-B journey distance	23	km	Ricardo assumption
Average distance for UK freight journey	94	km	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Average_distance_on_which_goods_are_carried_for_total_transport,_2012-2016.png
Average distance for Polish freight journey	221	km	
Sea-freight distance from the UK (Southampton) to Asia (Guangzhou)	9611	NM	https://sea-distances.org/
Sea-freight distance from the UK (Southampton) to Poland (Gdansk)	1069	NM	
Average distance for Asian freight journey	500	km	Ricardo assumption

Table 4: Summary of road transport modelling distances

Transport leg	Vehicle	A-B km/trip	Capacity / t	1. HERU			2. Co-mingled			3. Kerbside-Sort		
				Actual	#Trips	km/yr	Actual	#Trips	km/yr	Actual	#Trips	km/yr
Individual car	Car - diesel and petrol fleet	1	0.04	0.27	6.19	12.37						
Res/Food split-back RCV	ULS Diesel RCV	23	12.84				1.22	0.10	4.37			
Residual waste RCV	ULS Diesel RCV	23	12.84							1.20	0.09	4.30
MDR/food split-back RCV	ULS Diesel RCV	23	12.84				0.60	0.05	2.15			
Kerbside Sort RCV	Multi-compartment KS RCV	23	5.50							0.61	0.11	5.10
Garden waste RCV	ULS Diesel RCV	23	12.84				0.15	0.01	0.54	0.15	0.01	0.54
Mixed Organic RCV	ULS Diesel RCV	23	12.84				0.21	0.02	0.75	0.21	0.02	0.75
Non-ferrous transfer	Medium goods vehicle	23	2.40	0.03	0.01	0.58						
Ferrous transfer	Medium goods vehicle	23	2.40	0.07	0.03	1.34						
Glass transfer	Medium goods vehicle	23	2.40	0.17	0.07	3.26						
Bulk residual vehicle	Intermodal road transport	94	17.56				1.20	0.07	12.85	1.20	0.07	12.85
Bulk food vehicle	Intermodal road transport	94	17.56				0.03	0.00	0.32	0.03	0.00	0.32
Bulk MDR vehicle	Intermodal road transport	94	17.56				0.58	0.03	6.21			
Non-ferrous haulage	Intermodal road transport	94	17.56	0.03	0.00	0.32	0.01	0.00	0.11	0.01	0.00	0.11
Ferrous haulage	Intermodal road transport	94	17.56	0.07	0.00	0.75	0.02	0.00	0.21	0.02	0.00	0.21
Glass haulage	Intermodal road transport	94	17.56	0.17	0.01	1.82	0.14	0.01	1.50	0.16	0.01	1.71
Paper & card haulage	Intermodal road transport	94	17.56				0.27	0.02	2.89			
Paper haulage	Intermodal road transport	94	17.56							0.23	0.01	2.46
Card haulage	Intermodal road transport	94	17.56							0.09	0.01	0.96
Plastics haulage	Intermodal road transport	94	17.56				0.06	0.00	0.64	0.06	0.00	0.64
MRF rejects haulage	Intermodal road transport	94	17.56				0.09	0.01	0.96			
WTS rejects haulage	Intermodal road transport	94	17.56							0.02	0.00	0.21
Non-ferrous haulage in Asia	Intermodal road transport	500	17.56	0.03	0.00	1.71	0.01	0.00	0.57	0.01	0.00	0.57
Ferrous haulage in Asia	Intermodal road transport	500	17.56	0.07	0.00	3.99	0.02	0.00	1.14	0.02	0.00	1.14
Plastics haulage in Asia	Intermodal road transport	500	17.56				0.06	0.00	3.42	0.06	0.00	3.42
Paper & card haulage in Poland	Intermodal road transport	221	17.56				0.27	0.02	6.80			

Key: Actual = actual weight freighted, in tonnes
#Trips = [Actual] divided by [Capacity]
km/yr = 2 x [A-B km/trip] x [#Trips]

2.2.3 The co-mingled collection scenario

The WRATE scenario for a kerbside co-mingled collection is presented in Figure 4.

In the co-mingled collection scenario, the householder is provided with four bins for their waste. The first challenge is to model what fraction of each of the waste components in Table 2 is put in which bin by the householder. Using statistics from Defra and WRAP, Ricardo determined the waste diversion regime described in Table 5.

Table 5: Household waste diversion regime

Waste Fraction	MDR	Food to AD	Food to IVC	Organic Garden to IVC	Garden to Win	Residual	Arisings
Paper and card	14.7%					9.3%	24.0%
Plastic film	0.3%					3.5%	3.8%
Dense plastic	2.7%					3.5%	6.2%
Textiles						2.8%	2.8%
Abs. hygiene products						2.3%	2.3%
Wood						3.6%	3.6%
Combustibles						6.1%	6.1%
Non-combustibles						2.7%	2.7%
Glass	7.4%					0.5%	7.9%
Organic - Garden				7.2%	7.0%	0.0%	14.2%
Organic - Food		1.6%	2.6%			13.2%	17.4%
Ferrous metal	1.0%					2.1%	3.1%
Non-ferrous metal	0.5%					0.8%	1.3%
Fine material <10mm						2.0%	2.0%
WEEE						2.2%	2.2%
Hazardous materials						0.5%	0.5%
Total	**26.6%**	**1.6%**	**2.6%**	**7.2%**	**7.0%**	**55.1%**	**100.0%**

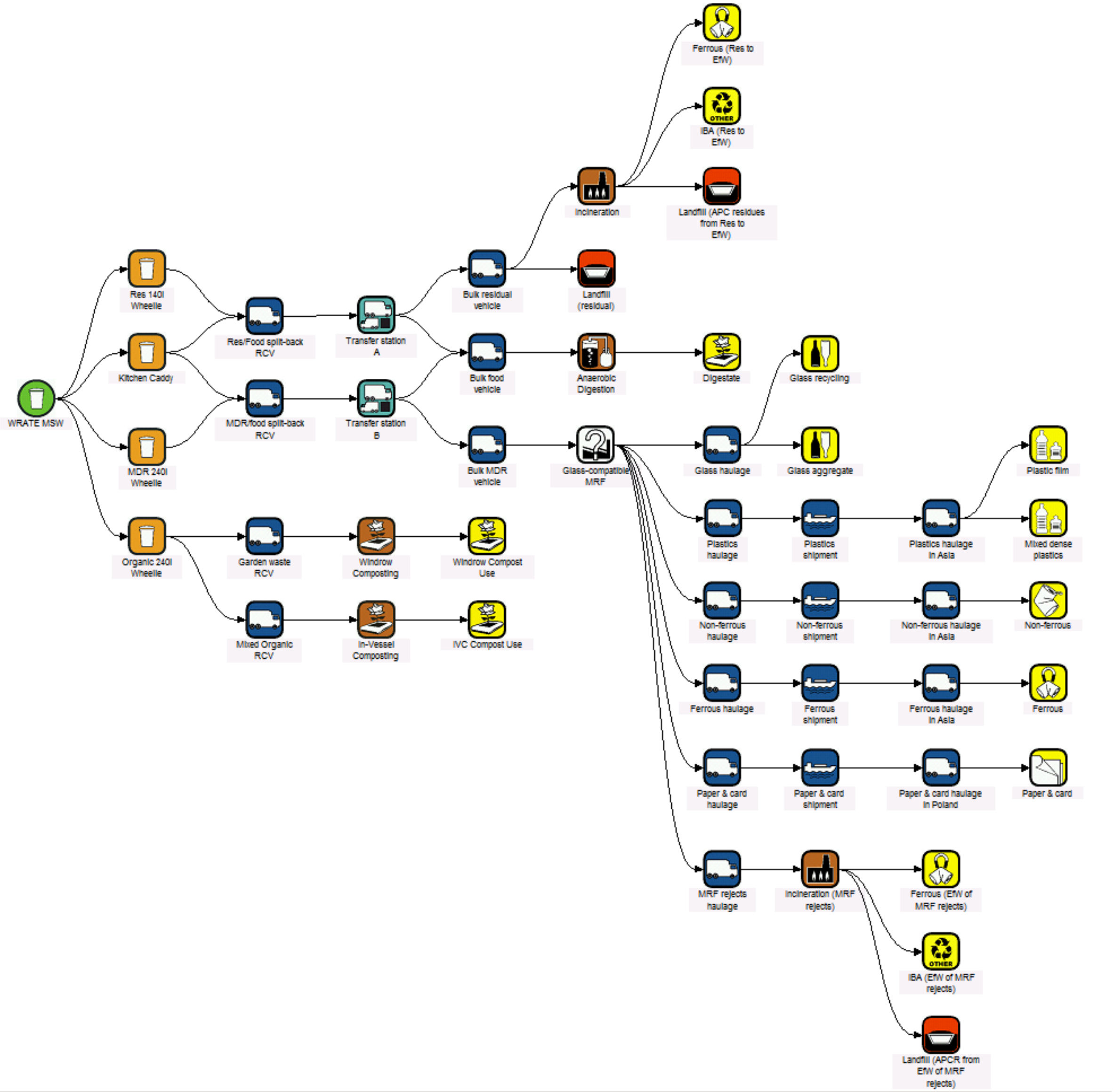
There is clearly some complexity around the organic waste stream, with some councils collecting source-segregated food waste (all of which is assumed to go to anaerobic digestion, AD), some collecting only garden waste (assumed to go to windrow, Win) and other collecting mixed food and garden waste (assumed to go to in-vessel composting, IVC). The figures above probably underestimate the amount of garden waste going to windrow and correspondingly overestimate the mixed organic waste going to IVC, but the differences between these two fates are relatively small so any error is inconsequential to the modelling results.

Ricardo's co-mingled scenario assumes an alternate-weekly system, in which food and residual waste is collected in the first week, in an RCV with a waste pod, and then food and mixed recyclables the following week, in the same vehicle. A separate, standard RCV is used to collect the organics. The organic waste is taken directly to an IVC or windrow facility, where the waste is turned into compost.

The rest of the waste is taken initially to a transfer station. From there, the source-segregated food waste is taken to AD, with the resulting digestate spread to land. The residual waste is split, with 71% going to energy from waste and the balance directly to landfill[4]. The scenario uses WRATE's model of the Chineham incinerator, which recovers ferrous metal for recycling and sends the bottom ash (with non-ferrous metal content) to recycling, which the APC residues go to hazardous landfill.

[4] Mechanical-biological treatment plants in the UK only accept a small amount of residual household waste, so are disregarded in this analysis. 71% is derived from the split of fates of UK waste reported by Defra.

Figure 4: The co-mingled collection scenario in WRATE



The mixed dry recyclables are taken from the transfer station to a glass-compatible materials recovery facility (MRF), with the recyclates being sent on to reprocessors in the UK (with 50% of the glass being sent to aggregate and 50% to glass recycling), Poland (mixed paper and card) or Asia (plastics and metals). The model assumes that 15% of incoming recyclates are lost as rejects and sent to incineration.

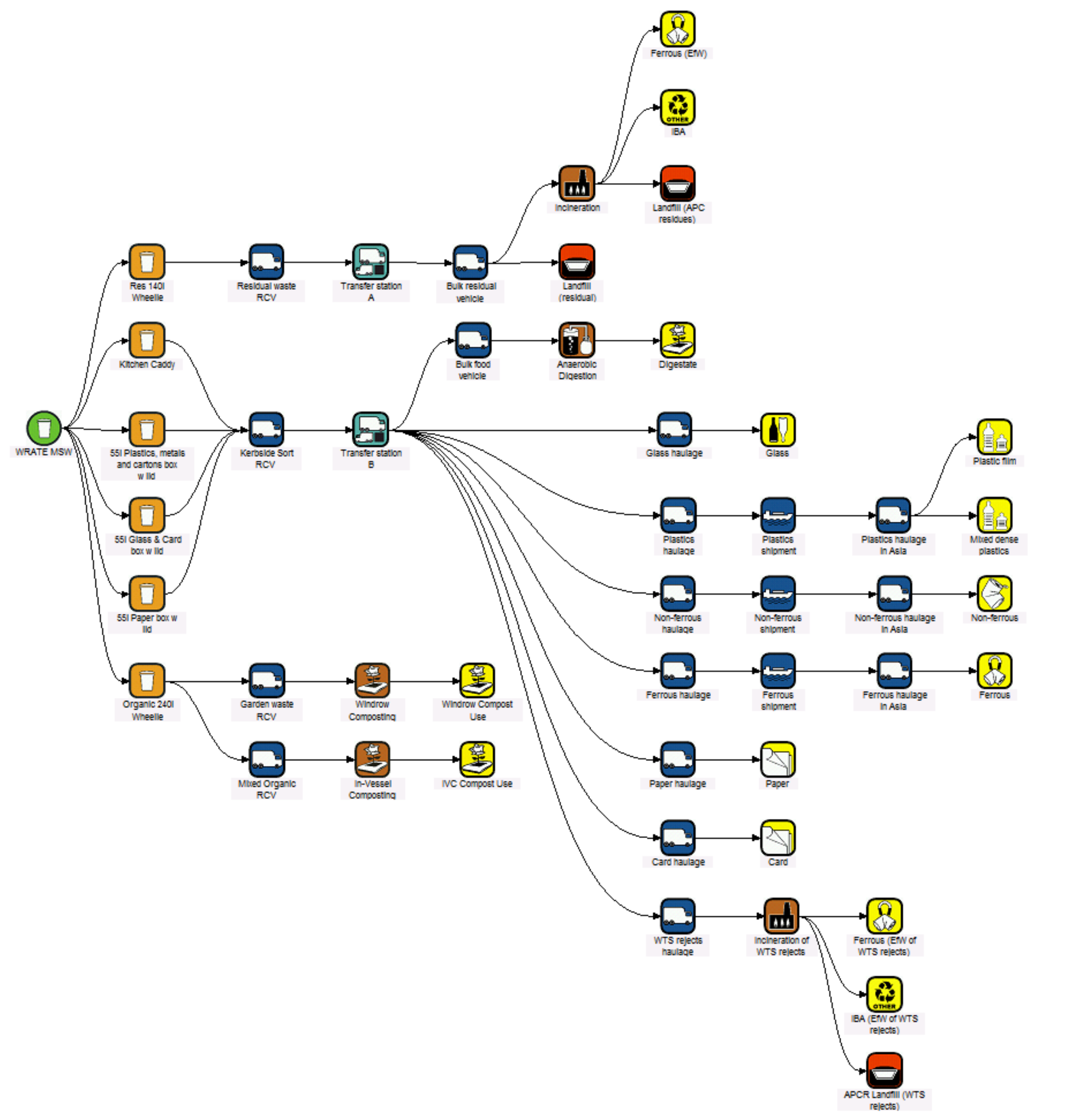
2.2.4 The kerbside-sort collection scenario

The WRATE scenario for a kerbside-sort collection is presented in Figure 5.

It was beyond the scope of this study to model the possible differences in diversion rates between co-mingled and kerbside-sort collection schemes, so the diversion figures used are the same as for the co-mingled scenario, outlined in Table 5, above. As can be seen from the figure, organics are handled as in the co-mingled scenario, as is the residual waste, except that it is now collected in a dedicated RCV.

In the kerbside-sort regime, householders are offered three bins for their recyclates, and asked to separate paper, glass/card and plastics/metals/cartons. At the kerbside, during collection, the RCV operatives further sort the materials as they add them into separate compartments in their RCV, together with the food waste. At the transfer station, the streams are kept separate so that they can be directly passed on to reprocessors without the need for the MRF. There is a small assumed reject fraction (3%) that is sent to incineration. All onward fates are the same as for the co-mingled collection, except that the higher quality of the source-separated paper and card means they can be sent to reprocessors in the UK, and 100% of glass is assumed to be recycled to glass (rather than having 50% turned into aggregate).

Figure 5: The kerbside-sort collection scenario in WRATE



2.3 Steps 3&4: Impact assessment (results) and interpretation

With the scenarios designed in WRATE, the modelling is done. WRATE automatically applies its database of emission factors to the life cycle inventory compiled from the scenarios, and presents the results in a user interface where the data can be analysed numerous different ways.

The top-level results are presented in Table 6. The figures present the estimated environmental impacts associated with handling one year's worth of unwanted materials from one (large) household, using the HERU, or a traditional co-mingled collection, or a traditional kerbside-sort collection. As the figures represent *impacts*, negative numbers are good (net benefits) while positive figures are net impacts.

Table 6: Top-level results from WRATE impact assessment

Impact Category	Code	Units	HERU	Co-mingled	KS-sort
Global Warming Potential	GWP	kg CO_2-eq	-285	-2	-52
Acidification Potential	AP	kg SO_2-eq	0.1	-0.9	-1.3
Abiotic Resource Depletion	ARD	kg Sb-eq	-6.9	-4.0	-4.3
Eutrophication Potential	EP	kg PO_4-eq	6.8	0.2	0.2
Human Toxicity Potential	HTP	kg 1,4-DCB-eq	-1,605	-1,070	-1,127
Freshwater Aquatic EcoToxicity Potential	FAETP	kg 1,4-DCB-eq	-123	-83	-89

2.3.1 Global warming potential analysis

Global warming potential (GWP, also known as the carbon footprint) is widely used as a proxy for the overall environmental impact. Although these results show the unreliability of this approach, it is nevertheless frequently considered to be the most important of the environmental indicators. Against GWP, the HERU is the most preferred scenario.

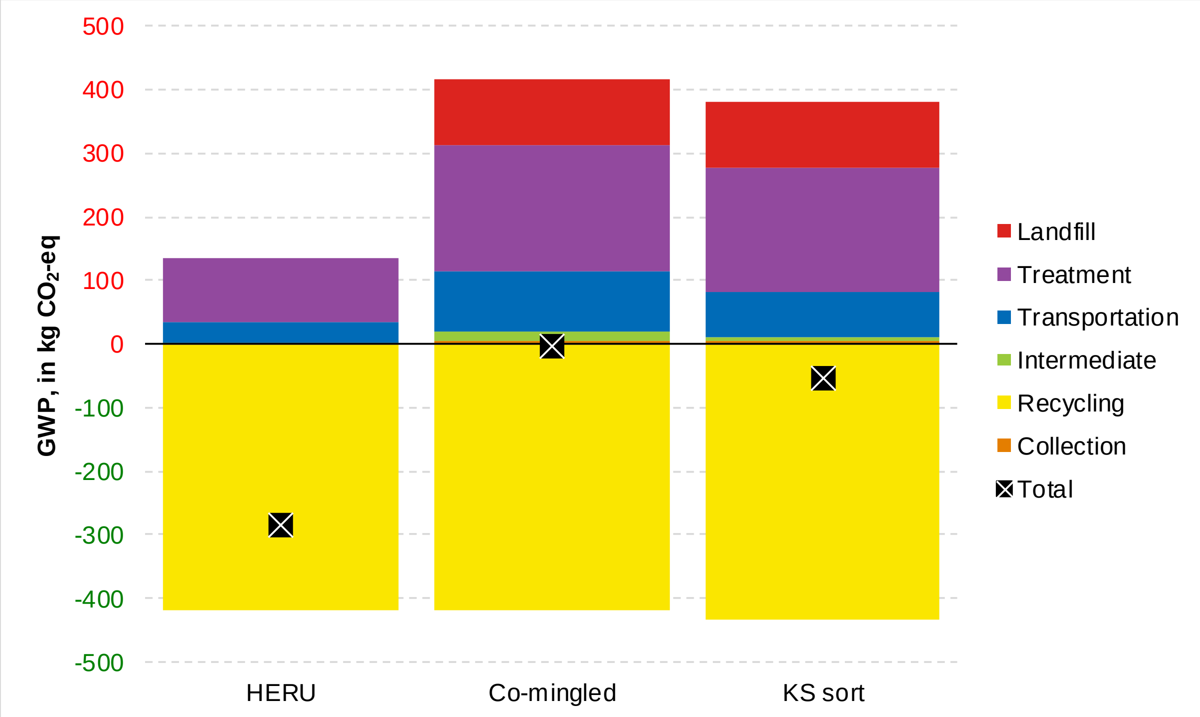
Focussing on GWP, we can disaggregate the top-level results above to explore how the different stages of the life cycle contribute to those overall results. A first level of disaggregation is depicted in Table 7 and Figure 6. In the latter, the totals are overlaid as points (white crosses on black squares) on the stacked columns, to account for the fact that there are negative and positive values both contributing to the totals.

We can see that, in all three scenarios, the net GWP saving arises solely because of the recycling activities that take place. Recycling materials displaces their conventional manufacturing methods, thereby avoiding the processes that would otherwise emit greenhouse gases. These savings are diminished by the impacts from the other life cycle stages – the carbon embedded in the bins used for collection, the operations at the intermediate transfer stations and material recovery facilities (MRFs), the transportation of the materials, and the impacts from the treatment processes and from landfill.

Table 7: Breakdown of GWP results by scenario

Life cycle stage	HERU	Co-mingled	KS-sort
Collection	0.4	5.4	4.2
Recycling	-420.4	-419.6	-433.8
Intermediate	0.8	14.2	5.5
Transportation	32.0	94.0	73.4
Treatment	103.0	199.5	194.1
Landfill	0.0	104.1	104.1
Total	**-285**	**-2**	**-52**

Figure 6: GWP results (in kg CO_2-eq) by life-cycle stage



2.3.2 The normalised results

One of the challenges with LCA is that it is difficult to compare the results across the different indicators. In Table 6 above we see that the HERU performed better for human toxicity, by a margin of ~535kg 1,4-DCB-eq, than the co-mingled scenario, but worse for EP, by ~6.6kg PO_4-eq. Which result is more significant?

LCA practitioners use “normalisation” to assist in making these comparisons. In WRATE, results can be normalised against “European person equivalents”, EPEs. Calculations were performed by the software authors to estimate the total contribution that Europe makes to the six environmental indicators, and these impacts were each divided by the population of Europe, yielding the factors in Table 8.

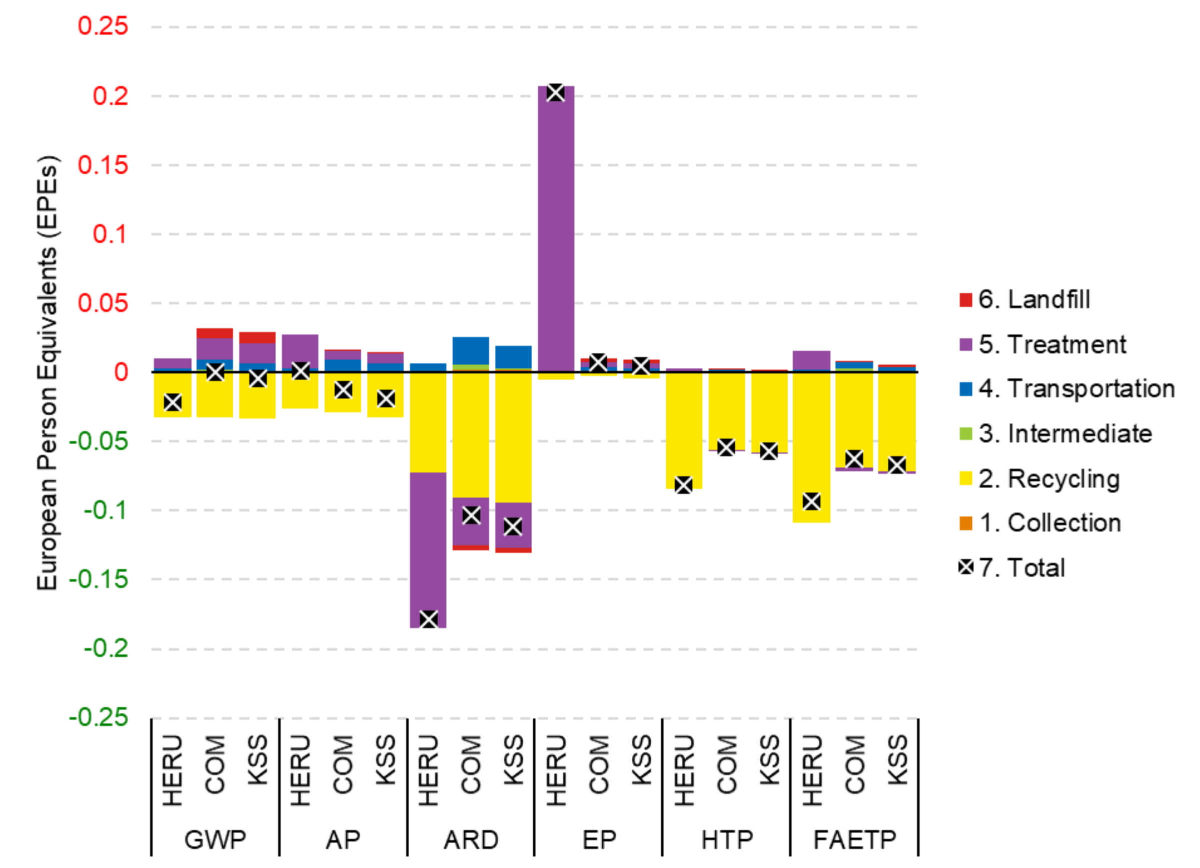
Table 8: Normalisation factors for European person equivalents (EPEs)

Impact Category	EPE	Units
Global Warming Potential	12,938	kg CO_2-eq / EPE
Acidification Potential	71.6	kg SO_2-eq / EPE
Abiotic Resource Depletion	38.8	kg Sb-eq / EPE
Eutrophication Potential	33.4	kg PO_4-eq / EPE
Human Toxicity Potential	19,699	kg 1,4-DCB-eq / EPE
Freshwater Aquatic EcoToxicity Potential	1,322	kg 1,4-DCB-eq / EPE

The factors indicate, for example, that the eutrophication potential (EP) attributable to one European person is 33.4kg PO_4-eq. This leads to the conclusion that the difference calculated above of 6.6kg PO_4-eq is equivalent to impacts of about 0.2 European people. By the same method, the difference in human toxicity potential (HTP) equates to [535/19,699=] 0.027 EPE. Before concluding that the EP impact is nearly ten times more important than the HTP, however, it is critical to note that this normalisation implicitly assumes that the population of Europe has an equal impact on all of these indicators – and this is very unlikely.

Accepting this caveat, the EPE normalisation technique does enable the presentation of all of the environmental indicators on one graph, as presented in Figure 7.

Figure 7: Normalised results (see Table 8 for key to abbreviations)

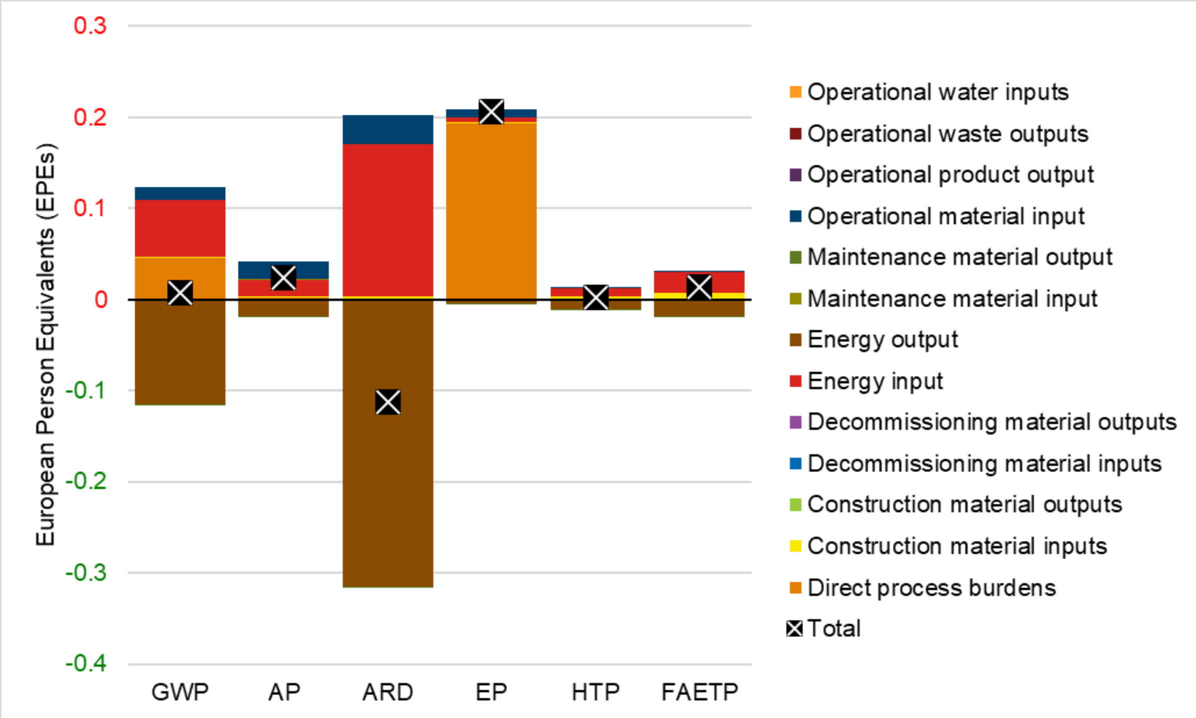


Presented this way, the single most striking impact is the EP impact from treatment within the HERU scenario. Also perhaps unintuitive is that, for recycling impacts (the yellow bars above), the HERU is outperforming the collection scenarios for three of the six indicators. These results are explored below.

2.3.3 Large HERU treatment impacts

Digging down another level into WRATE, it is possible to draw out the results within an individual category or even process down to the level of the different life cycle stages within the model. For the case of the HERU, this amounts to dissecting the UDP described in Section 2.2.2.1 to see how each of the different sections contributes to its overall environmental impact. Once again using EPE so that findings can be presented for all six indicators, the results are presented in Figure 8.

Figure 8: Process Impacts within the HERU UDP (in EPEs)



The graph shows that the EP impact is dominated by 'direct process burdens'. One further step down within WRATE reveals that the direct process burdens are specifically emissions of nitrates to sewer. This is because our theoretical nitrogen mass-balance calculations determined that most of the input nitrogen in the waste material will emerge as nitrate in the effluent.

It should be noted that the criterion is called "eutrophication *potential*", and is as such an indicator of the *potential* to cause eutrophication, rather than any suggestion that such eutrophication would certainly occur. In reality, these nitrates would be removed at the wastewater treatment works, using technologies such as ion exchange or reverse osmosis.

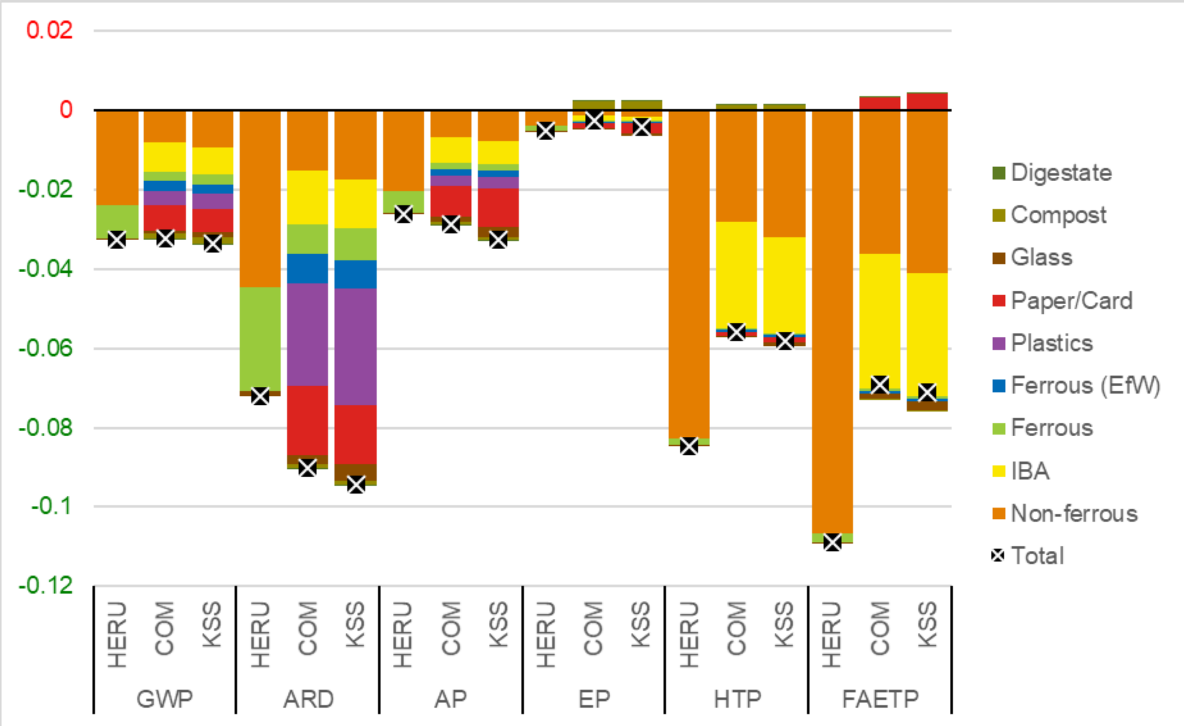
Now that nitrate emissions have been shown to be potentially important, this may be an aspect that can be investigated through better measurement of the emissions, and, if necessary, improved through better control or abatement, using technologies such as those mentioned above.

2.3.4 Recycling benefits

Figure 9 presents all the process contributions to the recycling benefits reported in the three WRATE scenarios. It can be seen that the benefits arising from the HERU are mostly attributable to the non-ferrous metal (aluminium) that passes through unit and is then taken to a bring bank for recycling. The ferrous metal makes a much smaller contribution, whilst glass is generally hard to see at all.

Looking at the freshwater aquatic ecotoxicity potential (FAETP) and human toxicity potential (HTP) results for the three scenarios, it is clear that recycled aluminium is dominating the results. (This happens because of the impacts manufacturing virgin aluminium has on these particular indicators). Revisiting the scenario designs, we find that the HERU is actually anticipated to recycle more metals and glass than the collection schemes, because none of these materials are lost in the HERU, and it is assumed that the householder will take all the residues to the local bring bank. Although this may at first sound a little optimistic, the lack of provision of any residual bin into which the materials might otherwise be disposed suggests that it is not actually unreasonable.

Figure 9: Analysis of Recycling Contributions (in EPEs)



2.3.5 Sensitivity Analysis – Electricity Grid Mix

The WRATE LCA tool has a large range of electricity grid mixes that can be used in the modelling. The tool differentiates between two so-called fuel mixes. The baseline fuel mix describes the percentages of each generation technology that are expected to be used (in a given country and a given year) to generate electricity. Any process in WRATE that consumes electricity, such as the HERU, is charged the environmental burdens of making the baseline electricity.

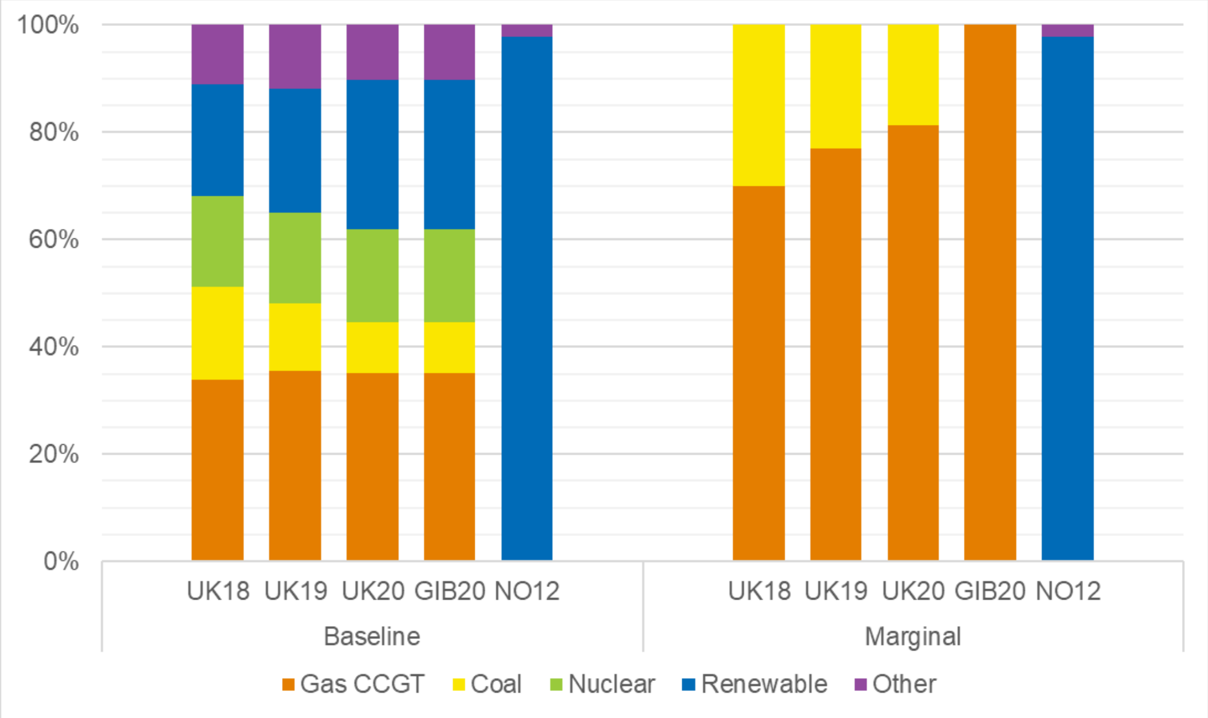
The second mix is the marginal fuel mix. This exists because, if a waste management technology is expected to produce electricity (the obvious example being incineration), it does not displace the baseline fuel mix. The UK grid would not reduce its production of electricity by nuclear or renewable sources if a new incinerator came on line; rather, whatever generation source that was operating “at the margin” would be the one to be reduced. In the UK, the marginal fuel mix is a combination of Gas CCGT and Coal.

In the three scenarios studied, the most significant impacts of the electricity grid mix arise from the consumption of baseline electricity by the HERU and the generation of electricity by incineration in the collection scenarios, offsetting marginal electricity.

WRATE has UK electricity mixes across many years, as well as selected years for other countries. It also has the 2015 UK Green Investment Bank electricity mix, modelled for 2020 and used for their project analyses and forecasts. **This is the default grid mix that we chose for this project because it is designed to be a reasonable proxy for UK electricity into the future**.

In this sensitivity analysis, we looked at the impact of changing from the GIB grid mix to the specific WRATE UK mixes for 2018, 2019 and 2020. We also included the grid mix from Norway in 2012 (“NO12”, the most recent available), to mimic the impact of moving entirely to renewable energy. The profiles of the baseline and marginal shares for these five electricity mixes are presented in Figure 10. It can be seen that, over the three years, the UK grid is gradually replacing coal with renewables. The UK20 and GIB20 baseline mixes are identical, but the GIB20 uses 100% Gas CCGT for its marginal electricity.

Figure 10: Evolution of Electricity Grid Mixes in WRATE



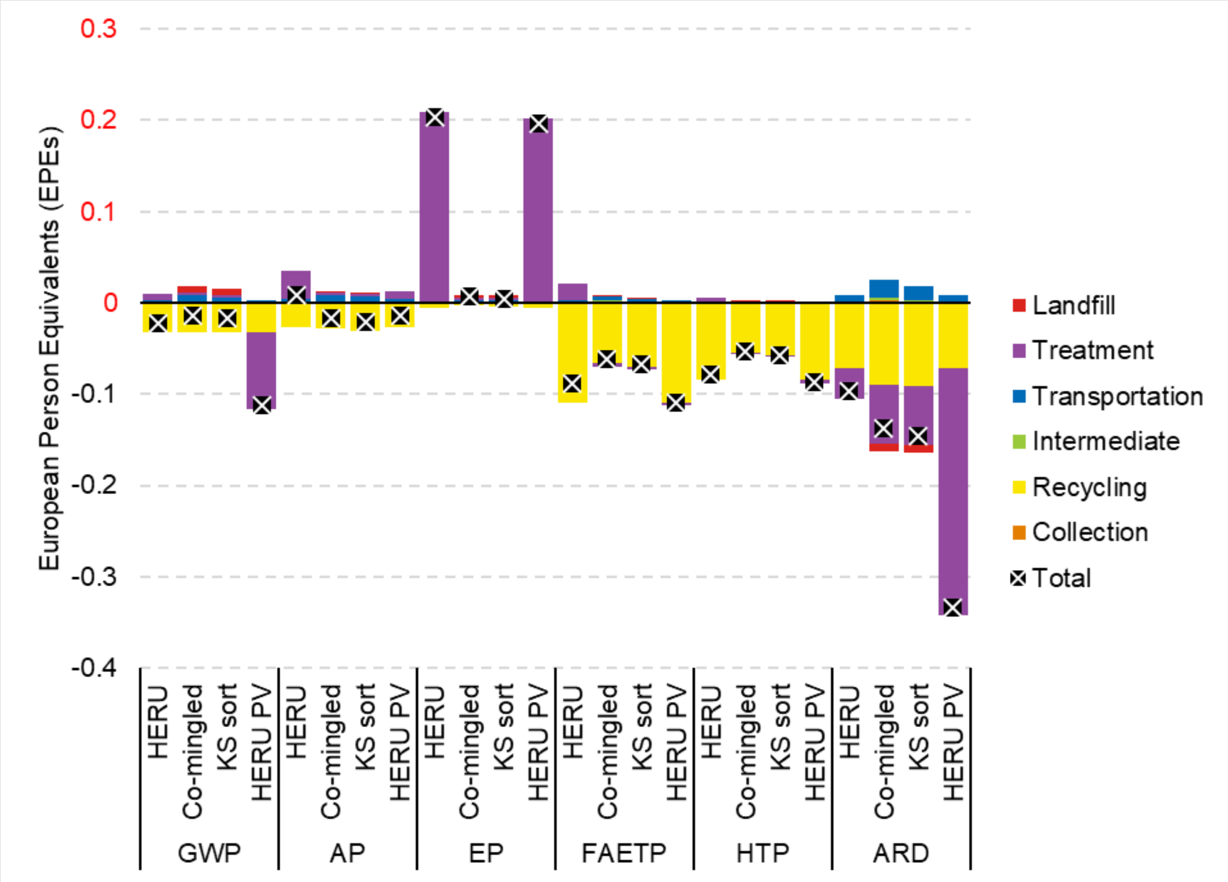
The impacts on the results (in EPE) of changing the electricity mixes are presented in Figure 11. For all six environmental indicators, the HERU scenario improves as the electricity mix gets greener, because there are smaller impacts arising from the electricity it consumes. Conversely, the collection scenarios deteriorate as they receive decreasing credits for offsetting fossil electricity. It is also clear that, as modelled, there is negligible difference between the two collection scenarios.

Figure 11: Impact of evolving grid mix on WRATE results

For eutrophication (EP), human toxicity (HTP) and freshwater aquatic ecotoxicity (FAETP), these trends make no material difference to the results; for EP, the nitrate emissions from the HERU scenario continue to swamp the result, while for the toxicity impacts, the HERU is marginally better across the board. For acidification (AP), the electricity mix only really influences the results at the extreme (NO12). However, for global warming (GWP) and abiotic resource depletion (ARD), the electricity mix is shown to be critical. The collection scenarios are preferred over the HERU if using the UK18 grid mix. With UK19 and UK20, the GWP and ARD results are relatively similar. However, once we move to the GIB20 and then beyond to a highly renewable energy mix such as NO12, there is a significant divergence and the HERU is notable superior to the collection scenarios.

The HERU team envisages that their technology would be one part of a suite of possible environmental home improvements, with another being a move from grid electricity to solar-PV cells on the house. Accordingly, Ricardo investigated the implications of powering the HERU with solar-PV energy, and found the results very similar to using the NO12 grid mix. It therefore becomes clear that, as the UK increases its use of renewable energy, both at grid level and at individual households, the HERU scenario will benefit from using that greener electricity and further improve its environmental credentials.

Figure 12: Comparison of scenarios including solar-PV HERU



3 Conclusions

This study sought to investigate the relative environmental impacts of managing waste using traditional waste collection systems, in comparison with using the HERU home pyrolysis system.

Our analysis found that the HERU delivered environmental results that were superior to those for the traditional collection schemes, for the indicators of global warming potential, abiotic resource depletion, freshwater aquatic ecotoxicity potential and human toxicity potential. In contrast, for acidification potential and eutrophication potential, the collection scenarios prevailed.

Analysis looking at the impacts of varying the UK grid mix revealed that, as the electricity becomes greener, the HERU scenario improves whilst the collection scenarios deteriorate (because the former consumes electricity and the latter produce it).

The detail in the WRATE results will enable the HERU team to further investigate and define their process during its ongoing development, to make its environmental performance even stronger. One particular area to investigate is the release of nitrates in its effluent, with the initial task to confirm that the levels are as predicted theoretically. Although the nitrates (if they exist) will likely be handled by a standard wastewater treatment plant without issue, it might be worthwhile for the HERU team to engage with a water company and explore what options would be available to reduce levels and whether they are worth adopting.

Discussions with the HERU team have also revealed some interest in capturing the carbon produced during the pyrolysis stage and, rather than combusting it, converting it to a bio-char. This would potentially remove a significant chunk of carbon emissions and produce a valuable by-product, so looks well worth further investigation.

Appendices

A The HERU UDP model in WRATE

This appendix provides information on the WRATE user-defined process (UDP) model that has been developed of the HERU. The series of tables that constitute the UDP are provided at the end of this section. Tables in WRATE that are blank (such as vehicles emissions, as there are no vehicles within the HERU) are not reproduced, for simplicity.

A few key design assumptions are provided in Table 9.

Table 9: Default Parameters and Assumptions

Description	Amount	Units	Comment
Lifetime	10	yr	Ricardo assumption
Waste per cycle	6	kg	
Cycles per day	1		
Operational days per year	364		
Electricity consumption per cycle	8	kWh	
Rate of detergent addition, per kg waste	0.1	l	Persil Bio Small and Mighty
Detergent concentration	32.5%		Persil is "15-30% anionic surfactant, 5-15% nonionic surfactant, soap"; mid-range sum is 32.5%
Combustion ash per cycle	200	g	As lye (potassium carbonate), sent to sewer
Input water per cycle	42	l	Can be bath/shower/rain water. Was 50l/cycle but improvements being made

A.1 HERU energy balance

The energy balance for the HERU is reproduced below.

Calorific value of input waste:	8.46	MJ/kg	[A]
Annual throughput of waste [6 x 364 =]:	2,184	kg	[B]
Total energy incoming in waste:	18,482	MJ	[C] = [A] x [B]
Annual electrical energy input [8 x 3.6 x 364 =]:	10,483	MJ	[D]
Total annual incoming energy:	28,965	MJ	[E] = [C] + [D]
Anticipated heat losses from HERU:	20%		[F]
Anticipated water heating losses from HERU:	10%		[G]
Net energy efficiency of HERU:	72%		[H] = (1-[F]) x (1-[G])
Annual heat energy produced by HERU:	20,855	MJ	[I] = [E] x [H]

A.2 HERU allocation table

The following pages reproduce the HERU process's allocation table.

Table 10: Parameters

Parameters		Typical Quantity				Allocation	Comment
Process Max Capacity (kg)		2184					
Annual Capacity (kg)		2184					
Lifespan (Years)		10					
Land take (ha)		0.001					

Table 11: Headline values

Headline		Default Value				Allocation	Comment
Waste Recovered [kg]		2184				=([USER_WASTE_FRACTIONS_TOTAL])	Waste recovered is assumed to equal the waste input.
Energy Recovered [MJ]		20855				=[PROC_EN_PRODUCTS.EXTERNAL_HEAT]	Energy recovered is assumed to equal the energy exported from the facility.
Land Take [ha]		0				=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[PROCESS_PARAM.LAND_TAKE]	

Table 12: Construction material inputs

Materials	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Stainless Steel	Undefined	50	Estimated		steel, low-alloyed, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.STAINLESS_STEEL.UNDEFINED]	Capital burden information from manufacturer.
Cast Iron	Undefined	13	Estimated		cast iron, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.CAST_IRON.UNDEFINED]	Capital burden information from manufacturer.
Copper	Undefined	1	Estimated		copper, primary, at refinery	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.COPPER.UNDEFINED]	Capital burden information from manufacturer.

Materials	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Brass	Undefined	4.4	Estimated		brass, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.BRASS.UNDEFINED]	Capital burden information from manufacturer.
Aluminium (virgin)	Undefined	1	Estimated		aluminium, primary, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.ALUMINIUM_VIRGIN.UNDEFINED]	Capital burden information from manufacturer.
Insulation Materials	Undefined	12	Estimated		glass wool mat, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.INS_MATERIALS.UNDEFINED]	Capital burden information from manufacturer.
Polyethylene (HDPE - virgin)	Undefined	4.5	Estimated		polyethylene, HDPE, granulate, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.POLYETHYLENE_HDPE_-_VIRGIN.UNDEFINED]	Capital burden information from manufacturer.
Steel (t)	Undefined	10	Estimated		steel, low-alloyed, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*(1/[PROCESS_PARAM.LIFESPAN_YEARS])*[CONSTR_INPUTS.STEEL_T.UNDEFINED]	Capital burden information from manufacturer.

Table 13: Maintenance material inputs

Material	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Aluminium	Undefined	0.1	Measured		aluminium, primary, at plant	=([USER_PROCESS_PARAM.MAX_CAP_MASS]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.MAX_CAP_MASS])*[MAINT_INPUTS.ALUMINIUM_AL.UNDEFINED]	
Brass	Undefined	0	Measured		brass, at plant	=([USER_PROCESS_PARAM.MAX_CAP_MASS]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.MAX_CAP_MASS])*[MAINT_INPUTS.BRASS.UNDEFINED]	
Copper	Undefined	0	Measured		copper, primary, at refinery	=([USER_PROCESS_PARAM.MAX_CAP_MASS]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.MAX_CAP_MASS])*[MAINT_INPUTS.COPPER.UNDEFINED]	

Table 14: Maintenance material outputs

Material	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Aluminium	Undefined	0.1	Measured		Aluminium Recycling	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*[MAINT_OUTPUTS.ALUMINIUM_AL.UNDEFINED]	
Brass	Undefined	0	Measured		brass, at plant	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*[MAINT_OUTPUTS.BRASS.UNDEFINED]	
Copper	Undefined	0	Measured		copper, secondary, at refinery	=([USER_PROCESS_PARAM.CAPACITY]/[PROCESS_PARAM.MAX_CAP_MASS])*([USER_WASTE_FRACTIONS_TOTAL]/[USER_PROCESS_PARAM.CAPACITY])*[MAINT_OUTPUTS.COPPER.UNDEFINED]	Assumed that maintenance output equates to the maintenance input.

Table 15: Typical waste composition

Waste		Quantity (kg)				Allocation	Comment
Paper and card		523.9					Composition aligned with WRATE MSW
Plastic film		83.2					
Dense plastic		134.8					
Textiles		60.9					
Absorbent hygiene products		51.1					
Wood		78.6					
Combustibles		133					
Non-combustibles		58.1					
Glass		172.3					
Organic		689.9					
Ferrous metal		66.8					
Non-ferrous metal		28.8					
Fine material <10mm		43.2					
Waste electrical and electronic equipment		48.7					
Specific hazardous household		10.5					

Table 16: Operational material inputs

Material	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Detergent	Gas Cleaning	70.98	Estimated		Detergent	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_MATERIAL_INPUTS.DETERGENT.GAS_CLEAN]	Detergent used to help suspend oil outputs in water

Table 17: Operational water inputs

Water	Subprocess	Quantity (kg)	Quality		Background	Allocation	Comment
Other Water Source	Process	15288	Estimated		Surface (River) Water	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_WATER_INPUTS.OTHER.PROCESS]	The unit can use collected rainwater and spent shower and bath water. Modelled as 'surface (river) water' to avoid burdens of purifying drinking water.

Table 18: Energy inputs

Energy	Subprocess	Quantity (MJ)	Quality		Background	Allocation	Comment
Electricity Grid	Process	10483	Measured			=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_ENERGY_INPUTS.GRID.PROCESS]	
Gas	Process	0	Estimated		natural gas, high pressure, at consumer	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_ENERGY_INPUTS.GAS.PROCESS]	

Table 19: Process outputs

Product	Quality	Quantity (kg)	Destination	Transport	Distance (km)	Allocation	Comment
Ferrous metal	Estimated	66.8	Recycling	Road	45	=[USER_WASTE_FRACTIONS.FERROUS_METAL]+[USER_WASTE_FRACTIONS.RDF_1_11]	Assume all incoming ferrous passes through for recycling
Non-ferrous metal	Estimated	28.8	Recycling	Road	45	=[USER_WASTE_FRACTIONS.NON_FERROUS]+[USER_WASTE_FRACTIONS.RDF_1_12]	Assume all incoming non-ferrous passes through for recycling
Glass	Estimated	172.3	Re-use	Road	45	=[USER_WASTE_FRACTIONS.GLASS]+[USER_WASTE_FRACTIONS.RDF_1_9]	Assume all incoming glass passes through for recycling

Table 20: Process energy production

Process energy production	Quality	Quantity (MJ)			Background	Allocation	Comment

External Heat	Estimated	20855			heat, natural gas, at boiler condensing modulating <100kW	=([USER_TOTAL.NET_CV]/[TYPICAL_TOTAL.NET_CV])*[PROC_EN_PRODUCTS.EXTERNAL_HEAT]	

Table 21: Process emissions (to air, water, groundwater and sewer)

Process emissions	Sub Process	Quantity (kg)	Destination	Quality	Background	Allocation	Comment
Sulphur oxides (SOx) SO2 and SO3 as SO2	Process	0	Air	Measured	Sulphur oxides (SO2 and SO3 as SO2) / air / kg	=([USER_TOTAL.SULPHUR_S]/[TYPICAL_TOTAL.SULPHUR_S])*[PROC_EMISSIONS.SULPHUR_OXIDES_SOXSO2_AND_SO3_AS_SO2.PROCESS]	Data from Brunel University.
Nitrogen oxides, NO and NO2 as NO2	Process	0.324	Air	Estimated	Nitrogen oxides (NO and NO2 as NO2) / air / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.NITROGEN_OXIDES,_NO_AND_NO2_AS_NO2.PROCESS]	Set at permitted NOx emission limit of 56mg/kWh
Carbon monoxide, fossil	Process	29.4	Air	Measured	Carbon monoxide, fossil / air / kg	=(([TYPICAL_WASTE_CV]/[USER_WASTE_CV])*([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL]))*[PROC_EMISSIONS.CARBON_MONOXIDE_FOSSIL.PROCESS]	Calculated by carbon balance, with fossil/biogenic split from waste composition and CO/CO2 split from Brunel University data
Carbon dioxide, fossil	Process	436.6	Air	Measured	Carbon dioxide, fossil / air / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.CARBON_DIOXIDE_FOSSIL.PROCESS]	Calculated by carbon balance, with fossil/biogenic split from waste composition and CO/CO2 split from Brunel University data
Ammonia	Process	0	Air	Estimated	Ammonia / air / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.AMMONIA.PROCESS]	Data from Brunel University.
Water	Process	0	Air	Measured	water / air / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.WATER.PROCESS]	Data from Brunel University.
Hydrogen sulphide (H2S)	Process	2.52	Air	Estimated	Hydrogen sulfide / air / kg	=([USER_TOTAL.SULPHUR_S]/[TYPICAL_TOTAL.SULPHUR_S])*[PROC_EMISSIONS.HYDROGEN_SULPHIDE_H2S.PROCESS]	Calculated by sulphur mass balance
Methane	Process	0	Air	Estimated	Methane (CH4) / water / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.METHANE.PROCESS]	Data from Brunel University.

Process emissions	Sub Process	Quantity (kg)	Destination	Quality	Background	Allocation	Comment
Water	Waste Water Treatment	15359	Sewer	Estimated	Water / water / kg	=[PROC_WATER_INPUTS.OTHER.PROCESS]+[PROC_MATERIAL_INPUTS.DETERGENT.GAS_CLEAN]	Ricardo assumption that all input water and detergent goes to sewer, and none further is generated
Oil	Waste Water Treatment	124.5	Sewer	Estimated	Hydrocarbons, unspecified / water / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.OIL.WASTE_WATER_TREATMENT]	Pyrolytic oils from the heating process. Mass calculated from carbon balance
Potassium, ion	Waste Water Treatment	60.7	Sewer	Estimated	Potassium, ion / water / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.POTASSIUM_ION.WASTE_WATER_TREATMENT]	Combustion ash to sewer modelled as potassium carbonate (lye). This is the potassium fraction.
Carbonate	Waste Water Treatment	95.9	Sewer	Estimated	Carbonate / water / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.CARBONATE.WASTE_WATER_TREATMENT]	Combustion ash to sewer modelled as potassium carbonate (lye). This is the carbonate fraction.
Carbon monoxide, biogenic	Process	68	Air	Measured	Carbon Monoxide (CO) / air / kg	=(([TYPICAL_WASTE_CV]/[USER_WASTE_CV])*([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL]))*[PROC_EMISSIONS.CARBON_MONOXIDE_BIOGENIC.PROCESS]	Calculated by carbon balance, with fossil/biogenic split from waste composition and CO/CO2 split from Brunel University data
Carbon dioxide - Biogenic	Process	1010.6	Air	Measured	Carbon dioxide, biogenic / air / kg	=([USER_WASTE_FRACTIONS_TOTAL]/[TYPICAL_WASTE_TOTAL])*[PROC_EMISSIONS.CARBON_DIOXIDE_BIOGENIC.PROCESS]	Calculated by carbon balance, with fossil/biogenic split from waste composition and CO/CO2 split from Brunel University data
Nitrate	Waste Water Treatment	64.4	Sewer	Estimated	Nitrate / water / kg	=([USER_TOTAL.NITROGEN_N]/[TYPICAL_TOTAL.NITROGEN_N])*[PROC_EMISSIONS.NITRATE.WASTE_WATER_TREATMENT]	Calculated by nitrogen mass balance

B Introduction to WRATE

The Waste and Resources Assessment Tool for the Environment (WRATE) software allows waste specialists in the public and private sector to measure and improve the environmental performance of their operations, by modelling current, planned and hypothetical waste management scenarios, from collection to final disposal, thereby identifying more environmentally preferable routes for the management of their wastes.

B.1 How WRATE Works

WRATE is a specialist LCA tool for the management of municipal solid waste (MSW), and therefore the system boundary is from “gate to grave”. The model starts at the point when materials are discarded into a waste management system (the gate), assuming they arise at no environmental cost, and follows those materials until they are recycled, composted, recovered, “lost” (such as gaseous emissions from a thermal process or water evaporation from a biological process) or disposed in landfill (the grave). The main implication of this streamlined approach is that WRATE is not easily adapted for modelling waste prevention.

B.1.1 WRATE Datasets

A process can range from a simple process, such as a bin, to a much more complex process, such as a thermal treatment plant. For each process, the Environment Agency compiled data on the resources used to operate the process and the emissions that occur to the environment when the process is operated. The Environment Agency also defined a series of allocation algorithms that link the feedstock inputs to the outputs of a process (recovered product or residual waste). These algorithms can be dependent on the waste composition input (fractional or elemental composition) the total quantity of the waste, or the properties of the treatment plant.

In this way, the WRATE developers produced over 120 standardised process datasets, or allocation tables, as presented in Table 22 below.

Table 22: WRATE Default Process Datasets

Containers (34) Sacks, bins, recycling banks…	***Treatment & Recovery…*** **Composting (8)** **Anaerobic Digestion (4)** **MBT-Aerobic (6)** **MBT-AD (4)** **MBT-Biodrying (4)** **SRF Production (2)**	 **Autoclave (2)** **Incinerators (6)** **Pyrolysers (2)** **Gasifiers (2)** **Cement Kiln (1)**
Transport (26) RCVs, ship, barge, train, car		
Intermediate Facilities (14) Transfer Stations, HWRC, Intermodal, MRF		
Recycling Processes (24) Ferrous, PAS100 Compost, Glasphalt etc.	**Landfill (6)** Clay Liner, Clay cap, etc. etc.	

As well as using default processes, the WRATE user has the option of creating user-defined processes (UDPs), in order to model as accurately as possible the particular waste process or facility of interest. UDPs are created by duplicating a default process’s allocation table and then modifying, adding and deleting relevant parameters. For thermal treatment plants, the most common parameters adjusted are the energy input and output, the metals recovered, the principal air emissions and the raw materials used (including air pollution control additives, such as urea and activated carbon).

B.1.2 Project Details

A “project” in WRATE may constitute several scenarios, all of which apply to one particular year in a particular country, handle the same amount of waste with the same composition, and use the same electricity mix. This means that any study on different waste compositions, or with different electricity mixes, must be conducted in multiple WRATE projects that cannot be compared within the software.

Before building the scenario details, the user has to enter project-wide details on three parameters:

Project information various textual details about the project, including the local authority covered, the year of study, and any peer reviewer’s comments;

Waste composition WRATE has almost 150 waste fractions from which to select, so most MSW compositions can be modelled accurately;

Electricity mix WRATE allows the user to choose a country and a year for the electricity mix. Using waste to produce electricity with offset a very different mix of alternative processes, depending on whether the process is in (for example) England or Norway, in 2002 or 2020.

Once these details are fixed, WRATE has a user-friendly interface for the entry of process data. A screenshot of the workspace is presented below in Figure 13.

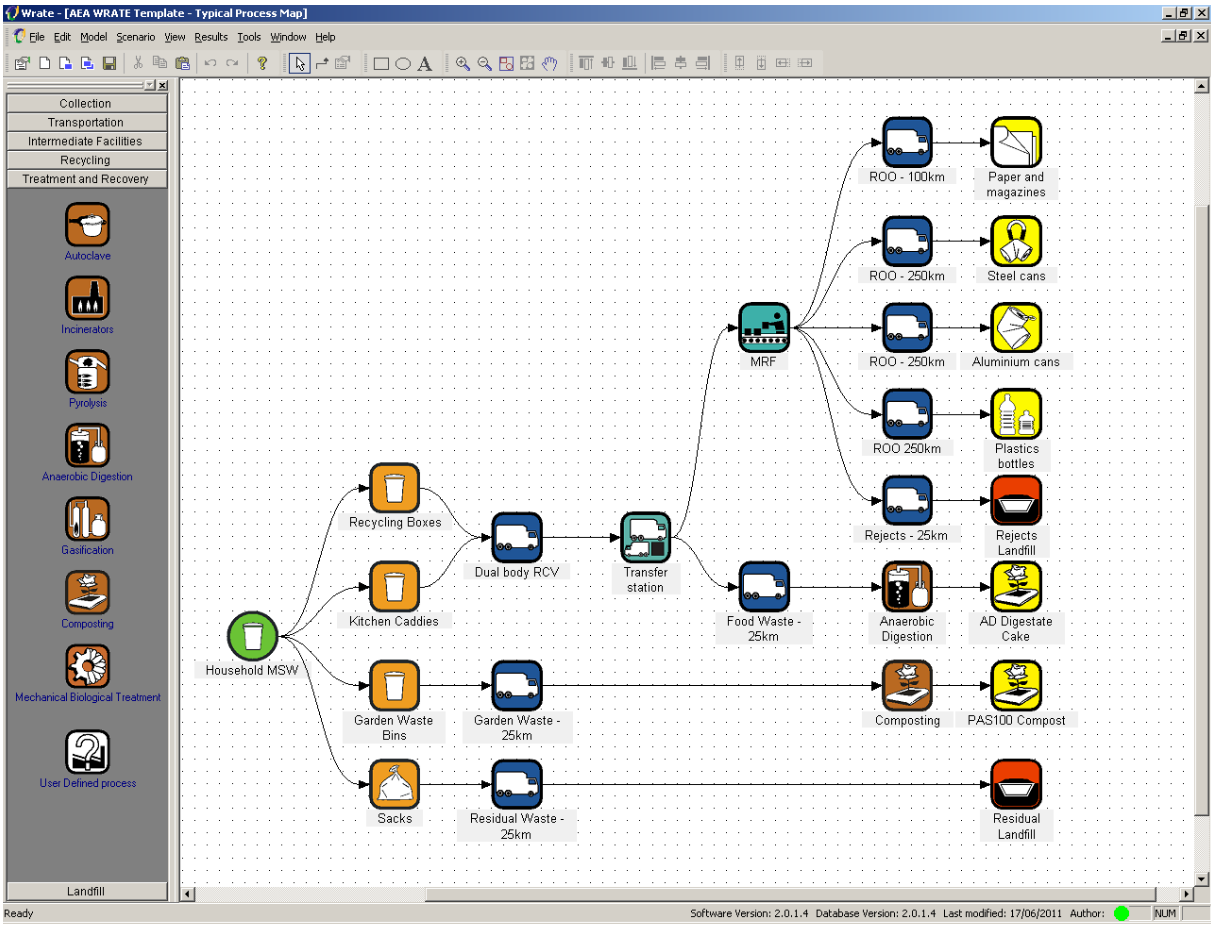
B.1.3 Scenario Building

A scenario is a collection of processes that together describe how a set waste is taken from point of arising to its end of life (either as a recyclate, compost, digestate, landfilled material or a loss in a process (such as combusted waste).

Building a scenario is a simple task to understand. Processes can be selected from the palette on the left hand side of the screen and dragged onto the screen (see Figure 13 below). A linking tool allows the user to pass waste from one process to the next, until all the required processes and flows have been described.

Things become more complex when one process has more than one output. The most obvious example, in the case of household waste, is the separation that occurs in the household, putting (in some instances) dry recyclables, garden waste, food waste and residual waste in different receptacles. In these cases, as well as creating the links, the user must stipulate how each waste fraction is distributed between the next processes. Once this is completed, the scenario design is finished. WRATE shows a green light if it finds no errors in the data entry. Otherwise, a red light appears, and this can be clicked to learn more about the source of the error.

Figure 13: WRATE's Workspace Interface



B.1.4 Results

WRATE calculates an environmental burden for the modelled system by using this information on process behaviour and a series of databases on the environmental cost of using resources or recovering materials and energy. The software compiles a life cycle inventory (LCI) which represents the environmental burden as the inputs and outputs that occur to and from the environment due to the existence and operation of the waste management system.

As described above, WRATE assumes that all the waste arises at no environmental cost. If the process produces recyclates, these are credited with whatever environmental impacts are avoided by not needing to create equivalent materials from virgin sources (minus any rejects). Similarly, any generated energy (heat or electricity) is credited in comparison to the heat or marginal electricity mix that is offset.

WRATE's results are presented as environmental burdens (such as the additional global warming potential created). The main implication of the offsetting described above is that overall results are frequently negative, reflecting the fact that, starting with "environmentally free" waste, the waste management process has a net benefit on the environment, reducing overall environmental impacts by offsetting the need to make materials or energy from virgin materials. This means that negative and low values are the most preferred.

WRATE reports against six default environmental indicators:

+ **Global Warming Potential** (GWP) is an assessment of the amount of carbon dioxide and other gases emitted into the atmosphere and liable to cause global warming. Apart from CO_2, the other major greenhouse gas for waste management tends to be methane, which is significantly more potent than CO_2. WRATE also weights emissions of other greenhouse gases according to the climate change potency to produce a carbon footprint expressed in CO_2 equivalents.

+ **Abiotic Resource Depletion** (ARD) is related to extraction of scarce minerals and fossil fuels. The abiotic depletion factor is determined for each extraction of minerals and fossil fuels based on the remaining reserves and rate of extraction.
+ **Human Toxicity Potential** (HTP) is a measure of the impacts on human health. Characterisation factors describe the fate, exposure and effects of toxic substances over an infinite time horizon.
+ **Freshwater Aquatic EcoToxicity Potential** (FAETP) is a measure of the adverse effects to aquatic organisms that result from being exposed to toxic substances. It is well known that fish can 'bioaccumulate' concentrations of mercury and other toxins. Mobile heavy metals are extremely toxic to aquatic life, so activities that reduce releases of heavy metals will be favourable in this assessment.
+ **Acidification Potential** (AP) relates to the release of acidic gases, such as sulphur dioxide, which have the potential to react with water in the atmosphere to form 'acid rain' and causing ecosystem impairment.
+ **Eutrophication Potential** (EP) is a reflection of released nitrate and phosphate levels. Nitrates and phosphates are essential for life but increased concentrations in water can encourage excessive growth of algae, reducing the oxygen within the water and damaging ecosystems.

The results from the six criteria can be expressed as a single normalised unit of measurement so they can be partially compared against each other. This unit is "European person equivalents", which represents the lifestyle impact one person has in Western Europe on the various criteria in a year. The number calculated is then equal to the effect an increase/decrease in population has against the six criteria. WRATE calculates results on an annual basis and for one given year only.

Results from WRATE can be provided at the process and scenario levels. Scenarios can be compared and a number of results formats are produced, suitable for communicating to non-technical audiences.

C HERU Technical Data

The calculations and assumptions used this report are supported by a separate technical annex in Microsoft® Excel®.

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