Completing the circle methodology

Below describes the methodology used for our analysis *Completing the circle: creating effective UK markets for recovered resources*, June 2018

Current plastic flows

Data on the demand, recycling, export and the amount of plastic that gets lost from our economy come from the Valpak and WRAP 2016 report, *Plastics spatial flow: an assessment of the quantity of un-recycled plastic in the UK*. This report is based on 2013 data and there have been some recent suggestions that the amount of material placed on the market is greater than was reported. However, the WRAP/Valpak report represents the most comprehensive and up to date analysis of plastic placed on the UK market in terms of quantities and end destinations, for both packaging and other plastic items.

The key figures from the report include:

- Total plastic arisings: 3,299kt, of which 2,260kt is packaging
- Total plastic collected for reuse, recycling or recovery: 1,104kt (33.5 per cent), of which 307kt (9.3 per cent of the total) are reused or recycled domestically, 649kt are exported and 148kt are sent for energy from waste.
- Total plastics in residual waste: 2,195kt, of which 1,378kt are sent to energy from waste and 815kt are sent to landfill.

For our analysis, material we consider 'lost or wasted' is that which goes to landfill, mechanical biological treatment (MBT) and energy from waste instead of to reuse, remanufacturing or recycling.

Estimated plastic flows using pull measures

The first assumption made for this graph is that the demand for plastic from consumers and businesses remains at the same level (3,300kt). We considered this reasonable as we are unsure at this stage how demand will evolve over the next decade, and recent trends for increasing consumption of plastic could stall or be reversed if policy aims to curb the prevalence of single use plastic. The increasing prevalence of plastic as a packaging choice, moreover, may continue to be balanced out by a trend towards lightweighting.

With polymer rationalisation and recyclability an increasing focus of industry and the government, we assumed that, in our ideal scenario, nearly all plastics placed on the market will be recyclable. (See the UK Plastic Pact, which commits producers of plastic packaging, accounting for 80 per cent of plastic placed on the UK market, to deliver 100 per cent recyclable plastic by 2025.)

For the recycling figure, we have assumed a 90 per cent collection rate (2,970kt), meaning 330kt would continue to be lost in that it does not enter the collection system. We also expect that some of this material (which we estimated to be seven per cent, or 208kt) would continue to be sent abroad for recycling.

From the remaining 2,762kt left in the UK recycling system, we have assumed a process loss rate of 15 per cent (414kt additional tonnes lost, making 744kt in total), which would represent an improvement on current loss rates from collection to final recyclate output, though an achievable one. Valpak's 2017 *Packaging recycling supply chain assessment* demonstrated that, in 2013, 73,752 tonnes of plastics entered Scottish materials recovery facilities (MRFs), 65,763 tonnes came out of MRFs, and 55,899 tonnes were made into recycled material. This represents a loss of 27.1 per cent from MRF gate to final reprocessing, but given the widely discussed challenges resulting from current collection systems (see Green Alliance's 2017 report, *Recycling reset: how England can stop subsidising waste*), we consider it reasonable to assume that this figure could be significantly improved upon. The improvement would come from both improved initial recyclability and improved collection methodologies, including standardisation and greater separation, resulting in fewer contaminants, as well as better sorting. This would leave 2,348kt as recyclate to be fed into production.

This amount of recyclate represents a substantial proportion (71 per cent) of total UK plastic demand, and would need to be coupled with improvements in recycling technology to be put to good use. It is currently possible to make most plastic polymers from 100 per cent recycled content, but current mechanical recycling technology does not allow for some polymers to be infinitely recycled. Expert commentators at our workshops (see the list in annex two of our report) suggested that levels beyond 50 per cent would require an overhaul of recycling technologies.

PET, the polymer used for fizzy drinks bottles, for instance, suffers from polymer shortening during the recycling process, which makes 100 per cent bottle to bottle recycling impracticable. Several companies, however, have worked on technical solutions that would enable closed loop recycling by rebuilding polymer chains at various stages: when the polymer is molten after extrusion (the Gneuss Processing Unit); before the polymer is extruded (the Erema Vacurema technology) or after extrusion (the Starlinger Solid State Polycondensation (SSP) technology). These are not widely used, however, because they add costs to the recycling process, which further damages the price of recyclate compared to virgin materials. Green Alliance considers that pull measures to support the use of recycled content could help companies to commercialise solutions to address current technical barriers and make recycled content more comparable to virgin material in price and technical performance.

Current steel flows

Data on imported iron ore and scrap steel used for domestic steel production is based on UK Steel, *Key statistics* 2016 (scrap steel excludes scrap arising within steelworks). Scrap steel arising is based on: scrap steel exports (7.3Mt, based on World Steel Association, 2017, *Steel statistical yearbook* 2017), scrap steel assumed to be lost (1Mt, based on JM Allwood, 2016, *A bright future for UK steel*) and scrap steel assumed to be used domestically (2Mt, UK Steel, Key statistics 2016). The latter is assumed to include imported scrap steel (0.3Mt, based on World Steel Association 2017), fabrication steel (0.8Mt, assuming fabrication scrap accounts for seven per cent of steel demand for manufacturing, based on JM Allwood, 2016, and data for apparent steel demand for manufacturing taken from World Steel Association, 2017) and 0.9Mt from domestic steel-containing products reaching end of life.

Estimated steel flows using pull measures

Current UK steel demand by sector is estimated based on: apparent steel demand as reported by the World Steel Association, 2017, from which fabrication scrap (0.8Mt) is subtracted, and the share of demand by sector is calculated using a ratio based on the current demand by sector as reported by BEIS, 2017, *Future capacities and capabilities of the UK steel industry*, figure 2 (in our study, ‘Other’ includes demand for all sectors that are not Construction, Machinery or Automotive).

Additional UK demand for recycled steel is assumed to be driven by recycled content targets. These result in an increase in recycled steel demand that is equal to the difference between the target content and current average recycled content (both of which vary depending on the sector), as summarised in the table below.

	Current UK steel demand by sector (Mt)	Average recycled content (current)	Target recycled content	Additional UK demand for recycled steel (Mt)
Automotive	0.7	16%	75%	0.4
Machinery	0.6	22%	50%	0.2
Construction	5.7	38%	75%	1.9
Other	2.7	28%	50%	0.6
Total				**3.1**

Current average recycled content is based on KE Daehn et al, 2017, ‘How will copper contamination constrain future global steel recycling?’, *Environmental Science and Technology*, 51, 6599-6606 (supporting information, table S24). Target recycled content values are based on Jaguar Land Rover’s reported targets for recycled aluminium content in vehicles by 2020 (SMMT, 2016 UK automotive sustainability report), assuming that recycled steel can achieve similar levels. Recycled content for construction is assumed to be able to achieve similar high proportions, while targets for remaining sectors are assumed to be lower based on current lower recycled content averages. Assumptions on recycled content targets were circulated for comments following the expert workshop.

Additional demand for recycled steel for construction was estimated assuming that steel demand would be reduced by the amount equivalent to the tonnes of reused steel (as estimated below).

Scrap steel required to meet the additional demand for recycled steel is calculated by multiplying 3.1Mt additional demand by the global average yield of recycling steel (89 per cent, based on JM Cullen et al, 2012, ‘Mapping the global flow of steel: from steelmaking to end-use goods’, *Environmental Science and Technology*, 46, 13048-13055).

Estimates for scrap construction steel suitable for reuse are based on: UK scrap steel arising (9Mt), of which 13 per cent is assumed to be construction scrap (1.4Mt, based on the share of construction scrap as reported by Serrenho et al, 2016) and of this, 50 per cent (0.7Mt) is assumed to be suitable for reuse (based on D Cooper and JM Allwood, 2012, ‘Reusing steel and aluminium components at end of product life’, *Environmental Science and Technology*, 46, 10,334-10,340).

Estimates for iron ore imports as a result of greater use of recycled and reused steel are based on: steel production via the blast furnace route, currently at 9.1Mt (UK Steel, *Key statistics* 2016), is estimated to drop to 5.3Mt as a result of displacement in demand from recycled and reused steel (assuming that overall steel production does not increase as a result of pull measures). Assuming that iron ore imports are reduced by the same proportion, new iron ore demand is estimated to be 7.2Mt.

Note that recycled and reused steel in this study are assumed to displace domestic virgin steel production and no assumptions have been made as to what share of imported steel may be displaced, nor about impacts on UK virgin steel products exported.

Emissions reductions for steel production are estimated based on the average carbon intensity for UK integrated steel plants (virgin steel) of 2.2 tCO_2/t of crude steel and of 0.6 tCO_2/t recycled steel for electric arc furnace plants. Data is based on WSP and DNV-GL, 2015, *Industrial decarbonisation & energy efficiency roadmaps to 2050: iron and steel*, p 36. Steel production volumes (based on estimated flows with pull measures) are assumed to be as follows: 5.3Mt via the blast furnace route and 4.9Mt via electric arc furnace.

Critical raw material flows in 2035

Assessment of future demand for critical raw materials is based on the forecast deployment of low carbon technologies to deliver the decarbonisation of the transport and energy sector, in line with the UK's decarbonisation commitments. We have previously argued that government should bring forward the band on new fossil-fuelled vehicles to 2030, and this assumption underpins the calculations presented in this study (a similar assessment was carried out also based the Committee on Climate Change's forecast deployment of EVs, see at the end of this section for more information). It should be pointed out that, given that these technologies have just recently entered the market, accurate assessments of the lifetime and material intensities are still subject to large uncertainty and should be taken as indicative.

Assumptions regarding technology deployment in 2035 used in this analysis are, as follows:

- we assume EV sales to be 100 per cent of new vehicles (cars and vans) sales by 2030, following an S-shaped uptake (based on Green Alliance, 2018, *How the UK can lead the electric vehicles revolution*); ratio of BEV and PHEV is based on Committee on Climate Change, 2013, *Pathways to high penetration of electric vehicles*; all vehicles are assumed to use lithium-ion batteries (material intensity is reported in the table below) and batteries are assumed to be replaced after eight years;
- wind turbine deployment is based on the forecast by National Grid, *Future Energy Scenarios* 2017, 'Two Degrees' scenario; the share of onshore (direct drive) DD-PMG turbines is assumed to be 44 per cent, that of onshore MS/HS-PMG turbines are assumed to be 28 per cent and that of offshore DD-PMG turbines 100 per cent in 2035 (based on DT Blagoeva, et al, 2016, *Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU*);
- battery storage deployment is based on that forecast by National Grid, *Future Energy Scenarios* 2017, 'Two Degrees' scenario (including transmission connected as well as distributed and micro-battery storage; we assume a conversion of 2.5MWh per MW deployed).

Alongside forecasting demand, we examined the technologies reaching end of life in 2035 to estimate materials potentially entering the recovery process. Technologies reaching end of life include:

- EVs sold in 2022, assuming an average vehicle lifetime of 13 years and that rare earth element-containing electric motors reach the end of life when the car is scrapped, as well as replacement and new batteries from vehicles sold in 2027 (assuming the lifetime of the battery in a car to be eight years); lifetime assumptions are based on Busch, et al, 2017, 'Closing the low-carbon material loop using a dynamic whole system approach', *Journal of cleaner production*, 149, 751-761; as pointed out earlier, assessments of the lifetime of these technologies is still subject to large uncertainties given their recent entry in the market;

- wind turbines deployed in 2010, assuming a lifetime of 25 years; data for deployment is based on RenewableUK 'Wind Energy Projects' database; lifetime assumptions are based on Busch, et al, 2017, 'Closing the low-carbon material loop using a dynamic whole system approach', *Journal of cleaner production*, 149, 751-761;
- battery storage (grid) deployed in 2022, assuming a lifetime of 13 years, based on National Grid, *Future Energy Scenarios* 2017, 'Two Degrees' scenario; lifetime assumptions are based on IRENA, 2017, *Electricity storage and renewables: costs and markets to* 2030.

Material intensity of technology, particularly for batteries, vary widely due to different chemistries that might be used and the fact that battery technology is still subject to active research. Values used in this report are based on average of material intensities reported by Busch, et al, 2014, 'Managing critical materials with a technology-specific stocks and flows model', *Environmental Science and Technology*, 48, 1298-1305; Busch, et al, 2017, 'Closing the low-carbon material loop using a dynamic whole system approach', *Journal of cleaner production*, 149, 751-761; and Blagoeva et al, 2016, *Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU*. Rare earth elements considered in this study only include neodymium, praseodymium and dysprosium.

The table below provides a summary of material intensities used in this analysis (which are assumed to be constant over time):

	Cobalt	**Rare earth elements**
EV - BEV (kg/vehicle)	5.15	0.62
EV - PHEV (kg/vehicle)	1.96	0.71
Wind turbine - DD-PMG (tonnes/MW)		0.23
Wind turbine - MS/HS-PMG (tonnes/MW)		0.04
Battery storage (kg/kWh)	0.195	

Recovery at end of life assumes 95 per cent collection rate of end of life vehicles (and the respective lithium-ion batteries). Collection of stationary storage and wind turbines is assumed to be 100 per cent. Materials contained in these technologies are assumed to be either lost (five per cent of vehicles not collected) or exported for recovery abroad.

Critical raw material flows 2035 with pull measures

Pull measures are expected to support the development of domestic recovery infrastructure that can support full recovery of materials from technologies collected at end of life (all technologies in the case of wind turbines and stationary storage, 95 per cent of vehicles and lithium-ion batteries in the case of EVs).

Reuse is assumed to take place for EV batteries to supply the forecast demand for stationary storage (reuse of cobalt is based on the material intensity requirements for battery storage listed in the table above). Reuse is also assumed to apply to 50 per cent of permanent magnets recovered from wind turbines and EVs, since magnets can retain their magnetisation for much longer than the lifetime of the product they are used in, making them in principle suitable for reuse. No material loss is assumed to take place with reuse.

Recycling is assumed to take place for the remaining EV lithium-ion batteries and stationary batteries reaching end of life, as well as for 50 per cent of permanent magnets recovered from wind turbines and EVs. Recycling rates are 90 per cent for rare earth elements, and 95 per cent for cobalt (based on Busch et al, 2014, 'Managing critical materials with a technology specific stocks and flows model', *Environmental science and technology*, 48, 1298-1305). While current recycling technologies achieve much lower recovery rates, particularly for rare earth elements, this report assumes that high recycling process efficiencies could be achieved in the long term, driven by availability and demand for secondary materials (as outlined by Busch et al, 2014). Losses resulting from the recycling process are included in the total material lost reported in the graphic.

Note that the analysis for critical raw material flows in 2035 (with and without pull measures) was also carried out using EV uptake based on the forecast by the Committee on Climate Change (Committee on Climate Change, 2013, *Pathways to high penetration of electric vehicles*), according to which 60 per cent of new vehicle sales in 2030 will be EVs. Assumptions for material intensities, technology lifetimes and rates of recovery are the same as detailed above. This assessment suggests that UK recovery could supply 18 per cent of domestic demand of rare earth elements and 34 per cent of cobalt in 2035.