Modelling the Cumulative Effect of Scrap Usage within A circular UK Steel Industry – Residual Element Aggregation

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Abstract:

To move away from the 'take-make-dispose (waste)' economy there is a drive to reuse and recycle materials. For the steel industry this means using more steel scrap rather than iron ore or direct reduced iron in the production processes. However, this has a consequence on the quality of the steel produced due to the presence of undesirable residual elements from steel scrap. In this work, the effect of the UK steel industry utilising national scrap stocks to meet the UK demand for steel has been explored through an iterative production model approach. Scrap qualities and volumes were obtained from compiled literature data in order to generate a reliable feed stock of material into the model. The scrap feed is considered in both the blast furnace – basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) production routes to model the likely enrichment of residual elements through multiple cycles of the materials use. It was found that with current scrap handling and production technologies (but not production capacity), and approximate current maximum allowed residual content specifications for steel processing and products, the UK could sustainably and safely migrate towards a 50/50 production split between BF-BOF/EAF processing of liquid steel by utilising the current national scrap stocks/projected availabilities. This shift would reduce the UK's steel industry emissions by almost 20%.

1. Introduction

1.1 The inherent drive for scrap based steel production

Steel production has two dominant routes for liquid processing. The Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, which processes raw iron ore to metallic iron by mainly carbon reduction (e.g. coke, injected pulverised coal) as seen in equation 1, and the Electric Arc Furnace (EAF) which can use predominantly steel scrap as a feedstock for producing new products, subject to scrap quality and product requirements.

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2 \quad [1]$$

Due to the need of removing oxygen from the iron compounds of ore in the BF-BOF route as in equation 1 (which is an ideal case of full conversion to CO_2 rather than the balance of CO and CO_2 which is actually produced) there is an inherent unavoidable production of 788 kg of CO_2 for every tonne of steel. This is a best case with 100% efficiency in the BF to make pure iron. This does not account for reduction of other impurities, the heat generation requirements or the entire BOF process which has the main function of removing excess carbon added to the iron through the blowing of oxygen to generate more CO_2 as in equation 2.

$$C + O_2 \rightarrow CO_2 \quad [2]$$

As an example, the blast furnace itself accounts for approximately half of the CO_2 emission of the entire integrated BF-BOF and downstream processing production of hot rolled coil with a total output of approximately 2.3 tonnes of CO_2 per tonne of hot rolled coil[1]. In comparison producing the same product utilising a high proportional scrap fed EAF system upstream produces only a fraction of the CO_2 emissions at 0.7 tonnes per tonne of hot rolled coil[2].

In addition to the raw total output of CO_2 for each production route, due to the inherent reduction required for the BF-BOF route, there is a significant difference in the direct and indirect CO_2 emission split between the two processes. Within the UK in 2012, the BF-BOF route was 94% direct emissions and 6% indirect, compared to a UK EAF manufacturer where 33% was direct emissions and 67% indirect[3]. Indirect emissions are mostly due to electricity production and as such if the UK grid were to be fully decarbonized BF-BOF steel manufacturing would still sit at 2.16 tonnes of CO_2 per tonne of steel, whereas EAF manufacturing would drop to 0.23 tonnes of CO_2 per tonne of steel; almost a 10^{th} of the integrated route.

With the position of UK government to reach net zero CO_2 emissions essentially as soon as possible, there is a clear drive for the steel industry to consider swapping to an EAF production route. However just considering the CO_2 emissions is not a suitable way for the production methods to be evaluated.

The EAF process route includes some technology based issues which have already been solved or are inherently not a problem in the BF-BOF route. The major issues include, process control due to the difficulty of understanding scrap heat transfer coefficients[4], nitrogen and hydrogen pick–up from carbon and ferro alloy sources (detrimental to certain steel grades such as interstitial free steels used for external automotive body components, where if nitrogen is >40 ppm ductility is greatly reduced causing failure during production)[5], production and utilization of EAF dust and the main focus of this paper, residual element enrichment and aggregation after multiple cycles of materials use.

1.2 Ferrous Scrap Availability in the UK

The UK is a net exporter of ferrous scrap, with over 9.3 Mt of ferrous scrap being exported in 2017. Annual scrap consumption in the UK currently stands at around 1 Mt of internally UK generated scrap and 1.4 Mt of imported scrap (with imported scraps being generally merchant grades for further processing and resale rather than those grades used directly by the steel industry)[6,7]. Since the closure of the integrated steel plant of SSI in Redcar in 2015, there has been a relatively stable steel production volume in the UK of approximately 7.5 ± 0.2 Mt[8]. As such if just the mass of iron required is compared against those available from scrap, the UK steel industry could convert to 100% scrap based steel production completely self-reliant on UK scrap generation.

Ferrous scrap is not all equal in quality and with regards to considering a sustainable high scrap use steel industry it can be split into two large families: “high-residual scraps (HRS)” (This group contains UK ferrous scrap grades - 0A, 1, 2, 3A, 3B, 4D, 6A, 6B, 6C, 6E, 7A, 7B, 9A, 9C, 9D, 10, 11A and 11B) and “low-residual scraps (LRS)” (This Group contains UK ferrous scrap grades – 4A, 4C, 4E, 4F, 4G, 8A, 8B, 12A, 12B, 12C, 12D, 13A and 13B)[9]. These groupings for this study are based on the typical levels of residual elements with regards to steel manufacturing, these include Cu, Ni, As, Pb, Sn, Sb, Mo, Cr, etc. The typical characteristic of these elements is that they are more noble with regards to oxidation than iron and/or can cause significant process or product implications at relatively low concentrations (<1 wt%)[10].

Scraps are currently classified more on their origin and sizes than on their elemental composition (with a few restrictions for composition specifically stated as exceptions). The specifications are tailored more towards limiting handling/ engineering implications such as excess oil and dirt causing fires or miss guided mass reporting's for a given shipment of the materials. This predominant categorisation methodology is a clear indication of the historic needs of the sector where scrap has been a high volume low value commodity material which is largely exported to countries with lower steel quality product production or cheap labour for manual sorting of the material on arrival. As such for a high-scrap high value future UK steel industry, scrap standards will need to evolve to be correlated to prospective metallurgical quality.

With regards to the volumes of each category of these scraps two approaches are used. Modelling the likely production of ferrous scrap from sources through understanding the material make-up, processing and in life use of our ferrous containing structures and consumer products, or there are reported volumes of scraps being exported by the UK HMRC (Revenues and Customs body of the UK).

Figure 1 shows a potential break down of the contributors to ferrous scrap by sector in the current market. The proportions are based on the average use of steel in the sectors at the time of current end of life manufacture and the product life expectancy accumulation. These two factors combine to give a weighting based not only on how much steel is used in a sector, where construction is the largest by far at over 50% of total steel usage in the UK, but also how quickly that steel comes back around into the scrap markets, where cans + metal boxes would be the sector with the shortest life cycle. These two factors balance resulting in the automotive sector offering the largest contribution to ferrous scrap tonnages per annum[11]. Unfortunately due to the nature of automotive products complexity and how they are processed at the end of life, large volumes of this material ends up in one of the more complex, in terms of density and cleanliness, of all the scrap categories. The values for each sector are: prompt scrap 12%, other industries 13%, boilers, drums/other vessels 5%, cans + metal boxes 7%, metal goods 13%, structural steelwork/buildings 8%, vehicles 20%, electrical engineering 5% and mechanical engineering 17%.

From the understanding of the typical steel use in each sector it is possible to segregate each sectors mass contribution into the appropriate scrap categories. The model developed in this work is specifically designed to interrogate future residual levels in steel, as a result specific scrap processing and handling is not considered and as such sub categories such as bailed or loose scrap is immaterial for this work. This allows us to reduce the matrix of scrap types used as inputs for the model. The resource "*Sustainable materials with both eyes open*" gives a good approximation of steel used in each sector and thus allows for portioning out of material into its respective scrap categories[12].

Table 1 gives a breakdown of the types of steel used and likely to be extracted from each of the sectors represented in Figure 1. Prompt scrap is the scrap arising from the manufacture of steel goods. Using the breakdown of steel used in each sector and knowledge of usual end-of-life treatment (such as dismantling and shredding) and legislation in place for certain materials (depolluting/chemical treatment) an estimate of scrap categories volume can be constructed as in Table 2 (taking an approximate total UK scrap generation of 10 Mt per annum for simplicity). Sources of guidance include those housed by the UK government[13], the BMRA[14] and personal communications. The categorising of this material for future steps of this model is only relevant with regards to the residual element level compositions. As such many of the categories can be combined as with the lack of need for size distinction and cleanness outside residual levels the sub categories are superfluous to the model outputs.

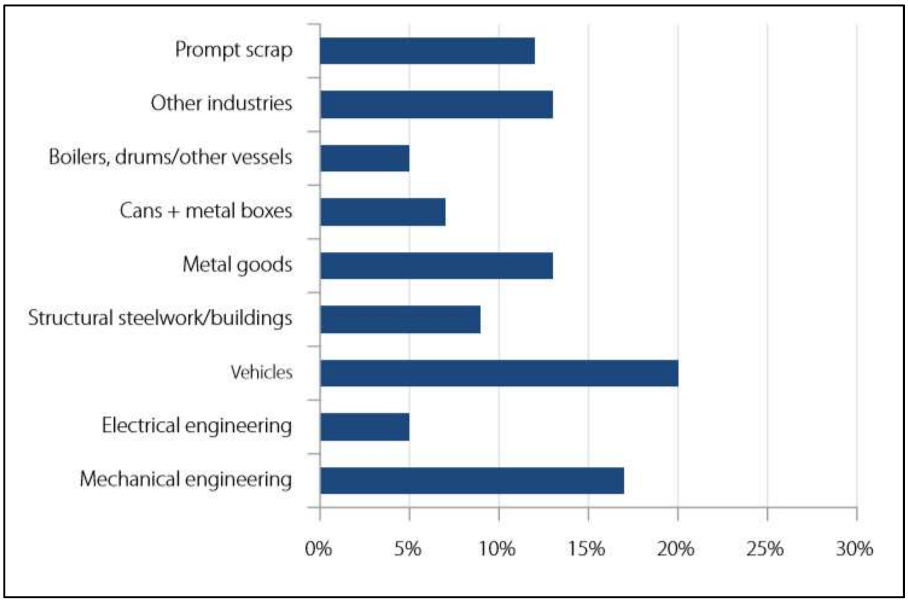

Figure 1. The current proportion of UK scrap production by manufacturing sector[11].

Table 1: A breakdown of the percentages of major steel usages in each manufacturing sectors developed through a combination of literature sources[12].

Sector	Steel type Used	% use in sector
Other industries	Structural Section	24
	Reinforcing Bar	54
	Hot rolled Rails	6
	Pipes	16
Boilers, drums/other vessels	Coated Cold rolled coil	100
Cans + Metal boxes	Tin-plated strip	100
Metal Goods	Hot rolled coil	30
	Hot rolled bar	20
	Plate	17
	Narrow strip	17
	Cast iron	16
Structural steelwork/buildings	Structural sections	25
	Reinforcing Bar	44
	Coated Cold formed strip	31
Vehicles	Welded cold rolled sheet	34
	Cast iron	23
	Roll HSS	12
	Cast alloy	7
	Drawn Wire	3

	Cast high carbon	5
	Hot rolled bar	11
	Hot stamped strip	5
Electrical engineering	High silicon electrical steel	30
	Cold formed Strip	30
	Reinforced cable	30
Mechanical engineering	Steel plate/bar	40
	Tubes	22
	Hot and cold rolled coil	22
	Cast Steel	6
	Wire rod	6

Table 2: A mass to category breakdown of the UK scrap landscape from a combination of literature resources, grade and volume normalized to 10 Mt.

Scrap Category	Category Mass (kt)
0A – Demo	1,054
1 – Thick Old	2,145
2 – Thin Old	1,468
3B – Fragmentised	2,851
6A – Cans + incinerated	760
7A – Turnings	110
8A – Manufacturing off-cuts	1,040
9A – Old cast iron + Rail	422
9D – Brake Discs and wheel drums	100
12A – New cast iron	50
Total	10,000

A second method to determine scrap volumes is by utilising known scrap export volumes, which gives similar results to the compiled literature values for comparable scrap categories[15]. The summary of the 2018 UK scrap exports is given in Table 3. Along with the export values, which only total 8.6 Mt, a scaling factor to 10 Mt is given for comparison against the Table 2 values. As previously mentioned approximately 1 Mt of scrap is used internally in the UK so this would not be captured in the export data. This extra used scrap brings the values close to the 10 Mt level again.

Table 3: A summary of UK ferrous scrap exports in 2018[15].

ISSB scrap Label	Mass exported (kt)	10 Mt total scaling (kt)	Equivalent scrap cat from Table 2.
Cast Iron	437.221	504.63	9A/9D
Turnings	98.898	114.17	7A
New Steel	120.322	138.87	8A/12A
Old Steel	3844.704	4437.48	0A/1/2
Fragmentised	2402.761	2773.22	3B
Scrap Ingots	0.249	0.29	N/A
Other Non-alloyed	384.341	443.60	6A/
Stainless	283.806	327.56	N/A
Other Alloyed	1085.174	1252.49	N/A
Rail	6.685	7.72	9A
Total	8664.161	10000	

The compiled literature approach results and export sales match well in general for the high residual grades such as the basic OA/1/2 grades and the 3B grade. The only major discrepancy which would have a major effect on the model is the quantity of new production scraps (prompt scrap) – cat 8A. This is significantly smaller in the export table (Table 3) than the literature model (Table 2). Given the fact one of the major users of scrap in the UK is a speciality steel EAF manufacture, there will be a disproportionate volume of this scrap used internally in the UK. As such this would give a disproportionate under representation of 8A in the export volumes and gives a clear explanation for the difference seen. As such the values from Table 2 were deemed a good approximation for actual values and were used in the residual accumulation model case studies discussed below.

1.3 Scope of the scrap driven steel production model

The model developed in this work utilises the information on CO_2 generation and scrap quality to evaluate the effects of proportional shifts in contribution to UK steel making between contributions of integrated (BF-BOF) and EAF production routes. This is assessed by considering the effects of cyclical scrap use balances on the internal supply of UK generated scrap.

2. Methodology

The base model functionality is built on three key factors:

1. The quality of scrap going into the processes
2. The effect of the processes on composition changes in steel
3. The iterative effect of the production process ratio on the next generation of scrap quality

The accuracy and effects of these three factors have a range of implications on the outputs of the model which will become apparent as the detail is discussed below.

2.1 Quality of scrap – Model Definitions

As previously mentioned the model focuses on residual elements in scrap and how these may aggregate over time as they are enriched in the steel through cyclical scrap based steel production.

As a result many of the intricacies of the scrap categories are irrelevant to the model, such as sizes, toxic nature and historic use of the material. The model purely considers residual concentration within the scrap. As seen above many of the UK scrap categories do not offer full specification on residual level content. This is a factor which needs to be deduced from combining further resources with the UK scrap categories specifications. The model currently has two potential scrap residual content data sets.

The first residual data set is acquired through comparing the UK scrap categories with the EU scrap standards[9,16]. The EU has issued a set of scrap standards for trading across the market, these standards, although similar to the UK in terms of specifying material sources, sizes and tolerable dirt levels, offer blanket guidelines on the categories chemistry tolerances. Table 4 presents the EU scrap grades, their specified chemistries and their equivalent UK scrap label. This is followed by Table 5, which is the result of splitting some of the cumulative element limits from EU standards to generate an input scrap matrix for the model.

Table 4: The EU scrap categories, their specified elemental composition limits and the closest equivalent UK grade deduced through description matching[16].

Scrap Family	Category	Aimed Analytical Contents (residuals) in %					UK cat Label
		Cu	Sn	Cr, Ni, Mo	S	P	

Old Scrap	E3	≤0.250	≤0.010	∑≤0.250			0A & 1
	E1	≤0.400	≤0.020	∑≤0.300			2, 5 & 9
New Scrap (Low Res)	E2	∑≤0.300					4 & 8
	E8	∑≤0.300					12 C
	E6	∑≤0.300					4 & 8
Shredded	E40	≤0.250	≤0.020				3
Turnings	E5H	Prior chemical analysis could be required					7B
	E5M	≤0.400	≤0.030	∑≤1.000	≤0.100		7A
High Res	EHRB	≤0.450	≤0.030	∑≤0.350			12 A
	EHRM	≤0.400	≤0.030	∑≤1.000			12 A
Incineration	E46	≤0.500	≤0.070				6

Table 5: The expected residual quantities of UK scrap categories as derived from EU standards.

UK Scrap ID	Cu %	Ni %	Sn %	Mo %	Cr %
0A	0.15	0.05	0.005	0.05	0.1
1	0.25	0.05	0.01	0.05	0.15
2	0.4	0.6	0.02	0.13	0.24
3B	0.25	-	0.03	0.05	0.25
6A	0.5	-	0.07	0.005	0.01
7A	0.4	0.43	0.03	0.1	0.56
8A	0.1	0.02	0.01	0.01	0.07
9A	0.4	0.02	0.01	0.01	0.07
9D	0.4	0.02	0.01	0.01	0.07
12A	0.1	0.02	0.01	0.01	0.07

The second method for acquiring a residual data set was through collaborating with industrial steel producers. Several UK manufacturers were asked for their internal elemental composition specification for the scrap grades utilised. These values were then averaged to create an anonymized data set as presented in Table 6. The specification for scrap grades the industrial collaborators used have resulted from many years of internal characterisation in order for them to safely and robustly use a variety of scraps from multiple sources in order to be flexible to the scrap market at a given time of purchasing.

Table 6: The residual quantities of scrap categories averaged from industrial contributors.

UK Scrap ID	Fe %	Cu %	Ni %	Sn %	Mo %	Cr %
0A	98.2	0.2	0.15	0.025	0.05	0.15
1	97.8	0.2	0.25	0.025	0.05	0.15
2	98.2	0.35	0.25	0.025	0.55	0.25
3B	97.1	0.35	0.1	0.021	0.3	0.25
6A	95.2	0.38	0.41	0.05	0.01	1.67
7A	97.1	0.25	0.25	0.02	0.06	0.25
8A	98.15	0.03	0.058	0.001	0.05	0.03
9A	92.7	0.05	0.2	0.011	0.05	0.02
9D	92.9	0.05	0.2	0.011	0.05	0.02
12A	98.2	0.15	0.15	0.02	0.05	0.1

Using the EU standards only allows the maximum levels of residuals under each categories to be outlined rather than the in use learned values from the industrial collaborators. Essentially Table 5 presents an expected worst case scenario with scrap purchased still being within its guided allowance, whereas Table 6 presents the qualities which are actually being produced. Thus table 6 is the values used in the case studies to follow in this article.

2.2 The Effect of Process on Composition

Due to the volumes, weight fractions of scrap and processing conditions created within the two processing routes, elemental refining/retention can vary across the BF-BOF and EAF liquid metal production technologies.

2.2.1 BF-BOF – Residual Behaviour

In the BF-BOF route scrap is added to the process in two places, the blast furnace and BOF. The volumes of scrap loaded into the BF are at such a low level (in the low single digit percentages) in any normal practice that the model will consider all scrap volumes within this processing route to be added to the BOF. In current practices scrap additions in the BOF can vary from 5-20% depending on a few factors such as the availability of hot metal, the cost of scrap versus hot metal, and the level of control required in final liquid steel (tighter control would require use of low residual scrap or lower volumes of scrap as they are the main source of residuals as opposed to any carry over from the BF).

The effect of the BOF on removal of residual elements is difficult to quantify. This is because of the lack of knowledge with regards to the true compositions of materials placed into the process. The hot metal from the blast furnace is always sampled and undergoes mass spectroscopy(an average hot metal composition from UK manufacturing sites over the last 2 years has been used for the model inputs presented), however the scrap compositions can only be assumed as those above (Table 6 at best accuracy), and they are either the weak definitions from the national/international scrap standards or those learned through inference of practice and back tracked upstream through the process – i.e. the scrap quality is defined by the product not by its own characterisation.

Pilot plant studies offer unique opportunities to infer refining performance of some elements. The European Research Fund for Coal and Steel (managed by the European commission) project “IMPHOS-Improved phosphorus refine”[17] published composition data for a set of pilot plant BOF experiments which were well characterized. The pilot plant BOF in this case was charged with hot metal produced by melting scrap in a small EAF before tapping into the BOF with no additional scrap. Compositions of the hot metal added and of the final steel were measured. With regards to tramp elements considered by the model chromium and copper were measured. Additional literature sources are coupled together with these IMPHOS characteristics to estimate percentages of final element compositions in comparison to their starting composition for Cu, Sn, Zn, Ni, Mo and Cr in Table 7[10,17–20].

Table 7: The retention rates of tramp impurities in the BOF process. Due to the preferential oxidation of Fe over Cu under BOF conditions Cu is seen to enrich[10,17–20]

Element	Cu %	Sn %	Zn %	Ni %	Mo %	Cr %
BOF Retention percentage	135	96	34	99	88	10

2.2.2 EAF – Residual Behaviour

As with the BOF there is an inherent difficulty in determining the removal or retention of residuals in the EAF as scrap is so poorly characterised with regards to the content for an individual bath of liquid steel production. This inhibits a direct method of measuring residual behaviour, however we can combine knowledge on how elements are removed in the process with fundamental thermodynamics and comparative studies between EAF and BOF performances.

Both the EAF and BOF are processes under oxidizing conditions with partial pressures of oxygen at approximately 10^{-8} bar. If this knowledge is combined with a processing temperature of 1600 ^{o}C it is possible to calculate, from Gibbs free energy, an affinity of each element to oxygen and thus its likelihood of partitioning to the slag phase in the process. Figure 2 presents a graphical representation (an Ellingham diagram) of the effect of temperature on Gibbs enthalpy of formation for undesirable elements typically reliant on the steelmaking stage of production for control. Iron is also included in the diagram for comparison.

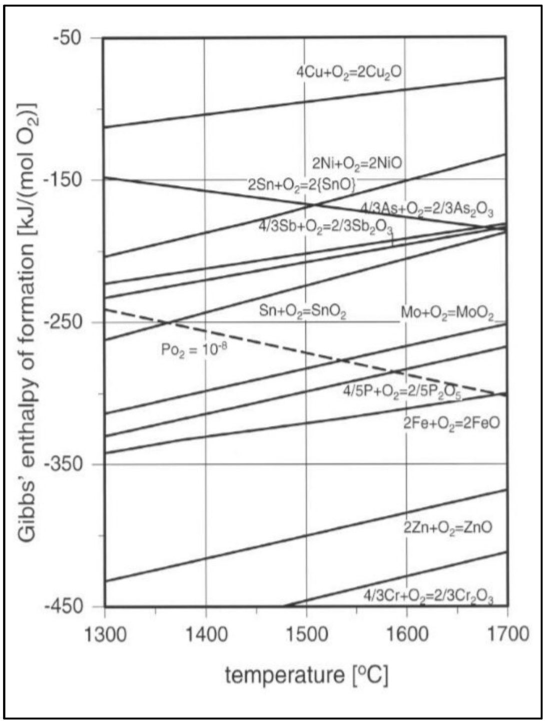

Figure 2. The effect of temperature on Gibbs free energy of formation for steelmaking impurities.[18]

From Figure 2 it is possible to obtain a level of oxygen reactivity for each element, in descending order: Cr, Zn, Fe, Mo, Sn, Sb, As, Ni and Cu. From this it can be seen why Mo, Sn, Sb, As, Ni and Cu are extremely difficult to remove in standard steelmaking practices and in fact from a purely chemical point of view are likely to enrich but not to reduce, as iron oxidizes preferentially.

As a second step sublimation of the impurities needs to be considered. Vacuum pressures of 1 to 5 mbar are usual in steelmaking conditions[4,10]. Combining vacuum pressures with a temperature of 1600 ^{0}C and an ideal Raoult's activity coefficient of 1 an estimate of sublimation rates of each elements in the process is possible. Figure 3 gives the liberation pressure of the residual elements depending on concentration. From Figure 3, of the considered residuals, only the Zn profile crosses the pressures seen under industrial steelmaking conditions. This combination of low sublimation negative pressures and the high affinity to oxygen combine to give the driving force for the high levels of Zn removal. These two factors are consistent across the two processes (BOF and EAF) and as such Zn removal will be considered to be the same in the EAF process as for the BOF for a comparison between these two routes.

Due to the smaller volumes typically processed in a single EAF batch as opposed to the BOF, the balance of Cr refining against iron yield is marginally modified in an unfavourable direction. Due to this, although possible, additional oxygen blowing into the EAF for Cr removal is generally avoided and as such the refining of Cr is considered to be reduced compared to the BOF. This balance results in approximately 12% Cr retention in the EAF.

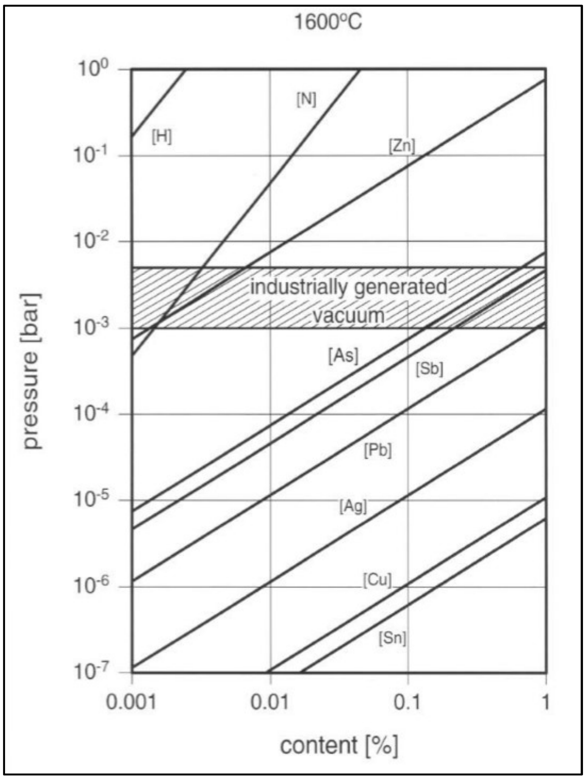

Figure 3. The sublimation pressures of steelmaking residuals with changing starting percentage.[4,10]

Due to the comparatively low levels of Mo in a melt compared to the other residual elements the reactions of Mo are generally considered to be rate limited with regards to chemical potential rather than driven by theoretical minimum. The EAF process runs on average longer than the BOF and as a result the retention rate of Mo is consider to drop to close to 85%.

This leaves Cu, Sn and Ni. These elements have low sublimation potential and low affinity to oxygen. All the retention values in the BOF study are either close to or above 100%. This is because their concentration is essentially less driven by the removal of the impurity, but actually by the preferential oxidation of iron into the slag phase causing enrichment. Iron oxide concentrations are similar if not slightly higher in EAF end process slags (~20%) compared to BOF end process slag (~18%) by approximately 2% on average. In addition the EAF process tends to be run with a higher slag/liquid-steel ratio. Meaning retention levels of these elements could be up to 4% greater than seen in the BOF[19].

The combination of these considerations gives rise to the estimated EAF retention percentages given in Table 8.

Table 8: The retention rates of tramp impurities in the EAF process.

Element	Cu %	Sn %	Zn %	Ni %	Mo %	Cr %
EAF Retention percentage	141	101	34	107	85	11

2.3 Iterative Scrap Compositions

This step of the model is where residual levels build up each time scrap is put back into the processes. With an aim to investigate the life-cycle effects on a closed border UK wide production strategy, where all scrap used is produced internally within the UK from purely UK based manufacturing/production processes. This would mean the only import of ferrous material to the UK is in virgin iron ore – whilst this is not representative of the current or near future situation it provides a hypothetical scenario for the consideration of residual element change.

Scraps such as the 8, 9 and 12 grades are treated in a relatively simple manner. This is that in these grades, essentially 100% of the material is a piece of high iron metal. As such the residual content of these grades will completely depend on the output chemistries from the previous iteration of the model. For example if 100% 8A was used in the EAF and it is assumed that no other additional chemistry alterations through alloying occurs, then the copper, tin and nickel contents would be higher for the input scrap into the next process, whereas zinc, molybdenum and chromium would be lower.

On the other hand scrap grades such as 3, 6 and 7 present a different condition. Take 6A as presented in Table 6 for example. 6A is for the large part thin walled packaging steel made from strip steel. Strip steel has some of the strictest overall residual level control requirements due to the processing the material goes through to be rolled to such thin gauges without slitting or cracking. All but the Sn and Mo levels in this scrap category are higher than the maximum content in the products that go into the scrap grade. As a result it can be considered that significant levels of contamination in the scrap grade from other materials – for example aluminium, copper, brass and stainless steel are likely 'contaminating' materials in this category due to the process of collection and incineration this scrap grade goes through.

To correctly manage this uncertainty a calibration of the scraps contaminants is made. This is done by taking the residual levels in the prompt scrap grade 8A with the assumption this is the cleanest the ferrous fraction of the contaminated grades could be and deducting these values to generate a contamination contribution to residual levels. Through each cycle of the model the contamination contribution then remains the same, as the model is considering a homeostatic level of scrap sorting and segregation, and the ferrous fraction residual levels are increased. As such if each scrap grade was used in the same quantities and through the same process each time the increments of residual level for every category will be the same across the matrix. The iterative treatment of scrap is presented as a flow diagram in Figure 4 using scrap grade 3B and an automotive application of steel as an example.

Mathematically this could be expressed as in equations 3, 4 and 5:

$$Cu_{Sg^o} = Cu_{CC^o} + Cu_{Fe^o} \quad [3]$$

$$Cu_{Sg^n} = Cu_{CC^o} + Cu_{Fe^{n-1}} \quad [4]$$

$$Cu_{Fe^n} = f(Cu_{Sg^n}) \quad [5]$$

Where Cu_{sg}^o is the starting copper content of the scrap grade, Cu_{cc}^o is the copper contamination due to the recycling process in the scrap grade, Cu_{Fe}^o is the starting copper content of steel in the scrap grade, n is the cycle number and f is the process retention function copper.

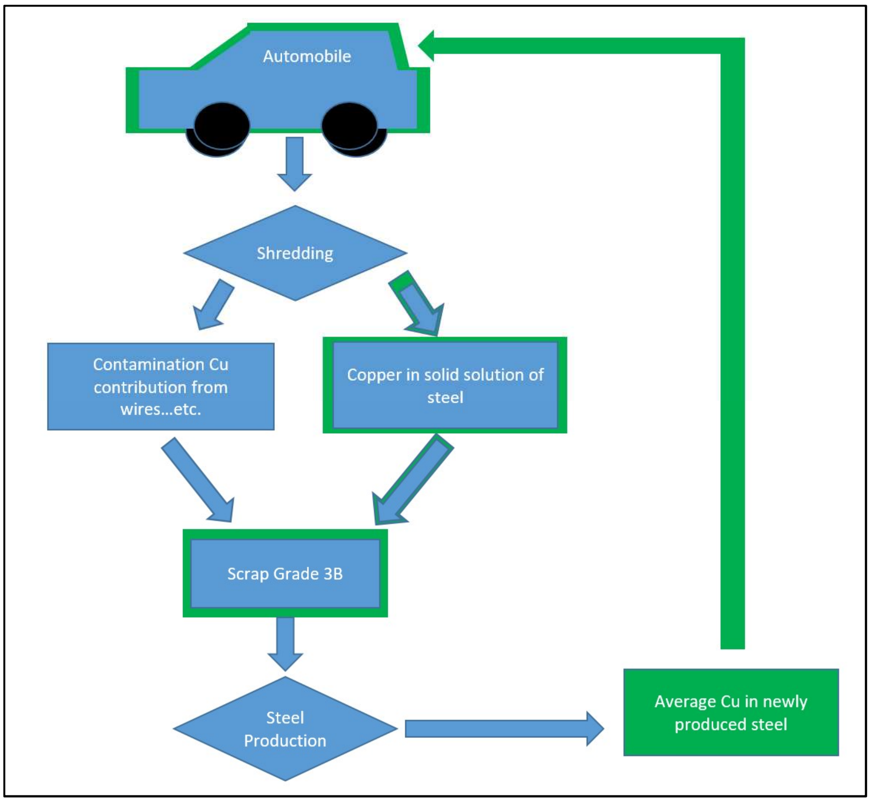

Figure 4. An example using Cu in the model treatments of iterative scrap residual enrichment due to cyclical material re-use. The initial process features are in blue while the cyclical build-up of residual elements and where they end up is in green.

3. Results:

The model has been run under several conditions in order to hone in on a potential sustainable production strategy for the UK moving forward. This includes:

1. All steel production via the BF-BOF route varying the ratios of high and low residual scrap grades
2. All steel production via the EAF route varying the ratios of high and low residual scrap grades

3. Varying ratios of BF-BOF/EAF production utilising high residual scraps in the BF-BOF route and low residual scraps in the EAF route as defined in Tables 1 & 2.

As the model has been developed due to the drive for reducing CO_2 emissions from the industry, within these case studies the BOF will be charged with 20 wt% scrap, as this is at the upper end of current industrial practice, which results in a lower CO_2 production per tonne of steel produced via the BF-BOF route compared with lower scrap content being used.

3.1 All steel production via the BF-BOF

This case study presents a worst case scenario with regards to CO_2 emissions from the industry. The UK steel industry currently sits at just under 70% production share via the BF-BOF route, and thus is already cleaner with regards to emission levels than a 100% BF-BOF route. However it is useful to see the bench marking of production under these circumstances.

For this scenario the effect of the changing ratio of high to low residual scrap usage in the BOF will be studied. The grouping of scrap categories in terms of high and low residual (HR and LR) are based on their starting weighted sum of Cu, Ni, Sn, Mo and Cr. From this, scrap categories OA, 1, 2, 3B, 6A, 7A and 12A are defined as high residual scraps and 8A, 9A and 9D are defined as low residual scraps. 100% of both high and low residual scrap charging as well as ratios of 90/10, 80/20, 70/30, 60/40 and 50/50 (HR/LR) are included.

A weighted average with respect to the scrap availabilities for each category as given in Table 2 was used to generate the input residual values within the high and low scrap categories, as well as an unweighted average of all scrap categories (average). Under this the cyclical conditions of Cu, Sn, and a residual equivalence (RE) value (equation 6 – derived from industrial practice for specific process requirements) are calculated and the results given in Figures 5, 6, and 7 respectively.

$$RE = Cu_{wt\%} + Ni_{wt\%} + 5xSn_{wt\%} + 10xMo_{wt\%} + Cr_{wt\%} \quad [6]$$

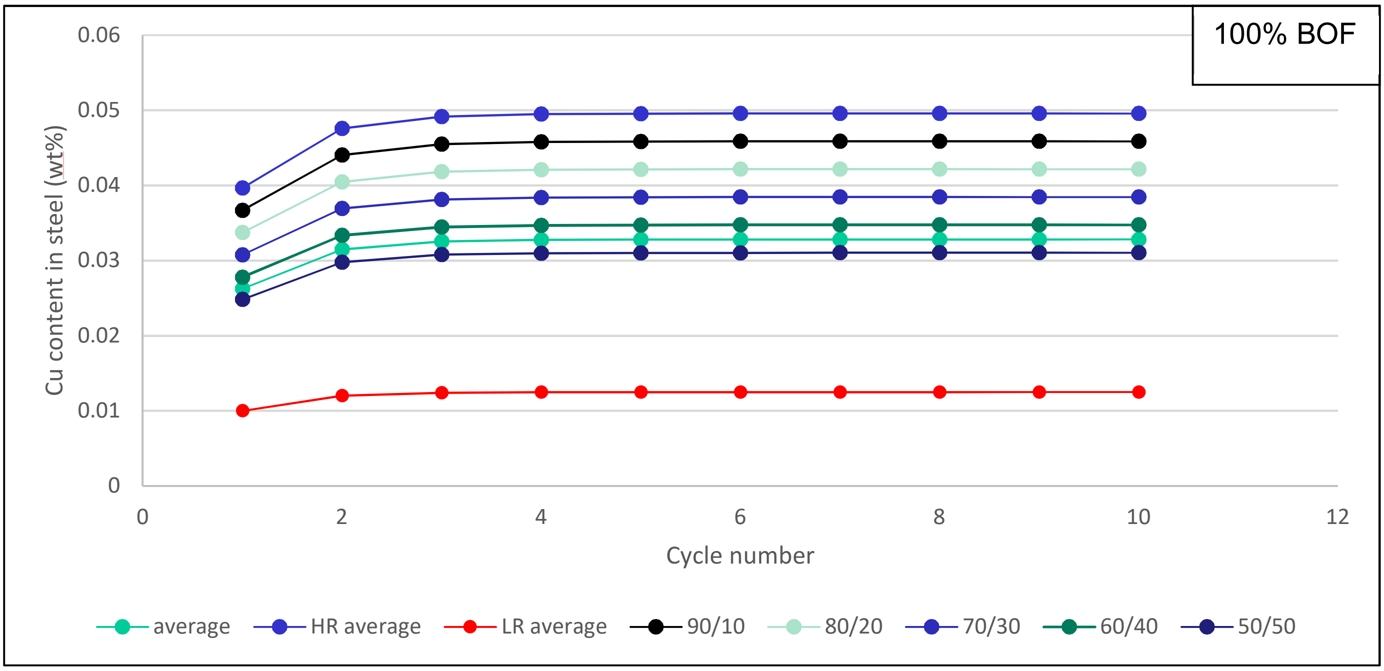

Figure 5. The cyclical aggregation of copper from producing steel in the BOF through closed border UK recycling of scrap at a 20% scrap content and average scrap copper contents. Where 'average' is produced from the average Cu content of all scrap grades, 'HR average' is produced from the weighted Cu average of HR scrap grades, 'LR average' is produced from the weighted Cu average of LR scrap grades and other data sets are produced from a percentage split of 'HR average/LR average' scrap usage.

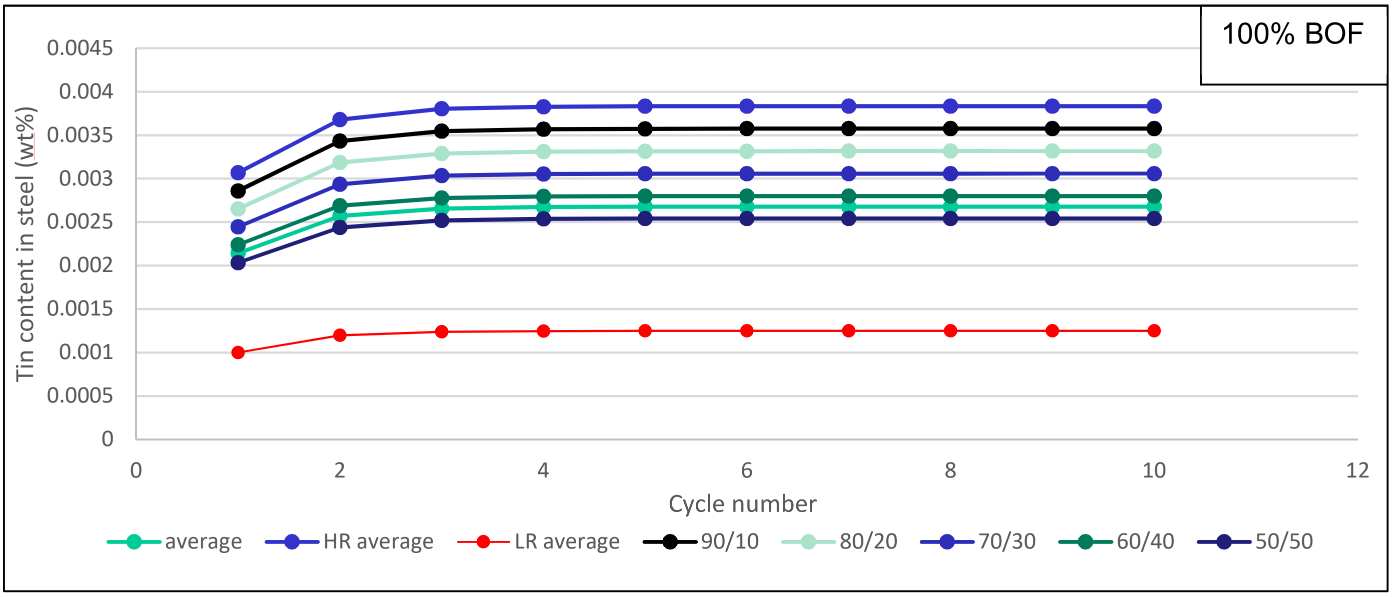

Figure 6. The cyclical aggregation of tin from producing steel in the BOF through closed border UK recycling of scrap at a 20% scrap content and average scrap tin contents. Where 'average' is produced from the average Sn content of all scrap grades, 'HR average' is produced from the weighted Sn average of HR scrap grades, 'LR average' is produced from the weighted Sn average of LR scrap grades and other data sets are produced from a percentage split of 'HR average/LR average' scrap usage.

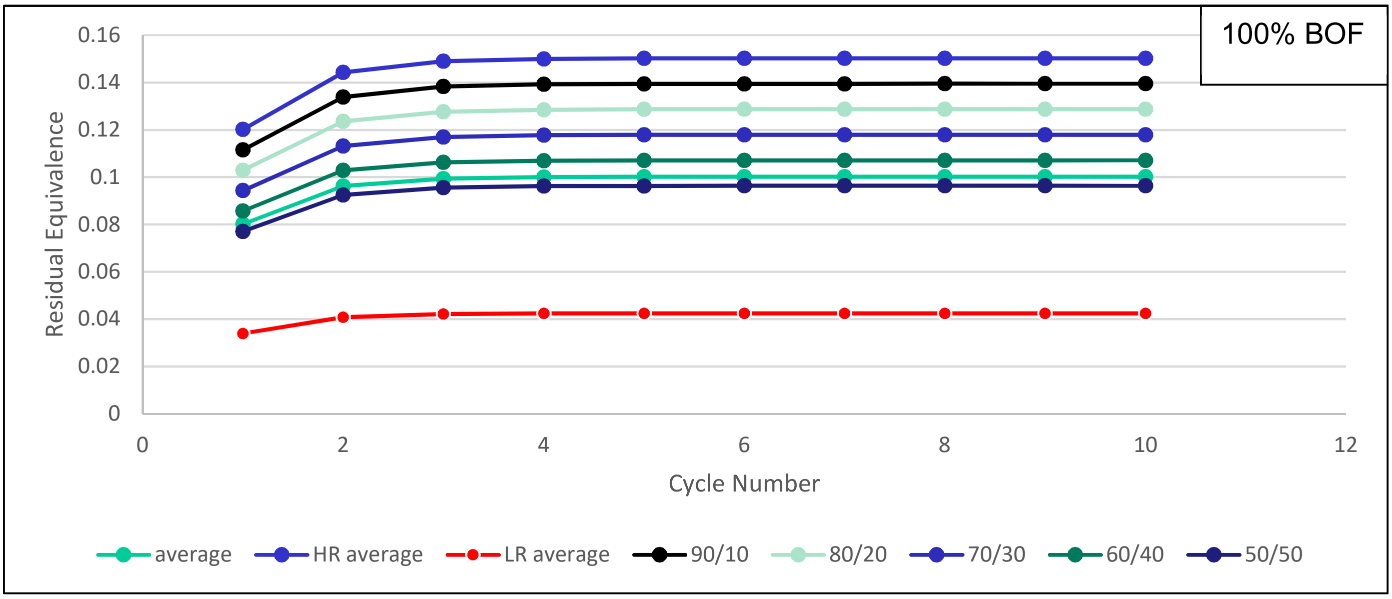

Figure 7. The cyclical aggregation of RE from producing steel in the BOF through closed border UK recycling of scrap at a 20% scrap content and average scrap RE contents. Where 'average' is produced from the average of all RE relevant elements of all scrap grades, 'HR average' is produced from the input of weighted average relevant elements to RE of HR scrap grades, 'LR average' is produced from the input of weighted average relevant elements to RE of LR scrap grades and other data sets are a percentage split of 'HR average/LR average' scrap usage.

3.2 All Steel production via the EAF route

This case study presents a best case scenario for the UK steel industry with regards to low CO_2 emissions. As previously stated the UK currently produces just over 30% of its steel via the EAF so a shift to 100% would be a major disruption to the industry.

For this scenario the same classification of scraps and their weighted averages are used as in the 100% BOF production case, however in this case study 100% scrap charging is considered as opposed to the 20% used in the BOF scenario. Figures 8, 9 and 10, present the effects of 100% EAF production on Cu, Sn and RE (equation 6) respectively.

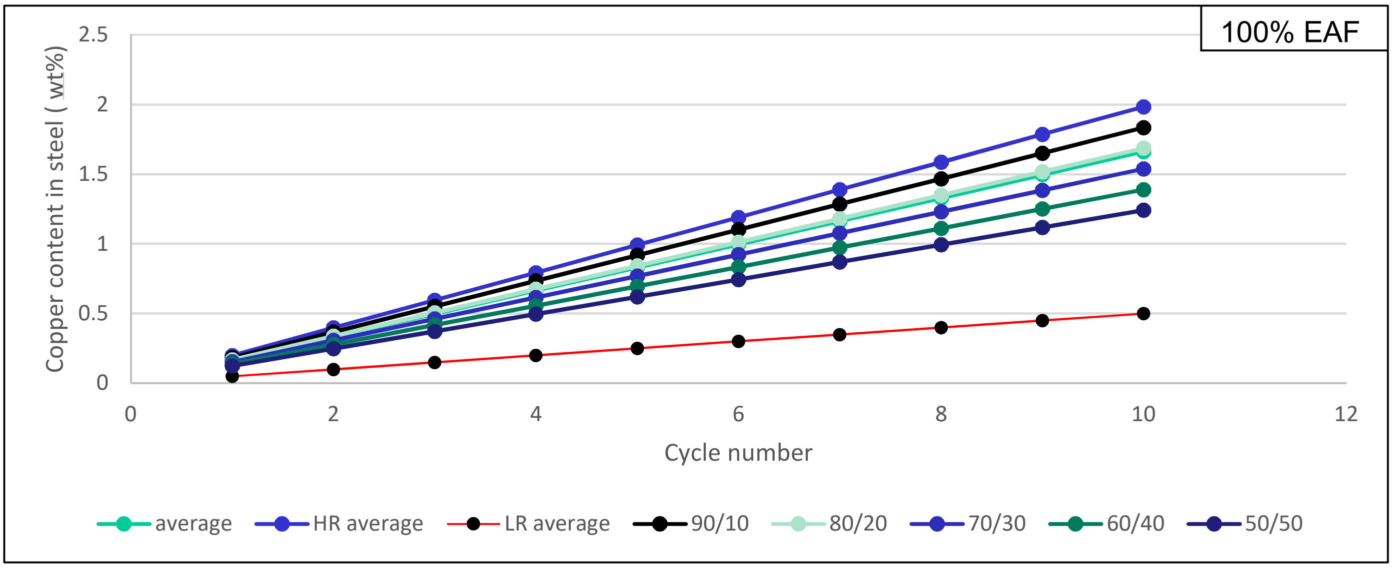

Figure 8. The cyclical aggregation of copper from producing steel in the EAF through closed border UK recycling of scrap at a 100% scrap content and average scrap copper contents. Where 'average' is produced from the average Cu content of all scrap grades, 'HR average' is produced from the weighted Cu average of HR scrap grades, 'LR average' is produced from the weighted Cu average of LR scrap grades and other data sets are produced from a percentage split of 'HR average/LR average' scrap usage.

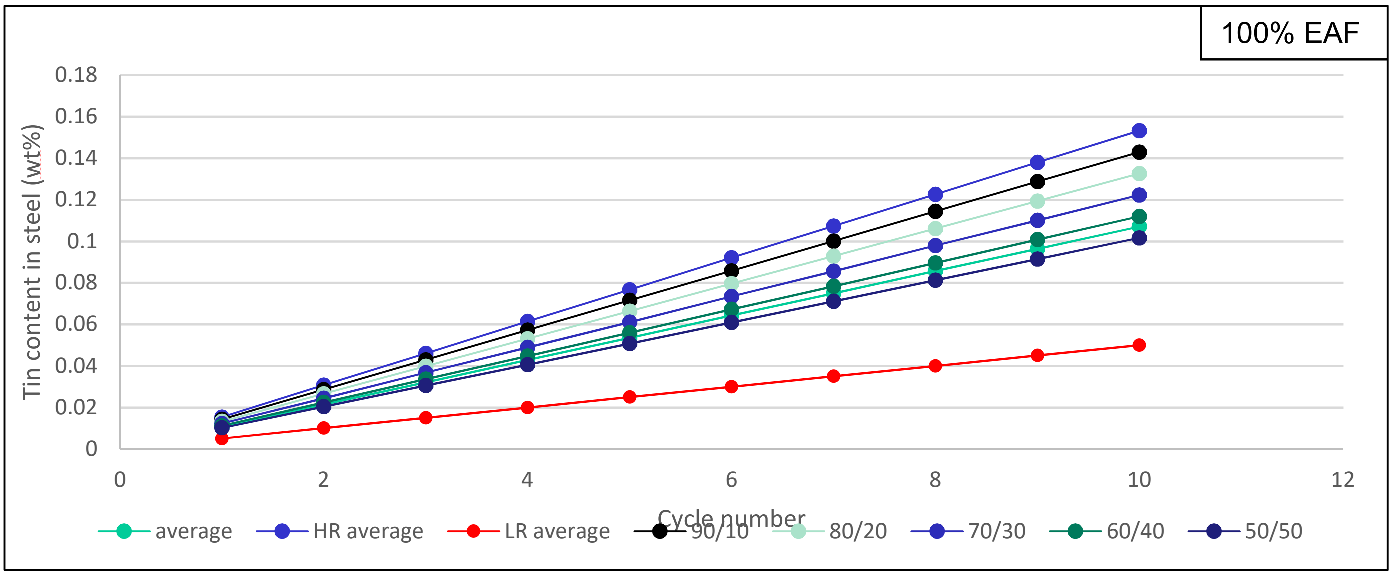

Figure 9. The cyclical aggregation of tin from producing steel in the EAF through closed border UK recycling of scrap at a 100% scrap content and average scrap tin contents. Where 'average' is produced from the average Sn content of all scrap grades, 'HR average' is produced from the weighted Sn average of HR scrap grades, 'LR average' is produced from the weighted Sn average of LR scrap grades and other data sets are produced from a percentage split of 'HR average/LR average' scrap usage.

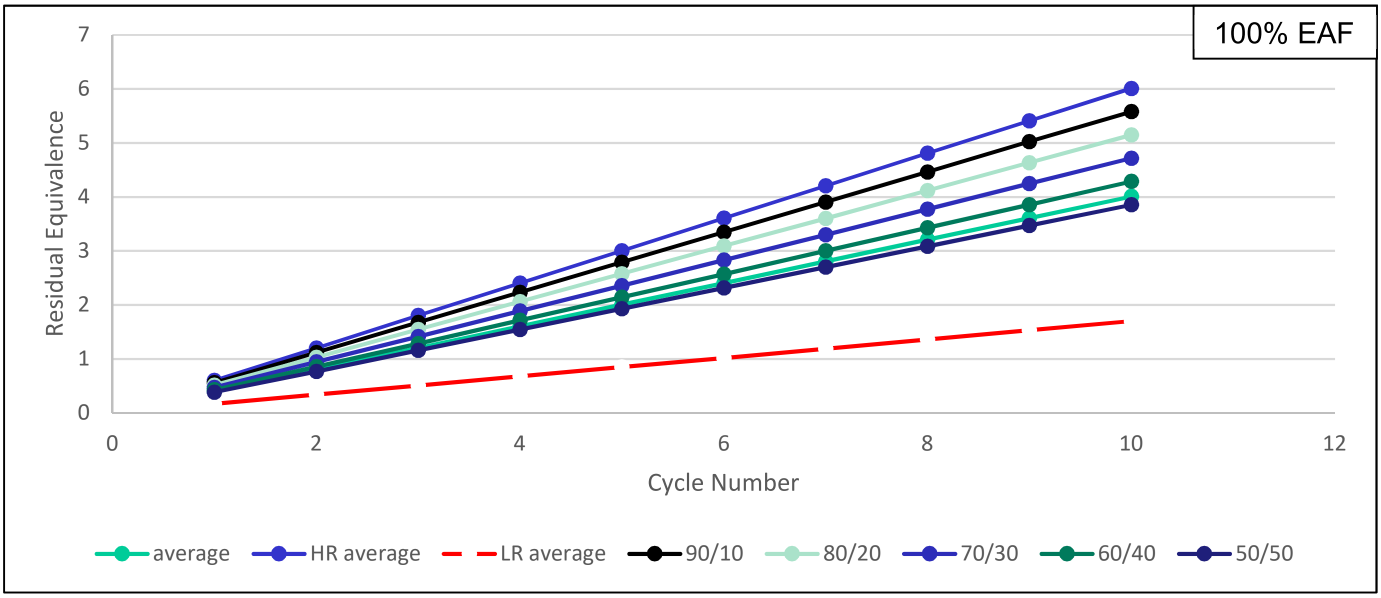

Figure 10. The cyclical aggregation of RE from producing steel in the EAF through closed border UK recycling of scrap at a 100% scrap content and average scrap RE contents. Where 'average' is produced from the average of all RE relevant elements of all scrap grades, 'HR average' is produced from the input of weighted average relevant elements to RE of HR scrap grades, 'LR average' is produced from the input of weighted average relevant elements to RE of LR scrap grades and other data sets are a percentage split of 'HR average/LR average' scrap usage.

3.3 The effect of proportional production via the BF-BOF and EAF

The final scenario considered in this paper is the effect of proportional production volumes between the BF-BOF and EAF processing routes. The model was run using the weighted average of HR scraps in the BF-BOF and the weighted average of LR scraps in the EAF route. The percentage of average production contributions between the BOF and EAF processes was then varied in 10% increments. The output for Cu, Sn and the residual equivalence are presented in Figures 11, 12 and 13 respectively.

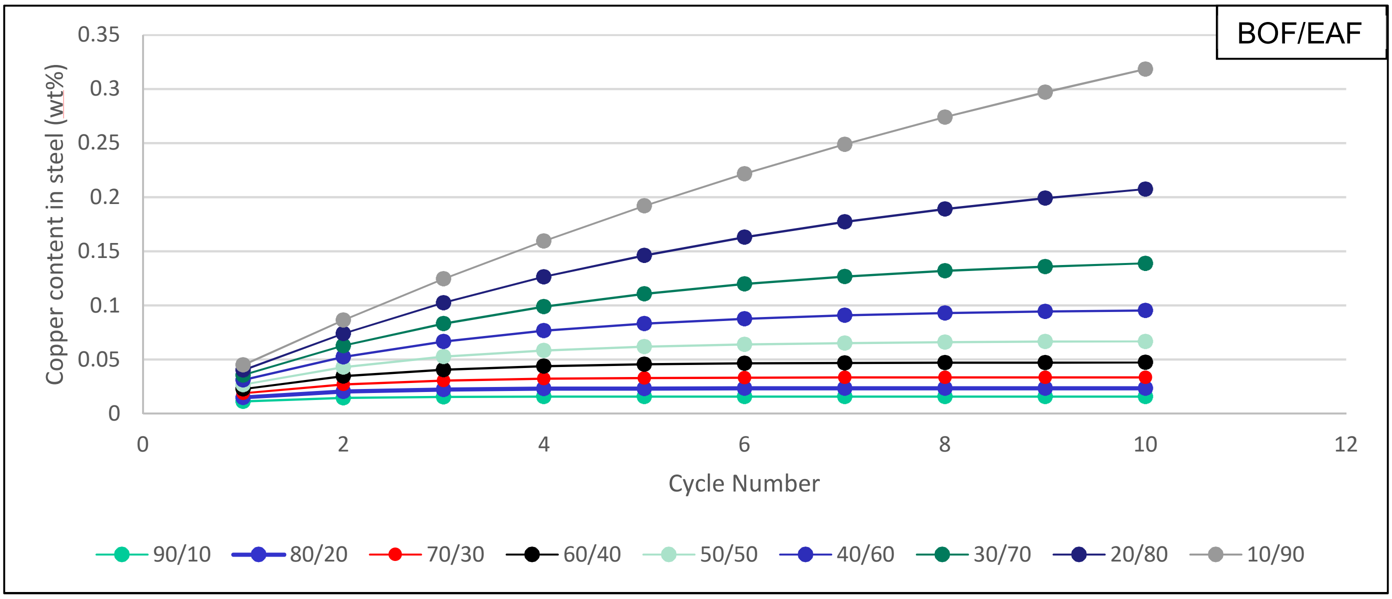

Figure 11. The cyclical aggregation of copper due to close border scrap recycling combining the effect of BOF and EAF as a percentage contribution of steel production utilising a weighted average of HR scrap in the BOF at 20% scrap loading and a weighted average of LR scrap in the EAF at 100% scrap loading.

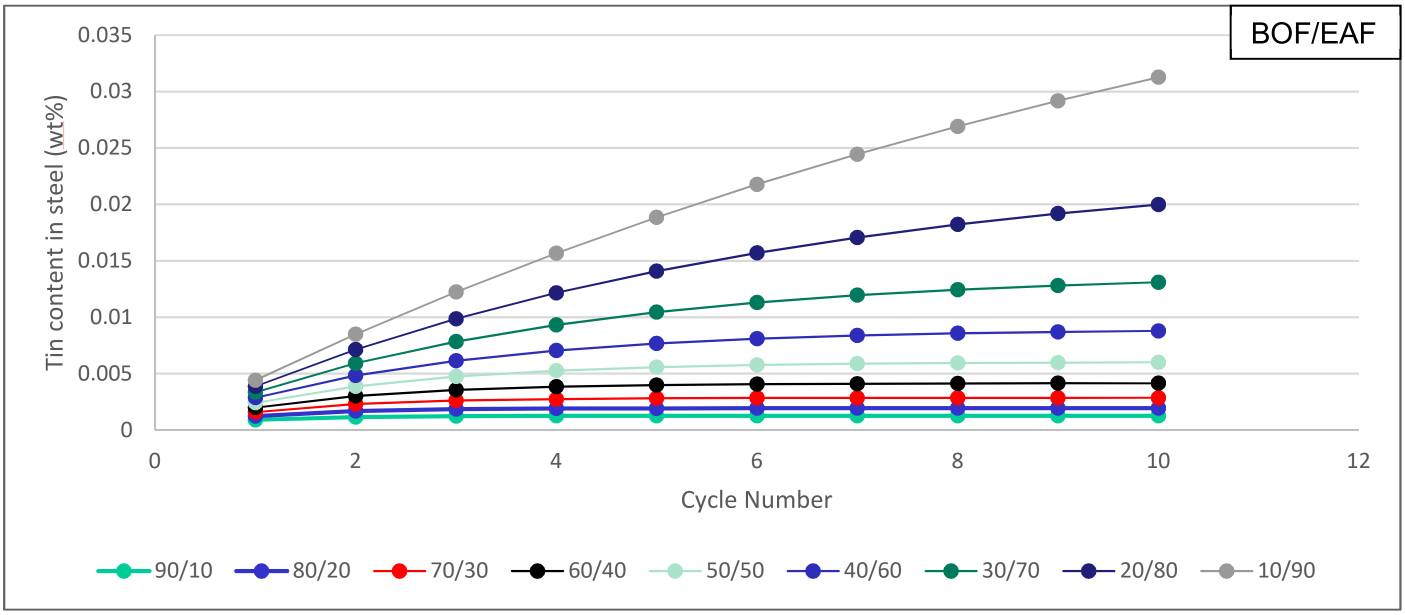

Figure 12. The cyclical aggregation of tin due to close border scrap recycling combining the effect of BOF and EAF as a percentage contribution of steel production utilising a weighted average of HR scrap in the BOF at 20% scrap loading and a weighted average of LR scrap in the EAF at 100% scrap loading.

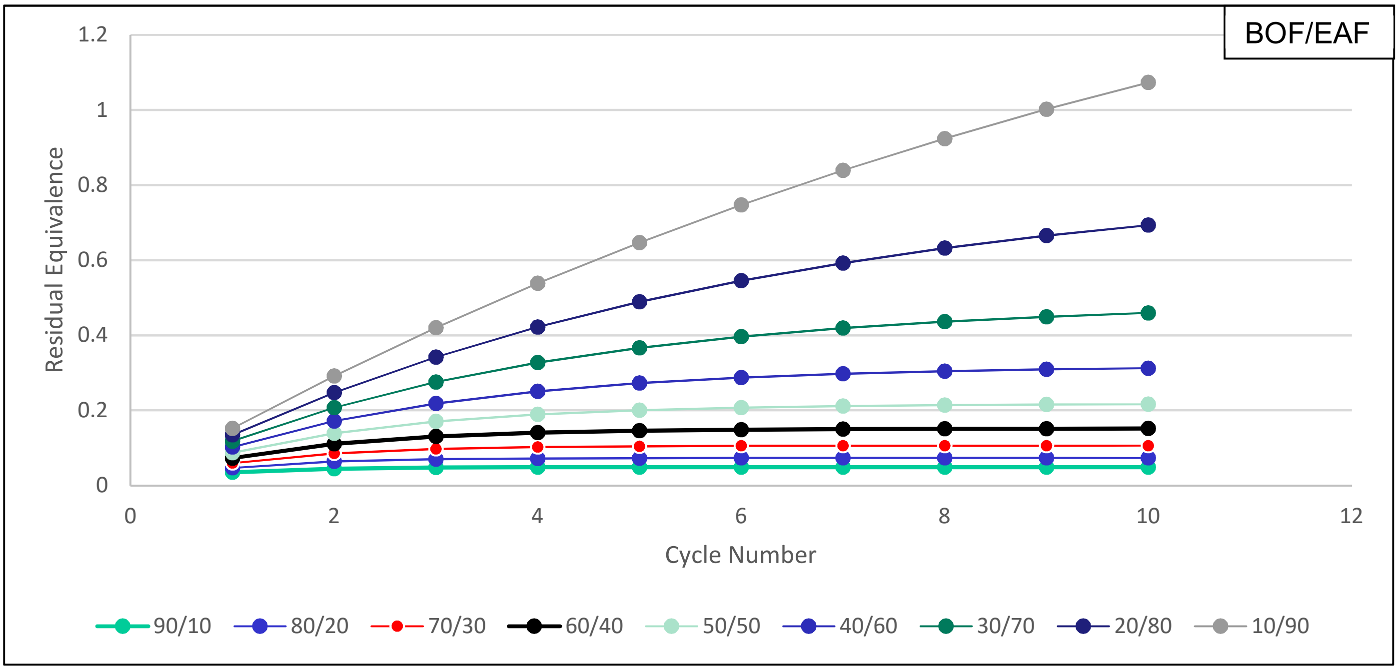

Figure 13. The cyclical aggregation of RE due to close border scrap recycling combining the effect of BOF and EAF as a percentage contribution of steel production utilising a weighted average of HR scrap in the BOF at 20% scrap loading and a weighted average of LR scrap in the EAF at 100% scrap loading.

So far the model has not considered the effects of scrap availability limits on the proportional volumes of each scrap type being loaded into the two processing routes. Assuming a UK steel demand of 10Mt (which is within the range of previously reported values when combining internally produced and imported semi-finished steel) to match that of the UK scrap supply volume, there is a limitation to how much steel could be made via the BOF route using only LR scraps. Specifically by combining the masses of scraps in categories 8A, 9A and 9D this gives a LR scrap availability of 1,562 kt in total. In addition to this open market scrap availability there are scrappage rates within steel mills themselves which could account for a significant portion of LR scrap availability and could be preferentially used in the EAF process, an assumption of 438 kt of internal scrap generation per annum is used as a nominal value for the purposes of this study to give around 20% LR scrap availability for the study. This results in a LR scrap availability of 2Mt.

The scenario of a maximum 2Mt of LR scrap in the weighted ratios available was used as an input to the model for the generation of 10Mt of steel. This results in combined production percentages, where greater than 20% production is via the EAF, which require HR scrap to be used in the EAF process. The results of this limited LR scrap supply on the residual equivalence average of the 10Mt are presented in Figure 14.

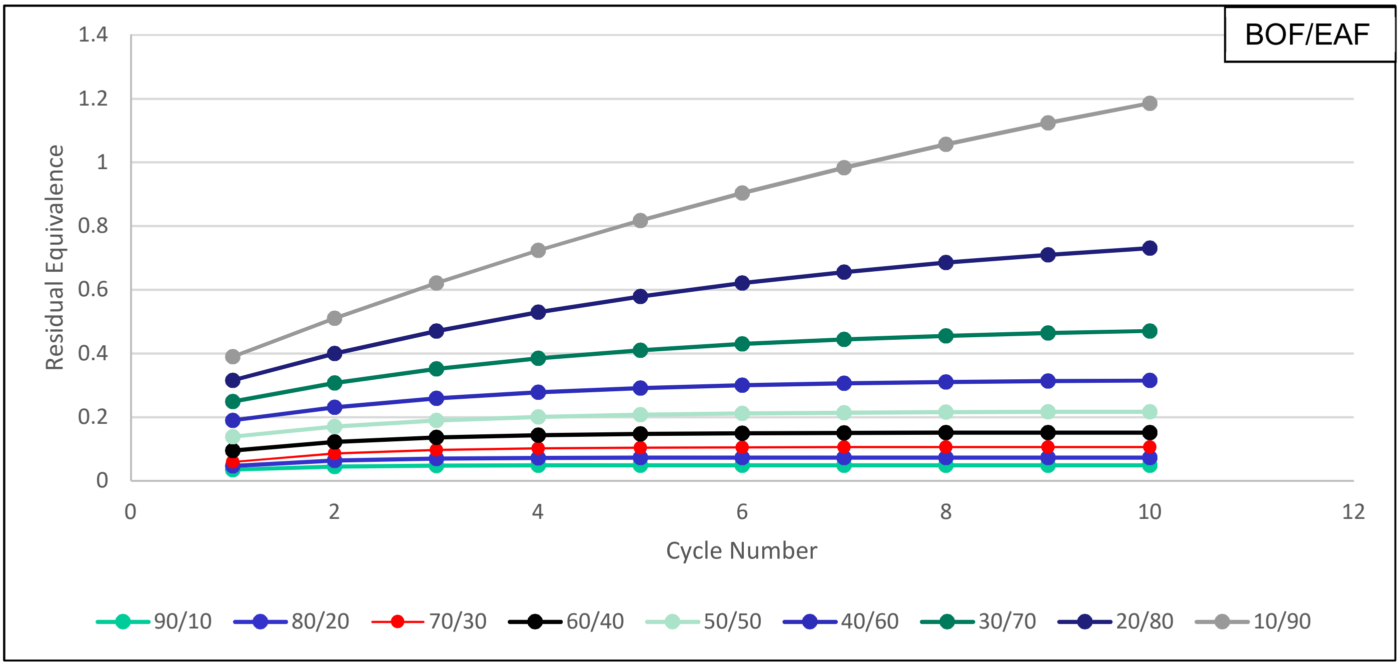

Figure 14. The average residual equivalence of 10Mt of steel produced with varying percentage split between BF-BOF and EAF production route, with a 2Mt limitation of LR scrap availability.

4. Discussion

4.1 The balance of processing routes

The BOF and EAF processing routes have very different profiles with regards to their residual level increases through iterations of processing material with the given technology.

The BOF has a profile of an early rise as the high scrap content is introduced however after each iteration the increase in Cu (figure 5), Sn (figure 6) and cumulative residual equivalence (figure 6) approximately plateau. The exact value of this plateau is dependent on the ratio of HR to LR scrap usage, with HR scraps causing the asymptotic nature of the curve to be at higher wt% contents. The fully scrap-based EAF on the other hand presents linear relationships with regards to any given scrap input ratio, with higher values being reached much sooner than via the BOF route as seen for Cu in figure 7, Sn in figure 8 and the cumulative residual equivalence in figure 9. Although the processing routes have marginally different capabilities in removal of residuals, with the BOF outperforming the EAF, the main contributor to both the lower absolute values via the BOF route and the asymptotic nature of the aggregation is due to the heavy dilution of residuals in the BOF by virgin iron ore being processed through the BF and being added to the BOF as hot metal (in these scenarios at 80% contribution levels of hot metal).

When the two routes combine a mixture of the two profiles is seen. Figures 10, 11 and 12 show the effect of varying the ratio of BF-BOF to EAF production. As the residual retention/enrichment effect of both processes are relatively similar, this profile can qualitatively be considered as a raw effect of using a varying HR/LR/hot-metal ratio as an overall UK strategy.

Four additional scenarios not bound by the predicted scrap availabilities of the UK are selected to calculate the effect of changing HR/LR/hot-metal ratios on the residual equivalence of 10Mt of produced steel and are presented in Figure 15, within the four cases the BOF is loaded with 20% scrap and the EAF with 100% scrap. These scenarios are:

1. 50/50*: A 50/50 production split via the BF-BOF/EAF with no limitation on LR scrap.
   a. Given a 10Mt production volume this equates to 4Mt of hot metal, 1 Mt of HR scrap in the BOF and 5 Mt of LR scrap in the EAF.
2. 70/30: A 70/30 production split via the BF-BOF/EAF with a limited LR scrap availability of 3Mt.
   a. Given a 10Mt production volume this equates to 5.6 Mt of hot metal, 1.4 Mt of HR scrap in the BOF and 3 Mt of LR scrap in the EAF
3. 60/40: A 60/40 production split via the BF-BOF/EAF with a limited LR scrap availability of 3Mt.
   a. Given a 10Mt production volume this equated to 4.8 Mt of hot metal, 1.2 Mt of HR scrap in the BOF, 1 Mt of HR scrap in the EAF and 3 MT of LR scrap in the EAF.
4. 50/50: A 50/50 production split via the BF-BOF/EAF with a limited LR scrap availability of 3Mt.
   a. Given a 10 MT production volume this equated to 4 Mt of hot metal, 1 Mt of HR scrap in the BOF, 2 Mt of HR scrap in the EAF and 3 Mt of LR scrap in the EAF.

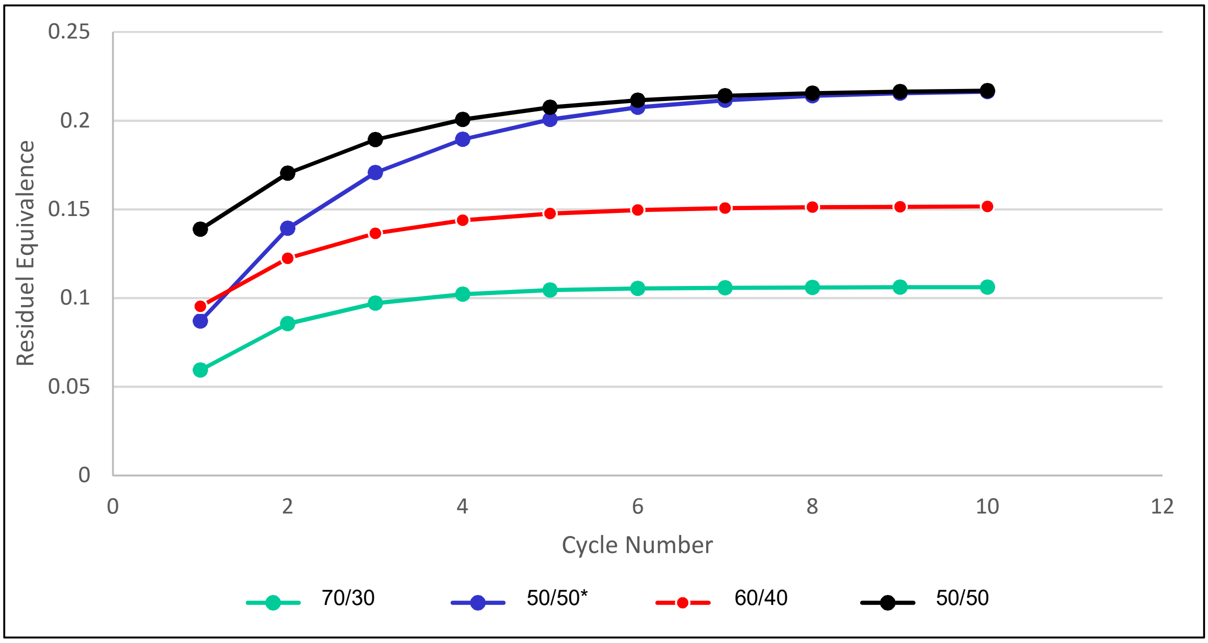

Figure 15. The effect of limited LR supply and production split on the trend of residual equivalence aggregation through cycle to produce 10 Mt of steel utilising 20% HR scrap in the BOF and 100% scrap with a maximum of 3Mt of LR scrap in the EAF.

Figure 15 clearly shows that the limitation of LR scrap availability has a large effect early on (the first 2 to 3 cycles). However as cycle number increases the limitation of LR scrap availability has an almost insignificant effect, especially when compared to the overall effect of the ratio split between production in the BF-BOF and EAF.

Considering scrap quantity and quality is difficult to measure or quantify, this could have a big effect on the viability of a production route split over the first few cycles of material in a closed materials loop system, this will be key to enabling a short term shift to lower CO_2 production of steel via the EAF route in the UK. However in the long term, the dilution effect of hot-metal drastically outweighs any variance in the scrap quantity or qualities and as such once a strategy balance between the two processes is struck upon, the industry can be clear at what level residuals are likely to aggregate towards in the longer term and as such can begin preparing for this through a quantitatively directed process and product development roadmap.

4.2 The effect of residual aggregation on production practice

The time it takes for material to circulate has a big effect on how relevant or problematic the aggregation of residual elements is. Literature sources provide life time expectancies of steel in varying products, the averages for a selection of specific and sectoral life cycles are presented in Table 9.

Table 9: The life cycle expectancy of steel when used in sector and specific applications[12].

Steel use	Average life cycle length (years)
Overall Average	38
Others	12.5
Domestic Appliances	10
Electrical Machinery	39
Mechanical Machinery	14
Rail	25
Line Pipe	30
Infrastructure	60
Construction	60
Ships	28
Trucks	9
Cars	12.5

The number of cycles material in these sectors would go through before the year 2050, the current target for net zero CO_2 emission, can then be calculated. These are presented on Figure 16 as vertical lines. By combining the life expectancies with volume of material used in each sector the overall steel life time average is also added to Figure 16. From this it can be seen that by 2050 material in trucks and domestic appliances would go through the recycling process twice, while cars, others and mechanical machinery would be into their second life cycle. The rest of the sectors would still be retaining material in their first life.

To make a comparison of the effects of production ratio split a comparison of these 2050 lines crossing residual equivalence lines can be made against typical residual content of steel grades produced for a given application.

The residual equivalence calculation as stated was developed as a way of safeguarding against the cumulative effects of the included elements on strip steel production. The limit several producers stick to in order to ensure consistent safe production of strip is 0.2. Strip is used in many, if not all, of the sectors. As such if a reading of 0.2 is taken the evidence shows that even in the first iteration of production (0 cycles) more than a 50% production via the EAF is close to or exceeding the acceptable levels of residuals on a national level.

From the literature approximately 50% of UK steel made and future demand is likely to be strip[21], and although not all strip has such tight constraints on residuals the vast majority does as it is a process restriction due to the thin gauges the material is rolled to, rather than product restriction. Long products such as rebar, free cutting steels and even those for high end applications such as aerospace grades, can have significantly lower restriction levels. For example rebar is sold on the market with copper levels of up to 0.4 wt%[22]. As such it is suggested that on a UK level, with strategic scrap management and production of low tolerance residual products via the BF-BOF route, a 50/50 split of BF-BOF/EAF would be achievable for both a short and long term outlook of the UK steel industry. Considering construction accounts for approximately 50% of steel demand produced in the UK, and approximately 50% of this demand is for rebar[12] (thus approx. 25% UK steel demand being rebar) there is scope to consider a 60% production via the EAF being a viable long term strategy for UK steel production while maintaining manageable residual contents with the current technological capabilities and scrap landscape.

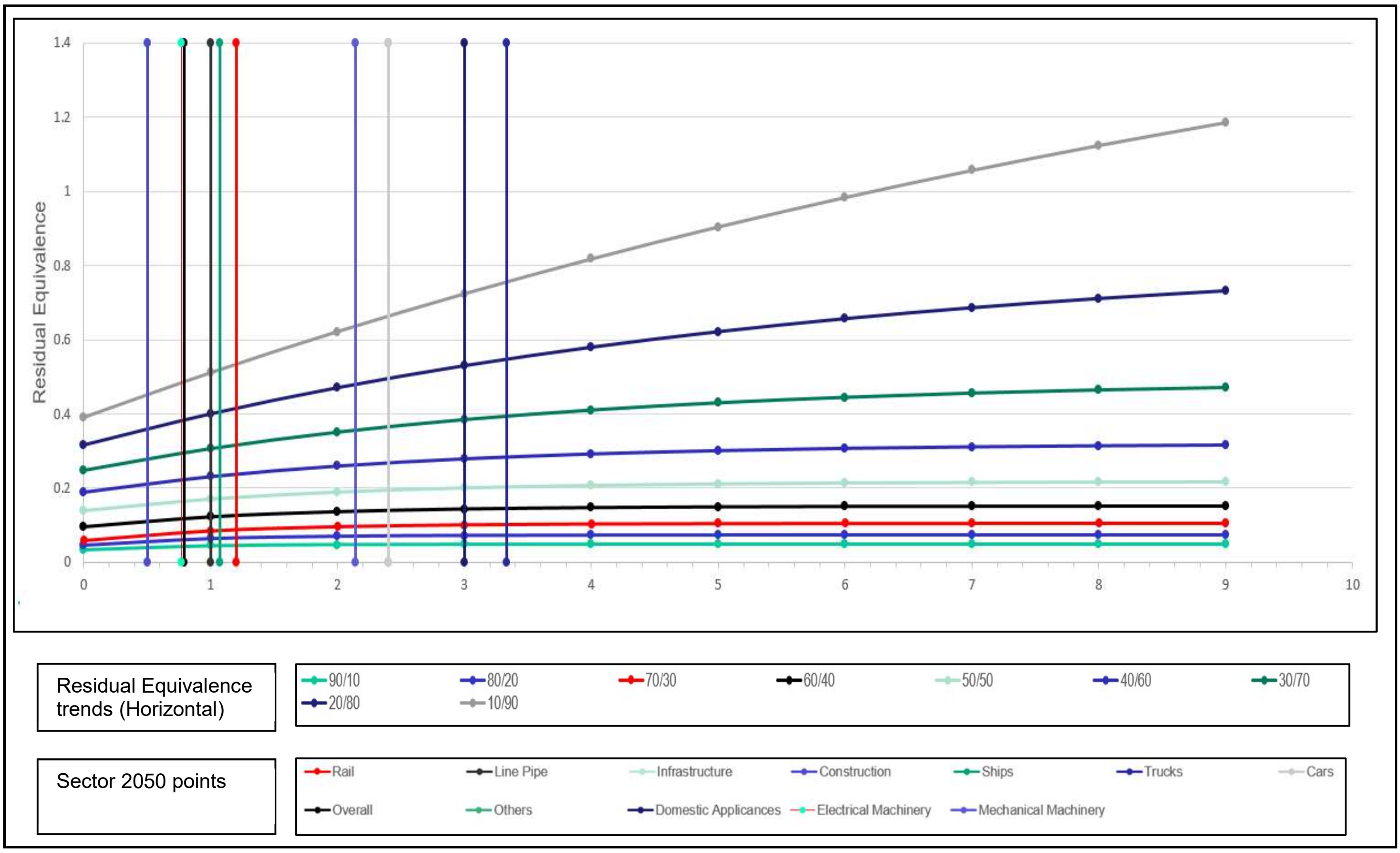

Figure 16. A comparison of sector steel life time as a function of material cycles by the year 2050 and the cumulative residual equivalence build-up which would occur via varying increments of BF-BOF/EAF production route share.

4.3 Additional considerations

Within this study there are numerous assumptions and modelled outcomes, however it is believed they are well understood, with factors such as scrap quality effects and scrap market share per category inherently addressed in the results analysis.

Despite this there is an overarching assumption which must be considered. The model only considers closed loop recycling of steel in the UK, there is no account for both imported semi-finished steel products and steel which is contained within imported steel goods. Steel from these sources would be of unknown production composition as any manufacturer could buy steel meeting their requirement from the numerous steel manufacturers around the globe.

The scrap landscape and production technologies vary on the local, national and international levels. However the UK's split of 70% integrated and 30% electric arc furnace production is not far from the current global average (70/30 BF/EAF) as reported by world steel in 2019[23]). Steel produced externally to the UK is thus likely to be mostly produced via the integrated steel process and be of low residual content in solid solution. The production of scrap from these steels both in prompt and end of life form would water down the residual build up in the scrap supplies – delaying the aggregation of tramp elements.

Despite this, from an ethical stand point, the authors believe this should not be considered when long term strategies for the UK steel industry are being considered. The reliance on overseas low residual scrap would essentially amount to exportation of CO_2 emissions from the industry to other countries, and the issue at stake is global warming, not national warming. The dilution of residual elements in scrap steel should thus be considered for confidence in the split of process route production, rather than an enabler of pushing the ratio of production further in favour of the EAF.

Table 10 presents the potential CO_2 emission per year of a UK steel industry producing 10 Mt of steel via the varying ratios of BF-BOF/EAF production (with the assumption the UK energy grid is maintained in its current efficiency and production technology split). As previously mentioned the UK steel industry is at approximately a 70/30 split, if producing 10 Mt this would mean 17.2 Mt of CO_2 being emitted by the industry per annum based on current technologies[2,3,24]. If a shift was made to what appears to be the technically capable production split of 50/50 BF-BOF/EAF a saving of 3.2 Mt of CO_2 per annum could be made. So, a shift to increasing another 20% of UK steel production via the EAF would be the same as the industry only producing under 8.2 Mt of steel compared to the model 10Mt. A significant step in the industry making progress towards net zero CO_2 emissions.

Table 10: The CO_2 output from a UK steel industry producing 10 Mt of steel per annum via varying ratios of production from integrated to EAF processing routes[2,3,24]

BF-BOF/EAF	90/10	80/20	70/30	60/40	50/50	40/60	30/70	20/80	10/90
Mt CO_2	20.4	18.8	17.2	15.6	14	12.4	10.8	9.2	7.6

5. Conclusions

The potential shift of the UK steel industry to high scrap usage as opposed to the current high fraction of hot metal production has been explored.

It was found that processing high residual scrap via the BF-BOF integrated steel production route at 20% charge allows for an effective plateau of tramp element levels at a given range of absolute values depending on the percentage of scraps used from the varying established UK scrap categories.

The opposite has been found for production via the EAF at 100% charge, where a continuing linear rise of residual build up would be seen in produced steel if a closed loop recycling of scrap was conducted purely via this technology.

Steel products have varying levels of control requirements for tramp elements and a high proportion of UK steel product demand is for reinforcing bar. Reinforcing bar can tolerate much higher levels of Cu, Sn, Mo, Ni and Ni than many other steel grades and as such offers a potential sink for highly tramp element contaminated scraps to allow for low residual scraps to be strategically utilised for high demand products/processes.

In addition the effect of scrap quality was explored showing that high volumes of cleaner scrap would enable notable lower levels of residual content in produced steel over the first 3-4 cycles of steel in use life times. However after this point the asymptotic nature of residual element enrichment is more controlled by the production split between the two processing routes than the starting scrap quality. This is important as with a target of 2050 emission reduction the first few life-cycles are what currently needs to be considered for effective rapid change.

When considering the UKs current and future steel demands the split of a 50/50 production route is considered to offer a sustainable and flexible level of scrap and hot-metal usage with regards to residual level maximums in processing and application of steel products. This would constitute a significant step of almost 20% CO_2 emission reduction from the industry per annum.

6. Acknowledgments

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