SI Mapping the global flow of aluminium: from liquid aluminium to fabricated goods

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1 Data sources for aluminium statistics

Table S1 presents a review of aluminium data sources. The table covers a wide range of data sources—global and regional associations, national statistical offices, trade organisations, research institutes, private media groups and companies—and specific examples are given from online databases through to company annual reports.

Organisation	Scope	Representation and data	Key data sources
International Aluminium Institute (IAI)	Global	IAI members represent 80% of global primary aluminium production and 27 member companies. It provides a global forum for aluminium producers and promotes a wider understanding of the key sustainably issues for aluminium.	Aluminium for future generations (IAI, 2008) Statistics, IAI website (IAI, nd)
U.S. Geological Survey (USGS)	Global (with US focus)	Tracks global bauxite ore extraction and resource stocks, aluminium production from ore and scrap, and more detailed US production and recycling statistics.	(USGS, nd)
European Aluminium Association (EAA)	Europe	Represents the European aluminium industry, collating data from European primary aluminium producers, rolled and extruded products associations.	*Environmental profile report* (EAA, 2008)
Organisation of the European Aluminium Recycling Industry (OEA)	Europe	Represents European (and other international) Refiners (cast alloys) and Remelters (wrought alloys) making products from mainly recycled scrap aluminium.	*Aluminium Recycling in Europe* (EAA/OEA, 2006)
The Aluminum Association	United States	Represents U.S. and Canadian producers of aluminium, aluminium recyclers, producers and suppliers of fabricated products	*Aluminum Statistical Review* (Aluminum Association, 2008)
Alcoa	Global (producer)	A global producer of primary aluminium and fabricated aluminium, and largest miner of bauxite and Refiner of alumina.	(Alcoa, nd)
Novelis	Global (producer)	Global producer of rolled aluminium sheet and foil products.	(Novelis, nd)
CRU	Global (media)	Provides business intelligence for global metal production, mining and other industrial sectors.	(CRU, nd)

Table S1—Review of aluminium data sources.

2 Constructing a map of global aluminium flows

In this section we describe the methodology for allocating aluminium flows and accounting for manufacturing yields, using data from a range of sources and while ensuring a consistent mass balance. The International Aluminium Institute (IAI 2008, IAI 2011) provides an overview of the major global aluminium flows and an extended breakdown of the global end-uses. However, to disaggregate the aluminium flows at a more detailed level requires the use of regional models from Europe and North America, alongside academic studies, company data and expert opinion, which is then scaled, reallocated and verified in the global mass balance.

2.1 Methodology

The global aluminium supply chain is divided into five major process steps, as shown in Table S2. For each of the five slices, we map the inputs (vector $\mathbf{x}$) onto the outputs (vector $\mathbf{y}$) using two matrices: an *allocation matrix* $\mathbf{A}$, which maps each input, by fractions, onto each output, and a *manufacturing yield matrix* $\mathbf{Y}$, which accounts for the material lost as scrap in transforming the input materials into output products. The two matrices are of equal size and are multiplied element wise, using the Hadamard product (symbol $\circ$).

Slices	Description
Electrolysis/ Melting	Alumina (extracted from bauxite ore) is converted using electrolysis to liquid aluminium ore. Aluminium scrap (from forming, fabrication and end-of-life) is melted in Remelters (to make wrought alloys) and Refiners (to make casting alloys).
Casting	Liquid aluminium is cast into slab, billet and alloy ingots, and subsequent remelting and casting in downstream facilities.
Rolling/ Forming/ Shape Casting	Slab ingots are hot rolled to plate and strip with some material undergoing further cold rolling and foil rolling, billet ingots are extruded or wire drawn and alloy ingots are shape cast, to produce a range of intermediate products.
Fabrication	Intermediate products are cut, joined, machined and assembled into fabricated products.
End-use	Fabricated products are allocated to end-uses in construction, and as vehicles, industrial equipment, and metal products.

Table S2—Major processes steps for aluminium are used to create the five vertical slices in the Sankey diagram.

Written formally:

$$\mathbf{y} = (\mathbf{A} \circ \mathbf{Y})\mathbf{x} \tag{1}$$

An equivalent loss vector $\mathbf{y}_L$ is defined as:

$$\mathbf{y}_L = \big(\mathbf{A} \circ (\mathbf{J} - \mathbf{Y})\big)\mathbf{x} \tag{2}$$

where **J** is a matrix of ones, of equal size to **Y** and **A.**

Four allocation matrices and four yield matrices are created to map between the five slices, and are populated using industrial statistics from a number of different sources. In some cases, the mapping is inferred, estimated or back calculated, if the direct values for the vectors or matrices are not available. For the yield matrices, care is taken to distinguish between different losses: scrap losses that are recycled; dross or skimming losses that include a percentage of aluminium that can be recovered during reprocessing; unrecoverable losses.

The data sources, calculations and assumptions for the global model are described from left to right along the Sankey diagram, covering these five process steps.

2.2 Electrolysis

The IAI (2008) global mass flow diagram shows a direct one-to-one mapping of alumina (73.3Mt), via electrolysis, to primary aluminium (37.8Mt). For our Sankey diagram only the aluminium content in the alumina is shown. The yield for electrolysis is not shown explicitly in the IAI (2008) global model of aluminium flows, so is instead calculated using the molar mass ratio of alumina (aluminium oxide, Al_2O_3 = 102g/mol) versus aluminium content in alumina (2x Al = 54g/mol). The alumina input to the electrolysis processes is 73.3Mt is multiplied molar mass fraction (54/102) to give an aluminium content of 38.8Mt. The IAI lists the aluminium output from electrolysis as 37.8Mt implying 1Mt of aluminium is lost during electrolysis, as oxidation in the dross and venting, at a yield of 97%

(excluding any internal scrap recycling during the casting process, which are discussed in §2.5 Ingot Casting).

2.3 Melting recycled scrap

The IAI (2011) dynamic model provides a breakdown of the scrap inputs for recycling, based on the scrap source as shown in Table S3. Note the different naming convention for scrap flows between our work and the IAI model, which we have changed to be more consistent with other metal MFA studies. From this point on we use only to our naming convention,

IAI model	Our model	Scrap flow
Traded new scrap (aluminium skimmings)	From casting	1.6Mt
Fabricator scrap	From forming	20Mt
Traded new scrap (from production of finished products)	From fabrication	9.5Mt
Old scrap	From end-of-life discards	8.3Mt

Table S3—Comparing naming conventions for scrap flows

The IAI model, however, treats recycling as a single processes when in practice it is performed in two distinct processes, known as *remelting* and *refining*.

Remelters produce wrought alloys (<10% alloy) which are used in rolled and extruded products. Remelters need clean scrap which is separated by alloy, limiting the scrap input to mostly industrial scrap from rolling, extrusion and drawings processes, with only small fractions of end-of-life scrap. Remelters blend scrap, of known quantity and alloy composition, along with new pure aluminium and metal alloys, to create the exact alloy compositions.

Refiners produce casting alloys (<20% alloy, mainly silicon) which are used in cast aluminium products. The higher allow concentrations and less stringent requirements for alloy composition allow scrap to be blended from a mix of all sources, including the majority of end-of-life scrap. Pure primary aluminium, usually in the form of small 'sow' ingots, is used to 'sweeten' casting alloys to achieve the desired composition.

A global breakdown of the scrap inputs to the remelting and refining could not be found, so instead we use European data and assume it is representative of the global aluminium flows. Boin and Bertram (2005) have performed a mass balance for aluminium recycling in the European Union members states (EU-15) from 1995 to 2004, with Table III reporting the EU aluminium scrap intake in 2002 allocated to Refiners and Remelters. This data is used to populate EU data in the first three columns in Table S4.

Ingot casting produces 1.6Mt of scrap (dross, also known as skimmings), which is allocated to Remetlers (0.7Mt) and Refiners (0.9Mt) based on the total cast aluminium in each process.

We then calculate the global allocation of scrap to Refiners and Remelters, by applying the European percentages to the global totals with some caveats. Ingot casting scrap is made up of dross and skimmings, and along with shape casting scrap from forming and fabrication processes, are assumed to be recycled in Refiners, because the high concentration impurities in the dross and the high alloy concentration of shape casting scrap prevent recycling into wrought products. The European data shows 57% (789kt/1376kt) of fabrication scrap being recycled in Remelters and this percentage is applied to the global data, noting there is no breakdown provided between wrought and cast products. This results in approximately 90% of the fabrication scrap from making wrought products being recycled in Remelters, with the remaining 10% (0.6Mt) being 'down-cycled' to Refiners.

Scrap type	**European Union (EU-15) (kt/year)**			**Global (Mt/year)**		
	Remelter[a]	**Refiner**	**Total**	**Remelter**	**Refiner**	**Total**
Ingot casting[b]	0	77	77	0	1.6	1.6
Forming[c]	3,050	871	3,921	10.1	9.9	20.0
from rolling/extrusion[d]	*3,050*	*217*	*3,267*	*10.1*	*1.1*	*11.2*
from shape casting[e]	*0*	*654*	*654*	*0*	*8.8*	*8.8*
Fabrication[f]	789	587	1,376	5.4	4.1	9.5
from wrought products				*5.4*	*0.6*	*6.0*
from cast products				*0*	*3.5*	*3.5*
End-of-life	392	1,429	1,821	1.8	6.5	8.3
Total[g]	**4,231**	**2,964**	**7,195**	**17.2**	**22.2**	**39.4**

Notes

[a] includes both tolled/purchased scrap and internal scrap for Remelters

[b] includes scrap from the product: dross (also known as skimmings) from ingot casting processes.

[c] labelled as 'Production Fabrication' in Boin and Bertram (2005), which can be broken down by scrap type

[d] includes scrap from the products: extrusion, rolling, foil, wire and cable, turnings

[e] includes scrap from the products: foundry scrap, dross (foundry), and turnings (foundry)

[f] labelled 'Manufacturing' in Boin and Bertram (2005), but with no breakdown between cast and wrought products

[g] excludes traded scrap

Table S4—European breakdown of scrap by Remelter and Refiner, which is scaled to calculate the global values in our model

The European data shows 78% (3050kt/3921kt) of forming scrap (from rolling/extrusion/shape casting) is recycled in Remelters. This percentage cannot be applied directly to global data forming scrap total of 20Mt, as this would result in 15.5Mt of scrap going to Remelters which is more than the demand for wrought products could sustain. Fortunately, the European data is sufficiently detailed to derive a breakdown of forming scrap between rolling/extrusion and shape casting. This shows 93% (3,050kt/ 3,267kt) of the forming scrap from rolling/extrusion being recycled in Remelters. This is rounded down to 90% to be consistent with the fabricator scrap percentage from above, and again results in 10% of forming scrap (1.1Mt) being 'down-cycled' in Remelters.

The European data shows only 22% of end-of-life scrap being recycled in Remelters, which is much lower than for forming and fabrication scrap, indicating how difficult it is to segregate end-of-life aluminium products into separate alloys. It is reasonable to assume that the balance of wrought products versus shape cast products for today's production (66%–34%) is the same as the fraction for collected scrap. Thus, if only 1.8Mt of wrought end-of-life scrap being recycled back into wrought products, this implies that approximately two-thirds (3.7Mt) of wrought end-of-life scrap is being 'down-cycled' to shape cast products, assuming no difference in the product lifetimes of wrought and cast products. This is a clear area for improvement for the industry.

Therefore, we can estimate that the total wrought scrap being downcycled (in Refiners) is equal to 6.1Mt . (0.7Mt casting scrap, 1.1Mt forming scrap, 0.6Mt fabrication scrap, 3.7Mt EOL scrap).

For remelting and refining, the IAI (2008, 2011) global model shows a combined 'metal losses' of 1.6Mt, made up of 0.6Mt loss from end-of-life processing (post-consumer scrap), 0.8Mt loss from aluminium skimmings for the casting processes, and 0.2Mt loss from fabricator scrap processing. Recycling yields are specific to the type of scrap being recycled: from ingot casting 50%; forming scrap 100%; fabrication scrap 98%; end-of-life scrap 93%. Losses are apportioned to remelting and refining based on the type of scrap in the allocation matrix, giving 1.4Mt of loss from refining at 94% yield and 0.2Mt from remelting at 99% yield. These losses are not recovered.

Based on these assumptions and calculations, Table S5 summarises the flows of scrap from all sources being supplied to Remelters, Refiners and Electrolysis.

	Mt/year	**To Remelter**	**To Refiner**	**To electrolysis**	**Total**
A=1+2	**Casting scrap/losses**[a]	**3.5**	**7.1**	**6.8**	**17.3**
1	internal scrap	1.8	4.4	3.8	10.0
2	recasting scrap	1.7	2.7	3.0	7.4
B=3+4	**Forming scrap**	**10.1**	**9.9**		**20.0**
3	from rolling/extrusion	10.1	1.1		11.2
4	from shape casting		8.8		8.8
C=5+6	**Fabrication scrap**	**5.4**	**4.1**		**9.5**
5	from wrought products	5.4	0.6		5.9
6	from cast products		3.5		3.5
D	**End-of-life scrap**	**1.8**	**6.5**		**8.3**
A+B+C	Industrial scrap[b]	18.9	21.1	6.8	46.8
A+B+C+D	**Total scrap**	**20.7**	**27.6**	**6.8**	**55.1**
Fraction lost (excl. internal scrap/recasting)					
E	Aluminium production[d]	16.3	19.9	37.8[c]	74.0
F=B+C	Industrial scrap	15.4	14.0		29.5
F/E	**Fraction lost**				**40%**
Fraction lost (incl. internal scrap)					
G	Aluminium production[d]	18.8	23.6	41.6[c]	83.9
H=B+C+1	Industrial scrap	17.2	18.4	3.8	39.4
H/G	**Fraction lost**				**47%**
Fraction lost (incl. internal and 70% recasting scrap)					
I	Aluminium production[d]	20.0	25.5	43.6[c]	89.1
H=B+C+1+2(x0.7)	Industrial scrap	18.4	20.3	5.8	44.5
H/G	**Fraction lost**				**50%**

Notes:

Some totals do not add up due to rounding.

[a] includes internal scrap and losses from Electrolysis, Remelters, Refiners and Recasting processes

[b] includes all internal scrap (including recasting)

[c] the pure aluminium 'sweetner' (which flows from Electrolysis to Remelting and Refining) is included only once in the calculation under Electrolysis, to avoid double counting

[d] The flow through production increases as more internally recycled scrap is included in the calculation

Table S5—Balance of annual global aluminium scrap and the calculation of the overall scrap fraction lost in manufacturing

We also calculate the overall scrap fraction lost during manufacturing under three different boundary conditions: (i) excluding any scrap from internal recycling loops or recasting scrap, (ii) including internal scrap from casting, (iii) including internal scrap from casting and assume 70% of all ingots are recast. This is discussed further in §2.5 Ingot Casting.

2.4 Dilution of scrap with pure aluminium

Scrap recycling requires the addition of pure aluminium aluminium to 'sweeten the melt' and obtain the desired alloy mix.

The IAI (2011) dynamic model and the EAA (2008) and EAA/OEA (2006) mass balances do not report the flow of pure aluminium 'sweetner' used in remelting. However, two additional sources suggest the fraction of pure aluminium aluminium input to Remelters could be in the order of 5%. Firstly, the AluNorf (2010) *Environmental Statement* shows a mass flow diagram for the remelting process, with 34kt of 'liquid metal' out of a total input to the process of 800kt, implying a pure aluminium 'sweetner' fraction of 4% (assuming 'liquid metal' is pure aluminium aluminium). Secondly, during a site visit to a remelting facility producing slab ingots from UBC (Used Beverage Container) scrap, we observed that 5% pure aluminium aluminium was added to correct the alloy composition.

Based on this evidence we chose a pure aluminium 'sweetner' fraction of 5% for Remelters. However, we note that the 'sweetner' used in Remelters does not affect the overall mass balance of wrought and cast products (in contrast to the 'sweetener' used in Refiners) as both the remelting output and the remaining primary aluminium are used in exclusively in wrought products.

Table S6 is used to calculate the pure aluminium sweetner fraction for Refiners.

Recycled (Mt/yr)	**Remelter**	**Refiner**	**Total**
Scrap input[a]	17.3	22.1	39.4
Less recycling losses[b]	0.3	1.3	1.6
Recycling output[c]	**17.0**	**20.8**	**37.8**
Demand (Mt/yr)	**Wrought**	**Shape cast**	**Total**
Cast ingot demand	47.0	27.0	74.0
Plus losses	0.7	0.9	1.6
Liquid Al demand[c]	**47.7**	**27.9**	**75.6**
Pure aluminium[e]	**31.7**	**7.1**	**37.8**[f]

Notes

[a] from Table S2

[b] based on the yields for each type of scrap through the recycling processes in the IAI (2011) mass flow model: ingot casting

ingots 50%; forming scrap 100%; fabrication scrap 98%; end-of-life scrap 93%.

[c] as liquid aluminium from ingot casting (dross and internal)

[d] the ingot casting yield is assumed to be the same (98%) for both wrought ingots and casting alloy ingots

[e] calculated as the balance between the Recycling Output and Liquid Al Demand.

[f] Equals the global primary aluminium production

Table S6—Global liquid aluminium balance of recycling scrap versus product demand, to determine the pure aluminium 'sweetner' used in Refiners.

The recycling scrap inputs to Remelters/Refiner and primary aluminium are balanced with the demand for wrought and shape cast products. The shortfall of recycled scrap in Refiners is made up using primary aluminium from Electrolysis.

The calculation shows that pure 'sweetner' makes up 25% (7.1Mt/27.9Mt) of the liquid aluminium demand for Refiners. This is much higher than the estimates given by industry which has been estimated to be as low as 2% for Europe (OEA, 2011). There are two possible sources of uncertainty. Firstly, the allocation of ingot casting losses between wrought and shape cast products, but this makes only a small difference to the 'sweetner' value. Secondly, uncertainty results from the scaling of European scrap data to find the global scrap inputs to Remelters and Refiner. However, using this approach is seems reasonable given the balance of wrought products versus shape cast products for Europe (71%-29%) and the World (67%-33%) are similar.

Reducing the fraction of pure aluminium 'sweetner' input to Refiners would require additional wrought scrap (from forming and fabrication) to be 'down-cycled' to lower quality grades. Either way the result is the same—pure aluminium or higher quality scrap is required to be down-cycled to meet the demand for shape casting products. Both dilution and down-cycling are thermodynamically irreversible and therefore materially inefficient.

In Table S7 we perform a second mass balance to check the accuracy of the pure aluminum 'sweetner' flows.

Recycled (Mt/yr)	**Remelter**	**Refiner**	**Total**
Recycling output[a]	**4.8**	**3.3**	**8.1**
Demand (Mt/yr)	**Wrought**	**Shape cast**	**Total**
Intermediate product demand[b]	8.3	3.4	11.7
Less exports			–0.4[c]
Plus forming scrap			4.6[d]
Plus ingot casting loss			0.1[e]
Cast ingot demand	11.3[f]	4.7[f]	16.0
Less imported ingots	–2.8[g]		
Liquid Aluminium demand	**8.6**	**4.7**	**13.3**
Pure Aluminium 'sweetner'[h]	**3.8**	**1.4**	**5.2**[i]

Notes

[a] Total of 8.1kt from fig. 21, EAA/OEA (2006), with 59% being recycled in Remelters (4231kt/7195kt, from Table S5)

[b] calculated from fig. 3, EAA/OEA (2006), which is broken into: rolled semis 4.4kt and extrusions 3.1Mt (both allocated to wrought), castings 3.1kt (allocated to shape castings); other (wire rods, powder, slugs) (allocated 70% to wrought, based on our global breakdown of 'wire' versus 'other castings')

[c] the 11.7kt includes 'exports' of 0.4kt shown in fig. 21, EAA/OEA (2006).
[d] labelled as 'fabricator scrap' made up of 3.4kt internal and 1.2kt traded, in fig. 21, EAA/OEA (2006).
[e] labelled as 'traded new scrap', in in fig. 21, EAA/OEA (2006).
[f] assumed to be the same breakdown as the Intermediate Product Demand
[g] the imported ingots are assumed to all be for wrought production.
[h] calculated as the balance between the Recycling Output and Liquid Al Demand.
[i] Equals the European primary aluminium production

Table S7—European liquid aluminium balance of recycling scrap versus product demand, to determine the pure aluminium 'sweetner' used in Refiners.

This uses 2004 European data from the EAA/OEA (2006) report (figure 3 and 21) and the scrap breakdowns in Boin and Bertram (2005, table III) that is summarised in our Table S5.

The resulting pure aluminium 'sweetner' flow is even higher, at 29% of the aluminium input to Refiners. However, this result relies heavily on the assumption that imported ingots are either from primary production or from Remelters, and therefore are destined for wrought production. It seems logical that primary aluminium ingots are more likely to be traded internationally, given electrolysis plants are large and often located at international sites where low-cost hydro-electricity is available, whereas refining is more localised in smaller facilities near to the sources of discarded scrap. In addition, any imported primary ingots used in Refiners would still count as 'sweetner'. Nevertheless, even if the 2.8kt of imported ingots were used for wrought and casting products on a pro-rata basis, the 'sweetner' fraction would still be as high as 14%.

Based on the mass balances described above we use 7.1Mt (25% of the input to Refiners) as the value for pure aluminium 'sweetner' in Refiners, but note that further bottom-up research into Remelters and Refiners is required to validate the sweetner values we have calculated.

2.5 Ingot casting

Three types of cast ingots are produced by electrolysis, Refiners or Remelters—slab, billet and alloy ingot—that are mapped directly onto types of intermediate products. We assume slab ingots, alongside continuous casting processes like twin rolling, are used to produce all strip and sheet intermediate products (including hot rolled strip, cold rolled sheet and foil). All billet ingots are allocated to extrusion and wire drawing products. Alloy ingots, are typically higher in alloy content and are assumed to be used exclusively for shape cast products and other destructive uses.

The casting of ingots creates both aluminium dross and internal casting scrap. Refiners and Remelters together create 1.6Mt of dross, called 'aluminium skimmings' by the IAI, which is recycled in the small scale facilities (included under Refiners in our Sankey diagram) where half is recovered as aluminium and the remaining half lost, according to the IAI (2011) dynamic model. This equates to a yield of 98% based on the total ingot casting of 74Mt. Dross, in the form of aluminium oxide, which is created during Electrolysis is recovered directly in Electrolysis process.

Internal casting losses (i.e. defects, sawing, scalping) are not reported by the IAI (2008, 2011), but are estimated to add 9% to the cast output based on a Remelter mass balance from AluNorf (2010), resulting in 3.8Mt of scrap from Electrolysis, 1.8Mt of scrap from Refiners, and 2.8Mt of scrap from

Remelters. (Table S5 shows the “internal scrap” supply to Refiners as 4.4Mt, equal to the sum of 1.6Mt ingot casting dross and 2.8Mt of internal casting scrap.)

In some cases ingots must be remelted and recast a second time to refine the alloy mix prior to downstream forming/casting processes, although fraction of recast aluminium could not be ascertained. This is shown on the Sankey diagram as a dotted vertical process line. If we assume all cast aluminium is recast and increases the cast requirement by 9%, then we can calculate a maximum additional scrap of 7.4Mt, split between 4.7Mt of wrought alloys and 2.7Mt of shape casting alloys. Alternaively, Table S5 shows that if 70% of all ingots are recast then the overall scrap fraction lost in manufacturing rises about 50%, meaning less than half of the cast aluminum makes it into an aluminium product.

Continuous casting processes offer an alternative to the batch ingot casting process and avoid the need for hot rolling the ingot. Approximately one-third of all cold-rolled sheet and foil is produced by continuous casting (Hamer et al. 2002), and we use this fraction in our model and adjust our yield calculation for Rolling accordingly. To date continuous casting routes have only been developed for sheet metal applications: which are typically non-heat treatable alloys with low alloy concentrations; where surface quality requirements can still be achieved; for thin sheet products which still permits significant reductions in sheet thickness during rolling needed develop the mechanical properties of the material. The yields for continuous casting is assumed to be equal to ingot casting (98%) with the same fraction of internally recycled scrap is applied (9%), however significant yield improvement results from eliminating the need for hot rolling which is described in §2.6 Forming.

In Table S8 we review ingot casting, remelting and sawing yields from literature, including details on the calculations and assumption used in each source, and show the yield values chosen for our model. The sources cover a range of different process, for different regions and production years, with material yields given for individual processes.

	Process steps	**IAI 2008**	**Milford et al. 2008**	**EAA 2008**	**AluNorf 2010**	**Our model**
1	Ingot casting (dross)	0.98	0.98	0.98		0.98
2	Remelter (dross)[1]			0.96[2]	0.96[3]	0.96
3	Remelter (internal)				0.96[4]	0.96
4	Sawing[5]		0.84–0.96	0.94[6]	0.95[7]	0.95

Notes

Yield equals the output (desired) divided by the inputs.

1 This yield calculation places any internal recycling of scrap inside the boundary, allowing just the dross losses to found

2 EAA (2008, tab.7.3, p.55) show Remelters outputs as 1,000kg of sawn ingot and 42kg of dross/skimmings, giving a yield of 96%.

3 Alunorf (2010, p.6) shows a 27kt loss from dross/swarf compared to an output of 773kt, giving a yield of 96% [= 773/(27+773)]

4 Alunorf (2010, p.6) shows an internal recycle of 36kt (not including sawing/scalping) compared to an output of 773kt, giving a yield of 96% [= 773/(36+773)]

5 Slab and billet ingots are normally sawn/scalped twice: the ingot is sawn to remove the ends post casting; the ingot is sawn/scalped to remove off-specification material prior to rolling. The recycled scrap loop resulting from sawing/scalping is additional to the 1.6Mt of casting loss and 20Mt of forming scrap shown in the IAI (2008) diagram. For clarity the cast house process is called sawing and the rolling process is called scalping.

6 EAA (2008, tab.3.6, p.29) shows 108kg of aluminium scrap input to the cast house for every 1,000kg aluminium output giving a yield of 89% (892kg/1000kg). This assumes the scrap input is all internally recycled scrap created during ingot

casting, which is valid for a primary cast house example. The yield of 89% is divided evenly between sawing here and scalping in the rolling process (shown in Table S9), giving a yield of 94%.

[7] A yield of 91% is calculated from Alunorf (2010, p.6), by comparing 146kt of sawing/scalping scrap with 1,609kt of aluminium input. The yield is divided evenly between sawing here and scalping in the rolling process (shown in Table S9), giving a yield of 95%.

Table S8—Ingot casting, remelting and sawing/scalping yields from literature

2.6 Forming

The demand for Rolling (hot, cold, foil), Extrusion, Wire Drawing and Shape Casting is back calculated from the vector of Intermediate products (see §2.7 Fabrication). We assume that: Hot Rolled Strip and Plate are produced by Hot Rolling only; Cold Rolled Sheet is produced by Hot or Twin Rolling plus Cold Rolling; Foil is Hot or Twin Rolling plus Cold and Foil Rolling. We assume one-third of all cold-rolled sheet and foil is produced by continuous casting (Hamer et al. 2002). This eliminates the need for Hot Rolling and Sawing/Scalping and avoids the scrap that would normally be created during these processes.

The IAI (2008) mass flow diagram gives the overall material yields for semi-fabricated products (intermediate products), equal to 73%, calculated as 20Mt of fabricator scrap compared to 74Mt of aluminium ingots. This overall yield is used as a constraint when populating the yield matrix with process level yield data from other sources.

The IAI (2011) estimate the material yields for semi-fabricator and fabricator scrap generation as shown in Table S9. The semi-fabricator step equates to our forming step, including rolling, extrusion and shape casting. However, the semi-fabricator yields are estimated based on categories of finished products (end-use goods) rather than by intermediate product categories. This is not as accurate as estimating yields of each forming process and in particular does not take into account the cascading and dividing flows from hot rolling, to cold rolling, to foil rolling. For example, Table S9 shows two packing categories, cans and other (foil) which both have a yield of forming yield of 70%, yet we know that this is unlikely because foil undergoes an additional rolling stage, leading to a lower forming yield. Therefore, in our study we chose to use alternative literature sources of forming yields, with the exception of wire drawings, which maps directly onto the 'Electrical-cable' category in the IAI data.

Finished products	**Semi-fabricator scrap**	**Fabricator scrap**
Bldg & Const	0.75	0.90
Transportation - Auto & Lt Truck	0.70	0.84
Transportation - Aerospace	0.50	0.60
Trans - Truck/Bus/Trailer/Rail/Marine/Other	0.70	0.80
Packaging - Cans	0.70	0.75
Packaging - Other (Foil)	0.70	0.75
Machinery & Equipment	0.70	0.75
Electrical - Cable	0.80	0.90
Electrical - Other	0.80	0.80

Consumer Durables	0.75	0.80
Other (ex Destructive Uses)	0.75	0.80
Destructive Uses	0.80	0.80

Table S9—IAI (2011) estimates of semi-fabricator and fabricator yields

Milford et al. (2011) in their paper track aluminium flow along the supply chain for three aluminium case study products—a car door panel, a beverage can, and a wing skin panel—providing ranges of material yields for 30 aluminium manufacturing processes. The *Environmental Profile Report for the European Aluminium Industry*, produced by the EAA (2008), provides mass balance diagrams for several key processes—casting, cold rolling, foil rolling, and extrusion—based on EU27 and EFTA country (Norway, Switzerland and Iceland) data. Cumulative yields can be calculated from the mass diagrams, and decomposed into average European material yield for individual processes.

The *Environmental Statement 2010* from AluNorf (2010) provides a 2009 mass balance diagram (p.6) for their aluminium rolling plant in Neuss, Germany, which is the largest aluminium rolling and melting plant in the world, shipping 1.2Mt of sheet in 2009. From the mass diagram, we can extract material yields for remelting, sawing/scalping, hot rolling and cold rolling processes. For shape casting processes, Schifo and Raida (2004, tab.30. p.53) provide metal casting yields for the United States in 2003 including for aluminium: investment/induction casting, die casting, permanent mould casting, lost foam casting and sand casting, ranging from 55%-70%. The 'other' category includes other high alloy cast product and destructive uses, and is solved so that the overall scrap generation is equal to the IAI (2008) value of 20Mt.

The material yields for the forming processes (rolling, extrusion and shape casting) from these literature sources are summarised in Table S10, including details on the calculations and assumption used in each source, and show the value used in our model. The sources cover a range of different process, for different regions and production years, with material yields given for either individual processes or as cumulative for a specific intermediate product (several process yields multiplied together).

Using sources other than the IAI to calculate the forming yields (in Table S10) and to quantify the flows of intermediate products leads to small discrepancies in the allocation of scrap flows. This is shown in Table S11 where our model yield values for forming scrap are allocated through to the end-use good categories, in order to compare with the IAI (2011) semi-fabricator yields from Table S9. Although we have constrained the overall forming yield scrap to match the 20Mt of forming scrap (IAI, 2008) we have allowed the individual forming yields for each process to vary, resulting in discrepancies ranging from -28% to 54% in the forming scrap when allocated to end-use good categories. Nevertheless, we believe that our approach taken to estimating yields for the forming processes directly, is more accurate and an improvement on the method used by IAI (2011) in their dynamic model.

	Process steps	Milford et al. 2008	EAA 2008	AluNorf 2010	Schifo et al. 2004	Our model
	Rolling					
5	Scalping[1]	0.87–0.95	0.94[2]	0.95[3]		0.95
6	Hot rolling	0.88–0.92		0.89		0.89
7	Cold rolling	0.95	*0.86*[4]	0.91		0.86
8	Foil rolling		*0.86*[4]			0.86
	Cumulative rolling yields[5]					
5–6	Plate rolling[6]					0.84
5–6	Hot rolling[6]	*0.77–0.87*		0.84		0.84
5–7	Cold rolling	*0.73–0.83*	0.72[7]	0.74		0.72
5–8	Foil rolling		0.63[8]			0.63
	Extrusion					
9	Extrusion		0.76[9]			0.76
10	Wire drawing					0.76[10]
	Shape casting					
11	Die castings				0.70	0.70
12	Permanent mould castings				0.65	0.65
13	Sand castings				0.60	0.60
14	Other					0.72[11]

Notes

Yield equals the output (desired) divided by the inputs. Yield values in italics are calculated for comparison, by multiplying together individual process steps, or dividing cumulative yield values. The process steps are number to show how cumulative yields are calculated.

1. Slab and billet ingots are normally sawn/scalped twice: the ingot is sawn to remove the ends post casting; the ingot is sawn/scalped to remove off-specification material prior to rolling. The recycled scrap loop resulting from sawing/scalping is additional to the 1.6Mt of casting loss and 20Mt of forming scrap shown in the IAI (2008) diagram. For clarity the cast house process is called sawing and the rolling process is called scalping.
2. EAA (2008, tab.3.6, p.29) shows 108kg of aluminium scrap input to the cast house for every 1,000kg aluminium output giving a yield of 89% (892kg/1000kg). This assumes the scrap input is all internally recycled scrap created during ingot casting, which is valid for a primary cast house example. The yield of 89% is divided evenly between scalping here and sawing in the casting process (shown in Table S7), giving a yield of 94%.
3. A yield of 91% is calculated from Alunorf (2010, p.6), by comparing 146kt of sawing/scalping scrap with 1,609kt of aluminium input. The yield is divided evenly between scalping here and sawing in the casting process (shown in Table S7), giving a yield of 95%.
4. Calculated by disaggregating the EAA (2008), cumulative cold rolling (fig.4.2) and foil rolling yields (fig.5.1) into individual processes, and dividing by the cumulative yield for Hot Rolling (5–6) of 84%.
5. Yields multiplied cumulatively from scalping to rolled product. These yields exclude the fraction being process by continuous casting (twin roll casting).
6. Plate rolling and hot rolling are assumed to have the same yield, which is calculated by multiplying the scalping and hot rolling yields.
7. Cumulative cold rolling yield from EAA (2008), fig 4.2 (average yield based on 76% of sheet production in Europe, 3,330kt).
8. Cumulative foil rolling yield from EAA (2008), fig. 5.1 (average yield based on 50% of foil production in Europe, 406kt).
9. Extrusion yield from EAA (2008), fig 6.1 (average yield based on 33% of extrusion production Europe, 978kt).
10. Assumed to be equal to the EAA (2008) extrusion yield. Note the IAI (2011) semi-fabricator yield for electrical cable (made from the drawing process) is slightly higher at 80% yield.
11. The 'other casting and destructive uses' yield is solved to match the IAI (2008) value of 20Mt for total forming scrap.

Table S10—Forming yields, including rolling, extrusion and shape casting processes

End-use good category	IAI 2011 Mt	Our model Mt	Discrepancy %
Construction			
Structural in buildings	1.3	1.8	-28%
Non-structural in buildings	1.7	1.9	-11%
Infrastructure	0.3	0.3	-16%
Vehicles			
Car, light truck	4.2	4.0	5%
Truck, bus, train, plane, ship	1.9	2.4	-21%
Industrial equipment			
Mechanical	1.9	1.8	3%
Electrical cable	1.3	1.1	26%
Electrical	0.7	0.7	3%
Metal products			
Drinks cans	1.4	1.9	-23%
Packaging foil	1.8	1.5	18%
Consumer durable	1.5	1.3	12%
Other castings/destructive	2.0	1.3	54%
Total	**20.0**	**20.0**	**0%**

Table S11—Forming scrap allocated to end-use goods for comparison with IAI (2011) data

2.7 Fabrication

The IAI (2011) dynamic model collates detailed data for net product shipments covering ten major regions of the world, from 1950–2007, which can be used to quantify the production of Intermediate Products (total 54Mt, pre-fabrication). Fabrication yields are taken directly from the IAI (2011) dynamic model (as shown in Table S9 under Fabricator Scrap) and applied uniformly to each Intermediate Product to generate a breakdown for 'finished products (which equates to our End-use vector). However, the IAI data for both Intermediate Products and End-uses is organised by end-use markets (i.e. buildings, transport, machinery), whereas a breakdown of intermediate product categories (i.e. rolled, extruded, shape-cast) is required for the Sankey diagram.

Therefore, in our model we start with the IAI's breakdown for 'finished products' and make minor adjustments to map their categories on our End-use vector categories and ensure that all categories are of similar magnitude:

- The IAI category of 'building and construction category' is divided into three Construction categories of Structural Buildings, Non-structural Buildings and Infrastructure. The allocation is based on Table 13 from the Aluminum Association (2008), covering 74% of the US building and construction market. Structural Buildings includes sidings, curtain walls, entrances, stores fronts, and manufactured housing. Non-structural Buildings includes windows, doors, screens, guttering, downpipes, awnings and canopies. Infrastructure includes bridges, streets and highways.
- A single category of Other Vehicles is created from the IAI categories transportation categories of 'aerospace' and 'truck/bus/trailer/rail/marine/other', because 'aerospace' would be too small as a category to show on the Sankey diagram by itself.

- A single category of Other Metal Products is created from the IAI categories of 'destructive uses' and 'other (ex-destructive uses)'.

Having determined the vector for End-uses, we then create a Fabrication allocation matrix and use the IAI (2008) yields to back-calculate the vector for Intermediate Products. The allocation matrix is based on the Aluminum Statistical Review (2008), which provides various historical breakdowns of North American 'semi-finished products' by end-use sectors, and in Table S12 we describe the specific data tables used to populate the matrix. Where data is incomplete we estimate the allocations based on expert opinion, in a process akin to a Sudoku puzzle, where each row of the matrix is balanced to match the End-use vector totals and are constrained so that the overall fabrication scrap matches the 9.5Mt from the IAI (2008) diagram. This process, including all data sources and assumptions, is described in Table S13.

Table	Coverage	Years	Description
9–Total Industry Net Shipments by Product	U.S. & Canada	1998–2008	Breakdown of Net Shipments and Net Shipments plus Imports into: sheet/plate, foil, extrusions, electrical conductor, wire, powder/past, and forgings/impacts.
11-U.S. Shipment of Aluminium Foundry Casting	U.S.	1998–2008	Breakdown of Aluminium Foundry Castings into: sand castings, permanent mould castings, die casting, and other.
12–Shipments by Major Market	U.S. U.S. & Canada	1997–2000 2001–2008	Breakdown of Net Shipments by End-use Categories (e.g. building/construction, transportation, consumer durables, containers/packaging, other)
13–Trends in Selected Markets	U.S. U.S. & Canada	1967–2000 2001–2008	Mapping of Intermediate Products (e.g. sheet/plate, extrusions, bare wire, etc.) onto End-use categories (e.g. building/construction, transportation, consumer durables, containers/packaging, other) and sub categories (e.g. windows, doors, trucks, cars, utensils, appliances, etc.). The table covers 70% of the Net Shipments in Table 12.

Table S12—Description of North American data from the Aluminum Association (2008).

In Table S13 we describe this allocation process for each type of End-use good, line by line.

End-use categories	Description of allocation process
Construction	
Structural in buildings	Based on table 13 we allocate: 56% to Sheet/Plate; 44% to Extruded Shapes. Sheet/Plate is assumed to be all Hot Rolled Sheet. This fraction is used as the final balance for the Fabrication Allocation Matrix, and is solved to give a 57%–43% split, almost identical to the Table 13 data. 'Structural' is assumed to include sidings, curtain wall, entrances, store fronts, and manufactured houses from Table 13.
Non-structural in buildings	Based on table 13 we allocate: 60% to Extruded Shapes; 39% to Sheet/Plate; 1% to Wire. Sheet/Plate is allocated 58% to Cold Rolled Sheet and 42% to Hot Rolled Sheet, with the fraction solved to balance the overall demand for Hot Rolled Sheet. 'Non-structural' is assumed to include sub-categories of windows, doors, screens, guttering, downpipes, awnings, and canopies.
Infrastructure	Based on table 13 we allocate: 48% to Sheet/Plate; 23% to Extruded Shapes; 16% to Castings; 13% to Pipe/Tube. Sheet/Plate is assumed to be all Hot Rolled Sheet. Castings is divided between Sand Casting, Permanent Mould Casting, and Die Casting based on the overall fractions for each of these casting processes. We assume that Pipe/Tube is produced by extrusion. 'Infrastructure' is assumed to include bridges, streets/highways.
Vehicles	
Car, light truck	Based on table 13 we allocate: 78% to Castings, 12% to Sheet/Plate, 8% to Extrusions, 2% to Foil. Castings is divided between Sand Casting, Permanent Mould Casting, and Die Casting based on the overall fractions for each of these casting processes. Sheet/Plate is divided equally between Cold Rolled Sheet and 50% to Hot Rolled Sheet.
Truck, bus, train, plane, ship	Based on table 13 we allocate: 39% to Castings; 33% to Sheet/Plate; 27% to Extrusions; 1% to Foil. Castings includes forgings and impacts is divided between Sand Casting, Permanent Mould Casting, and Die Casting based on the overall fractions for each of these casting processes. Sheet/Plate is divided equally between Cold Rolled Sheet and 50% to Hot Rolled Sheet.
Industrial equipment	
Mechanical	Mechanical equipment is assumed to have the same breakdown as 'Car/light trucks', except that Sheet/Plate is assumed to all be Plate.
Electrical cable	All electrical cable/wire is allocated to the end-use of Electrical Cable.
Electrical	We allocate 31% to Plate, with this fraction solved to balance the overall demand for Plate. The remaining is divided 50% to Cold Rolled Sheet and 19% to Hot Rolled Sheet
Metal products	
Drinks cans	All Drinks Cans are produced from Cold Rolled Sheet.
Packaging foil	We allocate 83% to Foil, with this fraction solved to balance the overall demand for Foil. The remaining 17% is allocated to Cold Rolled Sheet.
Consumer durable	We allocate: 60% to Sheet/Plate; 27% to Castings; 13% to Extrusions. Sheet/Plate is assumed to all be Cold Rolled Sheet. The Castings fraction is solved to balance the overall demand for Castings, and is then divided between Sand Casting, Permanent Mould Casting, and Die Casting based on the overall fractions for each of these casting processes. The Extrusions fraction is solved to balance the overall demand for Extrusions.
Other castings/destructive	We allocate: 58% to Castings; 42% to Other (e.g. destructive uses, powder, etc.). The Other fraction is solved to balance the overall demand for Other, and is similar to the IAI (2011) split of 53%–47%. Castings is divided between Sand Casting, Permanent Mould Casting, and Die Casting based on the overall fractions for each of these casting processes.

Notes

Table references are from Aluminum Association (2008).

Table S13—Use of North American data from the Aluminum Association (2008) to allocate Intermediate Products to End-uses.

References

Alcoa (nd) Alcoa website, http://www.alcoa.com/

Aluminum Association (2008) Aluminum Statistical Review for 2008; The Aluminum Association: Arlington, VA, 2008.

AluNorf (2010) Environmental Statement 2010. Aluminium Norf GMbH (AluNorf): Neuss, Germany, 2010, http://www.alunorf.com/english/sicherheit_umwelterklaerung.php/

Boin, U.M.J. and Bertram, M. (2005) Melting standardized aluminum scrap: a mass balance model for Europe. *Journal of the Minerals, Metals and Materials Society*, 57(8):26–33.

CRU (nd) CRU group website, http://www.crugroup.com/

EAA/OEA (2006) Aluminium recycling in Europe: the road to high quality products. European Aluminium Association (EAA) and Organisation of the European Aluminium Recycling Industry (OEA), http://www.world-aluminium.org/media/filer/2012/06/12/fl0000217.pdf/

EAA (2008) Environmental profile report for the European aluminium industry. European Aluminium Association: Brussels, http://www.alueurope.eu/environmental-profile-report/

Hamer, S.; Romanowski, C.; Taraglio, B. (2002) Continuous casting and rolling of aluminum: Analysis of capacities, products ranges and Technology, Light Metal Age 2002, 60, 6–17.

IAI (2008) Aluminium for future generations/2008 update; International Aluminium Association: London, 2008; http://www.world-aluminium.org/media/filer/2012/06/12/fl0000286.pdf/

IAI (2011) Dynamic model of aluminium stocks and flows (internal model); International Aluminium Association: London, 2011.

IAI (nd) International Aluminium Institute website, http://www.world-aluminium.org/Statistics/

Milford, R. L.; Allwood, J. M.; Cullen, J.M. (2011) Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors. Resour. Conserv. Recy. 2011, 55 (12), 1185–95.

Novelis (nd) Novelis website, http://www.novelis.com/

OEA (2011) *Personal communication, 1 August 2011.* Organisation of the European Aluminium Recycling Industry (OEA)

Schifo J.F. and Radia J.T. (2004) Theoretical/best practice energy use in metalcasting operations; U.S. Department of Energy Industrial Technologies Program: Washington, DC, 2004. http://prod.afsinc.rd.net/files/best%20practice%20energy-schifo-radia-may%202004.pdf/

USGS (nd) Mineral commodity summaries, U.S. Geological Survey, http://www.usgs.gov/