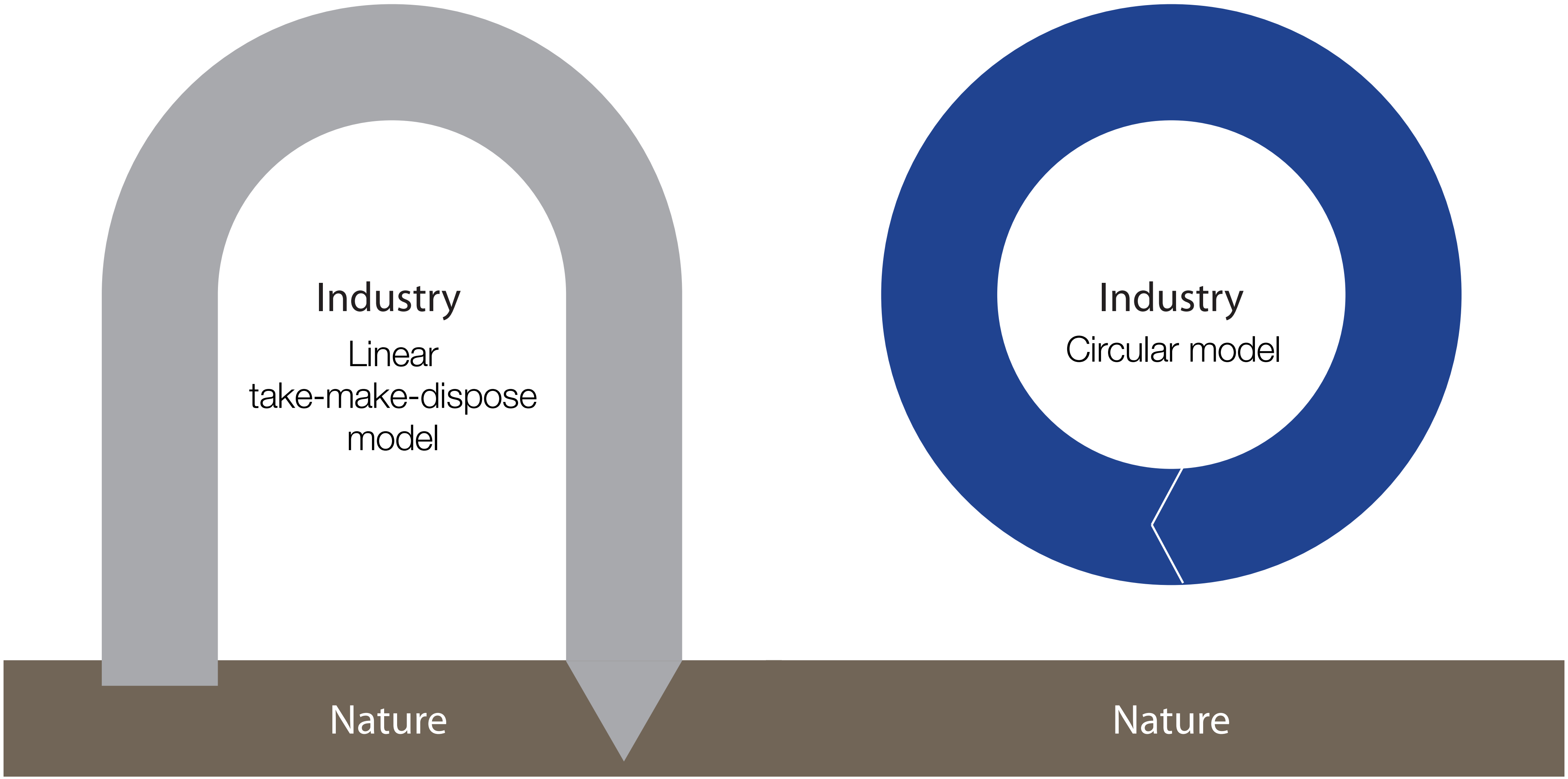
round and round we go

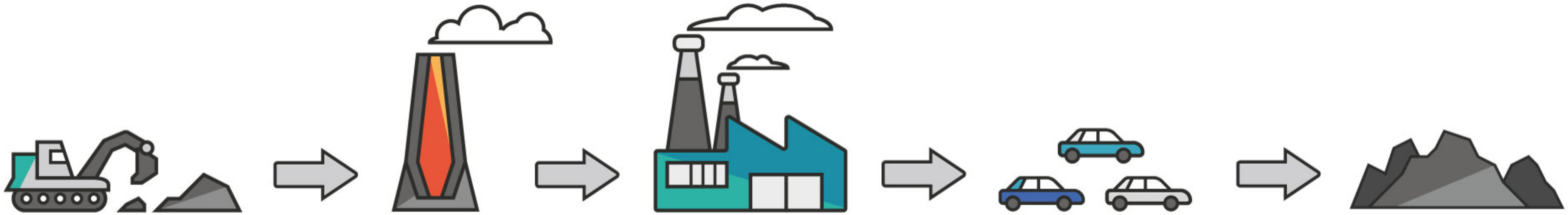
measuring the circularity of material cycles

Jonathan Cullen
jmc99@cam.ac.uk

An elegant solution ...

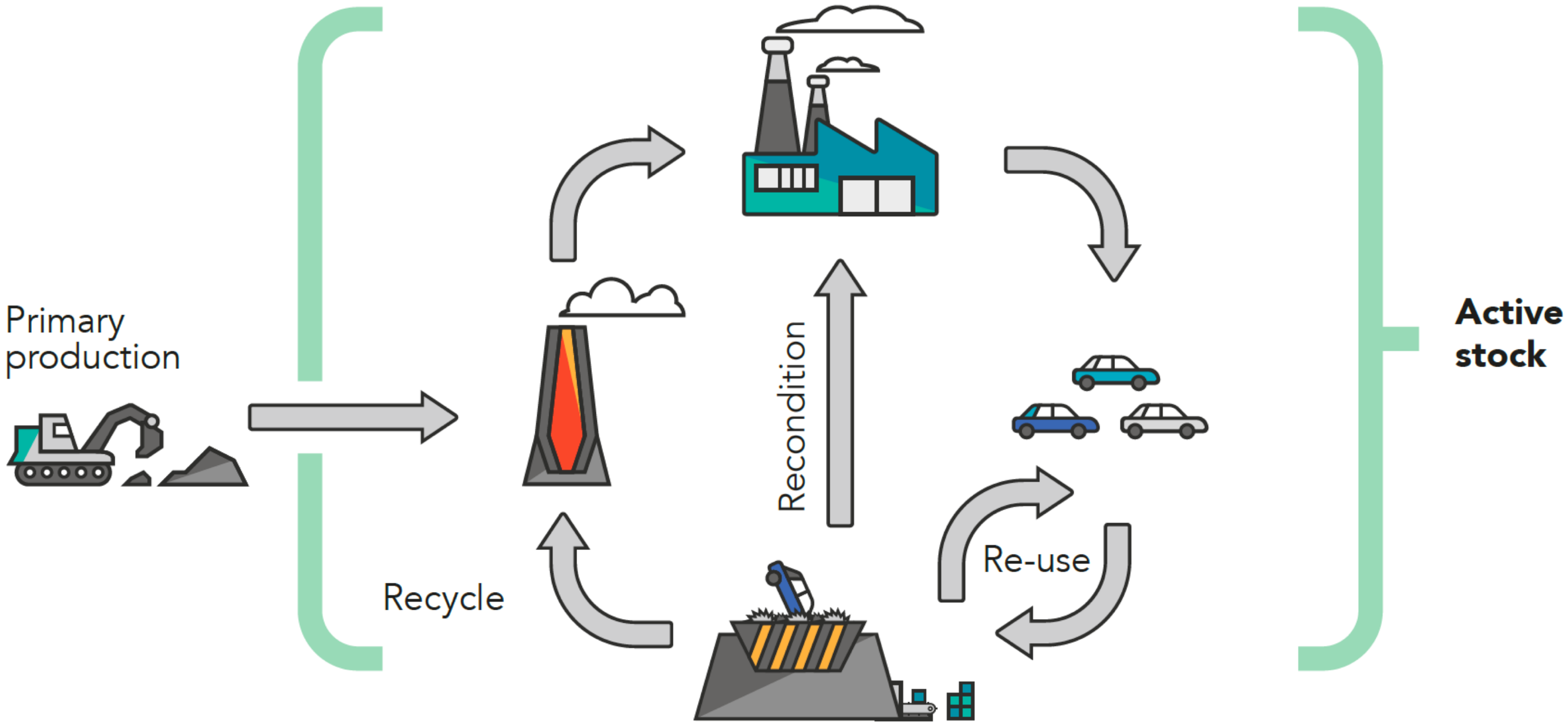


A linear materials economy



Ashby (2017)

A circular materials economy



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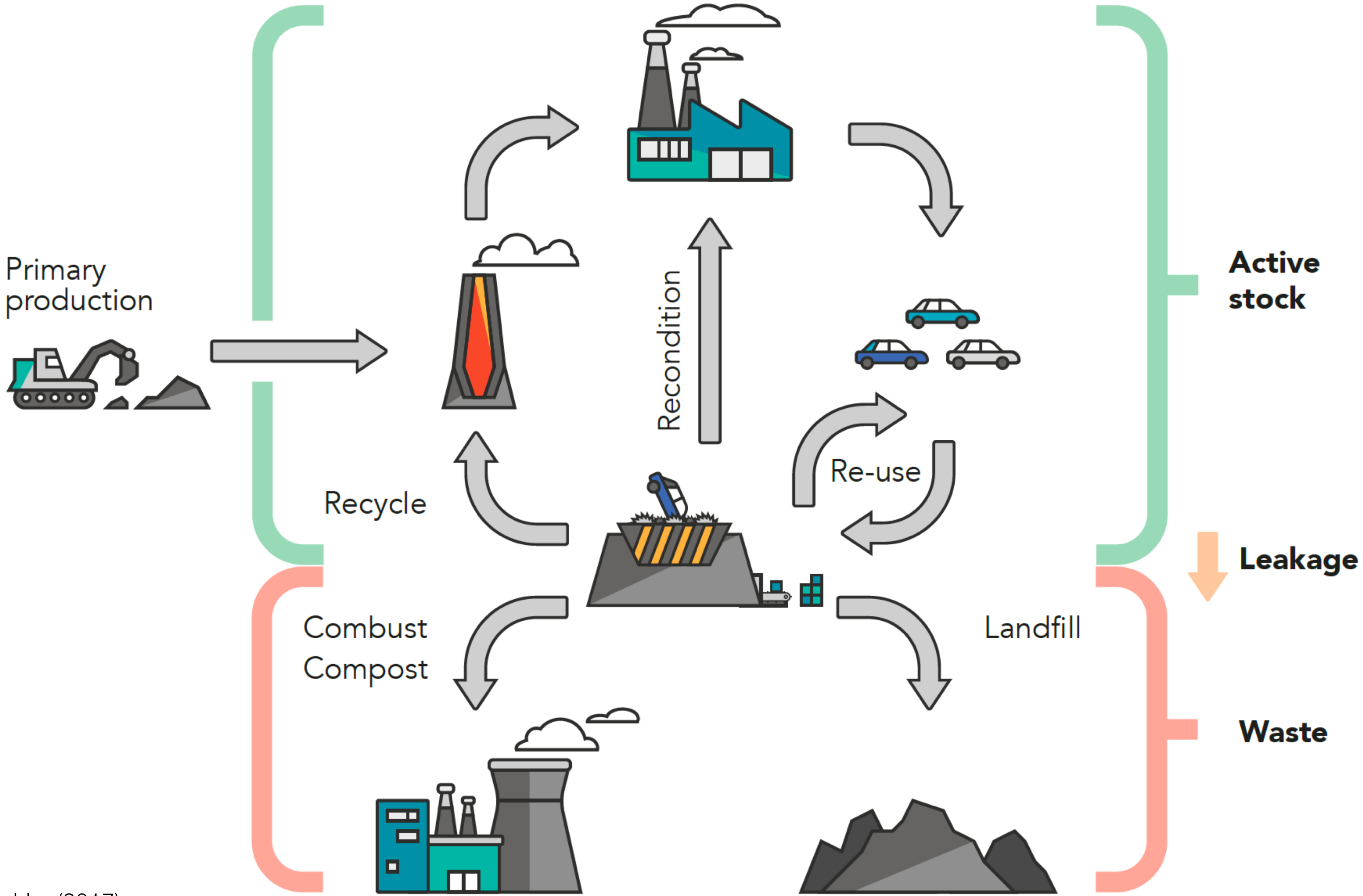
A circular materials economy



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Measuring circularity

CIRCULAR ECONOMY

Circular Economy

Theoretical Benchmark or Perpetual Motion Machine?

Jonathan M. Cullen

Department of Engineering, Cambridge University, Cambridge, United Kingdom

In 1911, the U.S. Patent Office ruled that applications for perpetual motion machines would not be accepted, unless accompanied—within a year of the filing date—by a working model. Perpetual motion machines, were described as operating "without the aid of any power other than that generated by the machine itself and which machine, when once started, will operate for an indefinite time" (The Inventor's Department 1911, 443)—a machine that goes round and around indefinitely without any input of energy. The Office viewed such applications as ". . . opposed to well-known physical laws . . . ". Today, the dream of perpetual motion and unlimited free energy lives on, but the physical laws governing motion have, thus far, refused to yield.

Perpetual motion remains a utopian

"Two guiding questions to ask when assessing EOL options for waste materials or products are: How much energy is required to restore the recovered material back to the desired material or product?, and, How does this quantity compare with obtaining the desired material or product from virgin or primary sources?"

sibility of a perfect CE, this ideal state might be renamed the theoretical CE. I acknowledge the caveat diminishes pith and promise and might complicate efforts to attract new adherents to the CE.

Material Losses and Energy Inputs

"A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times . . . " (EMF 2015, 2). Yet, CE, in practice, has often downplayed or conveniently overlooked material losses and energy requirements of closed loops. Material recycling is, almost without exception, assumed to benefit the environment. However, in practice, the material losses and

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Measuring circularity

Every loop around the circle creates dissipation and entropy.

New materials and energy must be injected into any circular material loop to overcome these losses.

To measure material circularity, we must consider:

- ★ **the quantity of materials cycled**
- ★ **the quality of materials cycled**

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Conserving the quantity of materials

We can define a simple ratio for the conservation of quantity:

$$\alpha = \frac{\text{recovered EOL material}}{\text{total material demand}}$$

A value of 1 would describe perfect circularity of quantity, where input demands and recoverable end-of-life outputs are balanced

Two specific issues make the prevention of material loss challenging:

- ★ **Dissipative material losses**
- ★ **Material stock dynamics**

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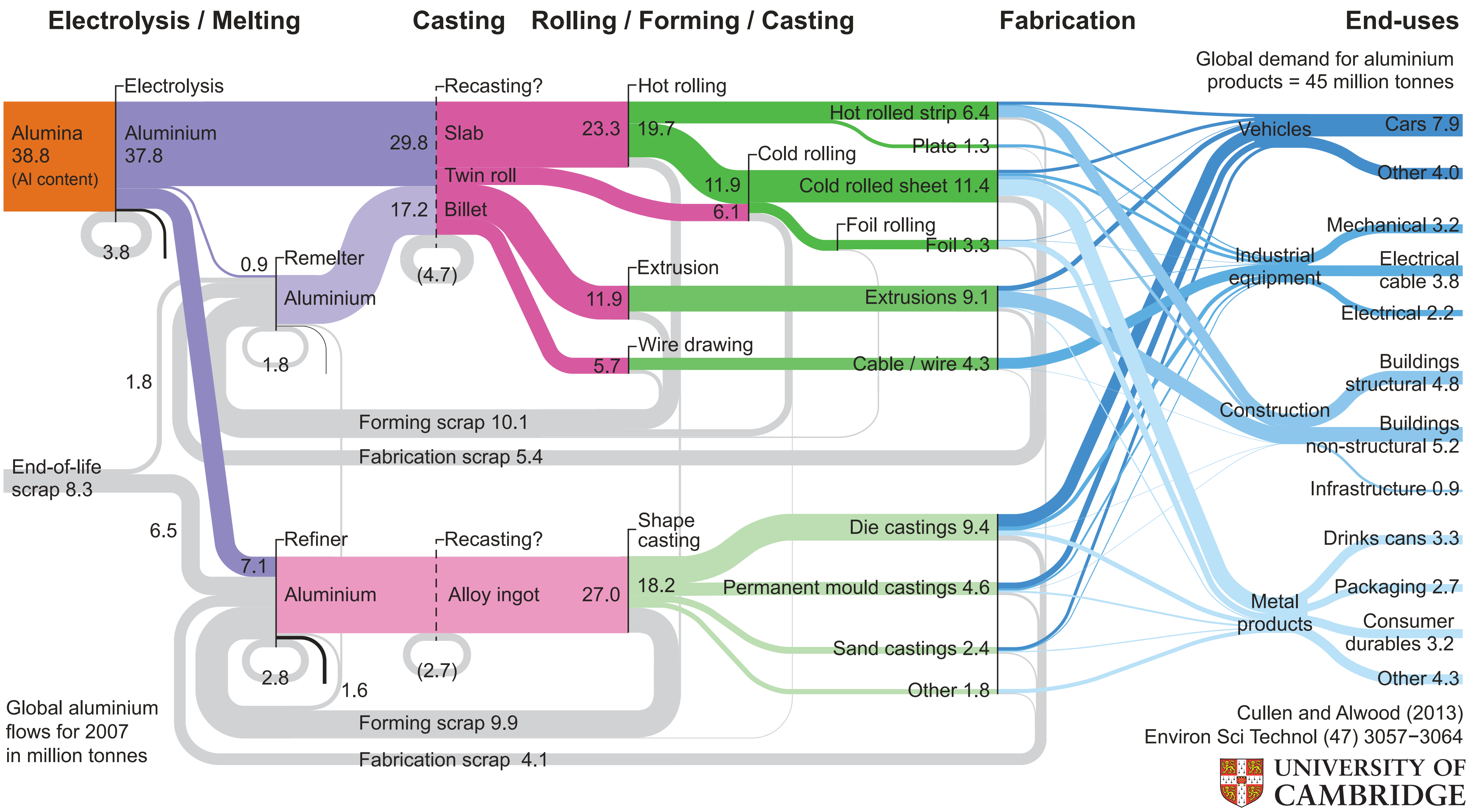
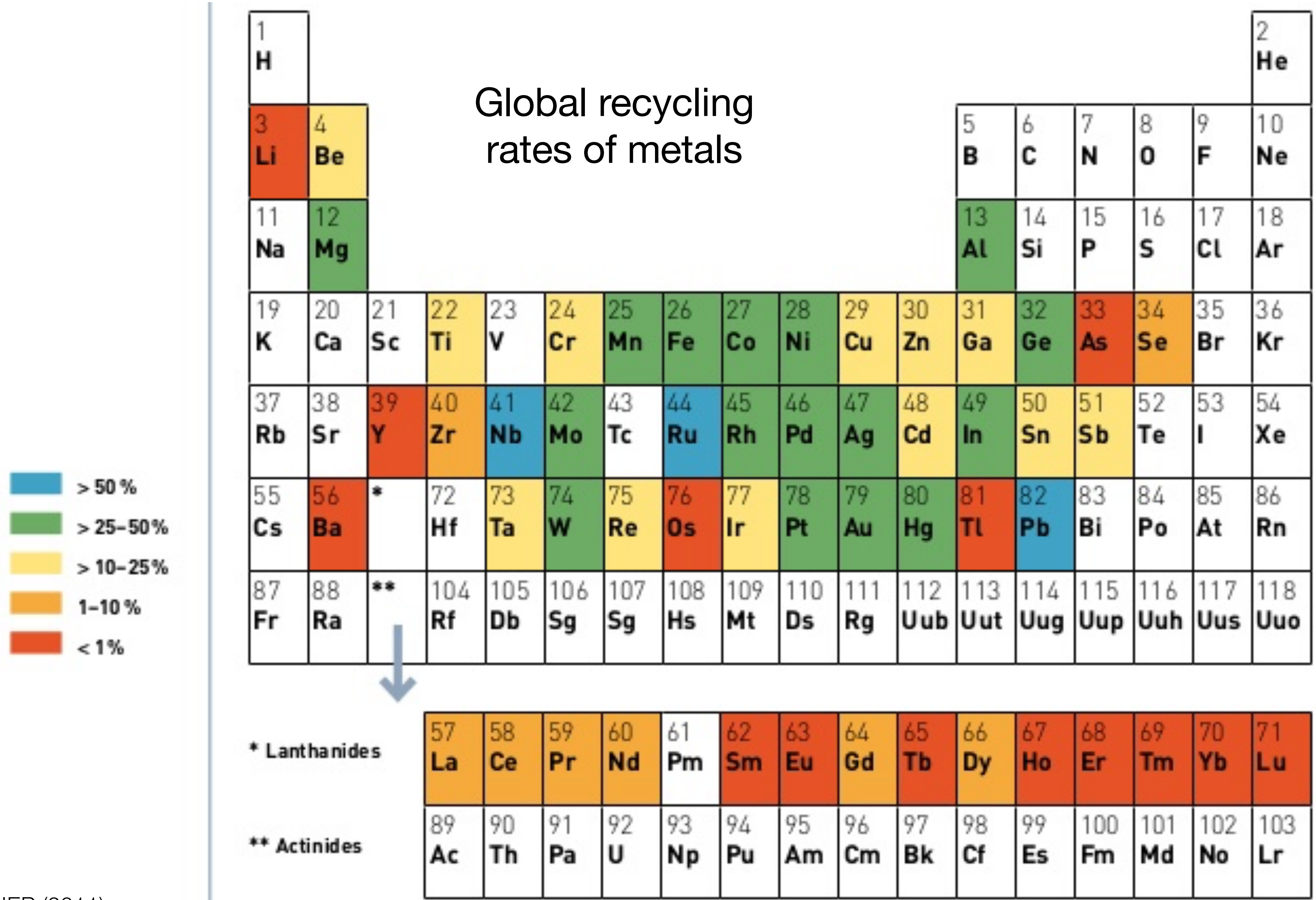
Dissipative material losses

Only end-of-life recycling counts



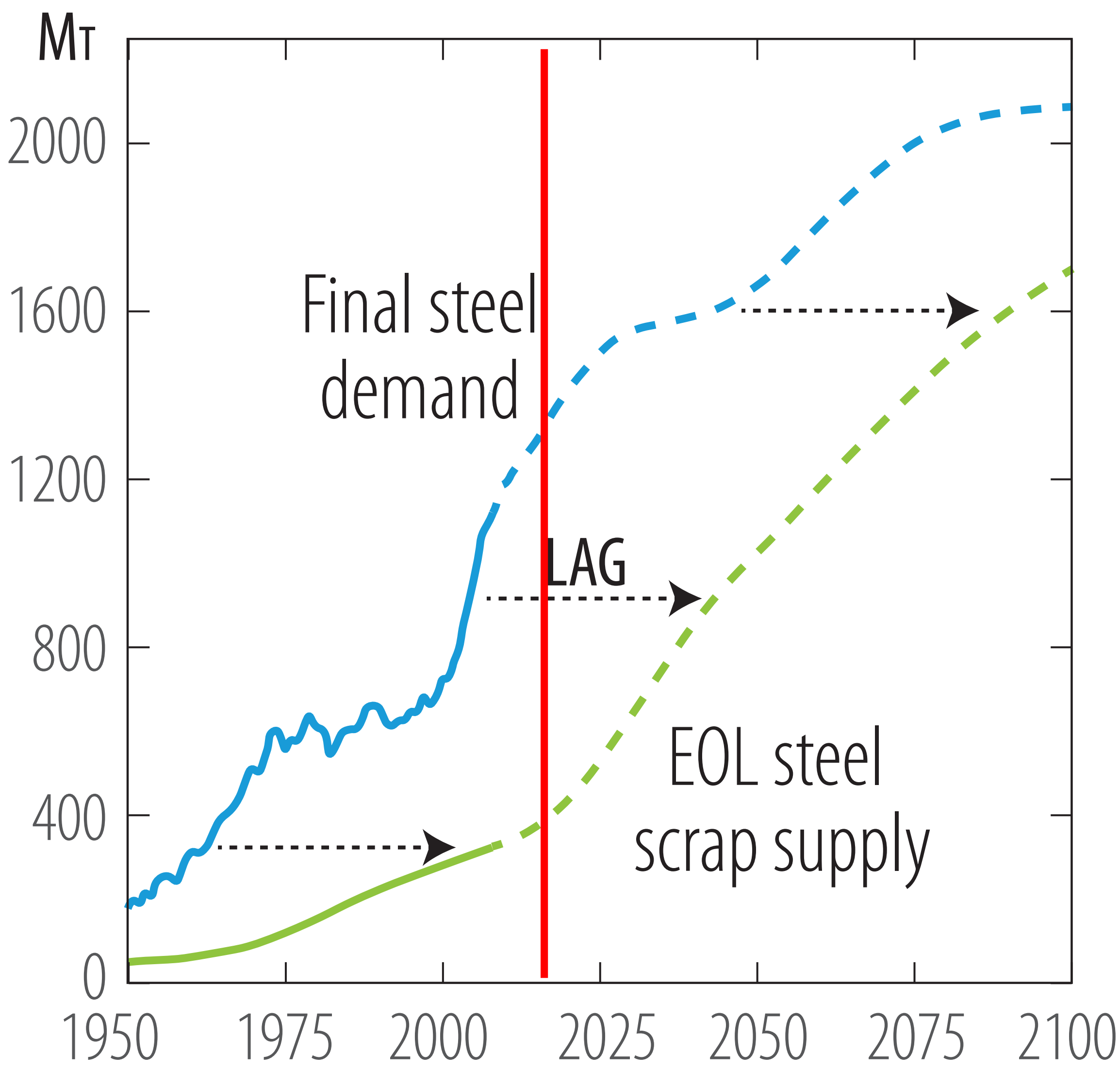
Cullen and Allwood (2013)

Dissipative material losses



UNEP (2011)

Material stock dynamics



- ★ **Products take materials hostage**
- ★ **Product lifetimes create a lag between demand and recovery**

Pauliuk, Wang, Müller (2013)

Measuring circularity : conserving quantity

	Steel	Concrete	Plastic	Paper	Aluminum
Recovered EOL material (Mt)	298	660	28	156	11
Total material demand (Mt)	1,500	32,800	299	408	54
α	**0.2**	**0.02**	**0.09**	**0.38**	**0.21**

$$\alpha = \frac{\text{recovered EOL material}}{\text{total material demand}}$$

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Conserving the quality of materials

Every loop around the circle
creates dissipation and entropy

Conserving the quality of materials

A simple ratio for the conservation of quality:

$$\beta = 1 - \frac{\text{energy required to recover material}}{\text{energy required for primary production}}$$

A value of 1 would describe perfect circularity of material quality, where no loss of material quality occurs with each recovery cycle

- ★ **The disorder of isolated systems increases over time**
- ★ **Entropy increases are always present in material processing, due to mixing, downgrading and downcycling processes**

Additional energy input is required to halt this material entropy increase and return the recovered materials back to their original useful state

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Conserving the quality of materials

Recycling requires energy to collect, sort, and remelt its constituent materials before they can be used again in manufacturing. Different materials require different amounts of energy for recycling.

Material downcycling occurs when it is not economic to restore materials to their original quality.

Material upcycling is only possible if even more energy is added to upgrade the material quality.

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Measuring circularity : conserving quality

	Steel	Concrete	Plastic	Paper	Aluminum
Recovered EOL material (Mt)	298	660	28	156	11
Total material demand (Mt)	1,500	32,800	299	408	54
α	**0.2**	**0.02**	**0.09**	**0.38**	**0.21**
Energy required:					
to recover material (MJ/kg)	6.7	3.4	9.6	23.4	7.6
for primary production (MJ/kg)	21.7	3.4	38.4	26.2	174
β	**0.69**	**0**	**0.75**	**0.11**	**0.96**

$$\beta = 1 - \frac{\text{energy required to recover material}}{\text{energy required for primary production}}$$

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Circularity index

	Steel	Concrete	Plastic	Paper	Aluminum
α	0.2	0.02	0.09	0.38	0.21
β	0.69	0	0.75	0.11	0.96
Circularity Index, CI	**0.14**	**0**	**0.07**	**0.04**	**0.20**

$$\text{Circularity Index, CI} = \alpha\beta$$

Current material loops are still far from circular

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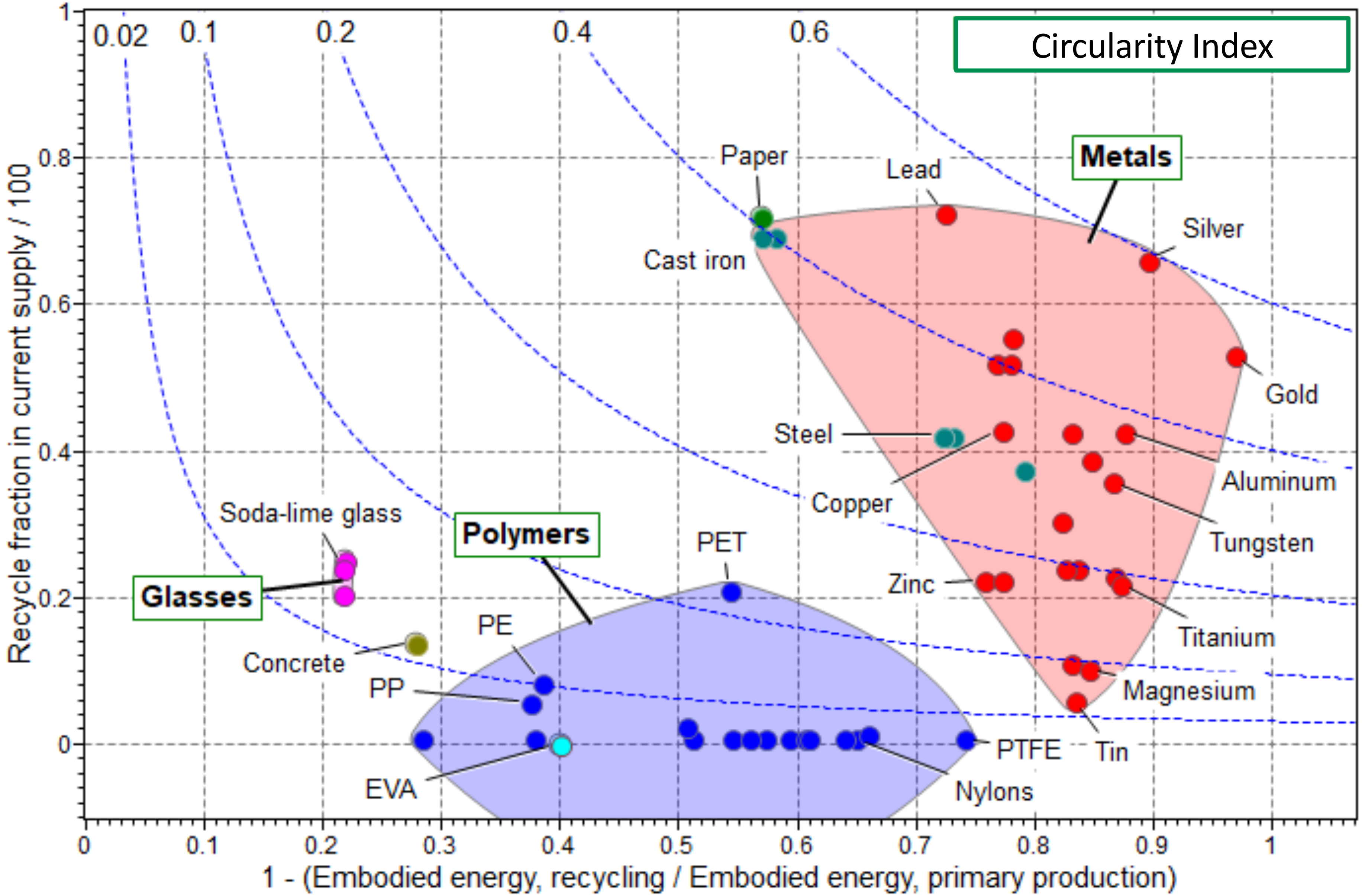
Circularity index for all materials



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A circular materials economy

- ★ **The circular economy is an aspirational ideal**
  Assessing the quantity and quality of material circularity shows we are still a long way from achieving circularity

- ★ **Recycling is not the only option**
  One needs to consider the energy input required for recycling (or down-cycling) for each material

- ★ **System resource maps are needed**
  Mapping energy and material flows across supply chains is important for assessing circular economy options

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