OPEN ACCESS

1st World Sustainability Forum
1-30 November 2011

www. wsforum.org

Article

Using transportation to assess optimal value chain configuration for minimal environmental impact

Benjamin McLellan [1,*]

[1] Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan.

E-Mails: b-mclellan@energy.kyoto-u.ac.jp

* Author to whom correspondence should be addressed; Tel.: +81-75-753-9173; Fax: +81-75-753-4745

Received: / Accepted: / Published:

Abstract: Transportation of feedstock, product and energy is key to forming the links in any supply chain. In terms of the overall environmental impact the transportation stages can also be a significant contributor. This paper examines the use of transportation to minimized environmental impacts of the supply chain, using the example of primary aluminium production from bauxite. A “radius of reduction” methodology is demonstrated using transport distance to balance the potential benefit of relocating production or utilising alternative facilities. This approach is shown to be a useful tool for supply chain planning, purchasing or sales strategy, and in a broader assessment of industry potential. The ability to reduce energy and emissions are shown to be highest, while the water usage and costs associated with a carbon tax are less avoidable through relocation.

Keywords: Life cycle; supply chain; environmental impact; energy; emissions; greenhouse gas;

---

1. Introduction

From the perspective of the supply chain, transportation is an integral and essential component that has implications for cost, efficiency and reliability of production. However, it is typically considered from the public nuisance or risk assessment perspectives rather than as an ideal opportunity for reduction of environmental impact. During the planning and design of operations in particular, transportation routes are frequently considered – for example, during an environmental impact assessment [1] – however, the transportation stage is not typically featured in an overall optimisation of the supply chain at the pre-construction phase except where cost is concerned. Furthermore, from the standpoint of environmental analysis, life cycle assessment (LCA) can include an amount of transportation for each contributing product or feedstock – however the opportunity to use this stage to reroute production between alternative facilities or to select a more appropriate site for key production units is not typically taken.

LCA has also been examined as a tool for improving environmental impacts of processes through integration in design [2-6]. Its use in decision-making has been highlighted in various industries, and applied to planning and design decisions [7-12]. Typically, the application of LCA in such situations has been as a measure of alternative process configurations, material inputs or pollution control technologies, and to identify the key areas of a product life cycle that should be the focus of impact reduction work.

The current study therefore takes a different approach in order to identify and optimise the location of each stage of the production process in order to minimise impacts and maximise benefits. This application of life cycle thinking offers a means of comparing life cycle routes that could be of benefit in the strategic planning of a value chain, or in the design of a vertically integrated operation.

The approach applies a "radius of reduction" that indicates how far a material or component can be transported between stages of the production cycle in order to benefit from cleaner or more efficient production lines [13]. Taking the transportation stages as a key step between stages in the value chain, we demonstrate that it is possible to utilise the radius of reduction to select a "best option" for siting geographically dispersed operations. Furthermore, transport stages in the life cycle can be critical in determining the overall benefit of alternative processing options, as they can contribute as much as some fixed operations in the life cycle (for example mining of iron ore contributes less than the transportation of that ore to steelmaking operations around the world [14]). The minerals production cycle for aluminium is used in this study as an example of the application of this technique.

2. Methods

This study examines the potential for utilising transportation to optimise the location of production to minimise environmental impact and maximise economic benefit. The approach is applied to the two following scenarios:

1. The mine operator / resource owner analyses the option to supply ore to the lowest impact production chain and to simultaneously examine whether a hypothetical onsite production chain (using local grid electricity) would be a better option
2. At the plant gate (refinery and smelter considered separately), operator analyses the option to reroute feedstock to produce elsewhere

The tool used for the comparisons is a "radius of reduction" [13] that indicates how far the product of one stage could be transported in order to reduce the impact of the remaining steps of the production cycle. This approach has previously been demonstrated at the level of international bulk minerals production cycles, whereas the current work seeks to examine its applicability to individual operations and supply chains.

Four levels of assessment are applied to each stage, in order to provide a more complete understanding of the benefits and impacts of alternative routes to production:

1. Energy reduction – processing efficiency
2. Energy emissions reduction – processing specific emissions
3. Energy impact reduction – water usage
4. Cost reduction – Carbon tax avoidance

Energy is the focus of the assessment, due to its significant implications for local and global environmental impact. From the perspective of energy use in the life cycle of a product, the primary energy usage for the life cycle (embodied energy) is often used as an overall indicator, and the efficiency or specific energy usage (per tonne output) is typically used for the individual units. Thus level 1 in the assessment calculates the radius of reduction for energy, based on the overall energy balance – i.e. how much transportation would be required to negate the energy saving of transporting the feedstock to an alternative plant location?

In level two, the emissions (specifically the greenhouse gas (GHG) emissions) are utilised to calculate the maximum distance that the feedstock could be transported to provide an overall reduction – either by utilising a lower emissions energy source or by production occurring at a facility with lower specific GHG per tonne of product. Level 3 applies the same process for water usage reduction – with the slight variation in that to apply this methodology for water the embodied water of transport (largely fuel production-associated) is utilised. As described below, this is a useful aspect of LCA data that can make the current approach widely applicable. Level 4 is particularly significant in the case study that uses data from Australian aluminium production. This final step utilises the methodology to examine the potential for reducing cost by avoiding carbon tax – or conversely, the minimum threshold at which it becomes attractive to move production elsewhere in order to benefit from lower carbon taxation. The cost figures are all in Australian dollars, with carbon tax as proposed by the Australian government. Although this exploratory work takes a limited set of indicators, the approach could perceivably be expanded to incorporate more impact categories – possibly with the aid of multi-criteria optimisation methods [15].

2.1 Radius of reduction

The "radius of reduction" (hereafter RR) [13] is introduced here as one tool for analysing the potential to reduce life cycle energy, emissions or other metrics by transporting the material elsewhere for processing. Inside this radius, overall energy usage or emissions may be reduced for a given original and final energy mix, while outside the RR the emissions from transportation will negate the benefit of processing elsewhere.

To determine the RR, we make the transport emissions (or energy, water, cost) equivalent to the difference in processing emissions for the given process stage at the initial (1) or final location (2). Rearranging gives the RR as per the example below for energy RR for aluminium smelting (see Table 1 for nomenclature):

$$RR_{E2} = \frac{(E_{Al})_2 - (E_{Al})_1}{M_{Al2O3} TE_{Al2O3}} \quad (1)$$

The RR is considered to be a useful tool because it gives a physically comparable indicator (distance in km), which can be produced and directly compared for multiple unrelated metrics. In application, this is similar to the ecological footprint concept [16-18] which equates various functions of the surface area of the globe into "global hectares". An RR can be calculated for any sustainability metric – as long as transportation impacts also register on the given metric. LCA is particularly useful from the environmental perspective, as the results of a fuel cycle analysis or LCA of a transportation mode can be utilised to link transportation to many impact categories that may not be directly significant. For example in the current assessment this is demonstrated with the water metric that is linked back to the water for extraction and processing of oil to fuel.

General RR equations, nomenclature and the values for key parameters that were used in the assessment are presented for each of the levels of assessment and the two scenarios: Level 1 (energy) Table 1; Level 2 (emissions) Table 2; Level 3 (water usage) Table 3; Level 4 (carbon tax avoidance) Table 4.

2.2 Case study description

The chosen case study to use as a demonstration of the proposed approach was the production of aluminium from bauxite in Australia. The case study is considered to be a useful example because there is available energy and emissions data reported by at least 3 mines, refineries and smelters in Australia and the International Aluminium Institute (IAI) has also reported global average LCA data for the aluminium industry [19] which is used for comparison.

Data for the assessment of specific mining and minerals processing operations were obtained from sustainability reports available online from major bauxite-alumina-aluminium operators:

- BHP Billiton: [20]
- Rio Tinto-Alcan: [21,22]
- Alcoa: [23]

General global average energy usage and emissions data were obtained from the IAI Life Cycle Assessment [19] and transport data were obtained from assessment elsewhere [13,24]. A basis year of 2010 was taken as a preference however in the case of Alcoa [23] and the IAI [19] this year was unavailable and the nearest alternative was taken – this is not expected to significantly affect the data quality or results.

Another advantage of using the aluminium production chain in Australia is that there are refineries and smelters based on significantly different primary energy source mixes – for instance, hydropower in Tasmania, natural gas in the Northern Territory, brown coal in Victoria and black coal in Queensland. This gives a wide scope for examining the potential for relocation of production. Furthermore, the production of primary materials is of great significance in a global society that suffers from distinct inequality in distribution of natural and human resources. Bauxite reserves are reasonably common but the largest reserves are highly centralised in a few countries [25].

Table 1. Nomenclature, equations and values for specific energy assessment (Level 1)

<table>
<tr><td></td><td colspan="16">Life cycle stages</td></tr>
<tr><td></td><td colspan="4">Mining</td><td colspan="2">Transport of bauxite
(RR_{E1})</td><td colspan="4">Refining</td><td colspan="2">Transport of Al_2O_3
(RR_{E2})</td><td colspan="4">Smelting</td></tr>
<tr><td rowspan="4">1. Energy</td><td colspan="4">M_{Bx} x E_{Bx}
5.3 x E_{Bx}</td><td colspan="2">M_{Bx} x TE_{Bx} x D_{Bx}
5.3 x TE_{Bx} x RR_1</td><td colspan="4">M_{Al2O3} x E_{Al2O3}
1.92 x E_{Al2O3}</td><td colspan="2">M_{Al2O3} x TE_{Al2O3} x D_{Al2O3}
1.92 x TE_{Al2O3} x D_{Al2O3}</td><td colspan="4">M_{Al} x E_{Al}
E_{Al}</td></tr>
<tr><td colspan="4">E_{Bx}
(GJ / t Bx)</td><td colspan="2">TE_{Bx}
(GJ / ntk)</td><td colspan="4">E_{Al2O3}
(GJ / t Al_2O_3)</td><td colspan="2">TE_{Al2O3}
(GJ / ntk)</td><td colspan="4">E_{Al}
(GJ / t Al)</td></tr>
<tr><td>M_1</td><td>M_2</td><td>M_3</td><td>M_G</td><td>Ship</td><td>Rail</td><td>R_1</td><td>R_2</td><td>R_3</td><td>R_G</td><td>Ship</td><td>Rail</td><td>S_1</td><td>S_2</td><td>S_3</td><td>S_G</td></tr>
<tr><td>0.1</td><td>0.1</td><td>0.04</td><td>0.07</td><td>1.7×10^{-4}</td><td>2.5×10^{-4}</td><td>10.8</td><td>9.7</td><td>10.7</td><td>12</td><td>1.7×10^{-4}</td><td>2.5×10^{-4}</td><td>70.3</td><td>74.3</td><td>55.8</td><td>55</td></tr>
<tr><td>*Equations for RR*</td><td colspan="10">$$RR_{E1} = \frac{(M_{Al2O3}E_{Al2O3} + M_{Al2O3}TE_{Al2O3}D_{Al2O3} + E_{Al})_2 - (M_{Al2O3}E_{Al2O3} + M_{Al2O3}TE_{Al2O3}D_{Al2O3} + E_{Al})_1}{M_{Bx}TE_{Bx}}$$</td><td colspan="6">$$RR_{E2} = \frac{(E_{Al})_2 - (E_{Al})_1}{M_{Al2O3}TE_{Al2O3}}$$</td></tr>
<tr><td>*Where:*</td><td colspan="16">Subscripts: Bx = bauxite; Al = aluminium; Al_2O_3 = alumina;
M_1, M_2, M_3 = mine 1-3 respectively; R_1, R_2, R_3 = refinery 1-3 respectively; S_1, S_2, S_3 = smelter 1-3 respectively;
M_G, R_G, S_G = global average data for bauxite mining, refining and smelting respectively;
D_{Bx}, D_{Al2O3} = distance of transportation of bauxite or alumina respectively;
M_{Bx}, M_{Al2O3}, M_{Al} = mass of bauxite, alumina and aluminium respectively;
E = energy usage
TE = transportation energy usage
RR_{E1} = radius of reduction for energy for refinery-smelter and intermediate transportation
RR_{E2} = radius of reduction for energy for smelter</td></tr>
</table>

Table 2. nomenclature, equations and values for emissions assessment (Level 2)

	Life cycle stages															
	Mining				Transport of bauxite (RR_1)		Refining				Transport of Al_2O_3 (RR_2)		Smelting			
2. Greenhouse emissions	M_{Bx} x Em_{Bx} 5.3 x E_{Bx}				M_{Bx} x TEm_{Bx} x D_{Bx} 5.3 x TEm_{Bx} x RR_1		M_{Al2O3} x Em_{Al2O3} 1.92 x Em_{Al2O3}				M_{Al2O3} x TEm_{Al2O3} x D_{Al2O3} 1.92 x TEm_{Al2O3} x D_{Al2O3}		M_{Al} x Em_{Al} 1 x Em_{Al}			
	Em_{Bx} (t CO_2 / t Bx)				TEm_{Bx} (t CO_2 / ntk)		Em_{Al2O3} (t CO_2 / t Al_2O_3)				TEm_{Al2O3} (t CO_2 / ntk)		Em_{Al} (t CO_2 / t Al)			
	M_1	M_2	M_3	M_G	Ship	Rail	R_1	R_2	R_3	R_G	Ship	Rail	S_1	S_2	S_3	S_G
	0.01	0.01	0.004	0.006	2.1×10^{-5}	6.2×10^{-6}	0.78	0.74	0.55	0.86	2.1×10^{-5}	6.2×10^{-6}	15.1	6.1	20.1	7.7
Equations for RR	$RR_{Em1} = \frac{(M_{Al2O3}Em_{Al2O3} + M_{Al2O3}TEm_{Al2O3}D_{Al2O3} + Em_{Al})_2 - (M_{Al2O3}Em_{Al2O3} + M_{Al2O3}TEm_{Al2O3}D_{Al2O3} + Em_{Al})_1}{M_{Bx}TEm_{Bx}}$										$RR_{Em2} = \frac{(Em_{Al})_2 - (Em_{Al})_1}{M_{Al2O3}TEm_{Al2O3}}$					
Where:	<u>Subscripts:</u> Bx = bauxite; Al = aluminium; Al_2O_3 = alumina; M_1, M_2, M_3 = mine 1-3 respectively; R_1, R_2, R_3 = refinery 1-3 respectively; S_1, S_2, S_3 = smelter 1-3 respectively; M_G, R_G, S_G = global average data for bauxite mining, refining and smelting respectively; D_{Bx}, D_{Al2O3} = distance of transportation of bauxite or alumina respectively; M_{Bx}, M_{Al2O3}, M_{Al} = mass of bauxite, alumina and aluminium respectively; Em = emissions of greenhouse gases TEm = transportation emissions of greenhouse gases RR_{Em1} = radius of reduction for emissions for refinery-smelter and intermediate transportation RR_{Em2} = radius of reduction for emissions for smelter															

Table 3. nomenclature, equations and values for embodied water assessment (Level 3)

	Life cycle stages															
	Mining				Transport of bauxite (RR_1)		Refining				Transport of Al_2O_3 (RR_2)		Smelting			
3. Embodied water	M_{Bx} x W_{Bx} 5.3 x W_{Bx}				M_{Bx} x TW_{Bx} x D_{Bx} 5.3 x TW_{Bx} x RR_1		M_{Al2O3} x W_{Al2O3} 1.92 x W_{Al2O3}				M_{Al2O3} x TW_{Al2O3} x D_{Al2O3} 1.92 x TW_{Al2O3} x D_{Al2O3}		M_{Al} x W_{Al} W_{Al}			
	W_{Bx} (kL / t Bx)				TW_{Bx} (kL / ntk)		W_{Al2O3} (kL / t Al_2O_3)				TW_{Al2O3} (kL / ntk)		W_{Al} (kL / t Al)			
	M_1	M_2	M_3	M_G	Ship	Rail	R_1	R_2	R_3	R_G	Ship	Rail	S_1	S_2	S_3	S_G
	1.02	1.02	0.03	0.49	1.8×10^{-4}	8.3×10^{-4}	3.22	3.51	2.02	7.92	1.8×10^{-4}	8.3×10^{-4}	1.08	0.8	1.10	1.00
Equations for RR	$RR_{W1} = \frac{(M_{Al2O3}W_{Al2O3} + M_{Al2O3}TW_{Al2O3}D_{Al2O3} + W_{Al})_2 - (M_{Al2O3}W_{Al2O3} + M_{Al2O3}TW_{Al2O3}D_{Al2O3} + W_{Al})_1}{M_{Bx}TW_{Bx}}$										$RR_{W2} = \frac{(W_{Al})_2 - (W_{Al})_1}{M_{Al2O3}TW_{Al2O3}}$					
Where:	Subscripts: Bx = bauxite; Al = aluminium; Al_2O_3 = alumina; M_1, M_2, M_3 = mine 1-3 respectively; R_1, R_2, R_3 = refinery 1-3 respectively; S_1, S_2, S_3 = smelter 1-3 respectively; M_G, R_G, S_G = global average data for bauxite mining, refining and smelting respectively; D_{Bx}, D_{Al2O3} = distance of transportation of bauxite or alumina respectively; M_{Bx}, M_{Al2O3}, M_{Al} = mass of bauxite, alumina and aluminium respectively; W = water usage TW = transportation embodied water RR_{W1} = radius of reduction for water for refinery-smelter and intermediate transportation RR_{W2} = radius of reduction for water for smelter															

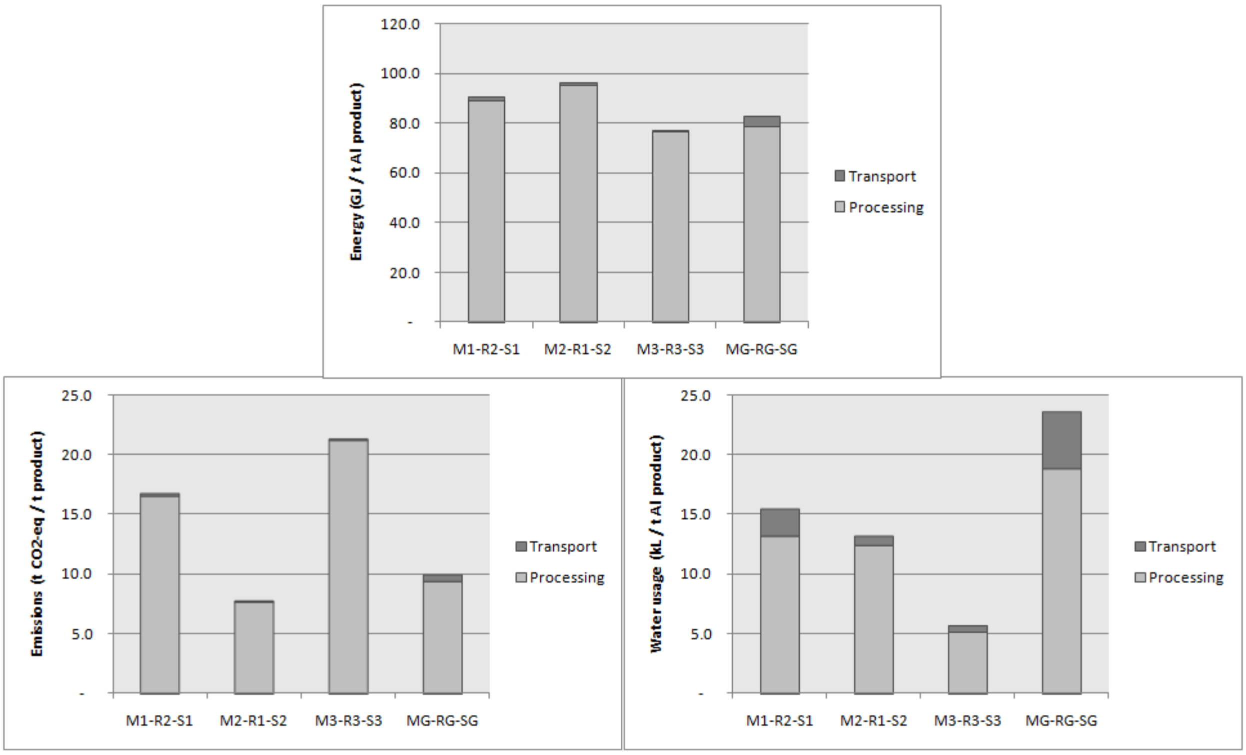
Table 4. nomenclature, equations and values for carbon tax assessment (Level 4)

	Life cycle stages																
	Mining				Transport of bauxite (RR_1)		Refining				Transport of Al_2O_3 (RR_2)		Smelting				
4. Carbon tax avoidance	M_{Bx} x C_{Bx} 5.3 x C_{Bx}				M_{Bx} x TC_{Bx} x D_{Bx} 5.3 x TC_{Bx} x RR_1		M_{Al2O3} x C_{Al2O3} 1.92 x C_{Al2O3}				M_{Al2O3} x TC_{Al2O3} x D_{Al2O3} 1.92 x TC_{Al2O3} x D_{Al2O3}		M_{Al} x C_{Al} C_{Al}				
	C_{Bx} ($ / t Bx)				TC_{Bx} ($ / ntk)		C_{Al2O3} ($ / t Al_2O_3)				TC_{Al2O3} ($ / ntk)		C_{Al} ($ / t Al)				
	M_1	M_2	M_3	M_G	Ship	Rail	R_1	R_2	R_3	R_G	Ship	Rail	S_1	S_2	S_3	S_G	
	0.3	0.3	0.1	0.1	0.02	0.03	17.9	17.0	12.6	19.8	0.02	0.03	346.2	140.8	462.4	176.5	
Equations for RR	$RR_{C1} = \frac{(M_{Al2O3}C_{Al2O3} + M_{Al2O3}TC_{Al2O3}D_{Al2O3} + C_{Al})_2 - (M_{Al2O3}C_{Al2O3} + M_{Al2O3}TC_{Al2O3}D_{Al2O3} + C_{Al})_1}{M_{Bx}TC_{Bx}}$										$RR_{C2} = \frac{(C_{Al})_2 - (C_{Al})_1}{M_{Al2O3}TC_{Al2O3}}$						
Where:	Subscripts: Bx = bauxite; Al = aluminium; Al_2O_3 = alumina; M_1, M_2, M_3 = mine 1-3 respectively; R_1, R_2, R_3 = refinery 1-3 respectively; S_1, S_2, S_3 = smelter 1-3 respectively; M_G, R_G, S_G = global average data for bauxite mining, refining and smelting respectively; D_{Bx}, D_{Al2O3} = distance of transportation of bauxite or alumina respectively; M_{Bx}, M_{Al2O3}, M_{Al} = mass of bauxite, alumina and aluminium respectively; C = cost of carbon tax TC = transportation cost RR_{C1} = radius of reduction for carbon tax avoidance for refinery-smelter and intermediate transportation RR_{C2} = radius of reduction for carbon tax avoidance for smelter																

3. Results

Results are presented here firstly for scenario 1 and then for scenario 2. In order to better frame the results of the RR assessment, the existing supply chain emissions, energy usage and water usage are presented in Figure 1. It is apparent that the global average case (MG-RG-SG) involves a significantly higher amount of transportation than the local Australian supply chains – largely due to the distance between bauxite / alumina production and smelters. No single existing supply chain performs best on all categories.

Figure 1. Value of indicators for total processing and transportation via existing routes



Expanding from the existing supply chains to all the alternative supply chains (ignoring company boundaries and current capacity constraints) the potential emissions for all routes are presented in Figure 2. In this figure, the potential for refining and smelting to occur at a theoretical production chain built at the mine site is also considered – using grid electricity and either natural gas (low case) or coal (high case) to supply thermal energy in the process. The energy usage of the plant is assumed to be the global average according to the IAI [19]. Transportation from the mine site is not included so as to allow direct comparison with the RR results in Figure 3.

Figure 2. Greenhouse gas emissions from alternative production routes - existing facilities and alternative theoretical onsite production

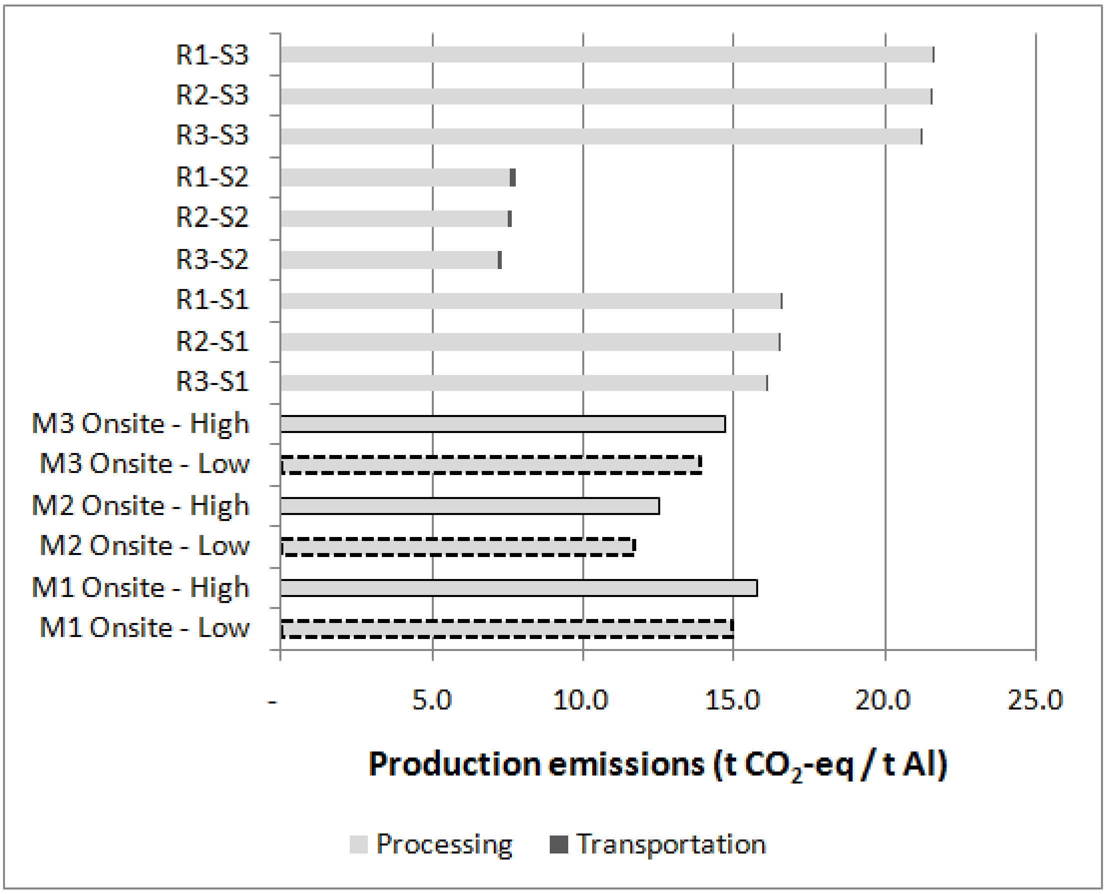


Figure 3. Radius of reduction for energy for existing operational alternatives

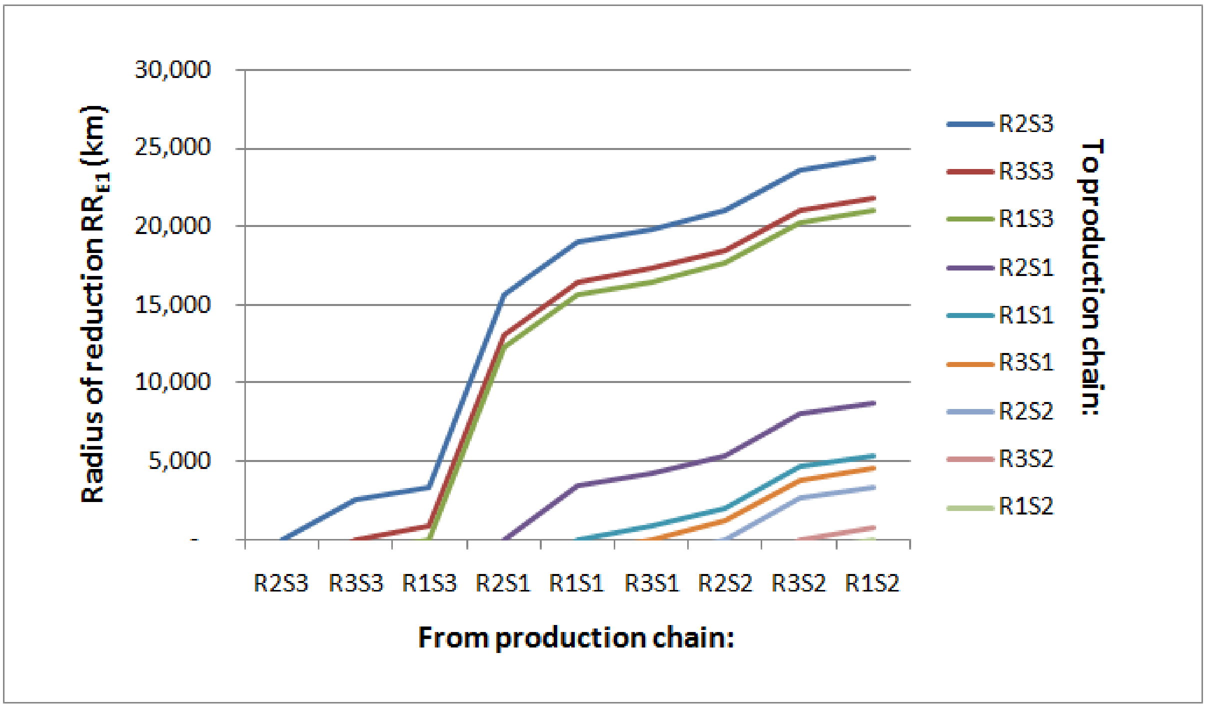


Figure 2 indicates that some potential reduction in emissions would be possible from onsite processing of bauxite to aluminium but that the most significant reductions would likely be achieved through utilizing smelter 2 (S2). Applying the RR approach shows the magnitude of this potential. Figure 3 and Figure 4 present the RR for energy and water respectively for the existing operational alternatives. The significance of the large energy usage of smelters compared to refineries is apparent in Figure 3, leading to smelter 3 (S3) being of highest potential for relocated production in terms of efficiency. Conversely, Figure 4 shows that the refinery usage of water is of highest impact, with refinery R3's low water usage leading to its preferability – although the RR is significantly lower for water than for energy.

Figure 4. Radius of reduction for water for existing operational alternatives

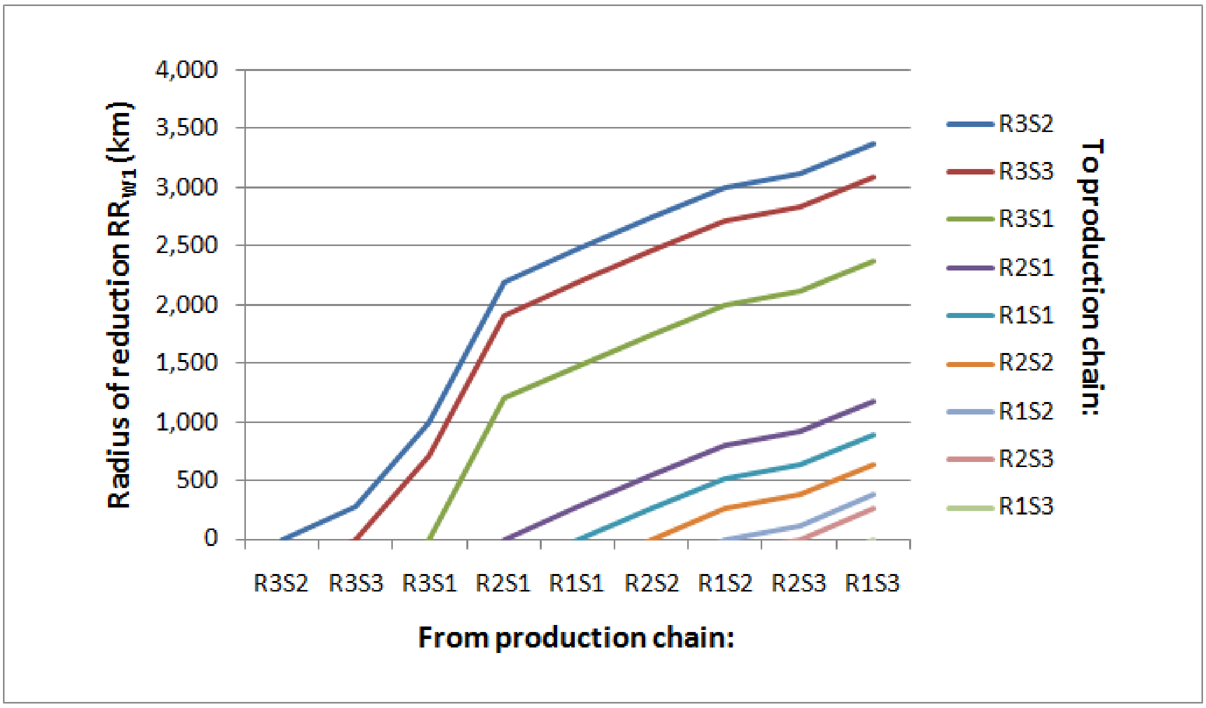
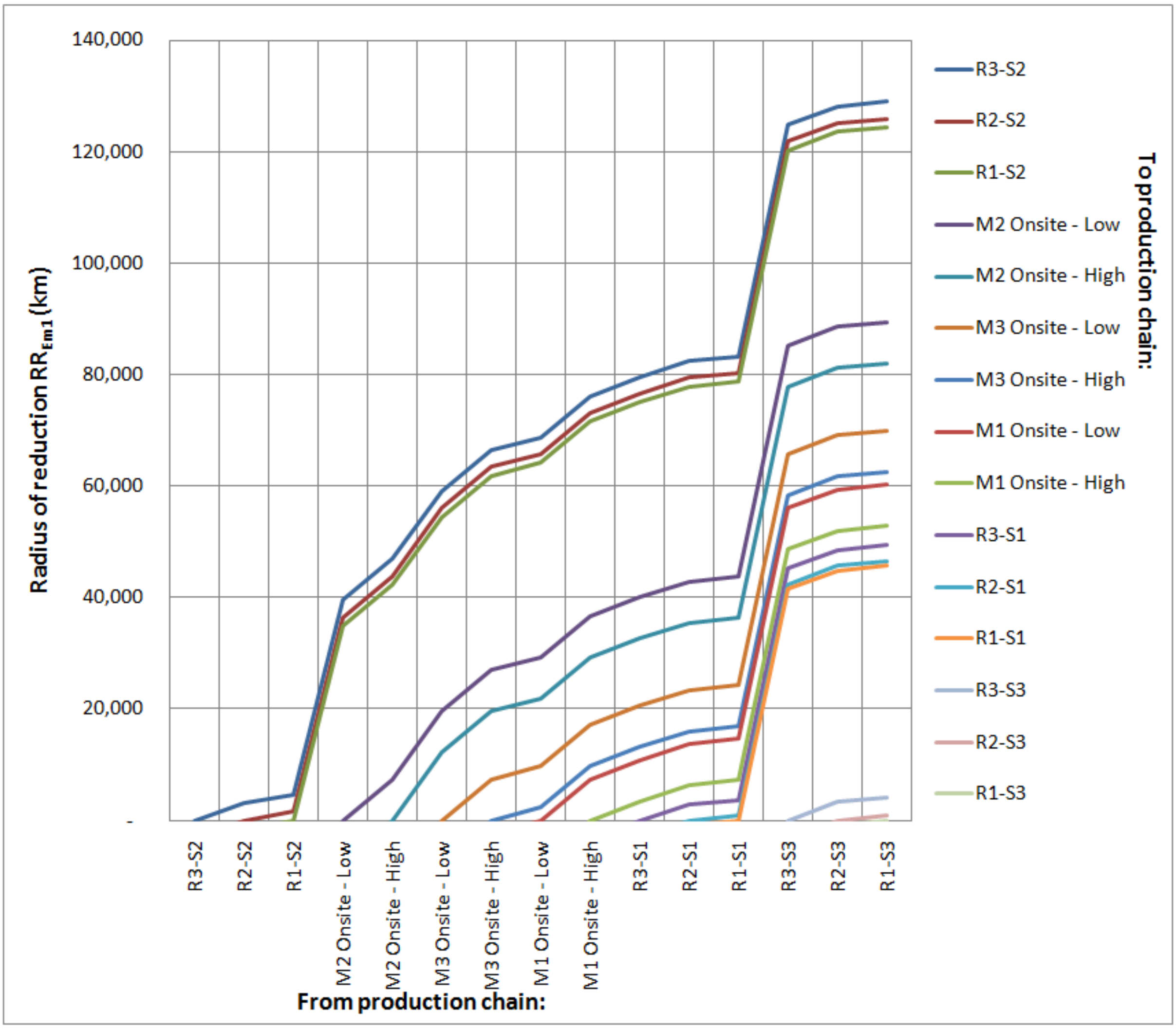


Figure 5 presents the RR for emissions for existing operational configurations and the alternatives of onsite processing. (Onsite processing is shown here as it becomes a useable comparison when the differences in emissions for production of grid electricity are included). It indicates that the RR for most alternative supply chains would be more than sufficient to enable processing at S2 – no matter where it was located in the world. The onsite processing options have some merit whereas smelters S1 and S3 would not be useful for reducing emissions.

Figure 5. Radius of reduction for emissions for alternative production chains



In regards to the particularly topical issue of a carbon tax, Figure 6 shows the current supply chain estimated carbon tax liability (based on the opening Australian carbon price of $23 / t CO_2-eq) and current cost of intermediate transportation. The figure indicates that the carbon tax liability in most cases (domestically) outweighs the currently incurred transportation cost. Figure 7 indicates that the potential for reducing supply chain costs by relocating production at this rate of carbon taxation is minimal – certainly much lower than the RR for emissions or energy. This means that the potential to take production offshore due to carbon tax-induced financial constraints is not particularly attractive.

Figure 6. Carbon tax and intermediate transportation cost comparison for existing supply chains

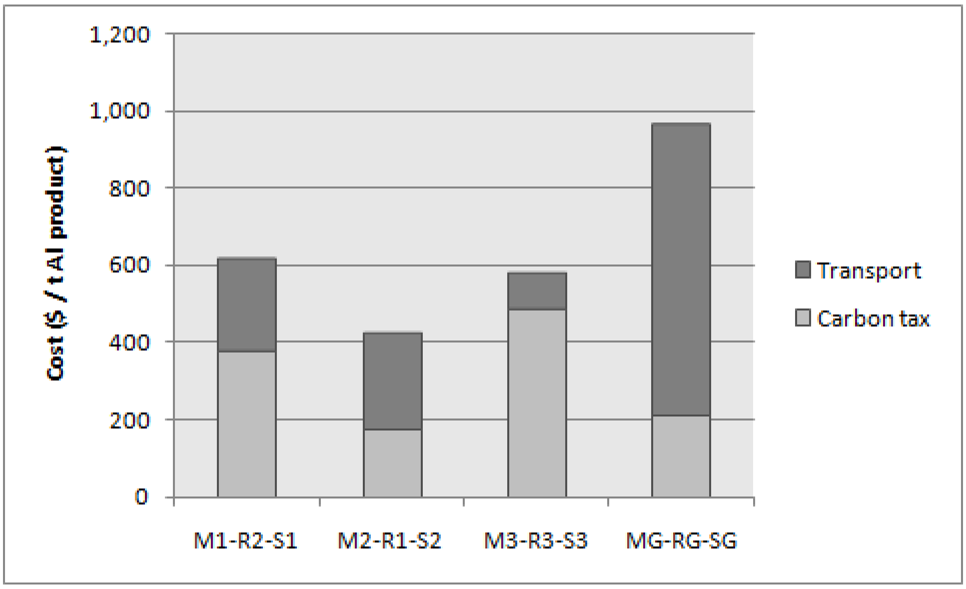
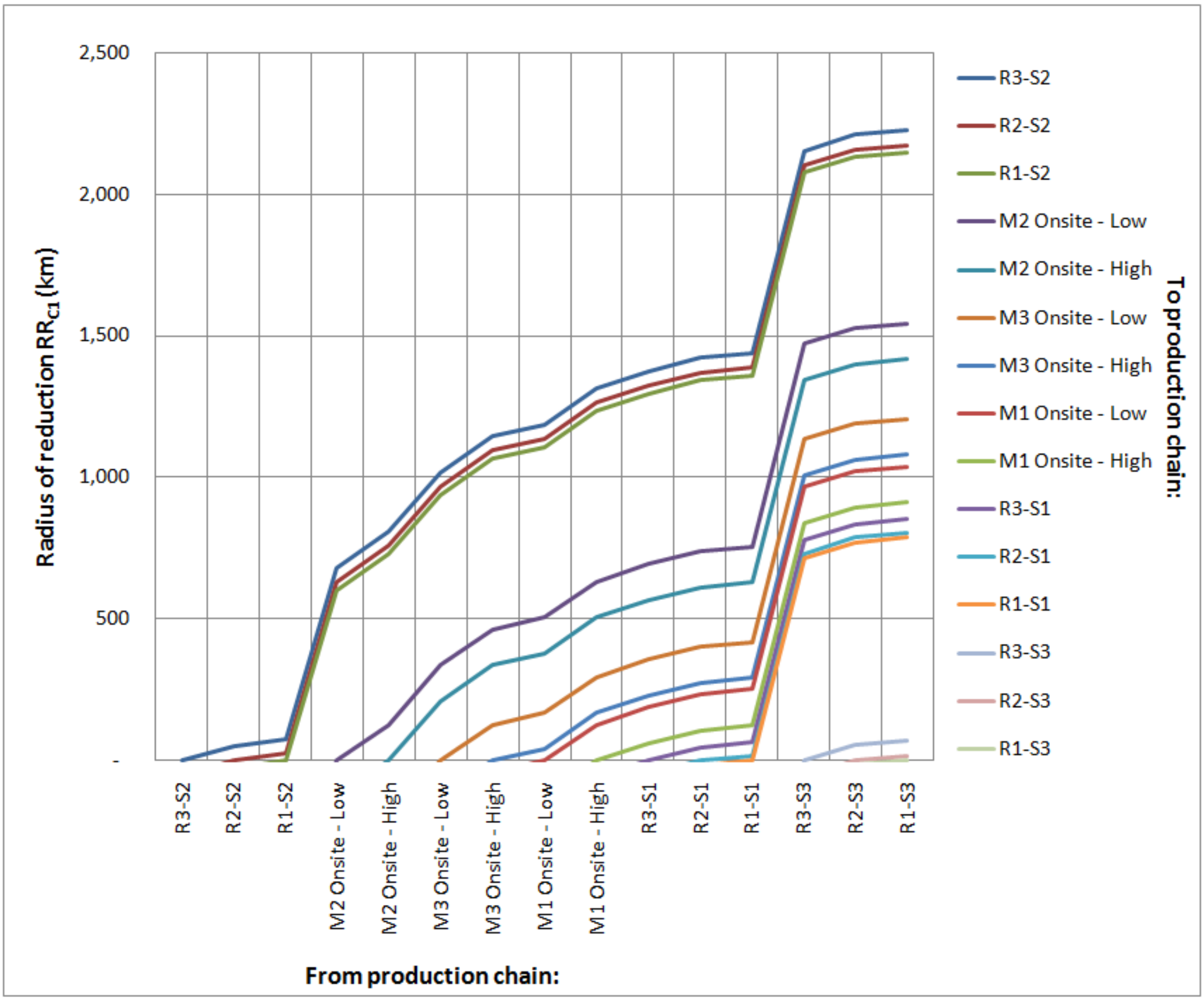


Figure 7. radius of reduction for avoidance of carbon tax for alternative supply chains



For the second scenario – in which the operator of a refinery or smelter considers the possibility of rerouting their feedstock to an alternative (lower impact) plant – the radii of reduction are shown in Table 5 (a) – (h). In all cases except for water usage, the smelters have the largest impact, and therefore the largest radius of reduction. When compared to the actual distance between operations (estimated using a “great circle” calculation) (see Table 6 for distances), it is apparent that only in a small number of cases is the radius of reduction greater than the actual distance between operations. The major exception is in the reduction of emissions from smelting, in which case the RR is great enough to allow transportation to anywhere in the world.

Table 5. Radii of reduction for the second scenario for refining and smelting (Where RR > Actual distance shown in bold)

(a) RR_{E2} Refining

Energy		From			
		R1	**R2**	**R3**	**RG**
To	**R1**		Best		2,762
	R2	2,493		**2,298**	5,256
	R3	195			2,958
	RG			Worst	

(b) RR_{E2} Smelting

Energy		From			
		S1	**S2**	**S3**	**SG**
To	**S1**		12,547		Best
	S2	Worst			
	S3	**45,510**	**58,056**		
	SG	**48,143**	**60,689**	2,633	

(c) RR_{Em2} Refining

Emissions		From			
		R1	**R2**	**R3**	**RG**
To	**R1**			Best	1,389
	R2	669			2,058
	R3	**4,011**	3,342		5,400
	RG	Worst			

(d) RR_{Em2} Smelting

Emissions		From			
		S1	**S2**	**S3**	**SG**
To	**S1**		Best	**125,304**	
	S2	**221,365**		**346,670**	**38,547**
	S3			Worst	
	SG	**182,818**		**308,123**	

(e) RR_{W2} Refining

Water		From			
		R1	**R2**	**R3**	**RG**
To	**R1**		608	Best	9,718
	R2				9,110
	R3	2,479	3,087		12,197
	RG	Worst			

(f) RR_{W2} Smelting

Water		From			
		S1	**S2**	**S3**	**SG**
To	**S1**		Best	192	
	S2	713		**905**	594
	S3			Worst	
	SG	119		310	

(g) RR_{C2} Refining

Cost		From			
		R1	**R2**	**R3**	**RG**
To	**R1**			Best	24
	R2	12			36
	R3	69	58		93
	RG	Worst			

(h) RR_{C2} Smelting

Cost		From			
		S1	**S2**	**S3**	**SG**
To	**S1**		Best	**2,163**	
	S2	**3,820**		**5,983**	665
	S3			Worst	
	SG	3,155		5,318	

Table 6. Distance between existing operations

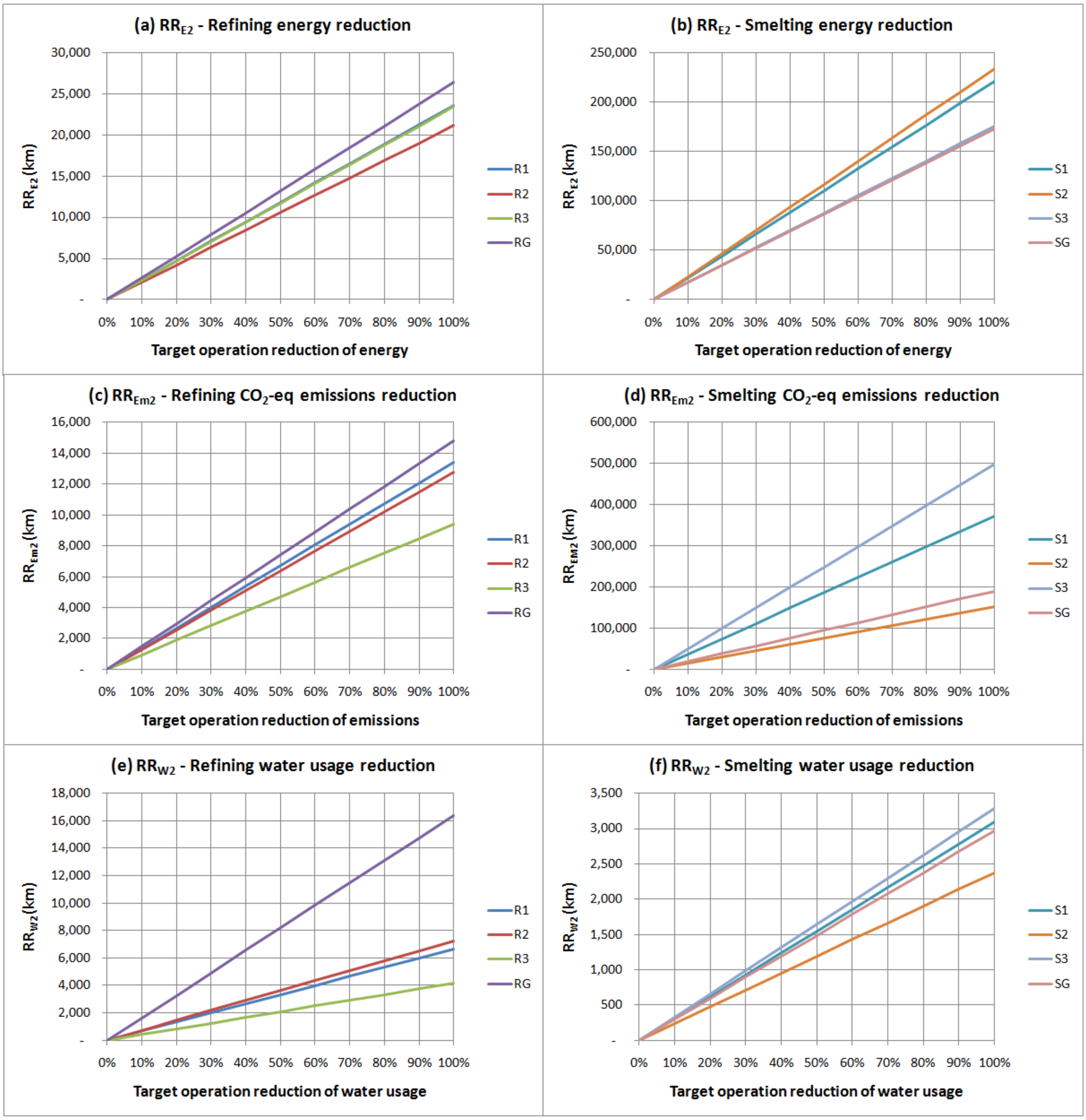
M1	M2	M3	R1	R2	R3	S1	S2	S3
M1	600	3500	600	1600	3500	2,500	4,600	4,700
	M2	3100	20	2000	3100	2,500	4,600	4,700
		M3	3100	3600	80	3600	2900	2700
			R1	2000	3100	2,500	4,600	4,700
				R2	3600	4	2,210	2,340
					R3	5,220	3,180	3,060
						S1	2000	1800
							S2	400
								S3

4. Discussion

The results of the radius of reduction assessment show that it is possible to identify both the preferred production chain and the realistic possibility of shifting production from a higher impact to a lower impact operation. In the above assessment, the magnitude of the difference between operations' impacts and the magnitude of the impact of transportation are the key determinants in identifying the optimal production chain. Furthermore, it identifies that onsite processing is not often the best alternative for a country reliant on fossil fuels for its energy supply. To further examine the potential for reduction, the RR approach is applied to each of the refineries and smelters to examine how far afield the feedstock could be shipped given theoretical reductions of impact up to 100%.

The graphs in Figure 8 show each of the radii of reduction for the indicators analysed – showing the relationship between the radius of reduction and the potential decrease in impact as a percentage of the current impact – for the case study refineries and smelters. Thus, to know the RR for moving alumina refining to obtain a 40% reduction in emissions we can read this off the chart moving from the x-axis to the y-axis for any of the refineries examined here. Or, if we alternatively, if we wish to know the required energy reduction to obtain a carbon neutral transfer of bauxite from one refinery to another (with a known distance between the locations), we can read from the y-axis to the x-axis. Furthermore, to know the RR for moving alumina refining between two current plants, we find the difference between the respective RR's at the 100% mark – the less positive the gradient, the lower the current refining impact (and therefore the more difficult it is to reduce impact by relocation).

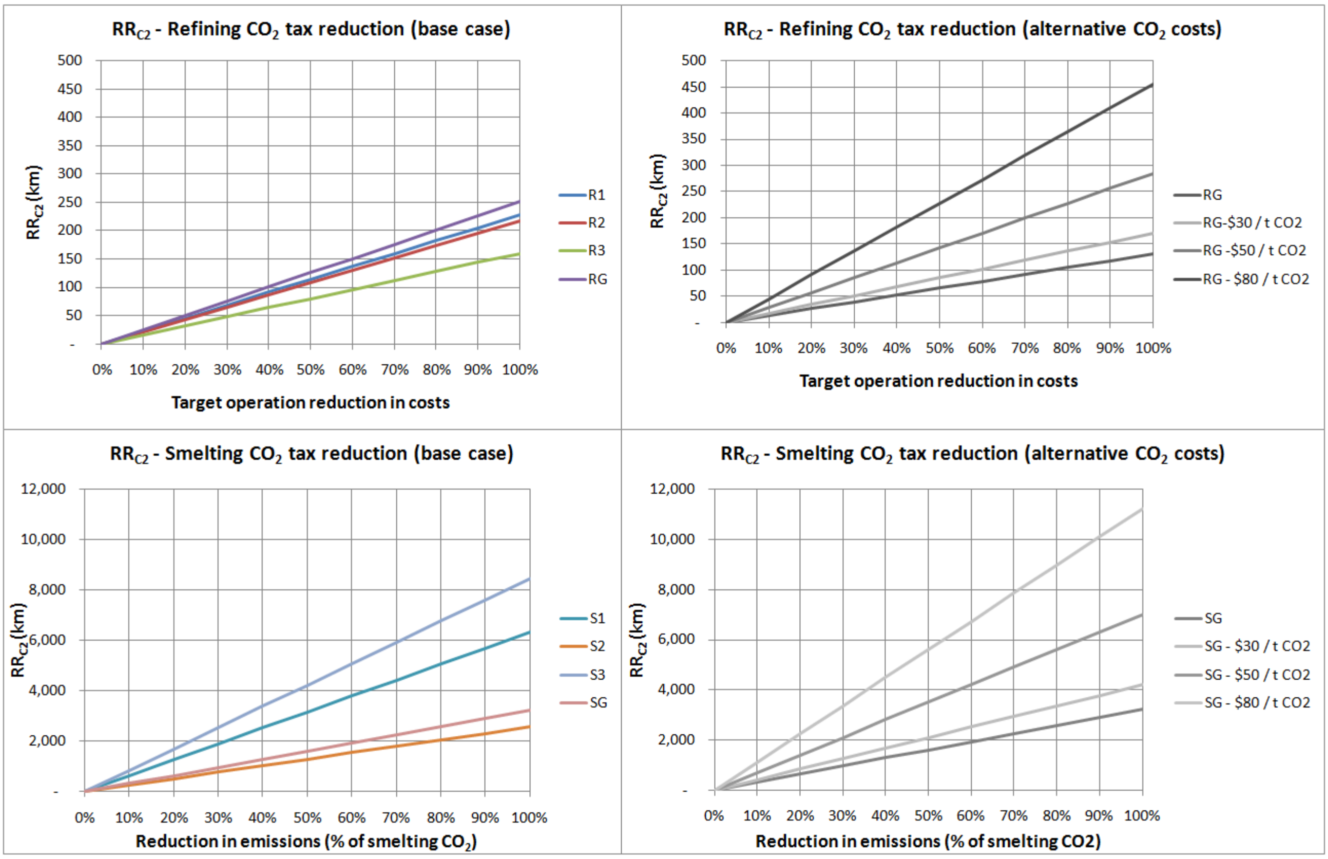
Figure 8. Radii of reduction (km) for energy, emissions and water usage at different levels of reduction (%) from base case



For smelting, water usage is again the lowest potential, whereas energy and emissions reduction could employ relocation to any global location. Likewise, in most cases water usage is the limiting factor for refining. This confirms the results of earlier assessment of the bauxite-aluminium supply chain on the international scale. The large RR for high levels of emissions reduction could be used to promote the opportunity for utilising renewable energy at operations in order to gain a competitive advantage. Aluminium and other non-ferrous metals are particularly well-placed to take advantage of renewable electricity, which could contribute significantly to reducing global minerals industry emissions [14].

Figure 9 illustrates the RR for reduction of carbon taxation liability by transporting bauxite or alumina from a refinery or smelter to an alternative, lower emissions facility. The current initial level of taxation will be \$23 per tonne of CO_2, but the RR for alternative higher tax rates(\$30, \$50 and \$80 per tonne CO_2) is also shown (for the general refinery and smelter, R_G and S_G). These graphs indicate that there is little incentive for companies to transfer their bauxite to alternative refineries – even at higher rates of taxation. In regards to smelting, there is fairly low domestic opportunity for carbon tax avoidance at the \$23 and \$30 rates, however an RR of 7,000km (at \$50 / t CO_2) would be sufficient to enable transfer of alumina to New Zealand (to utilise hydro electricity), and the higher rate of \$80 per tonne would be sufficient to make offshore processing in Norway, Iceland, Canada or Brazil attractive (as example low emissions countries [13] – although many non-carbon-taxing countries would become attractive within the maximum radius of 11,000km).

Figure 9. Radius of reduction and analysis of CO_2 Tax avoidance



The key premise that is demonstrated in this paper - that transport can be utilised to optimise life cycle impacts and benefits of production processes - could potentially be extended to the complete set of LCA results. The analysis of the life cycle can be undertaken in a stepwise fashion, to identify where the most appropriate location for each stage of the production cycle might be. Alternatively, a series of

RR contours may be plotted using GIS, so as to identify graphically whether there are any operations that could potentially contribute to reducing supply chain impacts.

There are of course additional, practical considerations that would stand in the way of operators selecting alternative production chains. Firstly, many of the existing production chains are vertically integrated operations owned in part or entirely by single large minerals corporations – they would be unlikely to accept feedstocks from outside their own company or send product to other company facilities. Furthermore, there is a constraint on the capacity of each individual facility – expansion may be possible, but this would need a period of years in order to complete a transfer of production from one site to another. Community and societal effects such as the loss or transfer of jobs are also important factors that might create a barrier to such a strategy.

Government or industry planning strategy may also apply this approach to quickly assess the implications and potential of alternative policy strategies. For instance, by legislating a carbon tax or an energy efficiency target, what is the potential for driving production offshore as a consequence.

One of the key limitations of the RR approach as it has been applied here is that it does not include intermodal transportation. This form of intermodal assessment would require an alternative or adapted approach, and might perceivably integrate pinch-type procedures [26,27]. The current form of the RR may be seen as a potentially useful initial selection or assessment tool rather, with detailed assessment of the supply chain being a later step in the process of route selection.

5. Conclusions

This paper demonstrates a new approach to identifying potentially more sustainable value chains. As a first-pass optimisation tool for the life cycle, the RR allows the selection of better routes for producing lower impact products using theoretical or existing value chain operations. One of the key advantages of this technique is that it allows the comparison of various sustainability impacts on a unified unitary basis. This technique may be made more readily applicable through development with GIS and potential use of pinch analysis procedures for intermodal transport applications.

In regards to reducing energy usage and emissions across the supply chain, there is demonstrated to be strong potential from the relocation of smelting domestically or internationally. In terms of water usage and avoiding the cost of a carbon tax, there is much less potential for improving supply chain impacts.

Conflict of Interest

The author declares no conflict of interest.

References

1. DIP, Guidelines for environmental impact statements under the integrated planning act 1997. In Department of infrastructure and Planning, Q.G., Ed. Queensland Government: Brisbane, 2007.
2. Azapagic, A., Life cycle assessment and its application to process selection, design and optimization. *Chemical Engineering Journal* **1999**, *73*, 1-21.
3. Azapagic, A.; Clift, R., Life cycle assessment and linear programming environmental optimisation of product system. *Computers & Chemical Engineering* **1995**, *19, Supplement 1*, 229-234.
4. Azapagic, A.; Clift, R., The application of life cycle assessment to process optimisation. *Computers & Chemical Engineering* **1999**, *23*, 1509-1526.
5. Stewart, M. Environmental life cycle considerations for design related decision making in minerals processing. PhD Thesis, University of Cape Town, Cape Town, 1999.
6. Stewart, M.; Petrie, J., Life cycle assessment for process design- the case of minerals processing. In *Clean technology for the mining industry*, Sanchez, M.; Vergara, F.; Castro, S., Eds. Concepcion, 1996.
7. Stewart, M.; Basson, L.; Alexander, B.; Petrie, J. In *Allied tools to lca in the process industries*, Second national conference on Life Cycle Assessment, Melbourne, Australia, 23-24 February, 2000; Melbourne, Australia, 2000.
8. Tsai, W.-H.; Lin, S.-J.; Liu, J.-Y.; Lin, W.-R.; Lee, K.-C., Incorporating life cycle assessments into building project decision-making: An energy consumption and co2 emission perspective. *Energy* **2011**, *36*, 3022-3029.
9. van Berkel, R. In *Life cycle assessment for environmental improvement of minerals' production*, 4th International and 25th National Minerals Council of Australia Environmental Workshop, Perth, 29 October - 2 November 2000, 2000; Perth, 2000; pp 501-514.
10. Vinodh, S.; Rathod, G., Integration of ecqfd and lca for sustainable product design. *Journal of Cleaner Production* **2010**, *18*, 833-842.
11. Zabalza Bribián, I.; Aranda Usón, A.; Scarpellini, S., Life cycle assessment in buildings: State-of-the-art and simplified lca methodology as a complement for building certification. *Building and Environment* **2009**, *44*, 2510-2520.
12. Sugiyama, H.; Hirao, M.; Mendivil, R.; Fischer, U.; Hungerbhler, K., A hierarchical activity model of chemical process design based on life cycle assessment. *Process Safety and Environmental Protection* **2006**, *00084*, 63-75.
13. McLellan, B.C., Optimizing location of bulk metallic minerals processing based on greenhouse gas avoidance. *Minerals* **2011**, *1*, 144-156.
14. McLellan, B.C.; Corder, G.D.; Giurco, D.P.; Ishihara, K.N., Renewable energy in the minerals industry: A review of global potential. *Journal of Cleaner Production* **2012**, *(Article in press)*.
15. Azapagic, A.; Clift, R., Life cycle assessment and multiobjective optimisation. *Journal of Cleaner Production* **1999**, *7*, 135-143.
16. Holmberg, J.; Lundqvist, U.; Robèrt, K.-H.; Wackernagel, M., The ecological footprint from a systems perspective of sustainability. *International Journal of Sustainable Development and World Ecology* **1999**, *6*, 17-33.
17. Robèrt, K.H.; Schmidt-Bleek, B.; Aloisi de Larderel, J.; Basile, G.; Jansen, J.L.; Kuehr, R.; Price Thomas, P.; Suzuki, M.; Hawken, P.; Wackernagel, M., Strategic sustainable development -- selection, design and synergies of applied tools. *Journal of Cleaner Production* **2002**, *10*, 197-214.
18. Wackernagel, M.; Moran, D.; White, S.; Murray, M., Ecological footprint accounts for advancing sustainability: Measuring human demands on nature. In *Sustainable development indicators in ecological economics*, Lawn, P., Ed. Edward Elgar Publishing Limited: Cheltenham, UK, 2006; pp 246-267.

19. IAI *Life cycle assessment of aluminium: Inventory data for the primary aluminium industry*; International Aluminium Institute: September, 2007.
20. BHP Billiton *2010 bhp billiton sustainability report*; BHP Billiton: Melbourne, 2010; p 54.
21. Rio Tinto Alcan *Bell bay 2010 sustainable development report*; Rio Tinto Alcan: George Town, Tasmania, 2010; p 36.
22. Rio Tinto Alcan *Gove 2010 sustainable development report*; Rio Tinto Alcan: Gove, Northern Territory, 2010; p 2.
23. Alcoa *Sustainability 09: Unlocking the solutions to sustainability*; Alcoa: Applecross, Western Australia, 2009; p 87.
24. Li, Y.; Corder, G.D.; McLellan, B.C., Transport in the minerals industry – contributions to greenhouse gas emissions and potential for mitigation. *Minerals Engineering* **2011**, *24*, 1430-1439.
25. USGS *Mineral commodity summaries 2010*; United States Geological Survey: Washington, January 26, 2010, 2010.
26. Kemp, I.C., *Pinch analysis and process integration*. 2nd ed.; Butterworth-Heinemann: London, 2007; p 396.
27. Tan, R.R.; Sum Ng, D.K.; Yee Foo, D.C., Pinch analysis approach to carbon-constrained planningfor sustainable power generation. *Journal of Cleaner Production* **2009**, *17*, 940-944.